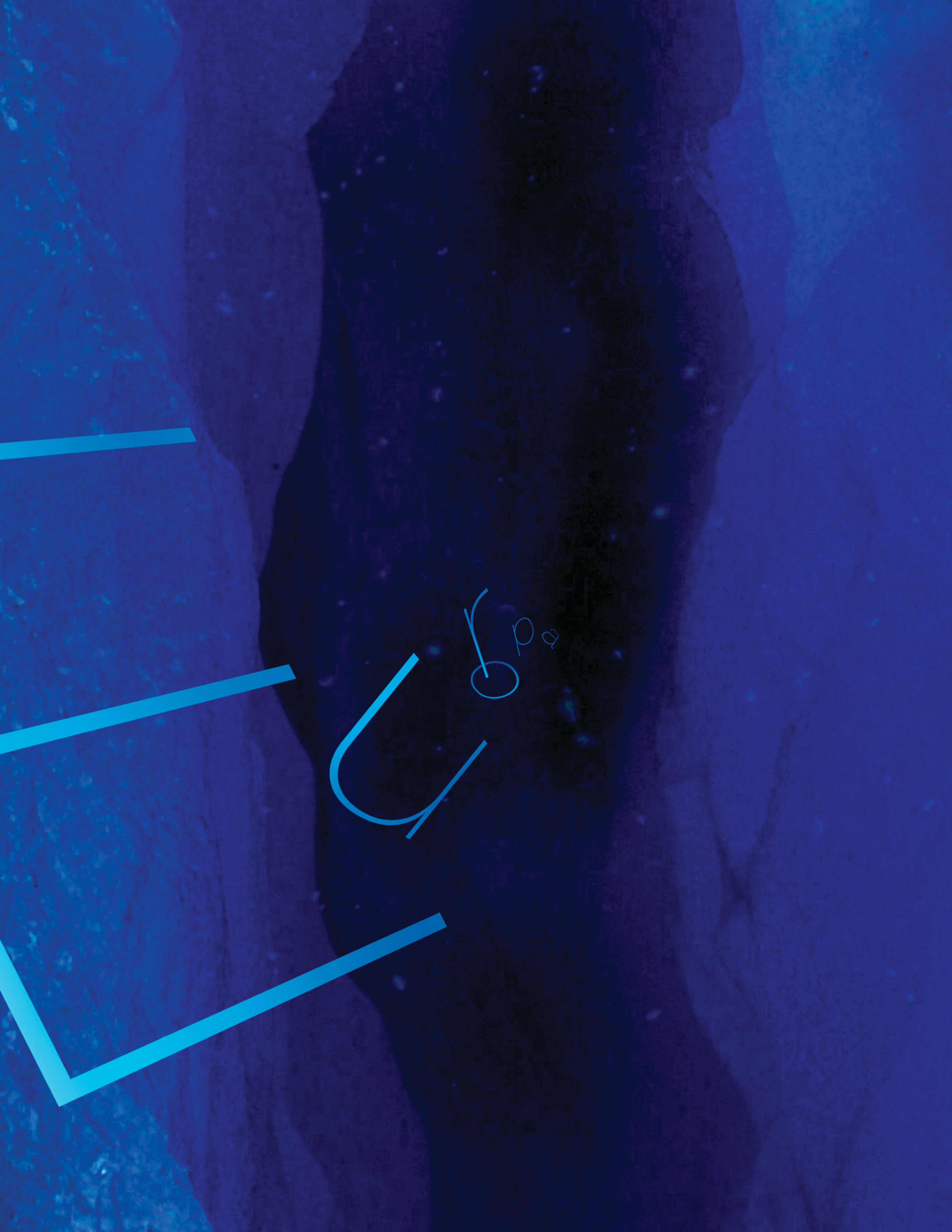
Jupiter Europa Orbiter

Jupiter Europa Orbiter Mission January 30, 2009 FINAL REPORT



Jupiter Europa Orbiter Mission Study 2008: Final Report

The NASA Element of the Europa Jupiter System Mission (EJSM)

Task Order #NMO710851

30 January 2009

Part of the research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Research described in this report was also carried out at the Applied Physics Laboratory, Johns Hopkins University and at the European Space Agency.

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and Caltech.

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30 January 2009

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A Joint NASA/ESA Endeavour

Europa Jupiter System Mission

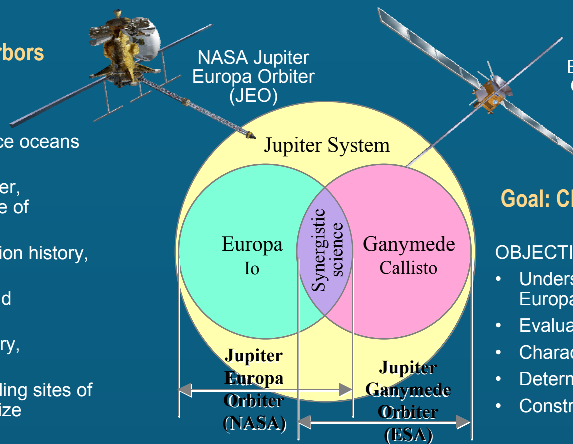
Science Theme: The emergence of habitable worlds around gas giants

A Future Mission Concept

Goal: Determine Whether the Jupiter System Harbors Habitable Worlds

OBJECTIVES:

- Characterize and determine the extent of sub-surface oceans and their relations to the deeper interior.
- Characterize the ice shells and any subsurface water, including the heterogeneity of the ice, and the nature of surface-ice-ocean exchange.
- Characterize the deep internal structure, differentiation history, and (for Ganymede) the intrinsic magnetic field.
- Compare the exospheres, plasma environments, and magnetospheric interactions.
- Determine global surface compositions and chemistry, especially as related to habitability.
- Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration.



Goal: Characterize the Processes Within the Jupiter System

OBJECTIVES:

- Understand the Jovian satellite system, especially as context for Europa and Ganymede.
- Evaluation the structure and dynamics of the Jovian atmosphere.
- Characterize processes the Jovian magnetodisk/magnetosphere.
- Determine the interactions occurring in the Jovian system.
- Constrain the origin of the Jupiter system.

Joint Jupiter Science Definition Team

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Two Flight Systems

- Independent launches allow flexibility in development cycles
- Highly capable instrumentation usable synergistically or independently
- Only JEO spends time in inner radiation belts
- Each flight system focuses on two of the four Galilean Satellites
- Enables full system coverage including Jupiter and its rings

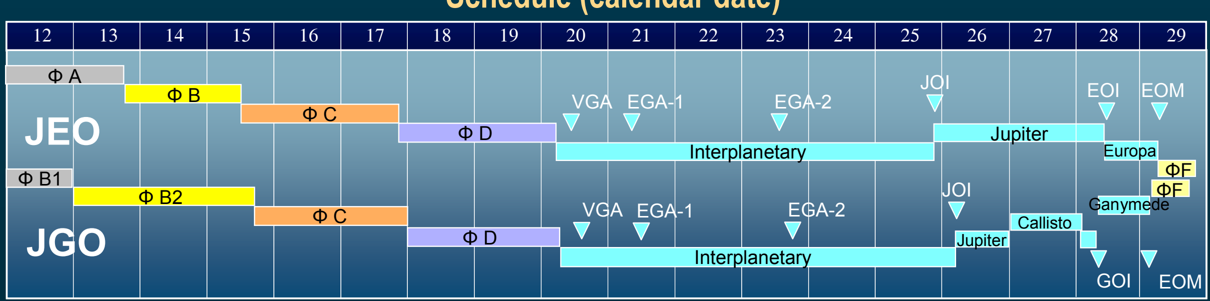
Jupiter Europa Orbiter (JEO)

Jupiter Ganymede Orbiter (JGO)

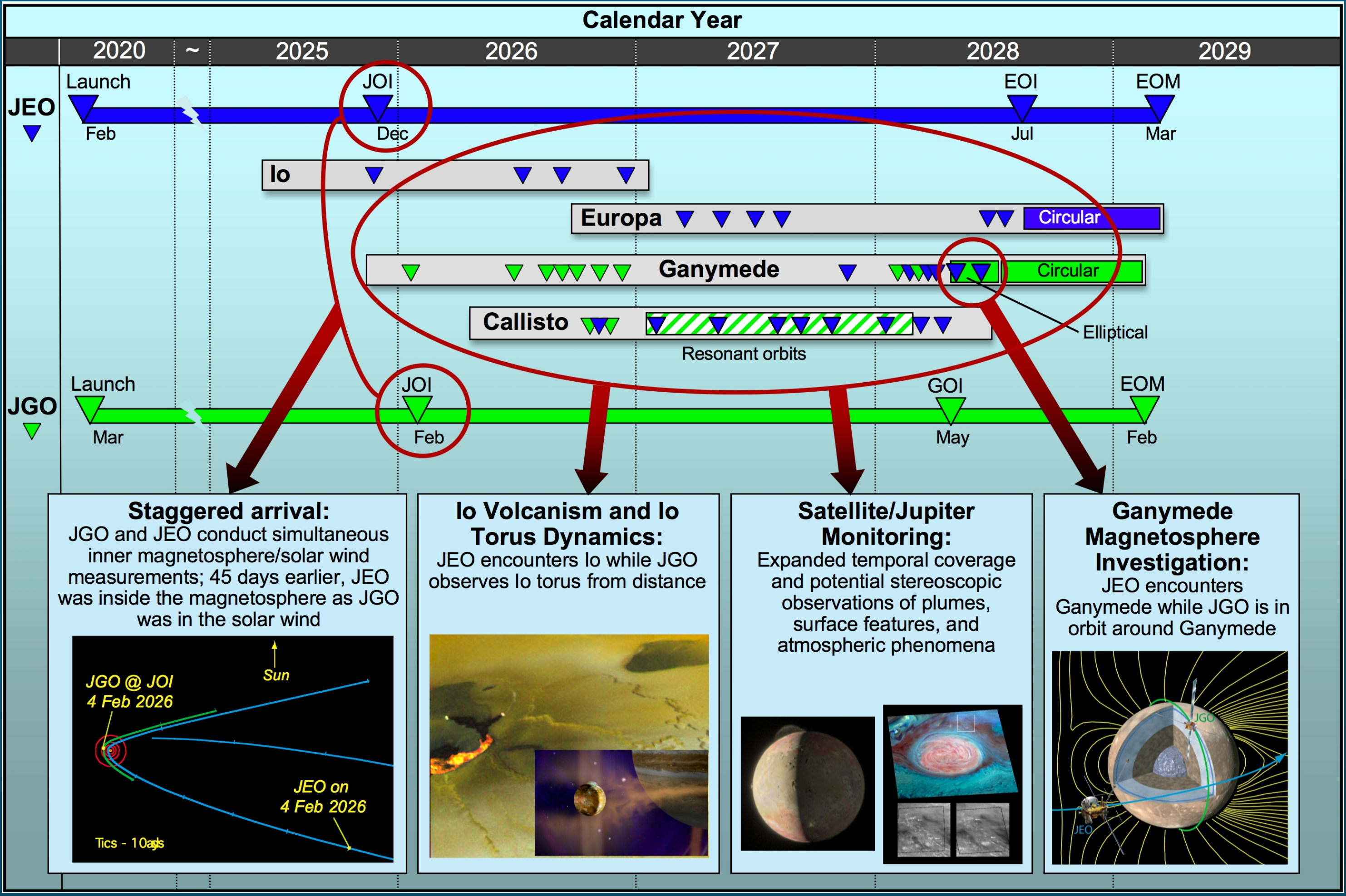
Model Payload

Instrument	Jupiter Europa Orbiter	Jupiter Ganymede Orbiter
Laser Altimeter	Single-beam @ 1064 nm, 50 m spot	Single Beam @ 1064 nm, 10 m spot
Radio Science	2-way Doppler with Ka transponder; USO	2-way Doppler with Ka-Band transponder; USO
Ice Penetrating Radar	Dual frequency: 50 and 500 MHz Vertical depths: 3 and 30 km, Dipole antenna: 30 m	Single frequency: 20-50 MHz Dipole antenna: 10 m
Visible-IR Spectrometer	Pushbroom with along-track scan system, two channels, 400-5200 nm	Pushbroom imaging spectrometer with scan system, two channels; 400-5200 nm
UltraViolet Spectrometer	EUV+FUV: 70-200 nm, scan system for stellar occultations	EUV: 50-110 nm FUV+MUV: 110-320 nm
Ion and Neutral Mass Spectrometer	Reflectron Time-of-Flight 1-300 Daltons	N/A
Thermal Instrument	Pushbroom imaging thermopile line arrays, 8-20 μm and 20-100 μm, 4 narrow filter bands	Imaging microbolometer array 7.4-21.7 μm, 4 narrow filter bands
Narrow Angle Camera	Panchromatic pushbroom plus nine color framing mode	N/A
Wide and Medium Angle Camera	Wide-Angle: pushbroom, 3-color + panchromatic; IFOV 1 mrad Medium-Angle: pushbroom, panchromatic, IFOV 0.1 mrad	WAC: framing camera, 12 filters, IFoV 2mrad MRC: pushbroom, 4-color + panchromatic, IFOV 0.25 mrad
Magnetometer	Dual tri-axial fluxgate sensors on 10 meter boom	Dual tri-axial fluxgate sensors on 3 meter boom
Plasma and Particles	Plasma Analyzer: Electrons: 10 eV to 30 keV Ions: 10 eV to 30 keV Particle Analyzer: Electrons: 30 keV to 1 MeV Ions: 30 keV to 10s of Mev	Plasma Analyzer: Electrons: 1 eV to 20 keV Ions: 1 eV to 10 keV Particle Analyzer: Electrons: 15 keV to 1 MeV Ions: 3 keV to 5 MeV ENA: 10 eV – 100 eV
Submillimeter Wave Sounder	N/A	Spectral range: 550-230 μm, 2 channels
Mass	**106 kg**	**73 kg**

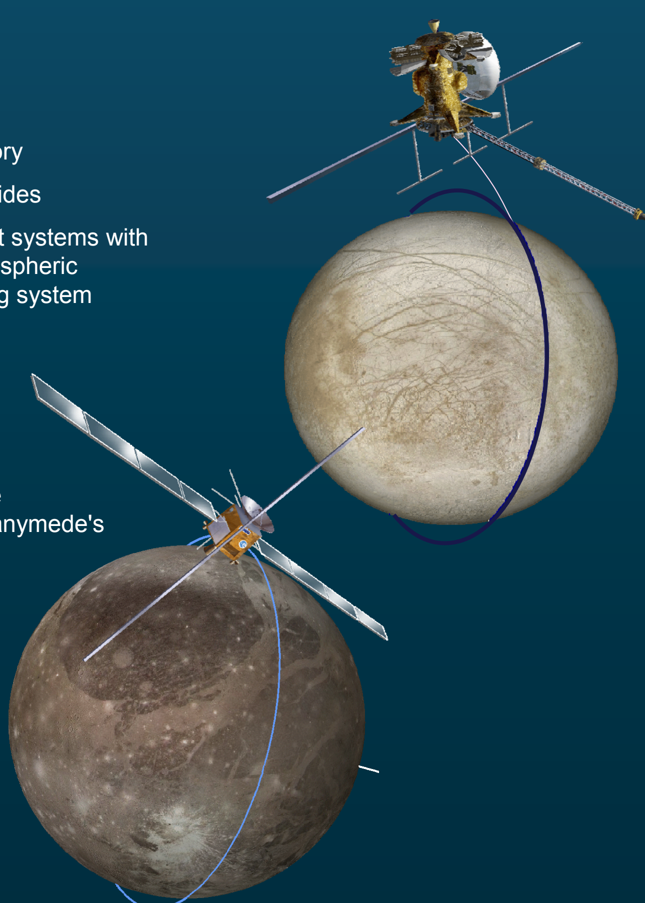
Schedule (calendar date)



Choreographed trajectories enable unique synergistic science throughout the mission



Mission Overview



- Two separate launches in 2020
- Both spacecraft would use Venus-Earth-Earth Gravity Assist (VEEGA) trajectory
- First spacecraft would be a pathfinder for second, improving satellite ephemerides
- Multi-year tours of Jovian system, including synergistic science from both flight systems with many flybys each of Io, Europa, Ganymede, and Callisto, continuous magnetospheric monitoring, regular monitoring of Io and Jupiter's atmosphere and Jupiter's ring system
- Spacecraft constantly and simultaneously monitor Jovian magnetosphere and/or the solar wind as they move in and out of the Jovian magnetosphere
- Mission design can tailor trajectories for specific geometries, including mutual satellite occultations for ionospheric and neutral atmospheric science, upstream/downstream magnetospheric measurements, stereoscopic satellite observations, especially of Io and its plumes, Jupiter atmosphere collaborative observations, especially of Jupiter's auroras, dual spacecraft exploration of Ganymede's magnetosphere, both individually and simultaneously
- Europa orbital phase
  - Initial, circular 200 km altitude orbit at 95º – 100° inclination
  - Transfer to 100 km orbit ~ one month after EOI
- Ganymede orbital phase
  - Initial, elliptical 200 km × 6000 km at 86° inclination
  - Final, circular 200 km orbit
- Flight systems would eventually impact Europa and Ganymede

The NASA Element of a Joint NASA/ESA Endeavour

Jupiter Europa Orbiter

Science Goal: Explore Europa to investigate its habitability

A Future Mission Concept

Why Europa? Why Now?

- Europa is the highest priority outer planet exploration target per 2007 NASA Science Plan, the 2006 Solar System Exploration Roadmap, and the 2003 planetary sciences “Decadal Survey”
- Investment over last decade has matured key technology such as rad-hard electronics and radioisotope power sources
- Galileo has revolutionized our understanding of Europa and its putative ocean pointing the way to the next exploratory step
- Robust payload answers compelling questions about Europa’s ocean and its potential habitability following a required ~30-month Jovian system tour rich in Io, Europa, Ganymede, and Callisto encounters, monitoring of Io, and observations of Jupiter’s magnetosphere and atmosphere

Science Objectives

A. Europa’s Ocean:

Characterize the extent of the ocean and its relation to the deeper interior

B. Europa’s Ice Shell:

Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange

C. Europa’s Chemistry:

Determine global surface compositions and chemistry, especially as related to habitability

D. Europa’s Geology:

Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration

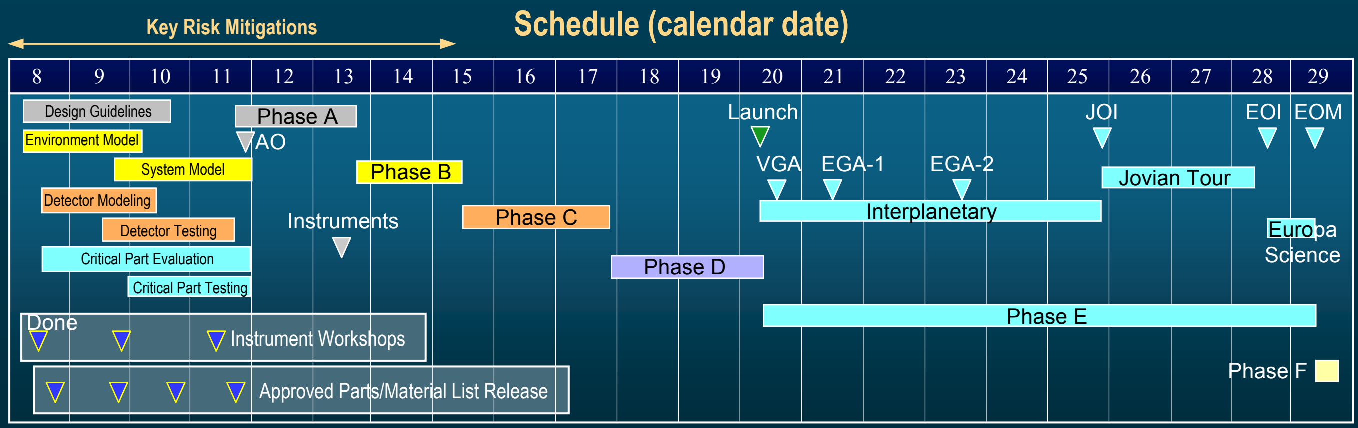
E. Jupiter System:

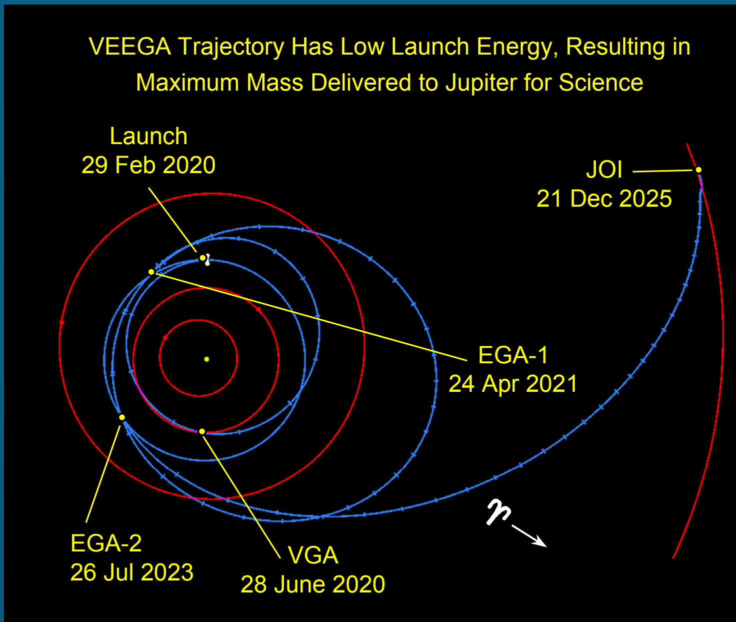
Understand Europa in the context of the Jupiter system

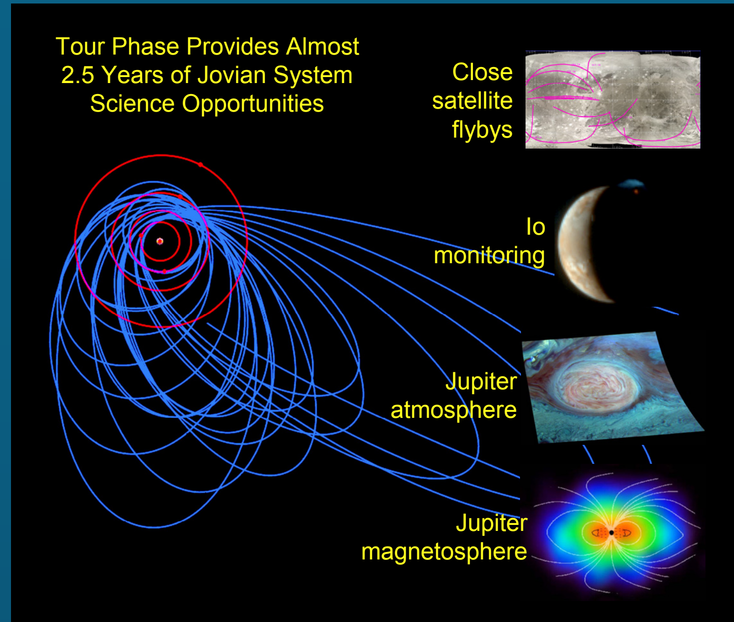
Model Payload

Team Investigations/Instruments	Characteristics (from 100 km altitude)
Ocean Team	
Laser Altimeter (LA)	Single-beam, 50 m spot; 1.064 μm
Radio Science (RS)	2-way Doppler with Ka translator; USO; X- & Ka-band via telecom subsystem
Ice Team	
Ice Penetrating Radar (IPR)	Shallow-mode 5 MHz & deep-mode 50 MHz with 1 and 10 MHz bandwidths, vertical depths of 3 and 30 km
Chemistry Team	
VIS-IR Imaging Spectrometer (VIRIS)	0.4 to >5.2 μm, 5 nm spectral resolution below 2.6 μm, and 10 nm above 2.5 μm; pushbroom with along-track scan mirror; 25 m resolution
UV Spectrometer (UVS)	70 – 200 microns; IFOV l mrad; scan system for stellar occultations; 100 m resolution
Ion and Neutral Mass Spectrometer (INMS)	1 – 300 daltons; FOV 10° x 40°
Geology Team	
Thermal Instrument (TI)	8 – 20 μm and 20 – 100 μm, 5 pixels cross-track, 250 m resolution
Narrow Angle Camera (NAC)	Panchromatic pushbroom plus nine color framing mode for OpNav; IFOV 0.01 mrad; 1 m resolution
Wide Angle Camera and Medium Angle Camera (WAC+MAC)	Wide-Angle: 3-color+panchromatic; IFOV of 1 mrad, pushbroom; Medium-Angle: panchromatic and 0.1 mrad, pushbroom modes
Fields and Particles Team	
Magnetometer (MAG)	Dual sensors; 10 m boom; 0 – 3000 nT
Particle and Plasma Instrument (PPI)	10 eV to 30 keV electrons and ions

Schedule (calendar date)

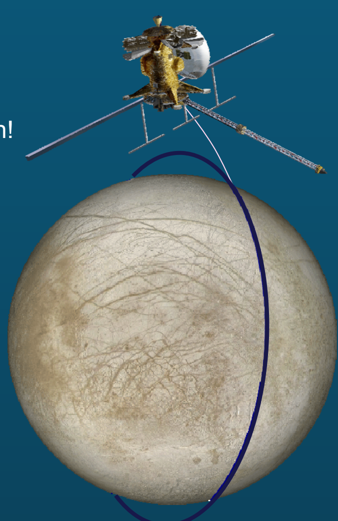






Mission Overview

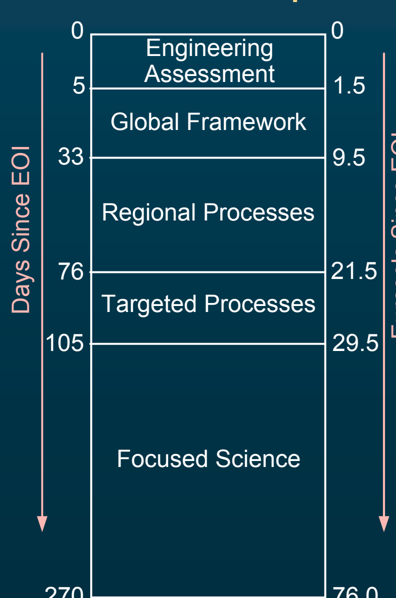
- Launch on Atlas V 551 in Feb 2020, $C_3 \leq 12.8$ km^2/s^2
- Venus-Earth-Earth Gravity Assist (VEEGA)
- Jupiter Orbit Insertion in December 2025
- 30-month Jovian system tour, featuring
  - 4 Io encounters, including a volcanic plume flythrough!
  - 6 Europa encounters before EOI
  - 6 Ganymede encounters, extensively exploring Ganymede's magnetosphere
  - 9 Callisto encounters, at least one near-polar
  - Continuous magnetospheric monitoring, regular monitoring of Io and Jupiter's atmosphere
- Europa orbit insertion in July 2028
- Initial, circular 200 km altitude orbit, 95° – 100° inclination
- Transfer to 100 km orbit ~one month after EOI
- 34 m DSN coverage
- Nine months in Europa orbit
- Flight system eventually impacts Europa



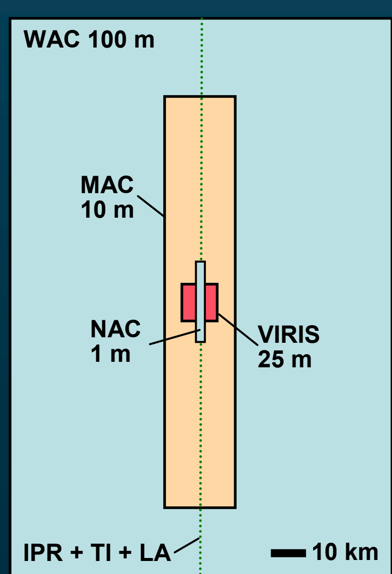
Flight System

- 5040 kg wet mass (43% system dry mass margin)
- 1714 kg dry mass (including 25% contingency)
- Model payload, 106 kg, 172 W (CBE)
- Five MMRTGs provide 540W
- Battery for peak power modes
- 3 m Two-axis gimbaled High Gain Antenna
- Two-way Doppler at both X-/Ka-band capability and USO for radio science gravity investigation
- Data rate of ~150 kb/s to DSN 34m at Ka-band
- Up to 7.3 Gb/day during Europa Science phase
- Bi-propellant MON/MMH prop. system (2260 m/s)
- Full Redundancy
- Rad-hardened electronics
- 192 kg shielding (CBE)
- 2.9 Mrad behind 100 mils Al design point
- 9-year lifetime
- Bioburden reduction plus radiation environment

Europa Science Campaigns



1st Campaign — 200 km
2nd – 4th Campaigns — 100 km



Nested FOVs provide for coordinated targeted observations (resolution/pixel from 100 km altitude)

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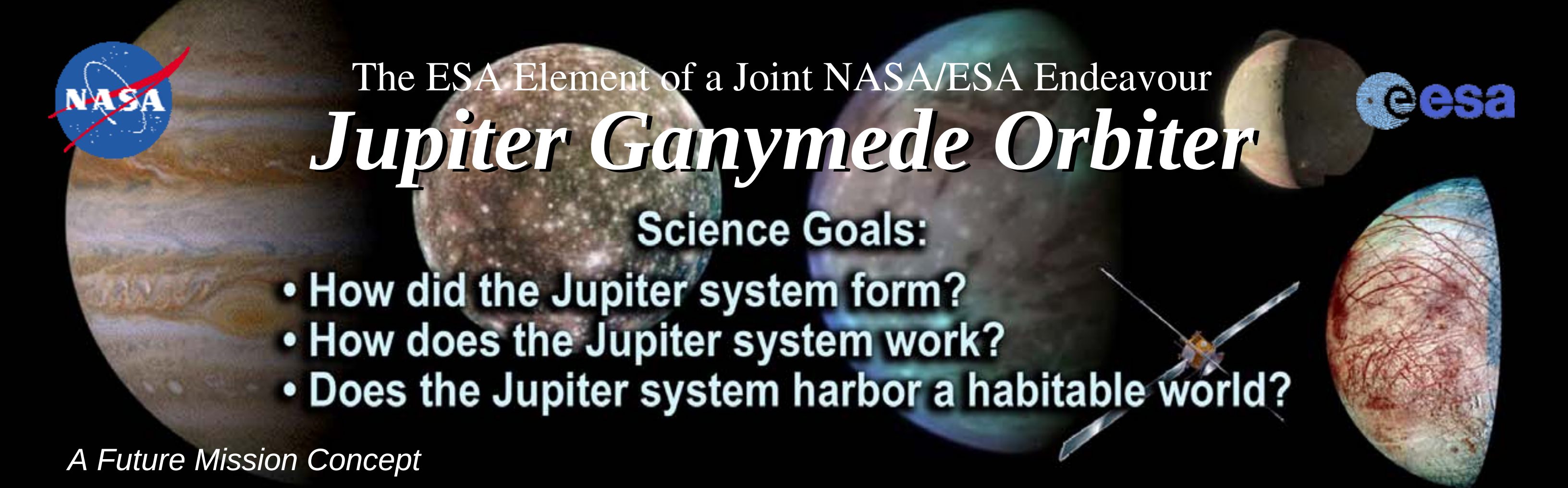


The ESA Element of a Joint NASA/ESA Endeavour

Jupiter Ganymede Orbiter

Science Goals:

- How did the Jupiter system form?
- How does the Jupiter system work?
- Does the Jupiter system harbor a habitable world?

A Future Mission Concept

Science Objectives

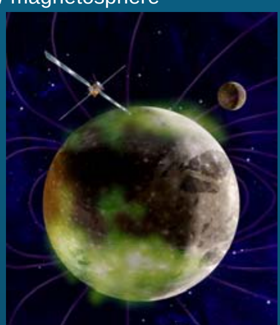
A. Ganymede:
Characterize Ganymede as a planetary object including its potential habitability.

B. Satellite System:
Study the Jovian satellite system.

C. Jupiter:
Study the Jovian atmosphere.

D. Magnetosphere:
Study the Jovian magnetodisk / magnetosphere

E. Jupiter System:
Study the interactions occurring in the Jovian system.



Model Payload

A 77 kg model payload including the following instruments has been identified:

Instruments	Characteristics
• Micro Laser Altimeter	Single beam: 1064 nm, 10 m spot
• Radio Science Package	Ka-band transponder Ultra Stable Oscillator
• Radar Sounder	Single frequency, 20 – 50 mHz, 10 m dipole antenna
• V/NIR Imaging Spectrometer	2 channel, 400 – 5200 nm
• UV Imaging Spectrometer	EUV: 50 – 110 nm FUV+MUV: 110-320 nm
• Thermal IR Mapper	4 band, 5 – 25 microns
• Wide Angle and Medium Resolution Camera	WAC: framing, 350 – 1050 mm MRC: pushbroom, 4 color + Panchromatic, 350 – 1050 mm
• Magnetometer	Dual triaxial sensors, 3 m boom
• Plasma Package	Cold plasma (Te < 10 eV), Electrons: 1 eV - 15 keV Ions: 1 eV 5 MeV, ENA: 10 eV – 10 keV
• Sub-mm Wave Sounder	2 channels, 550 – 230 microns

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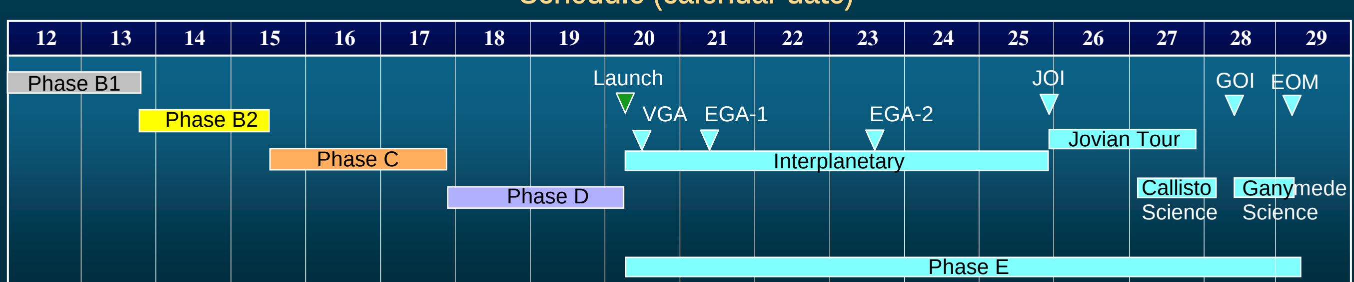
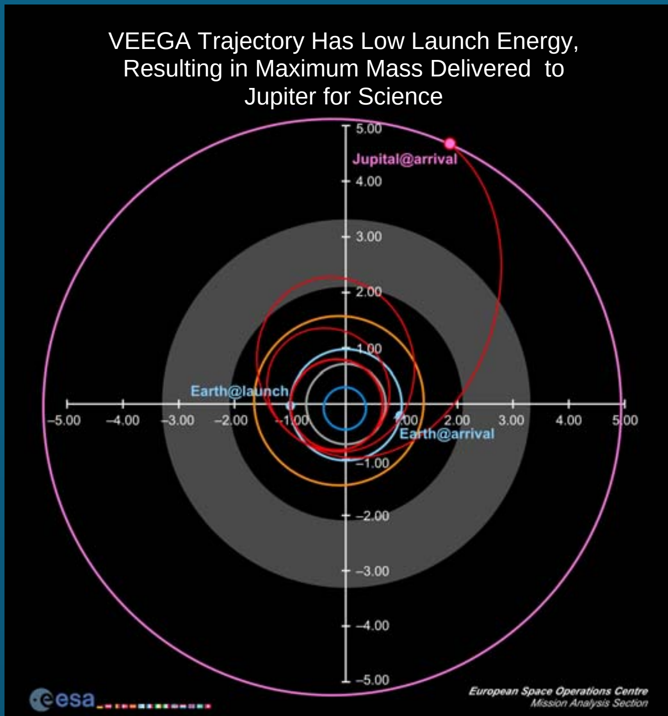
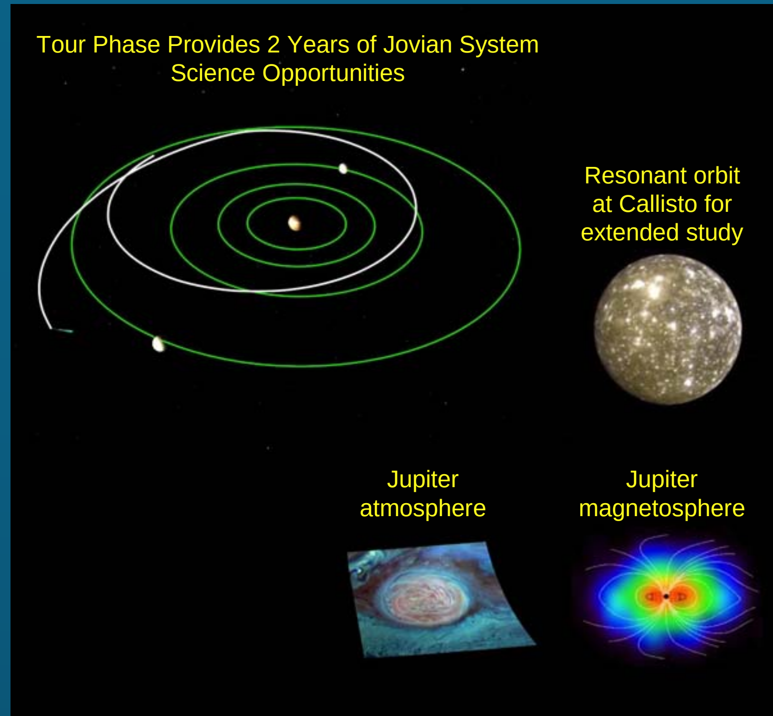
Schedule (calendar date)







Mission Overview

- Launch with Ariane 5 on March 23, 2020
- Venus – Earth – Earth Gravity Assist (VEEGA) trajectory to Jupiter
- JOI into 12.5 × 244 RJ (Jupiter radii) elliptical orbit on Feb 13, 2026 (transfer time to Jupiter: about 5.9 years)
- Sequence of swing-by's at Ganymede and Callisto (GCGC)
- Callisto Science Phase (duration 383 days): 19 Callisto flybys at altitude of 200 km using 2:3 resonant orbits, allowing for (quasi) global surface coverage
- Sequence of swing-by's at Ganymede and Callisto (CGG)
- Ganymede Orbit Insertion (GOI) into 200 × 6000 km elliptical orbit
- Ganymede elliptical orbit science phase (~ 80 days)
- Maneuver to reach a low altitude (200 km), circular, quasi-polar orbit
- Ganymede circular orbit science phase ~ 180 days
- End of nominal mission after 3254 days, i.e. about 8.9 years on Feb. 6, 2029
- Possible extension of nominal mission in circular phase; optional decrease of altitude
- Eventual impact on Ganymede's surface

Flight System

- 3493 kg launch mass (20% system dry mass margin)
- 1275 kg dry mass (including 20% margin, excluding adapter)
- Model payload; 73 kg (CBE)
- Deployable and rotating LILT solar arrays (area ~51 m2)
- Battery for peak power and solar eclipse modes
- 2.8 m Fixed High Gain Antenna
- Two-way Doppler at both X-/Ka-band capability and USO for radio science gravity investigation
- Data rate of 40 – 66 kb/sec to ESA ground station network at X-band
- 256 Gb solid state recorder
- Bi-propellant MON/MMH propulsion system (3035 m/s)
- Full Redundancy
- ~80 kg 8mm-Al-radiation shielding
- 100 krad radiation design point
- 8.9 year life-time

Science Campaigns

1. Jupiter Science phase (316 days): Jupiter's atmosphere; Ganymede and Callisto science (gravity and mag. fields, remote sensing) at flybys

2. Callisto Science phase (383 days using resonant orbits): detailed investigation of Callisto's surface, interior (including the putative subsurface ocean) and exosphere; additional Jupiter science

3. Ganymede elliptical orbit (80 days): detailed investigation of Ganymede's magnetosphere and its interaction with the Jovian magnetosphere; targeted remote sensing campaigns; high-precision determination of the gravity field to prepare for the next phase

4. Ganymede circular orbit (180 days): main science phase to investigate Ganymede's surface and interior including the ocean and the satellite's tidal response; coordinated targeted observations; sub-surface sounding of the ice shell; studies of Ganymede's exosphere

Ganymede:
1st Phase — 200 × 6000 km elliptical
2nd Phase — 200 km circular

Radiation exposures kept low to maximize use of heritage systems

Phase	Duration [days]	Rad Level [krad]*
Cruise	2156	2
Jupiter arrival to GGA2	179	2
GGA2 to GGA6	136	3
GGA6 to Callisto	57	5
Callisto Science	383	15
Callisto to Ganymede	83	3
Ganymede Science (elliptical)	80	20
Ganymede Science (circular)	180	32
Total	**3254**	**82**

* Upper limit behind 8 mm of Al, anticipate reduction with more accurate analysis at Ganymede

Foreword—Emergence of habitable worlds around gas giants

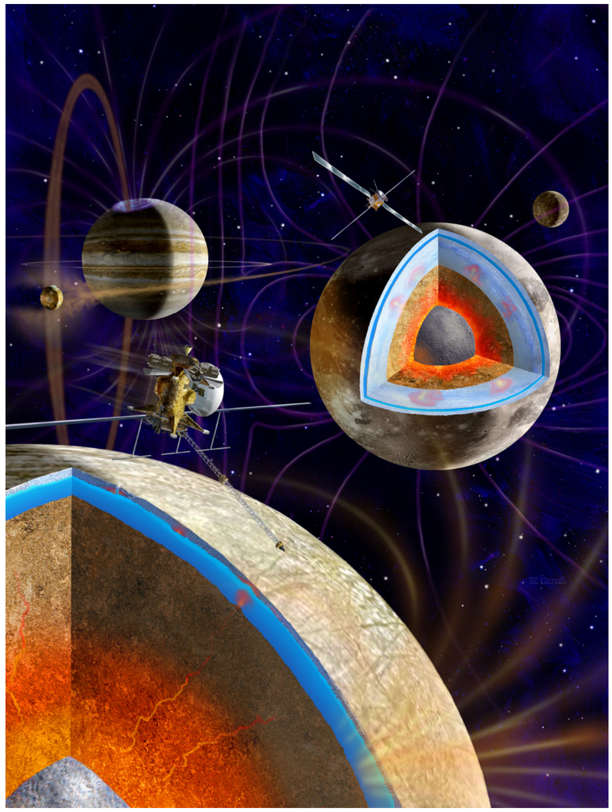
Some 400 years ago, discovery of the four large moons of Jupiter by Galileo Galilei spurred the Copernican Revolution and changed our view of the universe forever. Today Jupiter is the archetype for the giant planets of our solar system, and for the numerous giant planets now known to orbit other stars. Moreover, Jupiter's diverse Galilean satellites—three of which are believed to harbor internal oceans—are the central to understanding the habitability of icy worlds. On Earth, everywhere there is water there is life, so it is reasonable that the search for life in our solar system focuses on the search for water. The presence of water will indicate the best places to continue the search for life. If we find life, we will try to understand why it was able to take hold; just as important, if life is absent, we will want to know why.

By understanding the Jupiter system and unraveling its history from origin to the possible emergence of habitable environments, we will learn how gas giant planets and their satellites form and evolve. Perhaps more important, we will shed new light on the potential for the emergence of life in our celestial neighborhood and beyond.

The two sister spacecraft of the Europa Jupiter System Mission (EJSM)—the Jupiter Europa Orbiter (JEO) and the Jupiter Ganymede Orbiter (JGO)—will perform a choreographed dance to explore the Jupiter system and stud the processes that led to the diversity of its associated components and their interactions. The focus is to characterize the conditions that may have led to the emergence of habitable environments among its icy satellites, with special emphasis on the internally active ocean-bearing worlds, Europa and Ganymede.

Jupiter Europa Orbiter

The principal focus of this report, JEO, will conduct an orbital tour of the Jupiter system including close flybys of Io, Europa, Ganymede and Callisto before entering orbit around Europa. It will then carry out an intensive investigation of Europa, which may contain the most habitable environment in the solar system except for Earth.



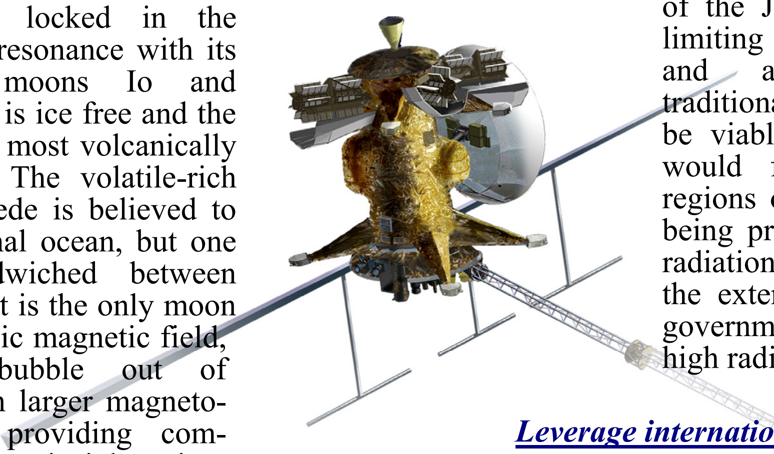
Europa is believed to have a saltwater ocean beneath a relatively thin and geodynamically active icy shell. Europa is unique among the large icy satellites because its ocean is in direct contact with its rocky mantle, where the conditions could be similar to those on Earth's biologically rich sea floor, powered by energy and nutrients that result from reactions between the sea water and rock. Consequently, Europa is a prime candidate in the search for habitable environments and life in the solar system. However, the details of the processes that shape Europa's ice shell and which control ocean-ice material exchange, are poorly known. The JEO mission goal is to:

Explore Europa to investigate its habitability.

JEO will operate in a very low-altitude orbit that enables it to assess electromagnetically the interior of Europa, observe its tidal flexing, and map the surface at high resolution. A sounding radar will probe the ice to characterize its three-dimensional variability and locations of shallow water. Mass spectroscopy, as well as thermal and hyperspectral imaging, will be used to investigate the chemistry and search for sites of recent activity. The most promising sites would be potential targets for a future landed astrobiological mission to Europa.

Europa Jupiter System Mission

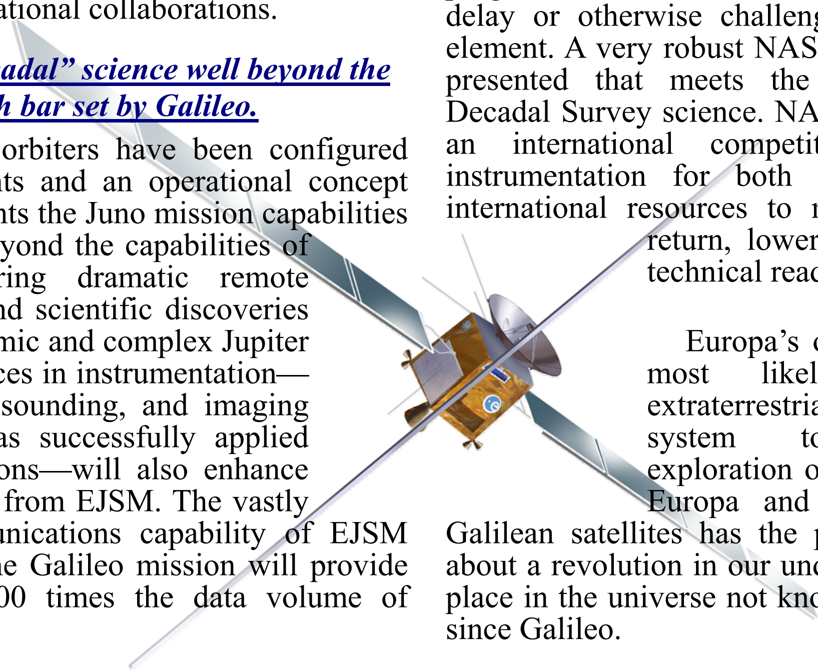
Working in concert, JEO and JGO will carry out a comprehensive investigation of the Jupiter System. This contains diverse objects, including Jupiter itself, minor satellites, the Jovian ring system, and the four large Galilean Satellites: Io, Europa, Ganymede, and Callisto.



Europa is locked in the Laplace tidal resonance with its neighboring moons Io and Ganymede. Io is ice free and the solar system's most volcanically active world. The volatile-rich moon Ganymede is believed to have an internal ocean, but one that is sandwiched between layers of ice. It is the only moon with an intrinsic magnetic field, carving a bubble out of Jupiter's much larger magnetosphere, and providing completely unique insights into satellite-planet magnetospheric interactions.

The EJSM mission architecture provides the optimal balance between science, risk, and cost using three guiding principles: achieve Decadal science; build on lessons learned; and leverage international collaborations.

Achieve "Decadal" science well beyond the high bar set by Galileo.



The EJSM orbiters have been configured with instruments and an operational concept that complements the Juno mission capabilities and go well beyond the capabilities of Galileo, ensuring dramatic remote observations and scientific discoveries about the dynamic and complex Jupiter system. Advances in instrumentation—such as radar sounding, and imaging spectroscopy, as successfully applied on prior missions—will also enhance the data return from EJSM. The vastly greater communications capability of EJSM compared to the Galileo mission will provide more than 3000 times the data volume of Galileo.

Build upon lessons learned from a very successful design and operational experience.

Galileo provided NASA with experience operating in high radiation environments, and both NASA and ESA have experience in implementing long-lived missions (including Voyager, Rosetta, Cassini, Galileo, and New Horizons). Lessons learned from these and other missions have been applied to reduce risk and lower cost.

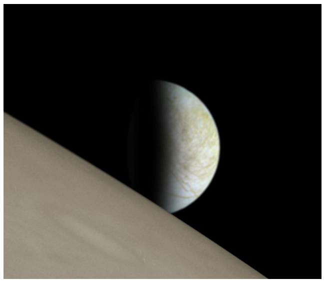
ESA's JGO will operate in the outer regions of the Jovian radiation belts, limiting its radiation exposure and allowing a more traditional solar architecture to be viable. The NASA's JEO would focus on the inner regions of the Jupiter system, being prepared for the higher radiation levels by leveraging the extensive NASA and US government experience with high radiation designs.

Leverage international collaboration.

EJSM would be a collaborative NASA-ESA effort designed to provide an outstanding flagship mission at relatively low cost. Because JEO and JGO are on separate launchers, the mission is robust to programmatic or technical factors that might delay or otherwise challenge either mission element. A very robust NASA-only mission is presented that meets the highest priority Decadal Survey science. NASA and ESA plan an international competition to furnish instrumentation for both spacecraft, using international resources to maximize science return, lower risk, and ensure technical readiness.

Europa's ocean may be the most likely abode for extraterrestrial life in the solar system today. In-depth exploration of the water world Europa and the other three Galilean satellites has the potential to bring about a revolution in our understanding of our place in the universe not known on this planet since Galileo.

1. EXECUTIVE SUMMARY



Europa and its parent planet Jupiter.

Some 400 years ago, discovery of the four large moons of Jupiter by Galileo Galilei changed our view of the universe forever. Today Jupiter is the archetype for the giant planets of our solar system, and for the numerous giant planets now known to orbit other stars, and Jupiter's diverse Galilean satellites—three of which are believed to harbor internal oceans—are central to understanding the habitability of icy worlds.

By investigating the Jupiter system, and unraveling the history of its evolution from initial formation to the emergence of possible habitats and life, insight is gained into to how giant planets and their satellite systems form and evolve. Most important, new light is shed on the potential for the emergence and existence of life in icy satellite oceans.

Europa and Ganymede are believed to be internally active and harbor internal salt-water oceans. They are straddled by Io and Callisto (which may also harbor a deep ocean), key satellite end-members that tell of the origin and evolution of the Jupiter system. If extrasolar planetary systems are analogous, then icy satellites could be the most common habitats in the universe—probably much more abundant than Earth-like environments which require very specialized conditions to permit surface oceans.

In 1995, Galileo arrived at Jupiter to conduct its follow-up on the key Voyager discoveries, especially at Europa. Galileo made many discoveries in the Jovian system, and provided extremely strong evidence of a near-surface global ocean on Europa. The Juno mission, scheduled for launch in 2011, will focus on Jupiter's deep interior and magnetosphere but will not address key science questions for the Galilean satellites and the integrated Jupiter system. Thus, a new flagship-class mission to the Jupiter system and its satellites is required to address top priority scientific questions.

1.1 Background

Using the extensive experience gained from Galileo, Cassini, New Horizons, Juno and Mars Reconnaissance Orbiter, the 2008 NASA Pre-phase A effort focused on refining the mature Europa mission concept with very robust technical and cost margins, executing a detailed risk reduction plan and integrating the ESA portion of the mission concept.

In 2007, NASA performed two Jupiter mission concept studies: Europa Explorer and Jupiter System Observer. At the same time, an ESA Jupiter proposal, *Laplace*, was submitted to the Cosmic Vision Programme call. JPL and APL teamed in 2008 to address the next step in the NASA study of this mission concept. The primary focus of the NASA 2008 effort was threefold:

- update the 2007 Europa Explorer with Jupiter system science (Jupiter Europa Orbiter, JEO),
- begin executing risk reduction activities related to radiation and planetary protection, and
- work with ESA to define a joint mission Europa Jupiter System Mission (EJSM) comprised of the JEO and the ESA *Laplace* orbiter (Appendix O).

The NASA contribution to EJSM, defined as JEO, is an Europa orbiter based in the previously studied line of Europa orbiters which culminated in 2007 as the Europa Explorer. The Ground Rules associated with the 2008 NASA study are summarized in **Table 1.1-1**. A summary of the 2008 effort for the JPL/APL team was to:

- Include Jovian *system science* as a Level 1 requirement (Section §2.4.6),
- Respond to NASA's 2007 TMC and Science panels, especially the Chemistry science objective, the radiation-induced effects on measurement quality and mitigation strategies (Appendix N),
- Refine the *radiation plan* described in the 2007 report and begin executing (§4.5, and Appendix F),
- Define *baseline, floor and NASA-only* JEO mission concepts, (§4.1),
- Conduct an assessment of the science value of NASA-ESA and NASA only missions with respect to the science goals in the 2003 NRC Decadal Survey (§2.7, Appendix L).

***Table 1.1-1.** NASA-provided ground rules provide framework for JEO study report.*

Power options	Solar, MMRTG or ASRG—costs and characteristics supplied for radioisotope power options
Planetary Protection	JEO: $\leq 10^{-4}$ of contaminating the Europan ocean
Launch Vehicle (LV)	Delta IV-H, Ares and Atlas family—costs given including launch services and nuclear processing
Technology Philosophy	Be conservative
Launch Dates	Nominally 2020 but investigate 2018–2022
DSN Capability	Ka band downlink available, current 70m equivalent capability available, current 34m available, DSN ground system throughput of 100 Mbits/s
International Contributions	<$1B consistent with Cosmic Vision Proposals

The architecture of two free-flying, independent flight elements was a result of both the 2007 NASA and ESA studies. All studies of mission architectures performed over the past decade to address investigation of a putative Europan ocean have concluded that a Europa orbiter is an essential element. Thus, the NASA component was set as the Europa Explorer concept from 2007. The ESA component, Jupiter Ganymede Orbiter (JGO), was not pre-determined and was the result of decomposition of the science objectives.

A JPL/APL engineering team was formed to continue the evolution of the JEO mission and to execute the risk mitigation activities discussed in §4.5 and Appendix F. In addition, the JPL/APL engineering team supported the ESA engineering team to flesh out the ESA element (Appendix J). Also, an international science team was formed to define the highest priority science and to work with the engineering teams to refine the flight element implementations.

The main focus of this report is JEO. Discussion of the ESA element, JGO, is limited to Sections 1.0, 2.1, 2.6, 2.7 (Science), 3 (Architecture), and 4.11 (Management) to add context for the JEO mission element. Further details on the integrated EJSM and the JGO mission element are given in the EJSM Joint Summary Report [JPL D-48440], the ESA JGO "Assessment Study Report of Laplace—EJSM-JGO (*2008*), SRE-PA/2008.064/ASAW", and in Appendix J of this report.

1.2 Science Objectives

An extensive international effort involving scientists from more than half a dozen countries established the EJSM overarching theme as:

The emergence of habitable worlds around gas giants

The Joint Jupiter Science Definition Team (JJSDT) was chartered to define the goals and objectives for the EJSM. The JJSDT is an international group of 27 US, 15 European, and 5 Japanese scientists, which, during the last 8 months, evaluated the US National Research Council's Planetary Science Decadal Survey, the ESA Cosmic Vision, the NASA 2007 Europa Explorer [*Clark et al. 2007*] and Jupiter System Observer studies [*Kwok et al. 2007*], and the 2007 ESA Cosmic Vission Programme Laplace Proposal [*Blanc et al. 2007*] to establish a comprehensive and integrated set of goals and objectives for EJSM addressing the nature and origin of the Jupiter system, especially its satellites, to build on previous results and anticipated results from Juno.

To understand the Galilean satellites as a system, Europa and Ganymede are singled out for detailed investigation. This pair of objects provides a natural laboratory for comparative analysis of the nature, evolution, and potential habitability of icy worlds. The primary focus is on in-depth comparative analysis of their internal oceans, current and past environments, surface and near-surface compositions, and their geologic histories. Moreover, objectives for studying the other two Galilean satellites, Io and Callisto were also defined. To understand how gas giant planets and their satellites evolve, broader studies of Jupiter's atmosphere and magnetosphere will round out the Jupiter system investigation.

The JJSDT worked with the engineering teams to define a two flight element mission to Jupiter and the Galilean satellites, with each flight element ending their prime mission in orbit at a Galilean satellite, one at Europa and one at Ganymede. The JJSDT and engineering team developed extraordinary mission concepts which provide extensive Jovian system science as well as focused icy satellite science.

Europa is essentially a rocky world with an outer ~100 km layer comprised of a relatively thin icy shell above a saltwater ocean. Its ocean is in direct contact with the rocky mantle below, making it unique among icy satellites in having a plausible chemical energy source to support life. However, the details of the processes that shape Europa's ice shell, and fundamental question of its thickness, are poorly known.

The science goal for the JEO element of EJSM is:

Explore Europa to investigate its habitability.

The objectives developed by the JJSDT to address this goal are:

- Characterize the extent of the ocean and its relation to the deeper interior,
- Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange (**Figure 1.2-1**),
- Determine global surface compositions and chemistry, especially as related to habitability.
- Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration.
- Understand Europa in the context of the Jupiter system.

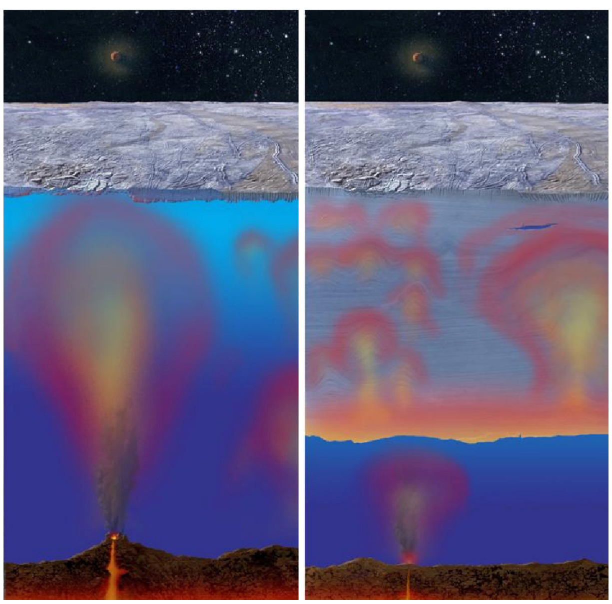


Figure 1.2-1. *The NASA Jupiter Europa Orbiter will address the fundamental issue of whether Europa's ice shell is ~few km (left) or >30 km (right), with different implications for processes and habitability. In either case, the ocean is in direct contact with the rocky mantle below, which can infuse the chemical nutrients necessary for life.*

Ganymede is believed to have a liquid ocean sandwiched between a thick ice shell above and high-density ice polymorphs below, more typical of volatile-rich icy satellites. It is the only satellite known to have an intrinsic magnetic field, which makes the Ganymede-Jupiter magnetospheric interactions unique in our solar system (**Figure 1.2-2**).

The science goals for the JGO element of EJSM are:

– ***How did the Jupiter System form?***
– ***How does the Jupiter system work?***
– ***Does the Jupiter system harbor a habitable world?***

The objectives which the JJSDT have developed to address these goals are:

- Characterize Ganymede as a planetary object including its potential habitability,
- Study the Jovian satellite system,
- Study the Jovian atmosphere,
- Study the Jovian magnetodisk/magnetosphere,
- Study the interactions occurring in the Jovian system.

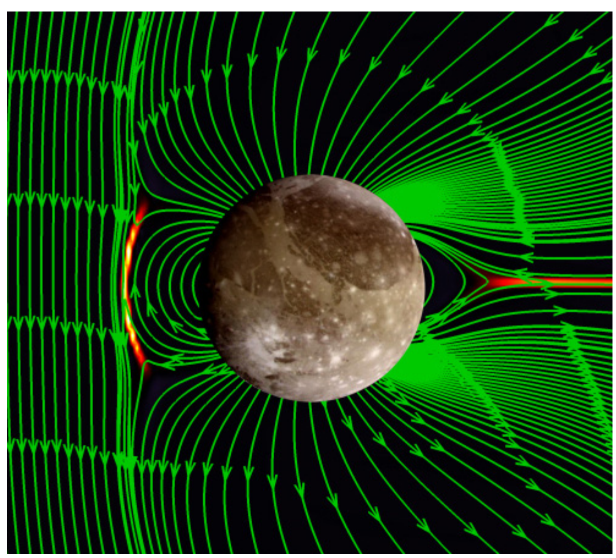


Figure 1.2-2. *The ESA Jupiter Ganymede Orbiter will determine how Ganymede's unique magnetic field interacts with Jupiter's, how the interactions vary with time, and the role of a convecting core and internal ocean.*

1.3 JEO Science Strategy

All-inclusive science objectives enable flexibility for the community to propose innovative techniques to address the science objectives without premature narrowing of potential instrumentation.

The JJSDT has taken the overall JEO science objectives and identified a set of investigations and measurements which would fully address the objectives. The full traceability matrix has been vetted with the science community and the approach is to be all inclusive. The JEO model payload presented uses only publicly available information and was selected to address the highest priority measurements without overly stressing the resources (cost, mass, power and risk). By taking this approach, the JJSDT acknowledges that not all measurements are fully addressed by the model payload.

This conservative strategy was taken intentionally for several reasons: 1) it allows those people with innovative or proprietary ideas to propose more capable instruments, 2) it balances the development risk and science value given publicly available information, 3) it demonstrates that the targets and mission are very exciting and scientifically rich, leaving room for innovative concepts, 4) it highlights how JEO provides direct benefit to the complementary and synergistic JGO science objectives and 5) it provides NASA Headquarters with information to best evaluate the cost vs. risk posture for JEO once the instruments are actually proposed via the Announcement of Opportunity process.

1.4 Architectural Implementation

This year's study has refined the EJSM concept to identify two free-flying flight elements executing an intricately choreographed exploration of the Jupiter System before settling in at the intriguing end states of Europa and Ganymede.

EJSM's NASA-led JEO and ESA-led JGO have both unique and overlapping science objectives while being designed to stand alone if necessary. JEO and JGO are both orbital flight systems using conventional bi-propellant propulsion systems and capable of carrying 11 specifically selected instruments. Ka-band downlink systems on both orbiters allow significant downlink capability while in the Jupiter system. The basic designs for the orbiters are very similar to previous large flight systems including Cassini, Mars Reconnaissance Orbiter and Rosetta. New technologies are not required to execute either current mission concept though new developments are required for JEO (radiation designs) and JGO (low-mass instruments). The development schedule for these missions is such that a technology developed by 2014/2015 could easily be incorporated if it enhances the mission capability. Current risk mitigation activities are under way to ensure that the radiation designs are implemented in the lowest risk approach. The robust baseline mission concepts includes mass and power margins well above what would be normal at this point. A summary of the flight elements is presented in **Table 1.4-1**.

JEO will encounter Io and spend significant time in the inner radiation belts at Jupiter. JGO's trajectory allows it to stay outside the highest radiation areas and therefore has solar arrays for its power source. The higher radiation levels experienced by JEO while staying in the main radiation belts, adds significant challenge to designing a solar mission which can meet the science objectives. Previous studies (Appendix C) indicate that a radioisotope powered mission is a good technical solution. For purposes of this study, radioisotope power is baselined, though no final decision would be made until the appropriate Launch Approval process is completed.

If NASA is forced to scale back on the scope of the mission, then a prioritized descope path has been developed in which the scientific and engineering capabilities can be resized to meet resources and programmatic needs. In this approach, a prioritized descope path (**Table 1.4-2**) was defined through the JJSDT, which reflects the combined insight of both the science and the engineering teams. Note that there are many reasons why it becomes necessary to take descopes. The actual order of descopes would be a function of the reasons a descope is required. If all descopes are taken, the NASA JEO floor mission would carry 7 instruments and would have more limited tour and Europa orbital phases. Because of the independence of the launches, the NASA-only mission is identical

Table 1.4-1. *The robustness of the Europa Jupiter System Mission elements have significant science complementary capability.*

	Jupiter Ganymede Orbiter	Jupiter Europa Orbiter 2008 Baseline	Jupiter Europa Orbiter 2008 Floor
Launch Vehicle	Ariane 5 ECA	Atlas V 551	Atlas V 541
Launch Month/Year	3/2020	2/2020	2/2020
Trajectory	VEEGA	VEEGA	VEEGA
Flight time to Jupiter (years)	6	6	6
Time in Jovian tour	28 months	30 months	20 months
Ganymede/Europa orbital lifetime	8.5 months	9 months	3.5 months
Number of Instruments including Radio science	11	11	7
Power source	Solar Arrays	5 MMRTG	5 MMRTG
Data volume	1.0 Tbits	4.5 Tbits	3.0 Tbits
Margins:			
Mass	>30%	43%	44%
Power	Not Available	33%	33%
Cost Reserve on Phases B-D	Not Available	37%	37%
Instruments:			
Laser Altimeter (LA)	X	X	X
Radio Science	X	X both ways Ka both ways USO	X both ways Ka down only
Ice Penetrating Radar (IPR)	X	X	X
Vis-IR Spectrometer (VIRIS)	X	X	Partial
Ultraviolet Spectrometer (UVS)	X	X	
Ion and Neutral Mass Spectrometer (INMS)	X	X	
Thermal Instrument (TI)	X	X	
Narrow Angle Camera (NAC)	-	X	
Wide-Angle Camera (WAC)	X	Combined	Combined
Medium-Angle Camera (MAC)	X		
Magnetometer (MAG)	X	X	X
Particle and Plasma Instrument (PPI)	X	X	Partial
Sub milliter Wave Sounder	X	-	-
Instrument Mass CBE (kg): (without shielding)	*77 kg*	*106 kg*	*61 kg*

to the JEO baseline mission and the descope path would be the same. The comparison of the JGO, JEO baseline and the JEO floor are shown in **Table 1.4-1**.

While the ultimate goal of JEO is to orbit Europa, its science scope is the entire Jovian system. Similarly, JGO will investigate the Jovian system, Callisto, and ultimately orbit Ganymede. Observations of the Jupiter system by the two flight elements will be both complementary and synergistic. A representative mission scenario is included in **Figure 1.4-1**.

Launched independently in early 2020, JEO and JGO would use chemical propulsion and Venus-Earth-Earth gravity assists to arrive at Jupiter ~6 years later. Although launch opportunities exist nearly every year, the mass delivered and flight times to Jupiter vary and can be traded (§5). After insertion into Jupiter orbit, both flight systems will perform tours of the Jupiter system using gravity assists of the Galilean satellites to shape their trajectories.

JEO enters the Jupiter system, using Io for a gravity assist prior to JOI. This strategy increases in the delivered mass to Europa by significantly decreasing the required JOI propellant in trade for a modest increase in the radiation shielding of the flight system. The JEO mission design features a 30-month Jupiter system tour which includes 4 Io flybys (including one at 75 km), 9 Callisto flybys (including one near-polar), 6 Ganymede flybys (including four at <1000 km), and 6 Europa

Table 1.4-2. *Final descope order based on science priorities identified by the JJSDT*

Descope Order	Descope Item
1	Ka-band Up (Ka transponder req.)
2	Color on the Narrow Angle Camera
3	Energetic particle capability
4	Ultra Stable Oscillator
5	Ion and Neutral Mass Spectrometer
6	OpNav Functionality
7	Reduce Europa Science Phase by 5.5 month
8	6 Interdisciplinary scientists
9	Thermal Instrument
10	Ultra Violet Spectrometer
11	ATLAS V 551 to 541
12	Tour Phase reduced by 10mo
13	Hybrid Soldi State Recorder
14	Descope IR Capability (Reduce to 0.9 – 5 μm, with decreased spatial and spectral resolution)
15	Narrow Angle Camera

flybys (including 3 early flybys at low altitude) along with ~2.5 years observing Io's volcanic activity, and Jupiter's atmosphere, magnetosphere, and rings. JEO enters orbit around Europa and spends the first month in a 200 km circular orbit and then descends to a 100 km circular orbit for another 8 months (**Figure 1.4-2**). The mission will end with impact onto Europa.

JGO uses a Ganymede gravity assist prior to JOI, thereby avoiding the main radiation belts of Jupiter. JGO's initial orbit is 13 × 245 R_J. After a ~10-month tour through the Jupiter system with close flybys of Ganymede and a couple of Callisto flybys, measuring the Jovian magnetosphere, and monitoring Jupiter, JGO begins a campaign of frequent, resonant flybys of Callisto for a total of 19 flybys. After ~1 year in this resonant orbit with Callisto, JGO moves to Ganymede and soon enters into an elliptical polar orbit (200 × 6000 km) for 80 days, collecting data and making measurements of Ganymede's magnetosphere. Afterward, JGO enters a 200 km near-polar circular orbit for high resolution observations of Ganymede for 180 days (**Figure 1.4-3**). The mission will end with impact onto Ganymede.

1.5 Launch Flexibility

Independent developments and launches create a very flexible implementation with multiple options for obtaining significant stand alone, complementary, and synergistic science to meet the science objectives.

The launches of JEO and JGO are *not* dependent on each other. Moreover, numerous parameters in the trajectory designs provide flexibility to alter interplanetary flight times, Jupiter tour lengths, and orbital insertion timing to adjust the overlap of the two flight systems in orbit at Jupiter. If one partner is unable to deliver its flight element or runs into significant development schedule delay, then the other flight element can be launched without waiting for the other element and still deliver a rich and exciting science mission.

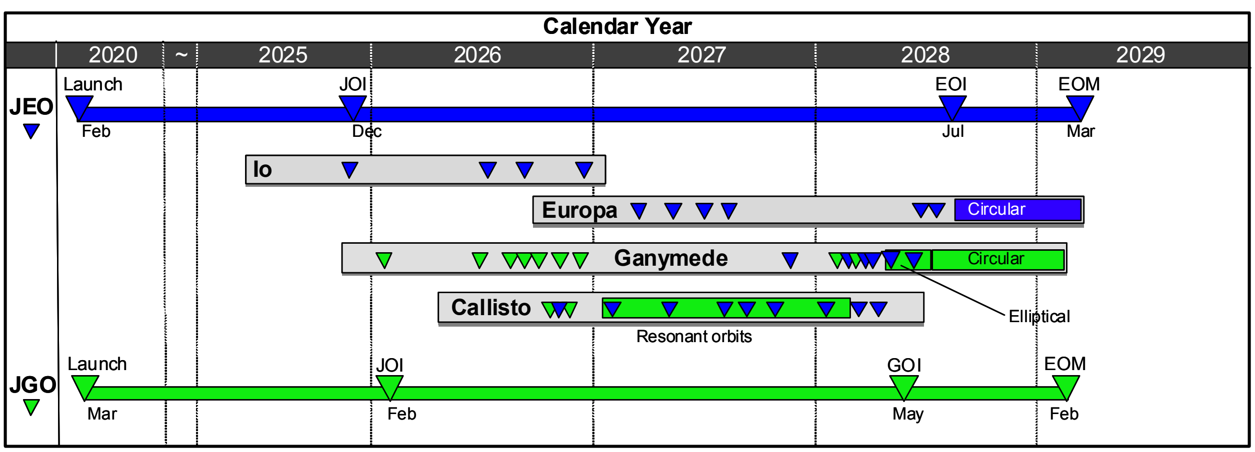


Figure 1.4-1. *The notional timeline for EJSM assumes JEO and JGO launches one month apart in 2020. The resulting possible synergistic observations of magnetospheric and other dynamic phenomena is unprecedented in planetary exploration.*

Figure 1.4-2. *The JEO flight system uses radioisotope power and delivers a complement of 11 instruments to explore Europa and the Jupiter System.*

1.6 Cost and Schedule

An implementation with specific attention to designing for the radiation and planetary protection requirements balances risk, cost and science.

Both NASA and ESA have estimated the costs for their deliverable portions of the EJSM. The estimation methods used by each agency are specific to the mission concept development process within the agency. NASA has extensively studied a mission to the Jupiter system and Europa for several years and is able to provide a fairly high fidelity cost estimate with element costs provided by the implementation organizations and reviewed by independent cost review boards.

The JGO cost estimate is classified, according to the ESA Cost Engineering Chart of Services (Issue 3), as Class 4 of a Moderate Complexity project, performed in a Normal time frame.

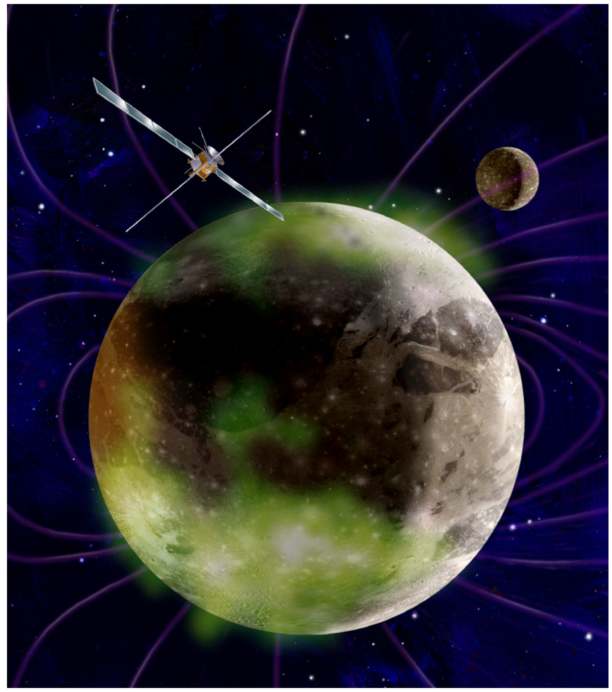


Figure 1.4-3. *By staying away from the highest radiation areas in the Jupiter system, JGO is able to use solar arrays to power a complement of 11 instruments and return ~1.0 Tbit of scientific data.*

1.6.1 NASA Costs

The current baseline JEO mission concept lifecycle cost estimate, Phase A through F, is $3.8B (RY) ($2.7B [FY07]). Reserves were applied to all costs, excluding the launch vehicle, at 10% for Phase A, 37% for Phases B–D, and 15% for Phases E and F. Early funding for additional support to the Instrument Announcement of Opportunity and radiation and planetary protection risk mitigation has been included in the Pre-Phase A risk mitigation and project formulation activities which are estimated at $38M (RY).

The Project cost assumes it would be categorized as a Class A via NPR 8705.4, “Risk Classification for NASA Payloads”, and as a Category 1 Project per NPR 7120.5D “NASA Space Flight Program and Project Requirements”. The estimates represent the full life cycle and conservatively assume that all engineering and assemblies and individual instruments will be re-designed to mitigate radiation and planetary protection risks (no box heritage assumed). No offsets have been taken for potential domestic or foreign contributions. Approximately 32% of the total mission costs go directly into the science community.

1.6.2 ESA Costs

In the current configuration the JGO will be within the Cosmic Vision L-Class mission cost estimate of 650M€. This estimate includes costs for the JGO flight element, the Ariane 5 launch, and ground segment and operations. It excludes the cost for the scientific instruments which are provided by industry or science institutes in ESA member states and funded nationally.

1.6.3 High Level Schedule

The development schedules for JEO and JGO are based on the standard development approaches used by NASA and ESA. The JEO schedule was developed in accordance with NPR7120.5D with specific considerations to reduce development risk associated with the challenging and time consuming radiation and planetary protection design developments. This schedule is shown in **Figure 1.6-1**.

1.7 Scope of FY08 Phase II Studies

The 2008 NASA JEO study focused on three specific areas: refining the NASA mission concept, reducing risk and integrating with ESA. The JEO mission concept was reviewed and updated to incorporate additional Jupiter System science and to take advantage of technology maturation. The resulting concept provides a mature evolution from previous concepts which can provide scientists with a vast amount of information to address both the specific JEO Goal and Objectives and the Decadal Survey science. The model payload described herein only takes advantage of publically available information allowing innovative or proprietary concepts to only enhance the mission capabilities. The 2008 concept is mature and can only be summarized for this report. Because of space constraint, much of the detail has had to be left out of this report and the focus is on communicating the basic concepts and key results. To more fully understand the current concept, the reports from 2006 and 2007 should be examined as well as the reports discussed and referenced in the appendices.

The 2008 study risk reduction activity resulted in a detailed plan for a multi-year risk mitigation approach and in the delivery of 27 design documents and tutorials which potential providers can use to mitigate the risk to their designs (§4.5 and Appendix F). An Instrument Workshop was held in June 2008 to engage potential instrument providers in the aspects of design which are most important. Many of these deliverables have been made public via the Outer Planets Flagship Mission website http://opfm.jpl.nasa.gov. Several of the documents are ITAR sensitive and publically releasable versions are in the process of being made available. Additional, design information is planned for public release during Pre-Phase A activities to reduce risk early in the project development phases to contain cost growth and risk.

The final activity for 2008 was the integration of JEO with the ESA *Laplace* concept into the EJSM. The JJSDT found a very natural partitioning of science with the ESA flight element complementing JEO's science while concentrating on Callisto and Ganymede. The allocation of primary focus allows both organizations to develop mission concepts within their experience base which can be flown independently to achieve

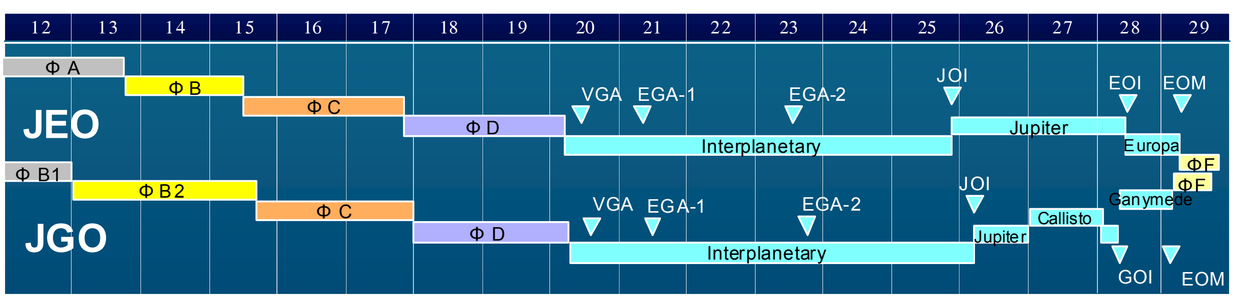


Figure 1.6-1. The concurrent but independent development of the JGO and JEO flight elements allow overlapping primary Jupiter System science enabling unprecedented observations of a single phenomenon from two different vantage points.

spectacular science, or in concert to achieve breathtaking science where the combination is greater than the sum of its parts.

1.8 Summary

The exploration of the Jupiter System is invaluable for providing insights our own solar system's evolution and into planetary architecture and habitability throughout the universe. For these reasons, both NASA's Solar System Exploration Decadal Survey and ESA's Cosmic Vision strategic document emphasize the exploration of the Jupiter system to investigate the emergence of habitable worlds.

Both the NASA-only and the NASA/ESA collaborative approach to Jupiter system and Europa/Ganymede exploration make the next giant leap in solar system understanding possible with a well-defined cost and risk posture for NASA. With better instruments, more focused tour objectives, extended time to study Io, Callisto, Europa, and Ganymede up close, and over three orders of magnitude more data return, JEO and JGO provide the opportunity to radically advance the knowledge of the Jupiter System and its relationship to the emergence of habitable worlds around gas giants.

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2. SCIENCE GOALS AND OBJECTIVES

2.1 The Europa-Jupiter System Mission: Overview

*Jupiter is the archetype for the giant planets of our solar system, and also for the numerous planets now known to orbit other stars. Jupiter's diverse Galilean satellites—three of which are believed to harbor internal oceans—are the key to understanding the habitability of icy worlds. Thus, the Joint Jupiter Science Definition Team (JJSDT) has identified **"The Emergence of Habitable Worlds Around Gas Giants"** as the overarching theme for a combined NASA-ESA mission to Jupiter and the Galilean satellites.*

Since the first extrasolar planets were detected in the late 1980s, the pace of discovery has increased tremendously [e.g., *Marcy et al. 2005*] and 10% of all sun-like stars may have planets. With existing discovery techniques, most of the known extrasolar planets are giants, much more akin to Jupiter than to Earth. Many Jovian planets are expected to have large icy satellites that formed in their circumplanetary disks, analogous to Jupiter's Galilean satellites.

The Galilean satellites Europa and Ganymede are both believed to be geologically active and to harbor internal saltwater oceans. They are straddled by Io and Callisto—key end-members in composition, activity level, and evolutionary state—which tell of the origin and evolution of the Jupiter system. If extrasolar planetary systems are similar, then icy satellites oceans may be much more abundant than Earth-like surface oceans which require very specialized conditions to exist.

The two Voyager spacecraft carried out the first detailed reconnaissance of the Jovian system as part of their "Grand Tour" of the outer solar system. The Jupiter-orbiting Galileo spacecraft returned a wealth of data about the Jovian system and the Galilean satellites, but was handicapped by the failure of its high-gain antenna to open. Galileo's subsequent data rate was orders of magnitude less than planned, resulting in a significant reduction in return of scientific data. The New Horizons spacecraft recently made a single flythrough of the system, making distant satellite and Jupiter observations.

A dual-spacecraft Europa-Jupiter System Mission (EJSM) affords a new opportunity for detailed scrutiny of the archetype gas giant planet and unprecedented study of its four diverse large satellites. It is invaluable for the insights it can provide into our own solar system and into planetary architecture and habitability throughout the universe. For these reasons, both the NASA-commissioned National Research Council (NRC) Solar System Exploration Decadal Survey [*2003*] and the European Space Agency's Cosmic Vision strategic document [*ESA 2005*] emphasize the exploration of the Jupiter system to investigate the emergence of habitable worlds.

2.1.1 The Joint Jupiter Science Definition Team (JJSDT) Process

Early in 2008, NASA and ESA appointed the Joint Jupiter Science Definition Team (JJSDT) as part of the EJSM study, drawing on the international scientific community (membership as described in detail in §6.1). Members were identified to represent the

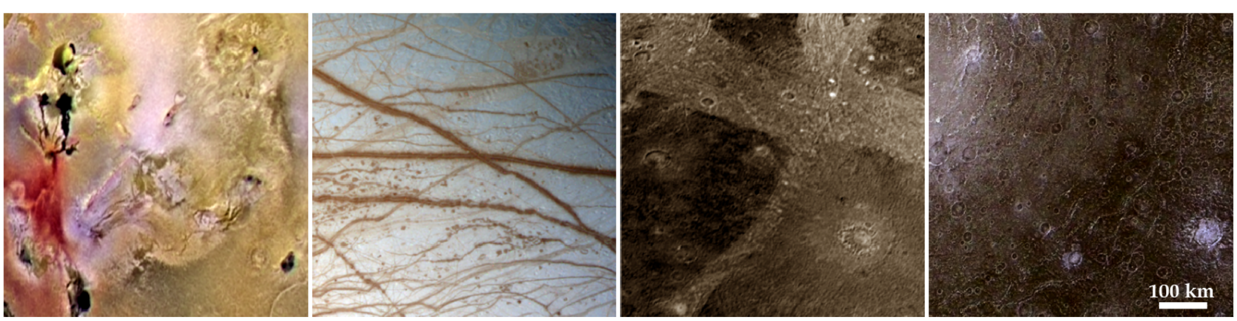

Figure 2.1-1. *The very diverse surfaces of the four Galilean satellites—Io, Europa, Ganymede, and Callisto—shown to a common scale. The level of geological activity and the degree of tidal heating decrease significantly with distance from Jupiter. The satellites provide a natural laboratory for understanding processes that control the emergence of habitable worlds around gas giants.*

broad science topics potentially to be addressed by EJSM, including individuals who had previous experience with planetary mission planning and operations. The JJSDT was co-chaired by Jean-Pierre Lebreton (who also served as the ESA Study Scientist) and Ronald Greeley; Robert Pappalardo served as the Study Scientist representing NASA.

The JJSDT was responsible for identifying the science goals, objectives, investigations, and nominal measurements to be made by EJSM, all in close coordination with the engineering and technical members of the study team. This coordination was critical in the design of the joint mission, ensuring that the science aspects were feasible, and that the technologists understood the scientific motivations for specific mission elements. The JJSDT process involved reviewing previous study documents from NASA, the NRC, ESA, and community assessments, including those from the Outer Planet Assessment Group (OPAG), and building on the current state of knowledge of the Jupiter system with a focus on Europa and Ganymede. The JJSDT met seven times (twice in Europe) and held teleconferences throughout the study period to carry out its charge. In addition, "splinter groups" involving subsets of the JJSDT met to address specialized topics, such as astrobiology and the Jupiter magnetospheric environment. At some meetings, scientists and technologists who were not part of the study team were invited to give presentations and provide additional expertise on relevant topics (§6.1).

Comments and input to the study were solicited from the wider planetary science community through formal presentations at two OPAG meetings (Boulder, Colorado in March 2008 and Tempe, Arizona in November 2008), and at various workshops, including a Jupiter-Europa International Science Workshop in Frascati, Italy in April, 2008, and an Outer Planet Flagship Mission Instrument workshop in Monrovia, California in June 2008. In addition, posters and presentations were given at various scientific meetings, including the Division of Planetary Sciences, the Geological Society of America, and the Lunar and Planetary Science Conference.

2.1.2 EJSM Theme, Goals, and Objectives: Overview

The overall EJSM theme of "**The Emergence of Habitable Worlds Around Gas Giants**" is addressed by specific objectives on the nature and origin of the Jupiter system, especially its satellites, building on previous missions and anticipated measurements from Juno. EJSM addresses the Jupiter system as a whole, with a primary focus on in-depth comparative analysis of the ice-rich worlds Europa and Ganymede. This includes characterizing the satellites' internal oceans, their current and past environments, their surface and near-surface compositions, and their geological histories.

Europa is essentially a rocky world with an outer ~100 km water-rich shell, comprised of a relatively thin icy crust above a saltwater ocean. Ganymede is believed to have a liquid ocean sandwiched between a thicker ice shell above and high-density ice polymorphs below, more typical of volatile-rich satellites. This pair of objects provides a natural laboratory for comparative analysis of the nature, evolution, and potential habitability of icy worlds.

EJSM has been crafted to include a NASA Jupiter Europa Orbiter (JEO) and an ESA Jupiter Ganymede Orbiter (JGO), as illustrated in **Figure 2.1-2**. The primary focus of NASA's JEO is Europa, but the science return encompasses the entire Jovian system by flybys of Io, Ganymede and Callisto, along with ~2.5 years observing Jupiter's atmosphere, magnetosphere and rings. Similarly, the primary focus of ESA's JGO is Ganymede, but it will include detailed investigation of Callisto, and its focused observations of the Jupiter system will complement those of JEO. Each flight system element has its own science goal(s), objectives, investigations, and measurements and concentrates on its own primary targets, while including overlapping science objectives (**Table 2.1-1**). While JEO and JGO are complementary and synergistic (see §2.6.2), both are designed as "stand-alone" mission elements, as a contingency.

The philosophy for accomplishing Jupiter system science with JEO is to emphasize that Jupiter system science that pertains directly or indirectly to the overall JEO goal of "Explore Europa to investigate its habitability"

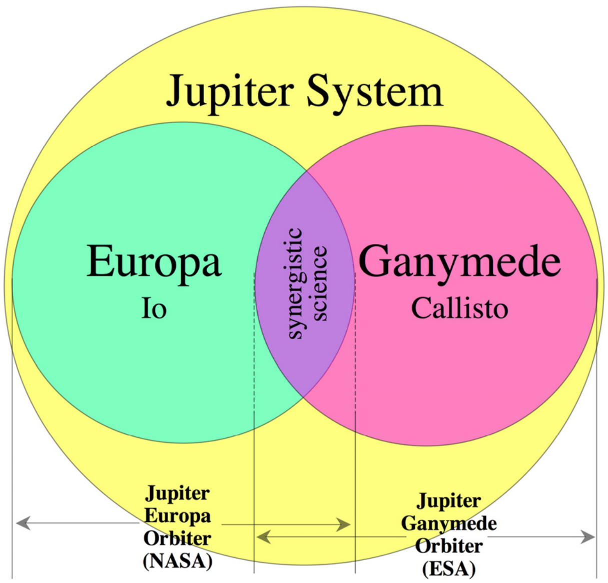

Figure 2.1-2 *The Europa-Jupiter System Mission (EJSM) has two spacecraft, each with specific scientific targets, and with overlapping science objectives. The NASA Jupiter Europa Orbiter (JEO) and the ESA Jupiter Ganymede Orbiter (JGO) each have satellite-specific objectives that complement each other, and are encompassed by and thus overlap with Jupiter system science, which is addressed by both flight systems.*

(**Table 2.1-1** and §2.4.1). Other Jupiter system science, though not strictly pertinent to Europa's habitability, is pertinent to the overarching theme of EJSM: "The emergence of habitable worlds around gas giants." Thus, JEO embraces all of Jupiter system science, while emphasizing that pertinent to Europa's habitability.

A Jupiter Magnetospheric Orbiter (JMO) is also being considered by the Japanese Space Agency (JAXA). If it comes to fruition, JAXA's JMO has the potential to focus on particles and fields observations of the Jovian magnetosphere, further increasing the overall mission synergy.

2.1.3 EJSM Science Section Purpose and Overview

In its entirety, this report emphasizes the science and implementation of the NASA JEO element of the EJSM. Overall, §2 summarizes the science rationale and notional implementation for the EJSM, notably the JEO element.

In §2.2, Europa's significance as the archetypical icy satellite is established, and previous recommendations are reviewed regarding the importance of Europa as a target for exploration, along with the Jovian system.

The current state of knowledge about Europa, its sibling satellites, and the many Jupiter system components are reviewed in §2.3. Six overarching scientific objectives are discussed, with the first five focusing on Europa: (1) Habitability, (2) Ocean and Interior, (3) Ice Shell, (4) Composition and Chemistry, (5) Geology, and (6) the Jupiter System. Some key scientific questions are identified, which can be addressed by the EJSM.

In §2.4, investigations and measurements are outlined for each of the six scientific objectives, relating the EJSM to focus areas laid out in recent guiding documents from NASA and the National Research Council. The scope and extent of investigations that are needed to definitively answer outstanding questions about Europa and the Jupiter System are discussed in detail, and this information is summarized in a comprehensive science traceability matrix.

Science implementation §2.5, shows how the investigations and measurements for each of the six scientific objectives will be accomplished by the EJSM. A planning payload, mission constraints, and data acquisition strategy are outlined. The science value of the investigations are evaluated.

In §2.6, the particular benefits of having two complementary and synergistic elements of the EJSM—JEO and JGO—are discussed. The science goals, objectives, and implementation strategy of JGO are discussed and opportunities for synergistic science that can be accomplished by the two EJSM spacecraft are identified.

Finally, §2.7 summarizes the relationship of EJSM to the recommendations of the NRC planetary Decadal Survey [*SSES 2003*].

2.2 The Relevance of Europa Exploration

Nearly 400 years after Galileo Galilei's discovery of Jupiter's moons advanced the Copernican Revolution, one of these moons—Europa—has the potential for discoveries just as profound.

Table 2.1-1. Theme, Goals, Objectives of the Europa Jupiter System Mission and Its Flight Elements

EJSM Theme:	The emergence of habitable worlds around gas giants	
Element:	**JEO**	**JGO**
Goal(s):	Explore Europa to investigate its habitability	How did the Jupiter system form? How does the Jupiter system work? Does the Jupiter system harbor a habitable world?
Objectives:	A. **Ocean:** Characterize the extent of the ocean and its relation to the deeper interior. B. **Ice Shell:** Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange. C. **Chemistry:** Determine global surface compositions and chemistry, especially as related to habitability. D. **Geology:** Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration. E. **Jupiter System:** Understand Europa in the context of the Jupiter system.	A. **Ganymede:** Characterize Ganymede as a planetary object including its potential habitability. B. **Satellite System:** Study the Jovian satellite system. C. **Jupiter:** Study the Jovian atmosphere. D. **Magnetosphere:** Study the Jovian magnetodisk /magnetosphere E. **Jupiter System:** Study the interactions occurring in the Jovian system.

Europa's icy surface (**Figure 2.2-1**) is thought to hide a global subsurface ocean with a volume more than twice that of Earth's oceans, and with temperature, pressure, and composition that are likely within the constraints of known life on Earth. Europa's surface is young, with an estimated age of about 60 million years [*Schenk et al. 2004, Zahnle et al. 2008*], implying that it is probably geologically active today. The essential elements required by life have fallen onto Europa throughout solar system history, are potentially still created by radiation chemistry at its surface, and may pour from vents at the ocean's deep bottom [*Baross and Hoffmann 1985, Pierazzo and Chyba 2002*]. On Earth, microbial extremophiles take advantage of environmental niches arguably as harsh as those within Europa's subsurface ocean [*Kelley et al., 2005, Deming, 2002*]. If the subsurface waters of this Galilean moon are eventually found to contain life, the discovery would spawn a scientific revolution in understanding of life in the universe.

2.2.1 Europa and the Galilean Satellites in the Emerging Context of Icy Satellite Oceans

It is now recognized that oceans probably exist within four of the Solar System's large moons (**Figure 2.2-2**). This includes the three icy Galilean satellites—Europa, Ganymede, and Callisto—as well as Saturn's large moon Titan. Tiny Enceladus at Saturn also might have a global ocean or localized sea. Among these ocean worlds, Europa is uniquely Earth-like, because its ocean is in direct contact with

Figure 2.2-1. *Europa's surface shows a landscape scarred by tectonic and cryomagmatic events. This image of the Conamara Chaos region at 11 m/pixel shows how parts of the surface have been broken up into giant plates, an event which occurred in recent geological history.*

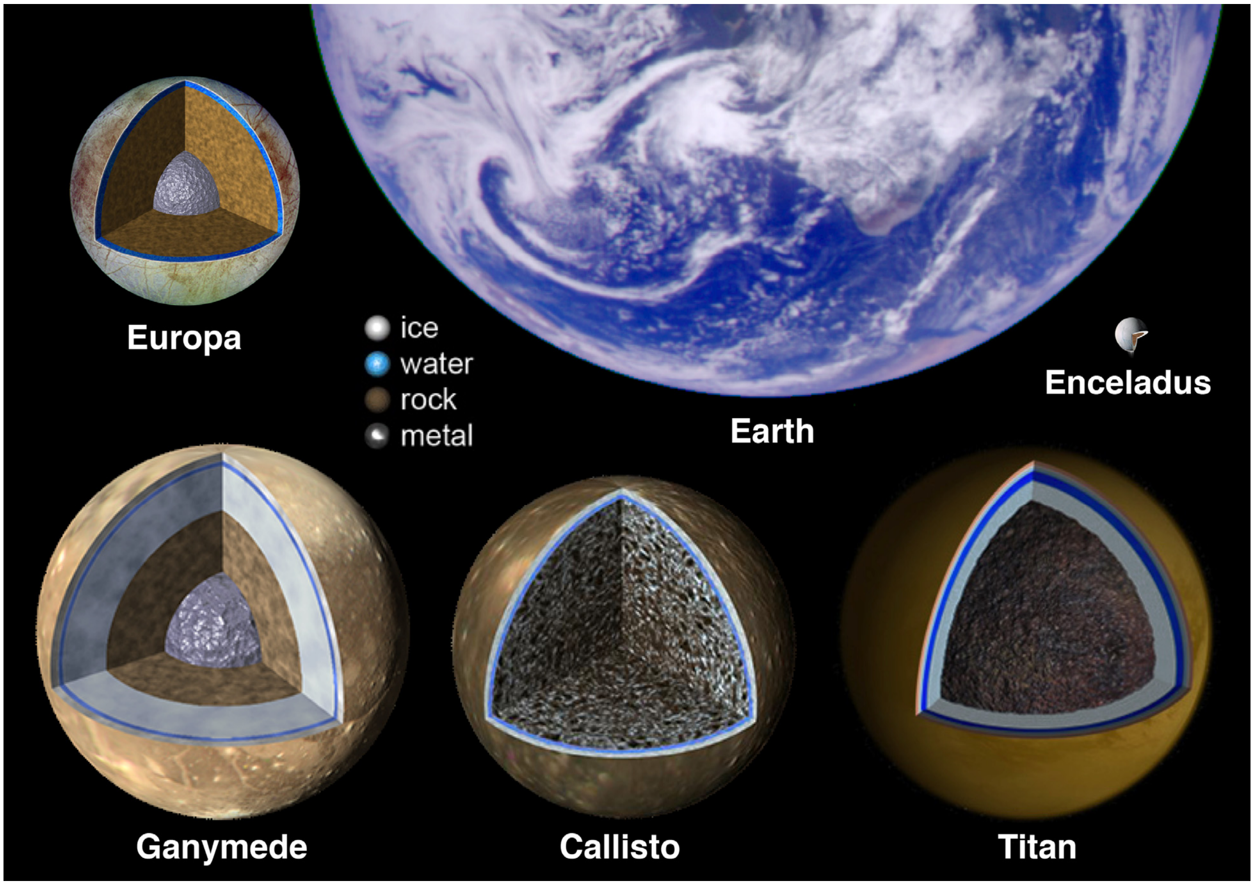

Figure 2.2-2. *The Solar System's ocean worlds. Europa is unique among the large icy satellites in that its ocean is in direct contact with the rocky mantle below. Thus like Earth's ocean, Europa's mantle may supply chemical nutrients directly to the water to support life. In contrast, the probable subsurface oceans of Ganymede, Callisto, and Titan are sandwiched between ordinary ice above and higher-density ices below, precluding direct input of nutrients from the mantle. An active area of research is whether tiny Enceladus contains an ocean. Each planetary body and its internal structure are shown approximately to scale.*

its mantle. This is in stark contrast to the larger moons Ganymede, Callisto, and Titan, which have much greater ice content, meaning that their oceans are sandwiched between ordinary ice above and higher-density ices below. Galileo magnetometer data indicate induced fields at both Ganymede and Callisto, indicating ocean layers tens of kilometers thick beneath about 150 km of ice [*Kivelson et al. 2004*], consistent with the expected depth to the ice-water boundary in these moons. Because Callisto is not tidally heated, it might require a small amount of interior ammonia to maintain an ocean within.

It is probable that Saturn's large moon Titan has a subsurface ocean, based on indications of nonsynchronous rotation of Titan's surface [*Lorenz et al. 2008*]. Modeling suggests that this is likely an ammonia-water ocean sandwiched between ordinary ice above and high-pressure ice polymorphs below [*Tobie et al. 2005*], rather than being in direct contact with Titan's mantle, like the oceans of Ganymede and Callisto. Titan might have internal activity and icy volcanism [e.g., *Lopes et al. 2007*] like Ganymede, or it might be internally dead like Callisto [*Moore and Pappalardo 2008*]. The Cassini spacecraft has recently confirmed that Titan also has surface lakes of ethane and methane [e.g., *Stofan et al. 2007*]. Some have speculated that exotic life might be able to exist in such hydrocarbon lakes [*Schulze-Makuch and Grinspoon 2005, McKay and Smith 2008*], though reaction kinetics at ~95 K make this seem very unlikely. Further Cassini observations—expected to continue well into the next decade—will investigate the nature of Titan's surface and subsurface, placing firmer constraints on its interior structure and level of geological activity.

Saturn's tiny moon Enceladus shows spectacular jets of water vapor and ice grains streaming from its surface, and emits measurable heat from its south polar region [*Porco et al. 2007*, *Spencer et al. 2007*]. It has been suggested that pockets of water might exist in the shallow subsurface of Enceladus, perhaps only a few tens of meters down [e.g., *Porco et al. 2007*]. Alternatively, heat to volatilize ice may be generated by shear heating, with tidal flexing causing the opposing sides of surface faults to grind back and forth against each other [*Nimmo et al. 2007a*], similar to a popular model for explaining the formation of ridges on Europa (§2.3.5). Either way, an ocean or sea may lie deep within Enceladus. Recent work has considered that Enceladus may represent a habitable environment [*Parkinson et al. 2008*, *McKay et al. 2008*], but the existence, composition, and long-term stability of an ocean within Enceladus remains uncertain. Ongoing Cassini observations and geophysical modeling are continually improving understanding of the source of the plumes, and the implications for liquid water and the habitability of Enceladus.

It is tantalizing to consider whether seas of ethane-methane or cold oceans of ammonia-water could be habitable environments. Such environments could be fascinating places to search for life <u>not</u> as we know it! However, it is much more tractable to focus our initial search on potential habitable environments in icy satellites that are comparable to those in which it is known that biology could work. Experience with life on Earth has shown that carbon-and-water-based life functions quite well throughout a considerable range of temperature, pressure, and chemical regimes.

The contemporary ocean of Europa is believed to provide just the right environment for icy world habitability (§2.3.1), so Europa is the natural target for the first focused spacecraft investigation of the habitability of icy worlds. Its candidate sources of chemical energy for life, direct mantle contact, relatively thin ice shell, and potentially active geology that brings oceanic material to the surface make it a recognized top priority for exploration. Moreover, Ganymede and Callisto provide two of the three known examples of oceans "sandwiched" between ice layers—although less attractive for habitability, investigating these oceans is important to understanding the evolution of large and volatile-rich icy moons. A Jupiter Europa Orbiter is the first critical step in understanding the variety and potential habitability of icy satellite oceans.

2.2.2 Previous Recommendations Regarding Europa and Jupiter System Exploration

Europa's high astrobiological potential and its complex interrelated processes have been previously recognized by a variety of groups, including the National Research Council (NRC) and NASA, who have noted Europa's extremely high priority for future exploration, and the relevance of the other Galilean satellites. **Table 2.2-1** reviews these recommendations, in order to provide context for the current study, its recommended goals, and the Jupiter Europa Orbiter concept.

There are many high-priority targets for exploration in our solar system, each offering potential for rich science return. Europa continues to top the priority list for the outer solar system because of its scientific potential, especially as it relates to habitability. The scientific foundation for a mission to Europa has been clearly set forth in the NRC Solar System Exploration Decadal Survey [*2003*] (see §2.7). The following sections summarize key aspects of the current state of knowledge, providing the scientific framework for JEO and EJSM.

2.3 Science Background for the NASA Jupiter Europa Orbiter

Although scientific studies of Europa go back to the pre-spacecraft era, understanding of the satellite has increased greatly in the past dozen years, since the Galileo spacecraft made the first close fly-bys of the satellite. In this extended section, the current state of knowledge regarding Europa is summarized. First, the broad cross-cutting focus area of habitability is discussed, followed by the specific scientific objectives of: ocean and ice shell, composition, geology, and the Jovian system.

***Table 2.2-1**. Previous Recommendations Regarding Europa and Jupiter System Exploration*

Committee	Report Title		Reference
NRC Committee on Planetary and Lunar Exploration (COMPLEX)	A Science Strategy for the Exploration of Europa	"[Europa] offers the potential for major new discoveries in planetary geology and geophysics, planetary atmospheres, and, possibly, studies of extraterrestrial life. In light of these possibilities, COMPLEX feels justified in assigning the future exploration of Europa a priority equal to that for the future exploration of Mars."	COMPLEX [1999]
NRC Solar System Exploration (SSE) "Planetary Decadal" Survey	New Frontiers in the Solar System: An Integrated Exploration Strategy	"Europa holds the most promise for increasing current understanding of the biological potential of icy satellites." "The first step in understanding the potential for icy satellites as abodes for life is a Europa mission with the goal of confirming the presence of an interior ocean, characterizing the satellite's ice shell, and understanding its geological history. Europa is important for addressing the issue of how far organic chemistry goes toward life in extreme environments and the question of how tidal heating can affect the evolution of worlds. Europa is key to understanding the origin and evolution of water-rich environments in icy satellites. **The SSE Survey endorses the current recommendations for a mission to orbit Europa**."	SSB [2003]
NRC Committee on Assessing the Solar System Exploration Program (CASSE)	Grading NASA's Solar System Exploration Program: A Midterm Review	"NASA should select a Europa mission concept and secure a new start for the project before 2011."	SSB [2007]
Outer Planets Assessment Group (OPAG)	Scientific Goals and Pathways for Exploration of the Outer Solar System	"OPAG affirms the findings of the Decadal Survey, COMPLEX, and SSES, that Europa is the top-priority science destination in the outer solar system"	OPAG [2006]
NASA Solar System Exploration Strategic Roadmap Committee	2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate	"Europa should be the next target for a Flagship mission." "It is critical to determine how the components of the Jovian system operate and interact, leading to potentially habitable environments within icy moons. By studying the Jupiter system as a whole, we can better understand the type example for habitable planetary systems within and beyond our Solar System."	NASA [2006]
NASA	Science Plan For NASA's Science Mission Directorate 2007–2016	Europa is "an extremely high-priority target for a future mission." "Although oceans may exist within many of the solar system's large icy satellites, Europa's is extremely compelling for astrobiological exploration. This is because Europa's geology provides evidence for recent material exchange between the icy surface and ocean, and the ocean might be supplied from above and/or below with the chemical energy necessary to support microbial life."	NASA [2007]
NASA Astrobiology Roadmap Committee	NASA Astrobiology Roadmap	"[E]xplore the Galilean moons Europa, Ganymede, and Callisto for habitable environments where liquid water could have supported prebiotic chemical evolution or life."	Des Marais et al. [2003]
Cosmic Vision Programme	ESA	"Explore *in situ* the surface and subsurface of solid bodies in the Solar System most likely to host—or have hosted—life." "Study Jupiter in situ…."	ESA [2005]
NASA Vision for Space Exploration	NASA	"[E]xplore Jupiter's moons … to search for evidence of life, [and] to understand the history of the solar system…."	NASA [2004]

2.3.1 Habitability

Europa's subsurface may harbor the key "ingredients" required to be considered a habitable environment: liquid water, a suite of essential elements, and a source of energy.

The likelihood that Europa has a global subsurface ocean hidden beneath a relatively young icy surface has profound implications in the search for past or present life beyond Earth's biosphere. Coupled with the discovery of active microbial life in seemingly uninhabitable terrestrial environments (microbial growth at sustained temperatures below –20°C, in highly concentrated brines, and under conditions of high radiation flux) [*Rothschild and Mancinelli 2001*], Europa takes on new importance as a primary target for exploring habitable worlds. Life as we know it **(Figure 2.3-1)** depends upon liquid water, a photo- or chemical-energy source, complex organics, and inorganic compounds

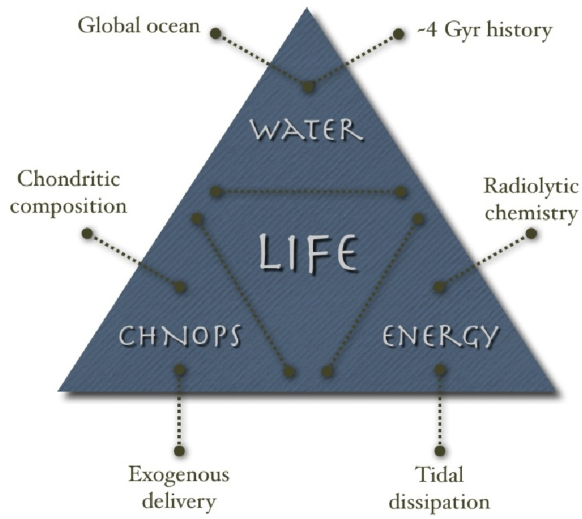

Figure 2.3-1. *Pyramid of habitability. Our present understanding of the conditions for life can be distilled down to three broad requirements: 1) a sustained liquid water environment (Europa's global ocean, which has likely existed for 4 Gyr), 2) essential elements (e.g., C,H,N,O,P,S) that are critical for building life (derived from Europa's primordial chondritic composition, plus exogenous delivery over time), and 3) a source of energy that can be utilized by life (surface radiolytic chemistry, and possible hydrothermal activity driven by tidal heating). The cycling of chemical energy into Europa's ocean over geological time scales is key to understanding habitability of the satellite. (Courtesy Kevin Hand.)*

of nitrogen, phosphorus, sulfur, iron and as many as 70 trace elements. Europa appears to meet these requirements and is distinguished by the potential presence of enormous volumes of liquid water and geological activity that promotes the exchange of surface materials with the sub-ice environment.

If previous life existed on Europa or persists today, two competing hypotheses explain its origin. The first suggests transfer of life to Europa from Earth or other worlds; however, survival seems unlikely given the intense radiation flux on Europa and the ~24 km/s collision velocities of meteorites with its surface. The other hypothesis suggests independent origins of indigenous biology. Despite extensive knowledge about life on Earth, we cannot be certain about when or how many times prebiotic chemistry in our solar system crossed the threshold to a microbiological world. Impact histories likely constrain the persistence of the earliest terrestrial evolutionary lineages to the end of the period of intense bombardment, although deep subsurface chemoautotrophs at kilometer depths could have survived even the largest impact events. Alternatively, the biosphere may have recovered from such cataclysmic events by secondary origins.

2.3.1.1 Europa: Ingredients for Life?

Given current information, we cannot know if life ever existed or persists today on Europa. However we can determine whether extant conditions are capable of supporting living organisms. Key to this question is the occurrence of liquid water beneath the icy surface and whether the geological and geophysical properties of Europa can support the synthesis of organic compounds and provide the energy and nutrients needed to sustain life.

Life on Earth occupies ecological niches sufficient in the supply of either chemical or radiation energy. Europa's global ocean has probably persisted from the origin of the jovian system to the present [*Cassen et al. 1982*], although its chemical characteristics likely evolved. Inferences from Europa's young surface and models suggest that an ocean and hydrothermal system may lie beneath a sheet of ice a few to tens of kilometers thick [*Greeley et al. 2004*]. Tidal deformation may drive heating and geological activity within Europa, and there could be brine pockets within the ice associated with impurities, partial melt zones, and clathrates. The potential occurrence of hydrothermal systems driven by tidal heating or volcanic activity could serve as a favorable environment for prebiotic chemistry or sustaining microbial chemotrophic organisms.

Cycling of water through and within the ice shell, ocean, and the permeable upper rocky mantle could maintain an ocean rich with oxidants and reductants necessary for the chemistry of life. In order to address this aspect of Europa's habitability a better understanding of the mantle and ice shell is needed.

Radiolytic chemistry on the surface is responsible for the production of O_2, H_2O_2,

CO_2, SO_2, SO_4, and other yet to be discovered oxidants. At present, mechanisms and timescales for delivery of these materials to the sub-surface are poorly constrained. Similarly, cycling of the ocean water through seafloor minerals could replenish the water with biologically useful reductants. If much of the tidal energy dissipation occurs in the mantle, then there could be significant cycling between the ocean water and rocky mantle. Conversely, if most of the tidal dissipation occurs in the ice shell, then the ocean water could be depleted in the reductants needed for biochemistry. Chemical cycling of energy on Europa is arguably the greatest uncertainty in the ability to assess the habitability of Europa.

2.3.1.2 Investigating Europa's Habitability

Geophysical measurements will set constraints on the potential habitability of Europa. A high priority is to characterize the ocean and its dynamic relationships with the ice shell including the nature of surface-ice-ocean exchange. Assessments of the geochemical environment will directly address the issue of whether the chemistry of Europa is compatible with habitability.

Important remote sensing measurements will focus on relative terrain ages and chemical composition, and on identifying the youngest regions of direct exchange with the ocean. Chemical analyses of these regions, and those known to be older and more radiolytically processed, will allow distinguishing among the variety of chemical signatures anticipated on the surface. Results would lead to understanding the processes which affect the habitability of Europa's ocean.

Any life forms actually in Europa's ocean would consist of microbial chemotrophs capable of synthesizing a vast array of complex organics. The detection of large, complex compounds with diverse functional groups (e.g., with N and P) in the youngest ice, but not in older ices, would be of great astrobiological interest. Were photosynthesis possible in the near surface, detection of related pigments could feasibly provide a biosignature.

Combined geophysical and compositional investigation could yield a strong, compelling case for a habitable subsurface ocean.

2.3.2 Ocean and Interior

Europa is continually flexed as it orbits, tugged and deformed by Jupiter's gravity. The satellite's response of bending, breaking, flowing, heating, and churning, enable the characteristics of its ocean and ice to be inferred. Europa also experiences the varying magnetic field of Jupiter, which generates induction currents in the interior and reveals the conductivity structure through its response. These external influences, in addition to Europa's internal thermal and chemical properties, create the possibility that Europa's interior is volcanically active. Geophysics both dictates and betrays the characteristics of Europa's ocean, as well as its ice shell and deeper interior.

The surface of Europa suggests recently active processes operating in the ice shell. Jupiter raises gravitational tides on Europa, which contribute to thermal energy in the ice shell and rocky interior [*Ojakangas and Stevenson 1989*], produce near-surface stresses responsible for some surface features [*Greeley et al. 2004*], and may drive currents in the ocean. Although relatively little is known about the internal structure, most models include an outer ice shell underlain by liquid water, a silicate mantle, and iron-rich core [*Anderson et al. 1998*]. Means to constrain these models include measurements of the gravitational and magnetic fields, topographic shape, and rotational state of Europa, each of which includes steady-state and time-dependent components. Additionally, the surface heat flux and local thermal anomalies may yield constraints on the satellite's internal heat production and activity. Results can be used to characterize the ocean and the overlying ice shell and to provide constraints on deep interior structure and processes.

2.3.2.1 Gravity

Observations of the gravitational field of a planetary body provide information about the interior mass distribution. For a spherically symmetric body, all points on the surface would have the same gravitational acceleration, while in those regions with more than average mass, gravity will be greater. Lateral variations in gravitational field strength thus indicate lateral variations in internal density structure.

Within Europa, principal sources of static gravity anomalies can be those due to ice shell thickness variations, or topography on the ocean floor, or internal density variations within the silicate mantle. If the ice shell is isostatically compensated, it will only yield very small gravity signatures. Gravity anomalies that are not spatially coherent with ice surface topography are presumed to arise from greater depths.

One of the most diagnostic gravitational features is the amplitude and phase of the time-dependent signal due to tidal deformation [*Moore and Schubert 2000*]. The forcing from Jupiter is well known, and the response will be much larger if a fluid layer decouples the ice from the interior, permitting unambiguous detection of an ocean, and characterization of the ocean and the bulk properties of the overlying ice shell. With an ocean that decouples the surface ice from the rocky interior, the amplitude of the semi-diurnal tide on Europa is roughly 30 m, which is in clear contrast to the ~1 m tide in the absence of an ocean [*Moore and Schubert 2000*]. Because the distance to Jupiter is 430 times the mean radius of Europa, only the lowest degree tides are expected to be detectable. **Figure 2.3-2** illustrates the degree-two tidal potential variations on Europa during a single orbital cycle. The tidal amplitude is directly proportional to this potential.

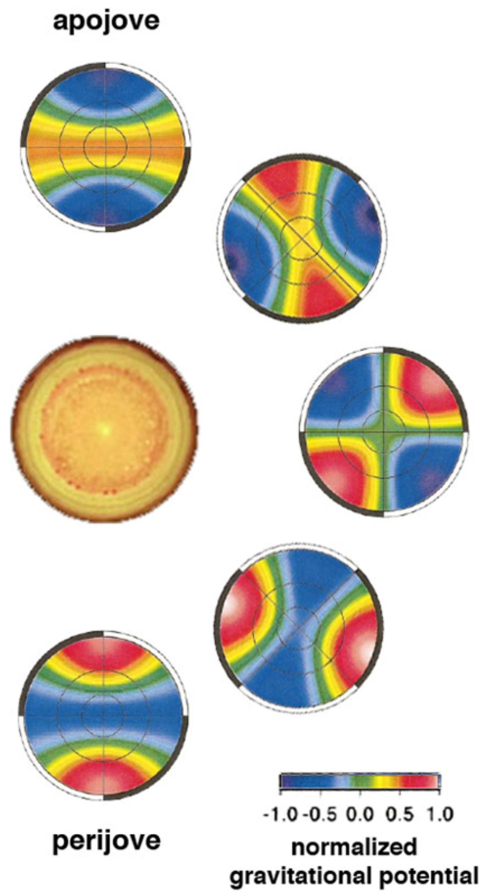

Figure 2.3-2. *Europa experiences a time-varying gravitational potential field as it moves in its eccentric orbit about Jupiter (eccentricity = 0.0094), with a 3.551-day (1 eurosol) period. Europa's tidal amplitude varies proportionally to the gravitational potential, so the satellite flexes measurably as it orbits. In this adaptation of a figure from* Moore and Schubert *[2000], we look down on the north pole of Jupiter as Europa orbits counterclockwise with its prime meridian pointed approximately toward Jupiter. Measuring the varying gravity field and tidal amplitude simultaneously allows the interior rigidity structure of the satellite to be derived, revealing the properties of its ocean and ice shell.*

2.3.2.2 Topography

Characterizing the topography is important for several reasons. At long wavelengths (hemispheric-scale), topography is mainly a response to tides and possibly shell thickness variations driven by tidal heating [*Ojakangas and Stevenson 1989*], and is thus diagnostic of internal tidal processes. At intermediate wavelengths (hundreds of kilometers), the topographic amplitudes and correlation with gravity are diagnostic of the density and thickness of the ice shell. The view of Mars provided by the MOLA laser altimeter [*Zuber et al. 1992*] revolutionized geophysical study of that body, and the same is expected at Europa. The limited topographic information currently available shows Europa to be very smooth on a global scale, but topographically diverse on regional to local scales. At the shortest wavelengths (kilometer-scale), small geologic features will tend to have topographic signatures diagnostic of formational processes.

2.3.2.3 Rotation

Tidal dissipation within Europa probably drives its rotation into equilibrium, with implications for both the direction and rate of rotation. The mean rotation period should almost exactly match the mean orbital period, so that the sub-Jupiter point will librate in longitude, with an amplitude equal to twice the orbital eccentricity. If the body behaves rigidly, the expected amplitude of this forced libration is expected to be ~100 m [*Comstock and Bills 2003*], but if the ice shell is mechanically decoupled from the silicate interior, then the libration could be three times larger. Similar forced librations in latitude are due to the finite obliquity, and are also diagnostic of internal structure in the same way. The rate of rotation will also change in response to tidal modulation of the shape of the body, and corresponding changes in the moments of inertia [*Yoder et al. 1981*].

The spin pole is expected to occupy a Cassini state [*Peale 1976*], similar to that of Earth's Moon. The gravitational torque exerted by Jupiter on Europa will cause Europa's spin pole to precess about the orbit pole, while the orbit pole in turn precesses about Jupiter's spin pole, with all three axes remaining coplanar. The obliquity required for Europa to achieve this state is ~0.1 degree, but depends upon the moments of inertia, and is thus diagnostic of internal density structure [*Bills 2005*].

An advantage of having a wide variety of different geophysical observations, all relevant to the internal structure of Europa, is that they reduce the ambiguity inherent in interpretations of measurements (see **FO-2**).

2.3.2.4 Magnetic Field

Magnetic fields interact with conducting matter at length scales ranging from atomic to galactic. Magnetic fields are produced when currents flow in response to electric potential differences between interacting conducting fluids or solids. Many planets generate their own stable internal magnetic fields in convecting cores or inner shells through dynamos powered by internal heat or gravitational settling of the interior. Europa does not generate its own magnetic field, suggesting that its core has either frozen or is still fluid but not convecting.

Europa, however, is known to respond to the rotating magnetic field of Jupiter through electromagnetic induction [*Khurana et al. 1998, Kivelson et al. 2000*]. In this process, eddy currents are generated on the surface of a conductor to shield its interior from changing external electric and magnetic fields. The eddy currents generate their own magnetic field—called the induction field—external to the conductor. This secondary field is readily measured by a magnetometer located outside the conductor.

The induction technique exploits the fact that the primary alternating magnetic field at Europa is provided by Jupiter, because its rotation and magnetic dipole axes are not aligned. It is now widely believed that the induction signal seen in Galileo magnetometer data [*Khurana et al. 1998*] arises within a subsurface ocean in Europa. The measured signal was shown to remain in phase with the primary field of Jovian origin [*Kivelson et al. 2000*], thus unambiguously proving that the perturbation signal is a response to Jupiter's field.

Although clearly indicative of a Europan ocean, modeling of the measured induction signal suffers from non-uniqueness in the derived parameters because of the limited data. From a short series of measurements, such as those obtained by the Galileo spacecraft, the induction field components cannot be separated uniquely, forcing assumptions that the inducing signal is composed of a single frequency corresponding to the synodic rotation period of Jupiter. Unfortunately, single frequency data cannot be inverted to determine independently both the ocean thickness and the conductivity. Nevertheless, the single frequency analysis of *Zimmer et al.* [*2000*] reveals that the ocean must have a conductivity of at least 0.06 S/m. Recently, *Schilling et al.* [*2004*] determined the ratio of induction field to primary field at 0.96 ± 0.3, leading *Hand and Chyba* [*2007*] to infer that the ice shell is < 15 km thick and the ocean water conductivity > 6 S/m. The large uncertainty in the conductivity estimates of the ocean water results from the poor signal-to-noise ratio of the induction signature obtainable from relatively short segments of Galileo flyby data. Observations from a Europa orbiter could improve the S/N ratio of the induction field by several orders of magnitude.

In order to determine the ocean thickness and conductivity, magnetic sounding of the ocean at multiple frequencies is required. The depth to which an electromagnetic wave penetrates is inversely proportional to the square root of its frequency. Thus, longer period waves sound deeper and could provide information on the ocean's thickness, the mantle, and the metallic core. Electromagnetic sounding at multiple frequencies is routinely used to study Earth's mantle and core from surface magnetic data [*Parkinson 1983*]. Recently, *Constable and Constable* [*2004*] demonstrated that data from orbit can be used for electromagnetic induction sounding at multiple frequencies. In the case of Europa, the two dominant frequencies are those of Jupiter's synodic rotation period (~11 hr) and Europa's orbital period (~85 hr). Observing the induction response at these two frequencies will likely allow determination of both the ocean thickness and the conductivity (see §2.4.2.2).

Some remaining key questions to be addressed regarding Europa's ocean, bulk ice shell properties, and deeper interior include:

- Does Europa undoubtedly have a subsurface ocean?
- What are the salinity and thickness of Europa's ocean?
- Does Europa exhibit kilometer-scale variations in ice shell thickness across the globe?
- Does Europa have a non-zero obliquity and if so, what controls it?
- Does Europa possess an Io-like mantle?

These questions, and how they may be answered by specific measurements, are further discussed in §2.4.2.

2.3.3 Ice Shell

Probing the third dimension of Europa's ice shell is essential to understanding the distribution of subsurface water and processes of ice-ocean exchange, which are key to determining Europa's habitability.

A detailed understanding of the internal structure of the ice shell is essential for unraveling the processes that connect the ocean to the surface. The structure and composition of the surface as observed by remote sensing is the result of material transport and chemical exchange through the shell. The thickness of the current ice shell is unknown, but estimates range from relatively thin (~ few km) to relatively thick (tens of km) *[Billings and Kattenhorn, 2005]*. The ice shell may have experienced one or more episodes of thickening and thinning [*Hussman and Spohn 2004*], directly exchanging material with the ocean at the base. Thermal processing may have also altered the internal structure of the shell through convection or localized melting. In addition, geological processes have altered and deformed the surface and transported material horizontally and vertically within the shell. Exogenic processes such as cratering and regolith formation have influenced the surface and deeper structure. Just as a geologist on Earth uses structural information in order to understand the dynamics of the Earth's crust, three-dimensional sounding of the ice shell will reveal the processes connecting the surface to the ocean.

2.3.3.1 Thermal Processing

The thermal structure of Europa's ice shell (apart from local heat sources) is set by the transport of heat from the interior. Regardless of the properties of the shell or the overall mechanism of heat transport, the uppermost several kilometers is thermally conductive, cold, and stiff. The thickness of this conductive "lid" is set by the total amount of heat that must be transported and thus a measurement of the thickness of the cold and brittle part of the shell is a powerful constraint on the heat production in the interior. The lower, convecting part of the shell (if it exists), is likely to be much cleaner, since regions with impurities should have experienced melting at some point during convective circulation (when the material was brought near the base of the shell) and the melt will segregate downward efficiently, extracting the impurities from the shell [*Pappalardo and Barr 2004*]. Convective instabilities also result in thermal variations in the outer part of the shell that may be associated with features at the surface of Europa (lenticulae and chaos), with scales ranging from 1 to 100 s of km. When warm, relatively pure ice diapirs from the interior approach the surface, they may be far from the pure-ice melting point, but may be above the eutectic point of some material trapped in the lid. This may create regions of melting within the rigid shell above them as the temperature increases above the flattening diapir **(Figure 2.3-3)**. The structural horizon associated with these melt regions would provide a good measurement of the thickness of the conductive layer. Other sources of localized

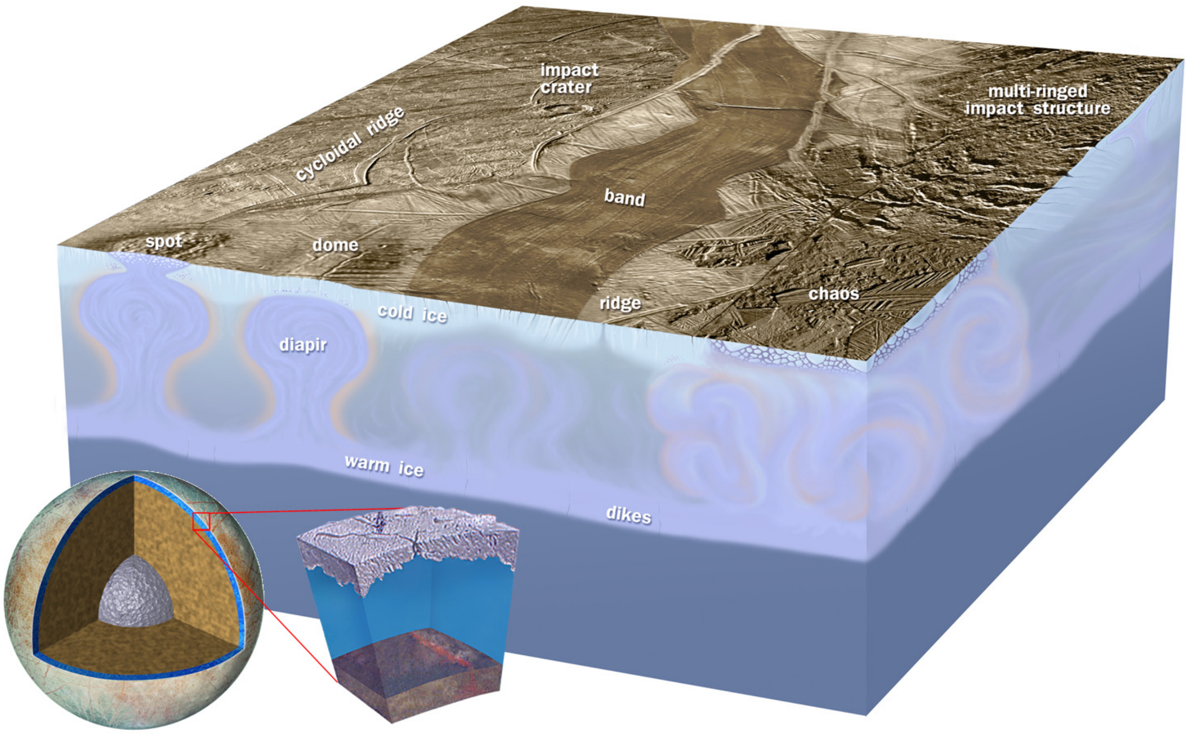

Figure 2.3-3. *Block diagram representation of Europa's ice shell, assuming a thick shell model of possible ice shell processes leading to thermal, compositional, and structural horizons. Convective diapirs (front of block diagram) could cause thermal perturbations and partial melting in the overlying rigid ice. Tectonic faulting driven by tidal stresses (upper surface) could result in fault damage and frictional heating. Impact structures (back right) are expected to have central refrozen melt pools and to be surrounded by ejecta.*

heating such as friction on faults may lead to similar localized melting [*Gaidos and Nimmo 2000*]. High horizontal resolution (a few hundred meters) is required to avoid scale-related biases. The ability to sound through regions of rough large scale terrain will also be essential. Detection of water lenses would require a vertical resolution of at least a few tens of meters.

2.3.3.2 Ice-Ocean Exchange

Europa's ice shell has likely experienced one or more phases of thickening and thinning, as the orbital evolution alters the internal heating due to tides [*Hussmann and Spohn 2004*]. The shell may thicken by processes similar to those for ice that accretes beneath the large ice shelves of Antarctica where frazil ice crystals form directly in the ocean water [*Moore et al. 1994*]. This model is characterized by slow accretion (freezing) or ablation (melting) on the lower side of the icy crust [*Greenberg et al. 1999*]. Impurities present in the ocean tend to be rejected from the ice lattice during the slow freezing process. Temperature gradients in this model are primarily a function of ice thickness and the temperature/depth profile is described by a simple diffusion equation for a conducting ice layer [*Chyba et al. 1998*]. The low temperature gradients at any ice water interface, combined with impurity rejection from accreted ice, would likely lead to significant structural horizons resulting from contrasts in ice crystal fabric and composition. Similarly, the melt-through hypothesis for the formation of lenticulae and chaos on Europa's surface implies that ice will accrete beneath the feature after it forms. This process will result in a sharp boundary between old ice (or rapidly frozen surface ice) and the deeper accreted ice. The amount of accreted ice would be directly related to the time since melt-through occurred and could be compared with the amount expected based on the surface age. Testing these hypotheses will require measuring the depth of interfaces to a resolution of a few hundred meters, and horizontal resolutions of a fraction of any lid thickness; i.e., a kilometer or so.

2.3.3.3 Surface and Subsurface Structure

Europa represents a unique tectonic regime in the solar system, and the processes controlling the distribution of strain in Europa's ice shell are uncertain. Tectonic structures could range from sub-horizontal extensional fractures to near-vertical strike-slip features, and will produce structures associated primarily with the faulting process itself through formation of pervasively fractured ice, and zones of deformational melt, injection of water, or preferred orientation of crystalline fabric. Some faults may show local alteration of pre-existing structure including fluid inclusions or simply by juxtaposition of dissimilar regions through motion on the fault. There are many outstanding questions regarding those tectonic features. A measurement of their depth extent and association with thermal anomalies or melt inclusions would strongly constrain models of their origins. In particular, correlation of subsurface structure with surface properties (length, position in the stratigraphic sequence, height and width of the ridges) will test hypotheses for the mechanisms that form the fractures and support the ridges. The observation of melt along the fracture would make these features highly desirable targets for future *in situ* missions.

Extensional structures observed on Europa (gray bands) may be particularly important for understanding material exchange processes. If the analogy with terrestrial spreading centers [*Pappalardo and Sullivan 1996*] is accurate, the material in the band is newly supplied from below and may have a distinct structure. The origin of the material in the bands may thus be constrained by sounding the subsurface. Bands and ridges typically have length scales of a few kilometers. Horizontal resolutions a factor of ten higher than this would be required to discriminate processes. For extensional structures, the ability to image structures sloping more than a few degrees is also necessary. Additionally, tens of meters of vertical resolution would be required to image near surface melt inclusions.

The impact process represents a profound disturbance of the local structure of the shell. Around the impact site, the ice is fractured and heated, and some melt is generated. The surface around the impact is buried to varying degrees with a blanket of ejecta. Finally, the relaxation of the crater creates a zone of tectonism that can include both radial and circumferential faulting. These processes all create subsurface structures which may be probed by sounding. An outstanding mystery on Europa is the process by which craters are erased from the surface. It may be possible to find the subsurface signature of impacts that are no longer evident at the surface, which would place constraints on the resurfacing processes that operate at Europa. Impact processes affect the structure of the ice shell to different extents depending on the size of the impactor, and it is possible that Europa's subsurface records events which have penetrated the entire thickness of the shell (at the time). Three types of structural horizons are expected to be derived from impact: the former surface buried beneath an ejecta blanket, solidified eutectic melts in the impact structure itself, and impact related fractures (e.g., a ring graben or radial fractures possibly including injected melt). Vertical resolutions on the scales of a few tens to hundreds of meters will be required to identify ejecta blankets and frozen melt pools. Detection of at least the edges of steep interfaces would aid in the identification of radial dikes, buried crater walls and circumferential fractures.

Remaining outstanding questions to be addressed about Europa's ice shell include:

- Is Europa's ice shell very thin and conductive or thick and convecting?
- Is there material transport from the ocean to the near-surface or surface, and vice-versa, and if so, what are the transport processes?
- What are the three-dimensional characteristics of Europa's geological structures?

Discussion of how these questions may be addressed using specific measurements is found in §2.4.3.

2.3.4 Composition and Chemistry

Characterizing the surface organic and inorganic composition and chemistry provides fundamental information about Europa's history and evolution, the properties and habitability of the subsurface and ocean, its interaction with the surface, and the role of exogenic processes.

The composition of Europa's surface records its history and evolution. Surface materials may be ancient, derived through time from the ocean, altered by radiation, or exogenic in origin. Europa's bulk density and current understanding of solar and stellar composition suggest the presence of both water and silicates. It is likely that the differentiation of Europa resulted in mixing of water with the silicates and carbonaceous materials that formed the moon, and resulted in chemical alteration and redistribution, with interior transport processes bringing a variety of materials from the interior into the ocean and up to the surface. The barrage of high-energy particles from Jupiter's magnetosphere leaves an imprint on the surface composition that provides clues to this environment, but can also complicate efforts to understand the formation, evolution and modification of the surface. Finally, surface materials can be incorporated into the subsurface and react with the ocean, or can be sputtered from the surface to form Europa's tenuous atmosphere.

2.3.4.1 Icy and Non-Icy Composition

Compositional information from Earth-based telescopic observations and data from the Voyager and Galileo spacecraft [e.g., *Kuiper 1957, Moroz 1965, Clark 1980, Dalton 2000, McCord 2000, Spencer et al. 2005*] show that the surface of Europa is composed primarily of water ice in both crystalline and amorphous forms [*Pilcher et al. 1972, Clark and McCord 1980, Hansen and McCord 2003*].

The dark, non-icy materials that make up much of the rest of Europa's surface are of extreme interest for unraveling Europa's geological history, and determining their composition is the key to understanding their origin. The spatial distribution and context of these materials at geologically relevant scales, which can be examined by JEO in far more detail than ever before, allows the processes that have formed the surface and the connection between the surface and the interior to be understood. This linkage provides important constraints on the nature of the interior, the potential habitability of sub-surface liquid water environments, and the processes and time scales through which interior materials are transported to the surface. Compositional variations in surface materials may reflect age differences indicative of recent activity, and the discovery of active vents or plumes would show current activity.

The non-ice components are known to include carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen peroxide (H_2O_2) and molecular oxygen (O_2) based on comparison of measured spectra with laboratory studies of the relevant compounds [*Lane et al. 1981, Noll et al. 1995, Smythe et al. 1998, Carlson 1999, 2001, Carlson et al. 1999a,b, Spencer and Calvin 2002, Hansen and McCord 2008*]. Spectral observations from the Galileo Near Infrared Mapping Spectrometer (NIMS) instrument of disrupted dark and chaotic terrains on Europa exhibit distorted and asymmetric absorption features indicative of water bound in non-ice hydrates. Hydrated materials observed in regions of surface disruption (**Figure 2.3-4**) have been suggested to be magnesium and sodium sulfate minerals (**Figures 2.3-5**) that originate from subsurface ocean brines [*McCord et al. 1998b, 1999*]. Alternatively, these materials may be sulfuric acid hydrates created by radiolysis of sulfur from Io, processing of endogenic SO_2, or from ocean-derived sulfates present in these deposits [*Carlson et al. 1999b, 2002, 2005*]. It is also possible that these surfaces are a combination of both hydrated sulfate salts and hydrated sulfuric acid [*Dalton 2000, McCord*

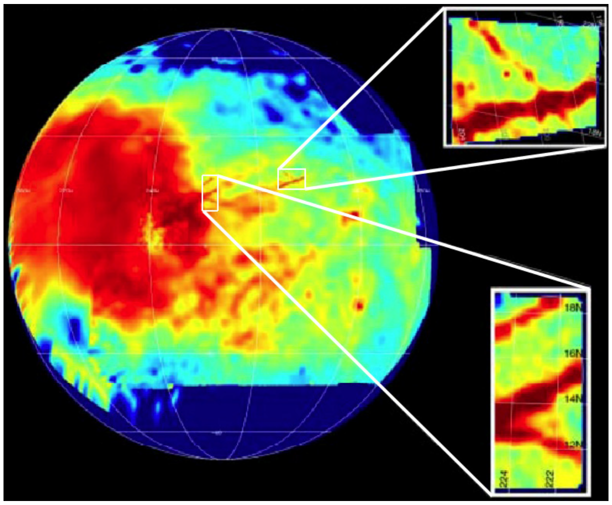

Figure 2.3-4. *The distribution of hydrated materials on Europa (red) correlates with geologically disrupted terrains and triple bands (insets), and with the trailing hemisphere.*

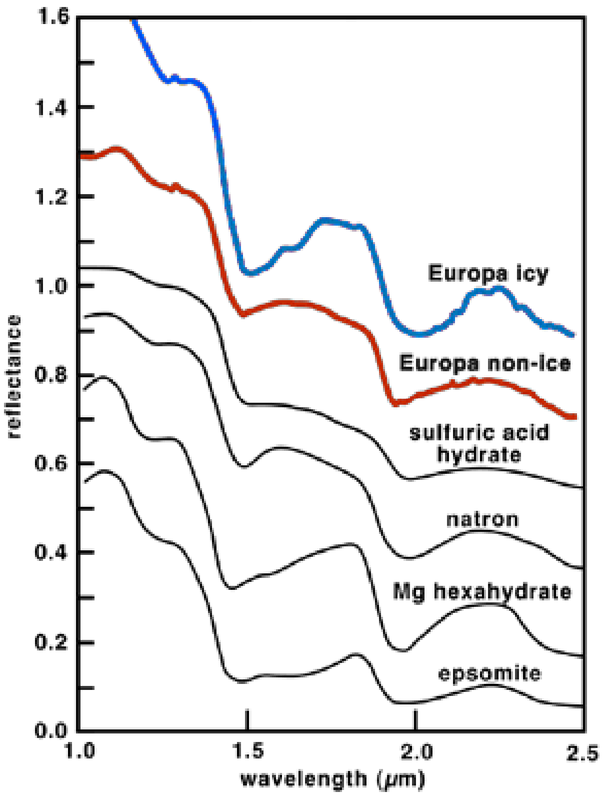

Figure 2.3-5. *Reflectance spectra of hydrated materials on Europa. Candidate materials for Europa's non-ice component include sulfuric acid hydrate (H_2SO_4•nH_2O) and various hydrated sulfate and carbonate salts [*McCord et al. 1999, 2002*].*

et al. 2001, 2002, Carlson et al. 2005, Orlando et al. 2005, Dalton et al. 2005], as suggested by linear spectral mixture analyses of disrupted terrains [*Dalton 2007*]. An ultraviolet absorption feature, discovered in Earth-based disk-integrated observations and HST [*Lane et al. 1981, Noll et al. 1995*] on Europa's trailing hemisphere and linked to bombardment by S^+ ions, was found in Galileo UVS high-resolution observations [*Hendrix et al. 1998, 2002*] to vary in strength with location on the trailing hemisphere and show a correlation with the NIMS-measured asymmetric water ice bands. An important objective of JEO is to resolve the compositions and origins of these hydrated materials.

Hydrated material was also reported in dark areas on Ganymede [*McCord et al. 2001*], which has a much less severe radiation environment than Europa. Such similarities suggest a common origin for these materials. Whether predominantly exogenic or endogenic, the interplay of chemical pathways and physical processes on these worlds can be studied together to better understand each.

Material in the space surrounding Europa also provides compositional clues. *Brown and Hill* [*1996*] first reported a cloud of sodium around Europa, and *Brown* [*2001*] detected a cloud of potassium and reported that the Na/K ratio suggested that endogenic sputtering produced these materials.

A broad suite of additional compounds is predicted for Europa based on observations of other icy satellites, as well as from experimental studies of irradiated ices, theoretical simulations, and geochemical and cosmochemical arguments. Organic molecular groups, such as CH and CN, have been found on the other icy Galilean satellites [*McCord et al. 1997, 1998a*], and their presence or absence on Europa is important to understanding Europa's potential habitability. Other possible compounds that may be embedded in the ice and detectable by high-resolution spectroscopy include H_2S, OCS, O_3, HCHO, H_2CO_3, SO_3, $MgSO_4$, H_2SO_4, H_3O^+, $NaSO_4$, HCOOH, CH_3OH, CH_3COOH and more complex species [*Moore 1984, Delitsky and Lane 1997, 1998, Hudson and Moore 1998, Moore et al. 2003, Brunetto et al. 2005*].

As molecules become more complex, however, their radiation cross-section also increases and they are more susceptible to alteration by radiation. Radiolysis and photolysis can alter the original surface materials and produce many highly oxidized species that react with other non-ice materials to form a wide array of compounds. Given the extreme radiation environment of Europa, complex organic molecules are not expected in older deposits nor in those exposed to higher levels of irradiation [*Johnson and Quickenden 1997, Cooper et al. 2001*]. However, diagnostic molecular fragments and key carbon, nitrogen, and sulfur products may survive in some locales. Regions of lesser radiation (i.e., the leading hemisphere) and sites of recent or current activity would be the most likely places to seek evidence of organic or derived products.

Improved spectral observations at significantly higher spectral and spatial resolution, together with detailed laboratory analyses under the appropriate temperature and radiation environment, are needed to fully understand Europa's surface chemistry. These data will provide major improvements in the identification of the original and derived compounds and the radiation environment and reaction pathways that create and destroy them.

2.3.4.2 Isotopic Constraints

The varying degree of preference for the lighter isotopes in many physical and chemical processes is expected to lead to mass fractionation effects that should be evident in isotopic ratios. Ratios of D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{16}O/^{17}O/^{18}O$, $^{34}S/^{32}S$ and $^{40}Ar/^{36}Ar$, and comparison among them, can provide insights into geological, chemical, and possible biological processes such as planetary formation, interior transport, surface evolution, radiolysis, atmospheric escape, and metabolic pathways.

The determination of isotopic ratios would provide a powerful indicator of several planetary processes. Exchange rates among the Earth's oceans, crust, mantle and atmosphere are closely linked to ratios of radiogenic noble gas isotopes; these have been used at Venus and Mars, for example, to better understand the evolution of their volatile reservoirs. In satellite systems around large gaseous planets such as Jupiter and Saturn, questions about the presence, extent and composition of a primordial circumplanetary disk surrounding the host proto-planet can be addressed by comparing isotope ratios measured at different satellites in the system with those measured in the host planet's atmosphere.

Endogenic processes on Europa and other Galilean satellites may have measurable effects on isotope compositions. Moreover, the exogenic processes of sublimation and sputtering should also cause isotopic fractionation. Differences in solubilities and clathrate dissociation pressures would cause materials and isotopes of interest to freeze or become enclathrated into Europa's ice shell in different proportions than found in the aqueous solution of the ocean. Such differences may be evident from comparison of the predominant ice-rich background terrain on Europa's surface with cracks, chaos regions and other features rich in non-icy material that may have been deposited directly from the ocean.

2.3.4.3 Relationship of Composition to Processes

Galileo's instruments were designed to study surface compositions at regional scales (**Figure 2.3-5**). The association of hydrated and reddish materials with certain geologic terrains, revealed by Galileo, suggests an endogenic source for the emplaced materials, although these may have since been altered by radiolysis. Many surface features with compositionally distinct materials were formed by tectonic processes, suggesting that the associated materials are derived from the subsurface. Major open questions include the links between surface composition and that of the underlying ocean and rocky interior [*Fanale et al. 1999, Kargel et al. 2000, McKinnon and Zolensky 2003*], and the relative significance of radiolytic processing [*Johnson and Quickenden 1997, Cooper et al. 2001, Carlson et al. 2002, 2005, Grundy 2007*]. For example, compositional variations associated with surface features such as chaos suggests that material may be derived from an ocean source, either directly through melting or eruptions, or indirectly through processes such as diapirism [*McCord et al. 1998b, 1999, Fanale et al. 1999, Orlando et al. 2005*] (see §2.3.5.2).

One of the critical limitations of the Galileo NIMS experiment was the low spatial resolution of the high-quality spectra and the limited spatial coverage due to the failure of the spacecraft's high-gain antenna. The spectra used to identify hydrated materials were typically averaged from areas ~75 km by 75 km [*McCord et al. 1998b, Carlson et al. 1999b*] (although a few higher-resolution "postage stamp" data sets were obtained and analyzed). This typical footprint is shown in **Figure 2.3-6,** illustrating the tremendous mixing of surface terrain types that occurs within an area of this extent; less than 10% of the NIMS footprint contains materials associated with ridges, bands, or fractures. In order to isolate and identify the young, non-ice materials associated with these structures, and look for spectral variations within geological structures, future observations must be able to resolve the non-ice materials at ~100 m scales.

In addition to compositional differences associated with recent geological activity, compositional changes related to exposure age also provide evidence for sites of recent or

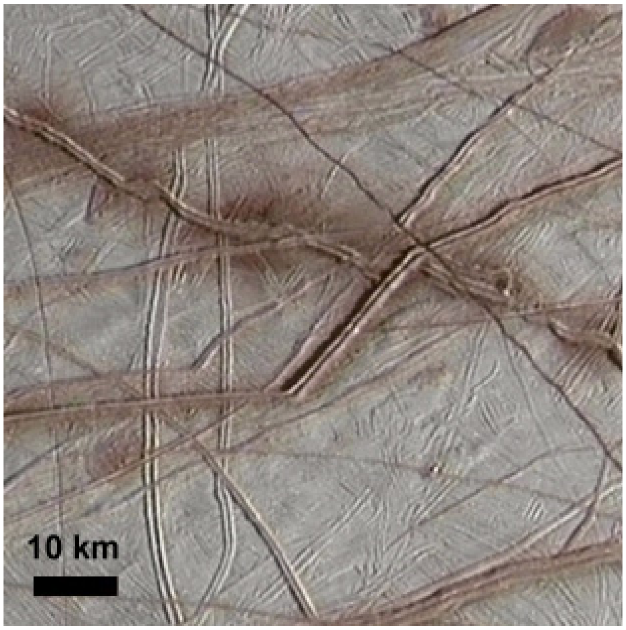

Figure 2.3-6. *This portion of a Galileo image is the size of a typical Galileo NIMS footprint, demonstrating how NIMS sampled multiple terrain types in each spectrum.*

current activity. The composition of even the icy parts of Europa is variable in space and time. Polar fine-grained deposits suggest frosts formed from ice sputtered or sublimated from other areas [*Clark et al. 1983, Dalton 2000, Hansen and McCord 2004*]. Equatorial ice regions are more amorphous than crystalline, perhaps due to radiation damage. Venting or transient gaseous activity on Europa would indicate present-day surface activity.

Exogenic processes are also a key part of Europa's composition story, but much remains unknown about the chemistry and sources of the materials being implanted. Magnetic field measurements by Galileo of ion-cyclotron waves in the wake of Europa provide evidence of sputtered and recently ionized Cl, O_2, SO_2 and Na ions [*Volwerk et al. 2001*]. Medium energy ions (tens to hundreds of keV) deposit energy in the topmost few tens of microns; heavier ions, such as oxygen and sulfur ions, have an even shorter depth of penetration, while MeV electrons can penetrate and affect the ice to a depth of more than 1 m [*Paranicas et al. 2002, and references therein*]. The energy of these particles breaks bonds to sputter water molecules, molecular oxygen, and any impurities within the ice [*Cheng et al. 1986*], producing the observed atmosphere and contributing to the erosion of surface features.

A major question is the exogenic versus endogenic origin of volatiles such as CO_2 and their behavior in time and space. CO_2 was reported on the surface of Callisto and Ganymede [*McCord et al. 1998a*], with hints of CO_2 [*McCord et al. 1998a*], SO_2 [*Smythe et al. 1998*] and H_2O_2 [*Carlson et al. 1999b*]. Recent analyses of the NIMS spectra indicate a concentration of CO_2 and other non-ice compounds on the anti-Jovian and trailing sides of Europa [*Hansen and McCord 2008*], suggesting an endogenic origin. Radiolysis of CO_2 and H_2O ices is expected to produce additional compounds [*Moore 1984, Delitsky and Lane 1997, 1998, Brunetto et al. 2005*]. Determining the presence and source of organic molecular compounds, such as CH and CN groups detected by IR spectroscopy at Callisto and Ganymede [*McCord et al. 1997, 1998*] and tentatively identified on Phoebe [*Clark et al. 2005*], would be important to evaluating the astrobiological potential of Europa, especially if there is demonstrable association with the ocean.

Some surface constituents result directly from exogenic sources. For example, sulfur from Io is transported by the magnetosphere and is implanted into Europa's ice. Once there it can form new molecules and may create some of the dark components on the surface. It is important to separate surface materials formed by implantation from those that are endogenic., and this can be done by quantitative analysis. For example, the detected Na/K ratio is supportive of an endogenic origin—and perhaps an ocean source—for sodium and potassium [*Brown 2001, Johnson et al. 2002, McCord et al. 2002, Orlando et al. 2005*].

Spatial variations can also help separate exogenic and endogenic processes. For example, comparison of spectra of disrupted terrain on the leading and trailing hemispheres, which encounter far different radiolytic fluxes, would help to isolate the effects of the radiation environment and unravel the endogenic and exogenic chemical processes that led Europa to its present state.

Regardless of origin, surface composition results from combinations of all these processes, and materials emplaced at the surface are subsequently processed by radiation to produce the observed composition [*Dalton 2000*]. For example, material derived from the ocean could be a mixture of dominantly Mg and Na salts. Na sulfates would be more vulnerable to radiative disassociation, producing sulfuric acid (H_2SO_4) [*Dalton 2000, 2007, McCord et al. 2001, 2002, Orlando et al. 2005*]. Such a mixture would allow for both indigenous salts and sulfuric acid, and could account for the origin of Na and K around Europa.

Some key outstanding questions to be addressed regarding Europa's chemistry and composition include:

- Are there endogenic organic materials on Europa's surface?
- Is chemical material from depth carried to the surface?
- Is irradiation the principal cause of alteration of Europa's surface materials through time?
- Do materials formed from ion implantation play a major role in Europa's surface chemistry?

Specific measurements that can be made to address these questions, are discussed in §2.4.4.

2.3.5 Geology

By understanding Europa's varied and complex geology, the moon's past and present processes are deciphered, along with implications for habitability. An understanding of Europa's geology provides clues about geological processes on other icy satellites with similar surface features, such as Miranda, Triton and Enceladus.

The relative youth of Europa's surface is inherently linked to the ocean and the effects of gravitational tides, which trigger processes that include cracking of the ice shell, resurfacing, and possibly release of materials from the interior. Clues to these and other processes are provided by spectacular surface features such as linear fractures and ridges, chaotic terrain, and impact craters.

2.3.5.1 Linear Features

Europa's unusual surface is dominated by tectonic features in the form of linear ridges, bands, and fractures (**Figure 2.3-7**). The class of linear features includes simple troughs and scarps (e.g., **Figure 2.3-7 g)**, double ridges separated by a trough, and intertwining ridge-complexes. Whether these represent different processes or stages of the same process is unknown. Ridges are the most common feature type on Europa and appear to have formed throughout the satellite's visible history (**Figure 2.3-7**, **j** and **i**). They range from 0.1 to > 500 km long, are as wide as 2 km, and can be several hundred meters high. Cycloidal ridges are similar to double ridges, but form chains of linked arcs.

Most models of linear feature formation include fracturing in response to processes within the ice shell [*Greeley et al. 2004*]. Some models suggest that liquid oceanic material or warm mobile subsurface ice squeezes through fractures to form the ridge, while others suggest that ridges form by frictional heating and possibly melting along the fracture shear zone. Thus, ridges might represent regions of material exchange between the surface, ice shell, and ocean, plausibly providing a means for surface oxidants to enter the ocean. Some features, such as cycloidal ridges, appear to initiate as a direct result of Europa's tidal cycle [*Hoppa et al. 1999*].

Bands reflect fracturing and lithospheric separation, much like sea-floor spreading on Earth, and most display bilateral symmetry [e.g., *Sullivan et al. 1998*] (**Figure 2.3-7**, **b** and **d)**. Their surfaces vary from relatively smooth to heavily fractured. The youngest bands tend to be dark, while older bands are bright, suggesting that they brighten with time. Geometric reconstruction of bands suggests that a spreading model is appropriate, indicating extension in these areas, and possible contact with the ocean [*Tufts et al. 2000, Prockter et al. 2002*].

The accommodation of extensional features remains a significant outstanding question regarding Europa's geology. A small number of contractional folds were found on the surface [*Prockter and Pappalardo 2000*], and some sites of apparent convergence within bands have been suggested [*Sarid et al. 2002*], but these are insufficient to accommodate the extension documented across Europa's surface. Some models suggest that ridges and local folds could reflect such contraction, but the present lack of global images, topographic information, and knowledge of subsurface structure precludes testing these ideas.

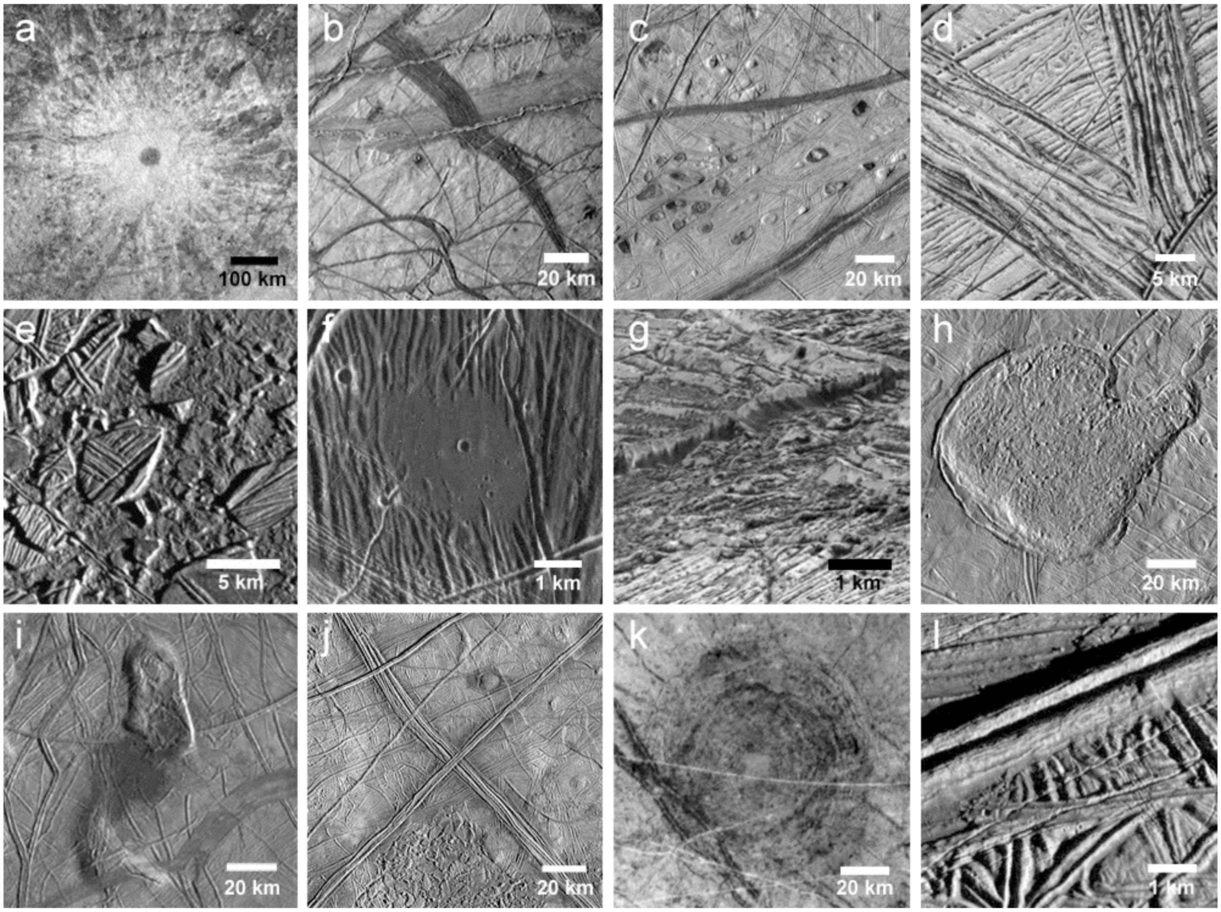

Figure 2.3-7*. Europa is a cryological wonderland, with a wide variety of surface features. Many appear to be unique to this icy moon. While much was learned from Galileo, it is still not understood how many of these features form, or their implications for Europa's evolution. Shown here are: (a) The impact crater Pwyll, the youngest large crater on Europa; (b) Pull-apart bands; (c) Lenticulae; (d) Pull-apart band at high resolution; (e) Conamara Chaos; (f) Dark plains material in a topographic low, (g) Very high resolution image of a cliff, showing evidence of mass wasting; (h) Murias Chaos, a cryovolcanic feature which has appears to have flowed a short distance across the surface; (i) The Castalia Macula region, in which the northernmost dome contains chaos and is ~900 m high; (j) Regional view of two very large ridge complexes in the Conamara region; (k) Tyre impact feature, showing multiple rings; and (j) One of Europa's ubiquitous ridges, at high resolution.*

Fractures are narrow (from hundreds of meters to the ~10 m limit of image resolution) and can exceed 1000 km in length. Some fractures cut across nearly all surface features, indicating that the ice shell is subject to deformation on the most recent time-scales. The youngest ridges and fractures could be active today in response to tidal flexing. Subsurface sounding and surface thermal mapping could help identify zones of warm ice coinciding with current or recent activity. Young ridges may be places where there has material exchange between the ocean and the surface, and would be prime targets as potential habitable niches.

2.3.5.2 Chaotic Terrain

Europa's surface has been disrupted to form regions of chaotic terrain, in the form of subcircular features termed lenticulae, and irregular-shaped, generally larger chaos zones. Lenticulae include pits, spots of dark material, and domes where the surface is upwarped and commonly broken (**Figure 2.3-7 c** and **f**). *Pappalardo et al.* [*1998, 1999*] argued that these features are typically ~10 km across, and possibly formed by upwelling of compositionally or thermally buoyant ice diapirs through the ice shell. In such a case, their size distribution would imply the thickness of the ice shell to be at least 10–20 km at the time of formation.

An alternative model suggests that there is no dominant size distribution and that lenticulae are small members of chaos [*Greenberg et al. 1999*], formed through either direct material exchange (through melting) or indirect exchange (through convection) between the ocean and surface [e.g., *Carr et al. 1998*]. Thus, global mapping of the size distribution of these features can address their origin.

Chaos is generally characterized by fractured plates of ice that have been shifted into new positions within a background matrix (**Figure 2.3-7 e**). Much like a jigsaw puzzle, many plates can be fit back together, and some ice blocks appear to have disaggregated and "foundered" into the surrounding finer-textured matrix. Some chaos areas stand higher than the surrounding terrain (**Figure 2.3-7, h** and **i**). Models of chaos formation suggest whole or partial melting of the ice shell, perhaps enhanced by local pockets of brine [*Head and Pappalardo 1999*]. Chaos and lenticulae commonly have associated dark, reddish zones thought to be material derived from the subsurface, possibly from the ocean. However, these and related models are poorly constrained because the total energy partitioning within Europa is not known, nor are details of the composition of non-ice components. Subsurface sounding, surface imaging, and topographic mapping [e.g., *Schenk and Pappalardo 2004*] are required to understand the formation of chaotic terrain, and its implications for habitability.

2.3.5.3 Impact Features

Only 24 impact craters ≥ 10 km have been identified on Europa [*Schenk et al. 2004*], reflecting the youth of the surface. This is remarkable in comparison to Earth's Moon, which is only slightly larger but far more heavily cratered. The youngest Europan crater is thought to be the 24 km-diameter Pwyll, (**Figure 2.3-7 a**) which still retains its bright rays, and likely formed less than 5 Myr ago [*Zahnle et al. 1998*]. Complete global imaging will provide a full crater inventory and allow a more comprehensive determination of the age of Europa's surface, and help identify the very youngest areas.

Crater morphology and topography provides insight into ice layer thickness at the time of the impact. Morphologies vary from bowl-shaped depressions with crisp rims, to shallow depressions with smaller depth-to-diameter ratios. Craters up to 25–30 km in diameter have morphologies consistent with formation in a warm but solid ice shell, while the two largest impacts (Tyre, [**Figure 2.3-7, k**] and Callanish) might have punched through brittle ice about 20 km deep into a liquid zone. [*Moore et al. 2001, Schenk et al. 2004*].

2.3.5.4 Geological History

Determining the geological histories of planetary surfaces requires identifying and mapping surface units and structures and placing them into a time-sequence.

In the absence of absolute ages derived from isotopic measurements of rocks, planetary surface ages are commonly assessed from impact crater distributions, with more heavily cratered regions reflecting greater ages. The paucity of impact craters on Europa limits this technique. Thus, superposition (i.e., younger materials burying older materials) and cross-cutting relations are used to assess sequences of formation [*Figueredo and Greeley 2004*]. Unfortunately, only 10% of Europa has been imaged at a sufficient resolution to understand temporal relationships among surface features; for most of Europa, imaging data is both incomplete and disconnected from region to region, making the global surface history difficult to decipher.

Where images of sufficient resolution (better than 200 m/pixel) exist, it appears that the style of deformation evolved through time from ridge and band formation to chaotic terrain [*Greeley et al. 2004*], although there are areas of the surface where this sequence is less certain [e.g., *Riley et al. 2000*]. The mechanism for the change in geological style is uncertain, but a plausible mechanism for the change is one in which Europa's ocean is slowly cooling and freezing out as the ice above it is thickening. Once the ice shell reaches a critical thickness, solid-state convection may be initiated, allowing diapiric material to be convected toward the surface. A thickening ice shell could be related to a waning intensity of geological activity.

Given the relative youth of Europa's surface, such a fundamental change in style might seem unlikely over the last ~1% of the satellite's history, and its activity over the rest of its ~4.5 billion year existence can only be speculated upon. Four possible scenarios have been proposed (**Figure 2.3-8**):

(1) Europa resurfaces itself in a steady-state and relatively constant, but patchy style;

(2) Europa is at a unique time in its history, having undergone a recent major resurfacing event;

(3) Global resurfacing is episodic or sporadic;

(4) Europa's surface is actually much older than current cratering models suggest.

From the standpoint of the dynamical evolution of the Galilean satellite system, there is good reason to believe that Europa's surface evolution could be cyclical. If so, Europa can experience cyclical variations in its orbital characteristics and tidal heating on time scales of perhaps 100 million years.

Global monochrome and color imaging, coupled with topography and subsurface sounding, would enable these evolutionary models to be tested. Europa's surface features generally brighten and become less red through time, so albedo and color can serve as a proxy for age [*Geissler et al. 1998*]. Quantitative topographic data [*Schenk and Pappalardo 2004*] can provide information on the origin of geologic features and may show trends with age. Profiles across ridges, bands, and various chaotic terrains will aid in constraining their modes of origin. Moreover, flexural signatures are expected to be indicative of local elastic lithosphere thickness at the time of their formation, and may provide evidence of topographic relaxation [e.g., *Nimmo et al. 2003, Billings and Kattenhorn 2005*].

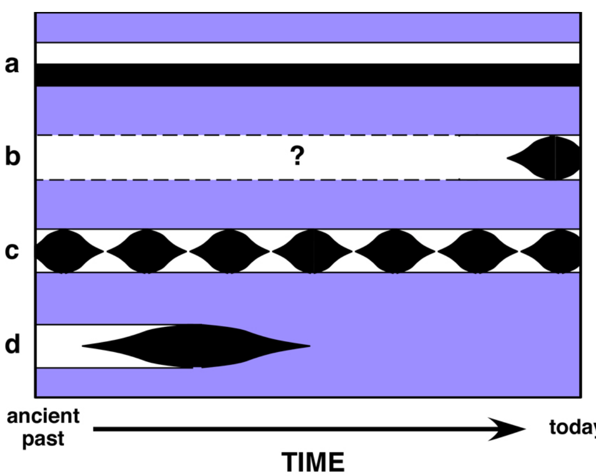

Figure 2.3-8: Possible evolutionary scenarios for Europa's surface. (a) Steady-state, relatively constant resurfacing; (b) Unique time in history with recent major resurfacing event; (c) Global resurfacing is episodic or sporadic; (d) Surface is older than cratering models suggest. Mapping data from JEO when related to system data as a whole, will help to distinguish among these models [after Pappalardo et al. 1999].

2.3.5.5 Characterizing Potential Future Landing Sites

A capable lander has been identified as a high priority follow-up to a Europa Orbiter if Europa is found to be a habitable environment at present with active material exchange between subsurface water and the near surface [*SSB 2003*, *NASA 2006*]. Soft landed missions will require high-resolution images (~1 m/pixel or better) to assess the surface on scales needed for safe surface access. The roughness and overall safety of potential landing sites can also be characterized through radar scattering properties, photometric properties, thermal inertia, and detailed altimetry. Such data will also illuminate fine-scale processes that create and affect the regolith, including mass wasting, sputter erosion, sublimation, impact gardening, and frost deposition. Along with corresponding high-resolution subsurface sounding, these observations would help to assess possible mechanisms and likely sites of recent material exchange with the subsurface ocean. Characterizing the global radiation environment will also greatly aid in the choice of a landing site. These datasets will provide for hazard assessment, while imaging, radar, compositional, and thermal mapping will identify sites of greatest scientific interest and will yield data vital for the coupled engineering and scientific assessment of possible future landing sites.

Some remaining outstanding questions related to Europa's geology include:

- Do Europa's ridges, bands, chaos, and/or multi-ringed structures require the presence of near-surface liquid water to form?

- Where are Europa's youngest regions?
- Is current geological activity sufficiently intense that heat flow from Europa's interior is measurable at the surface?

Questions such as these regarding Europa's geology can be answered using specific measurements, as discussed in §2.4.5.

2.3.6 Jupiter System

Europa cannot be understood in isolation, but must be considered in the context of the entire Jovian system, through study of its parent planet Jupiter, its sibling satellites, and the magnetic field and particle environment.

Europa formed out of the Jovian circumplanetary disk and has since evolved through complex interactions with the other satellites, Jupiter, and Jupiter's magnetosphere. In order to understand the potential habitability of Europa and icy moons in general, it is critical to understand how the intricately related components of the Jovian system originated and evolved, and how they currently operate and interact. This requires observations of the other Galilean satellites, the Jovian magnetosphere and particle environment, the planet Jupiter itself, and the minor satellites and ring system. The Jupiter system science background section that follows emphasizes connections to Europa and its potential habitability, while touching on additional important Jupiter system science. The discussion is organized into five themes: satellite surfaces and interiors, satellite atmospheres, plasma and magnetospheres, Jupiter atmosphere, and rings, dust and small moons.

2.3.6.1 Satellite Surfaces and Interiors

The present environment of Europa depends in part on how it formed and evolved. Europa itself does not record its early surface history. However, its neighboring satellites—Io, Ganymede and Callisto—provide clues to Europa's origin, evolution, and potential habitability, through studies of their surfaces, interiors (**Figure 2.3-9**). They are also of great scientific interest on their own.

Io. The innermost of the Galilean satellites, Io is undergoing intense tidally driven volcanism. Io is important for understanding Europa because it illuminates Europa's own tidal heat engine and provides a window on Europa's silicate interior, and also because it is a potentially major source of contamination of Europa's surface. But Io is also fascinating in its own right, as an extreme, readily-studied, example of interior, volcanic, atmospheric, and plasma processes that are important throughout the solar system.

Io's density of 3530 kg m^{-3} suggests a primarily silicate interior [*Keszthelyl et al. 2004*]. A 4:2:1 Laplace resonance between Io, Europa, and Ganymede as they orbit Jupiter leads to tidal flexing of the order of ~100 m at Io's surface, generating the heat that powers global volcanism [*Yoder and Peale 1981*].

Galileo data indicate the presence of extensive moon-plasma interactions near Io but appear to rule out a strong intrinsic dipolar magnetic field. Io's moment of inertia inferred from Galileo of 0.377 MR^2 (M and R = satellite mass and mean radius, respectively), suggests that the satellite is differentiated into a metallic core and silicate mantle [*Anderson et al. 2001*]. Io is thought to have a large Fe-FeS core. The apparent lack of an intrinsic magnetic field suggests that the silicate mantle

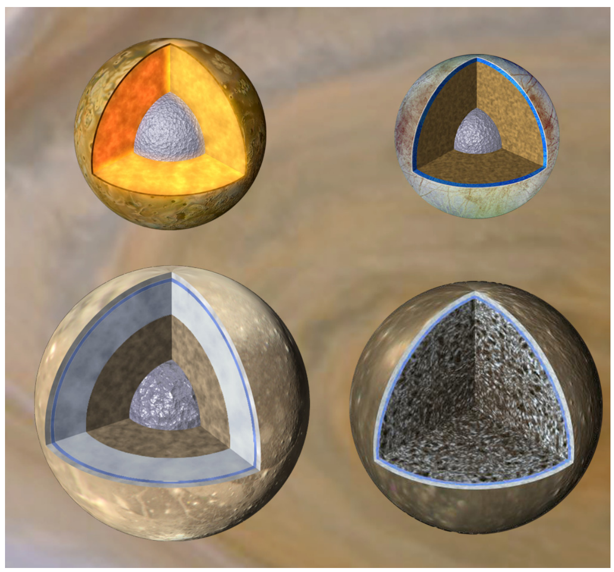

Figure 2.3-9*. Simple models of the interior structures of the Galilean satellites based on Galileo data. All three ice-covered moons are believed to harbor oceans (blue); Europa's is the only ocean that lies beneath a thin ice shell and in direct contact with its rocky mantle. Within Callisto, the degree of ice-rock differentiation is highly uncertain. The satellites are shown to scale, along with the western edge of Jupiter's Great Red Spot (background).*

is currently experiencing sufficiently strong tidal heating to prevent cooling and, therefore, there is no convective dynamo in the putative iron core [*Wienbruch and Spohn 1995*].

Io's mantle appears to undergo a high degree of partial melting (~5–20% molten [*Moore 2001*]) that produces mafic to ultramafic lavas dominated by Mg-rich orthopyroxene, suggesting a compositionally undifferentiated mantle. Silicate volcanism appears to be dominant, although secondary sulfur volcanism may be locally important. The heat flux inferred from long-term thermal monitoring of Io exceeds 2 W/m^2, making Io by far the most volcanically active solid body in the solar system (**Figure 2.3-10**) [*Nash et al. 1986, Veeder et al. 2004, McEwen et al. 2004, Lopes and Spencer 2007*]. This heat flow is probably higher than can be supported by steady-state tidal heating.

Despite the high heat flux, the existence of numerous mountains up to 18 km high indicates that the lithosphere is at least 20–30 km thick, rigid, and composed mostly of silicates with possibly some sulfur and sulfur dioxide (SO_2) components [e.g., *Carr et al. 1998, Schenk and Bulmer 1998, Turtle et al. 2001, Jaeger et al. 2003*]. The thick lithosphere can only conduct a small fraction of Io's total heat flux, and Io may lose its heat primarily by magmatic transport through the lithosphere [*O'Reilly and Davies 1981, Carr et al. 1998, Moore 2001*]. Io's rapid resurfacing rate (Io has no known impact craters) requires a gradual subsidence of its lithosphere, which could cause a compressional lithospheric environment that may help to explain the formation of Io's numerous mountains [*Schenk and Bulmer 1998*].

High-temperature volcanism (≥1300°C) suggests superheated mafic to slightly ultramafic magmas, though these temperatures are lower limits and higher temperatures are possible. Silicate lavas, sulfur, and sulfur dioxide materials interact in a complex and intimate way, and volcanic styles include massive inflating lava flow fields; major, explosive, high-temperature outbursts; and overturning lava lakes. Volcanic plumes erupt both from central vents and lava flow fronts (**Figure 2.3-11**) where surface volatiles are remobilized. Volcanism and sputtering on Io feed a unique patchy and variable atmosphere,

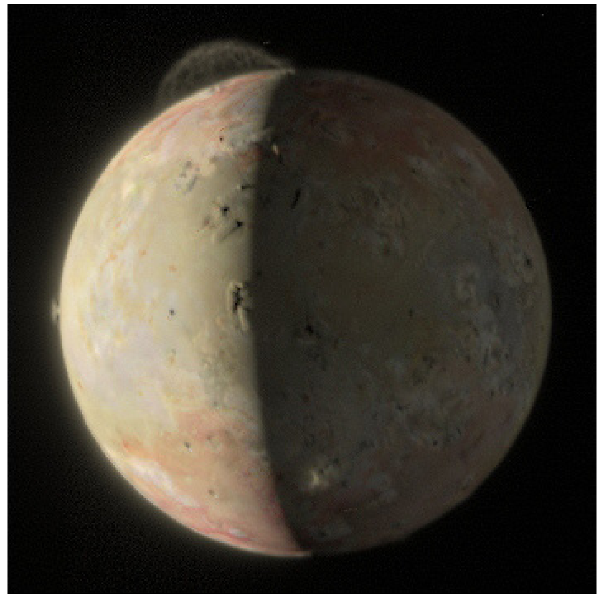

Figure 2.3-10*. Volcanic plumes on Io, as imaged by the LORRI instrument on the New Horizons spacecraft at a distance of 2.5 million km (35 Rj). A 290 km high plume from the volcano Tvashtar (top) shows detailed structure. A 60-km high symmetrical plume from the volcano Prometheus (left) has been active during all spacecraft flybys since Voyager. Long-term observations and flybys with JEO will provide unprecedented detail of Io's dynamic volcanism.*

in which sulfur, oxygen, and sodium become ionized to form Io's plasma torus, neutral clouds, and aurorae. Sublimation of SO_2 frost is also a source of Io's thin atmosphere; the relative contributions of sublimation and volcanism to the atmosphere are not well understood. Electrical current flows between Io and Jupiter and produces auroral footprints in the Jovian atmosphere. Near the ionospheric end of the Io flux tube, accelerated electrons interact with the Jovian magnetic field and generate decametric radio emissions [*Lopes and Williams 2005*].

There is an apparent paradox between Io's putative ultramafic volcanism and the widespread intensity of the volcanism on Io, which might be expected to produce extreme differentiation and thus silica-rich eruptions (at the current rate, Io would have produced a volume of lava ~40 times its global volume over the last 4.5 Gyr). The resolution of this paradox requires either that Io only recently

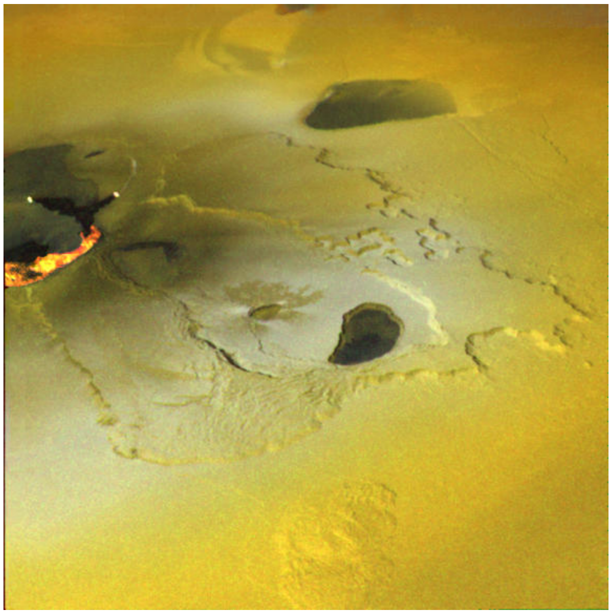

Figure 2.3-11. *In the Tvashtar region of Io, active glowing volcanic flows (left) were observed by the Galileo spacecraft. A series of volcanic calderas were observed over several years by Galileo in this region. At one time, a 25 km long, 1–2 km high curtain of lava was erupted, followed by a plume of gas that rose 385 km above the surface, blanketing areas as far as 700 km away.*

entered the tidal resonance and became volcanically active, or that wholesale recycling of Io's lithosphere is sufficient to prevent extreme differentiation [*McEwen et al. 2004*].

Galileo's study of Io's dynamic processes was severely hampered by its low data rate. Major volcanic events were missed entirely or seen only in disconnected snapshots, and only a small sample of its diverse landforms was studied in any detail (for instance, the 2001 Surt eruption seen from Earth [*Marchis et al. 2002*] was 20 times brighter than anything seen by Galileo).

Outstanding science issues for Io include understanding the mechanisms responsible for the formation of its surface features, determining the surface compositions and the implications for the origin and evolution and transport of surface materials. Specific issues relate to these science areas: a) understanding Io's heat balance and tidal dissipation, and their relationship to Europa's tidal evolution; b) Io's active volcanism for insight into rare, major volcanic events and their effect on the surface and atmosphere; c) the relationships among volcanism, tectonism, erosion and deposition; d) the silicate and volatile components of Io's crust; e) the composition of material escaping from Io which would help to distinguish endogenic and Io-derived materials on the surface of Europa.

Additional gravity data during Io flybys will place more stringent constraints on interior structure. New discoveries are likely, e.g., gravity anomalies similar to that detected by Galileo on a Ganymede flyby [*Palguta et al. 2006*]. Determination of Io's pole position and changes in the location of the pole with time might be possible with high resolution imaging; these observations would also place constraints on the satellite's shape and, thus, internal structure. It might also be possible to determine any secular acceleration of Io in its orbit through the combination of Doppler tracking and high-resolution imaging, thus constraining the orbital and tidal evolution of the system. Heat flow mapping would place important constraints on theories of tidal dissipation in Io and on the satellite's internal structure and thermal and orbital evolution and those of its sibling Galilean satellites.

Ganymede. Ganymede is the solar system's largest satellite, exceeding Mercury in diameter, and is the only satellite known to have an intrinsic magnetic field. Its surface can be broadly separated into two geologically distinct terrains—bright and dark [*Shoemaker et al. 1982, McKinnon and Parmentier 1986, Pappalardo et al. 2004*]. Dark terrain covers 1/3 of the surface and is dominated by impact craters with a variety of morphologies. It is ancient (perhaps essentially primordial), and appears grossly similar to the surface of Callisto [*Prockter et al. 1998*]. In addition to craters, dark terrain also displays hemisphere-scale sets of concentric troughs termed furrows, which are probably the remnants of vast multi-ring impact basins, now broken up by subsequent bright terrain tectonism.

Bright terrain forms a global network of interconnected lanes, separating the dark terrain into polygons. Within the bright terrain is an intricate patchwork of smooth bright surfaces and material with closely spaced parallel ridges and troughs, termed grooves (**Figure 2.3-12**). The grooves are dominated

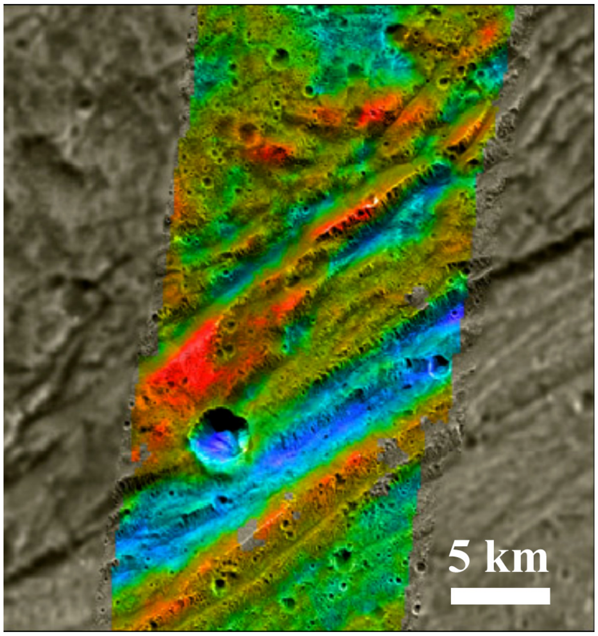

Figure 2.3-12. *High-resolution stereo topography of a grooved terrain boundary on Ganymede from Galileo's G28 orbit. Red is high, blue is low, and total topographic range is ~800 m.*

by extensional tectonic features, and morphologically and genetically have much in common with terrestrial rift zones [*Parmentier et al. 1982, Pappalardo et al. 1998b*]. Bright terrain exhibits the full range of extensional tectonic behavior, from wide rifting, to narrow rifting, to possible examples of crustal spreading (much like the smooth bands on Europa). Although the ultimate driving mechanism for groove formation is uncertain, there are many intriguing possibilities that it may be tied to the internal evolution of Ganymede and the history of orbital evolution of the Galilean satellite system [*Showman et al. 1997*].

Ganymede's surface composition is dominated by water ice [*McKinnon and Parmentier 1986*]. The edge of the bright polar "caps" appears to follow the magnetospheric boundary between open and closed field lines [*Khurana et al. 2007*], which provides an opportunity to examine differences in space weathering processes on the same surface under different conditions. Beyond the polar caps toward equatorial regions, are found dark non-ice materials, which may be hydrated frozen brines similar to those inferred for Europa; other minor constituents of Ganymede's surface include CO_2, SO_2, and some sort of tholin material exhibiting CH and CN bonds [*McCord et al. 1998*]. There is also evidence for trapped O_2 and O_3 in the surface, as well as a thin molecular oxygen atmosphere, and auroral emissions are concentrated near the polar cap boundaries [*McGrath et al. 2004*], but there are no ionospheric indications from Galileo radio occultation data of an equatorial atmosphere. To the extent that surface composition may reflect magnetospheric irradiation effects that depend on the intrinsic magnetic field, global distributions of some species may provide information on age and variability of the present magnetic configuration.

Analysis of Galileo data from several close flybys indicate that Ganymede's moment of inertia is 0.31 MR^2. The factor of 0.31 is the smallest measured value for any solid body in the solar system [*Anderson et al. 1996*]. Three-layer models, constrained by plausible compositions, indicate that Ganymede is differentiated into an outermost ~800 km thick ice layer and an underlying silicate mantle of density 3000–4000 kg/m3. A central iron core is allowed, but not required, by the gravity data. The existence of Ganymede's magnetic field, however, supports the presence of such a metallic core. Galileo gravity data also indicate that Ganymede has internal mass anomalies, possibly related to topography on the ice-rock interface or internal density contrasts [*Anderson et al. 2004, Palguta et al. 2006*].

Galileo magnetometer data provide tentative evidence for an inductive response at Ganymede, which again suggests the presence of a salty internal ocean within 100–200 km of Ganymede's surface. However, the inference is less robust than at Europa and Callisto, because the existing flyby data are equally well explained by an intrinsic quadrupole magnetic field (superposed on the intrinsic dipole), with an orientation that remains fixed in time [*Kivelson et al. 2002*]. Additional flybys are needed to resolve this ambiguity. The Ganymede surface is more cratered and ancient than Europa's, consistent with a much thicker outer shell of solid ice. Ganymede's probable ocean is of intrinsic astrobiological interest, and Ganymede also provides an example of how an intrinsic magnetic field can protect a body from radiation. .

Magnetometer data acquired during several close flybys show that Ganymede has an intrinsic magnetic field strong enough to generate a mini-magnetosphere embedded within the Jovian magnetosphere (**Figure 2.3-13**) [*Kivelson et al. 1996*]. A model with a fixed Ganymede-centered dipole superposed on the ambient Jovian field provides a good first-order match to the data and suggests equatorial and polar field strengths of ~719 and 1438 nT, respectively; these values are 6–10 times the 120 nT ambient Jovian field at Ganymede's orbit. Detection of numerous electromagnetic and electrostatic waves and measurements of energetic particles close to Ganymede confirm the inference of a magnetosphere. The most plausible mechanism for generation of Ganymede's intrinsic field is dynamo action in a liquid-iron core [*Schubert et al. 1996*].

With its mix of old and young terrain, ancient impact basins and fresh craters, and landscapes dominated by tectonics, icy volcanism, or slow degradation by space weathering, Ganymede serves as a "type example" for understanding many icy satellite processes throughout the outer solar system. Understanding this largest example of an icy satellite surface will provide insight into how this entire class of worlds evolves differently from the terrestrial planets.

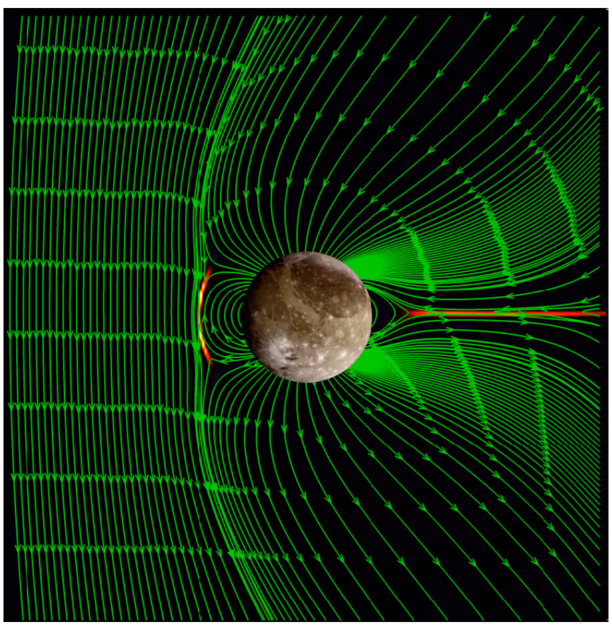

Figure 2.3-13. *Ganymede's magnetosphere, simulated by* X. Jia, UCLA, 2007. *Field lines are green; current perpendicular to B is represented by color variation. Note intense currents flow both upstream on the boundary between Jupiter's field and the field lines that close on Ganymede, and downstream in the reconnecting magnetotail region.*

The role of icy volcanism in modifying the surfaces of outer planet satellites is an outstanding question about which little is truly understood. Like many other icy satellites, there is ambiguous evidence for cryovolcanic processes modifying the surface of Ganymede. Given the physical difficulties in getting cryovolcanic melt up to the surface of an icy satellite [*Showman et al. 2004*], the nature and abundance of cryovolcanic deposits gives insight into the structure and functioning of icy satellite interiors. It is critical to learn whether cryovolcanism is widespread or rare in the formation of bright terrain on Ganymede, with implications for its role on other icy satellites.

Another outstanding question to assess for Ganymede is the driving mechanism for the origin of the grooved terrain. Has Ganymede's surface been disrupted by tidal forces, internal convection, and/or phase changes in its interior? What are the relative roles of tectonism and cryovolcanism in the resurfacing that formed the grooved terrain? Because grooved terrain analogous to that on Ganymede exists on other icy satellites, understanding the processes that occurred on Ganymede will lead to understanding of resurfacing mechanisms on icy satellites generally.

As a final example, craters are found on Ganymede in a huge range of sizes, morphologies, degradation states, and stages of modification, and as such form a basis for understanding different crater forms in icy surfaces throughout the solar system. All these studies would benefit from the huge increase in spatial coverage enabled by a new mission's greatly improved data rates compared to Galileo.

Callisto. As the outermost large satellite of Jupiter, Callisto is the least affected by tidal heating and the least differentiated, thus offering an "endmember" example of satellite evolution for the Jovian system [see reviews in *McKinnon and Parmentier 1986, Showman* *and Malhotra 1999,* and *Moore et al. 2004*]. Accordingly, assessing its internal structure, geologic history, compositional evolution, impact cratering history, and radiolysis of its surface are important to understanding the evolution of the Jovian satellites.

Galileo gravity data plus the assumption of hydrostatic equilibrium suggest that Callisto's moment of inertia is 0.355 MR^2, suggesting that it has a partially differentiated structure containing an ice-rich outer layer less than 500 km thick, an intermediate ice-rock mixture with a density near 2000 kg/m^3, and a central rock/metal core [*Anderson et al. 1998*]. However, if Callisto's degree-2 gravity structure is not hydrostatically balanced, then Callisto could be more or less differentiated than the moment of inertia suggests. This could have major implications for understanding satellite formation. Pre-Galileo models suggested that Ganymede and Callisto formed from debris in a proto-Jovian disk in ~10^4 years; however, for Callisto to be undifferentiated, its formation time must have exceeded 10^6 years [*Canup and Ward 2002, Mosqueira and Estrada 2003*].

Galileo magnetometer data indicate that Callisto has an inductive magnetic response that is best explained by a salty ocean within 200 km of the surface [*Khurana et al. 1998, Kivelson et al. 1999, Zimmer et al. 2000*]; properties of the ice phase diagram strongly suggest that the ocean on Callisto (and Ganymede) lies ~160 km below the surface. Maintaining an ocean in Callisto today either requires stiffer ice rheology than is generally assumed (to slow down the convective heat loss) or existence of antifreeze (ammonia or salts) in the ocean. However, reconciling partial differentiation with the existence of the ocean is difficult: some part of the uppermost ice layer must remain at the melting temperature to the present day, while the mixed ice-rock layer must never have attained the melting temperature.

Along with the discovery of Callisto's conducting, probably fluid sub-surface layer, major Galileo discoveries about Callisto include the absence of cryovolcanic resurfacing, and the inference of surface erosion by sublimation. Callisto's landscape at decameter scales, and particularly its lack of small craters, is unique among the Galilean satellites, and might be akin to that of cometary nuclei.

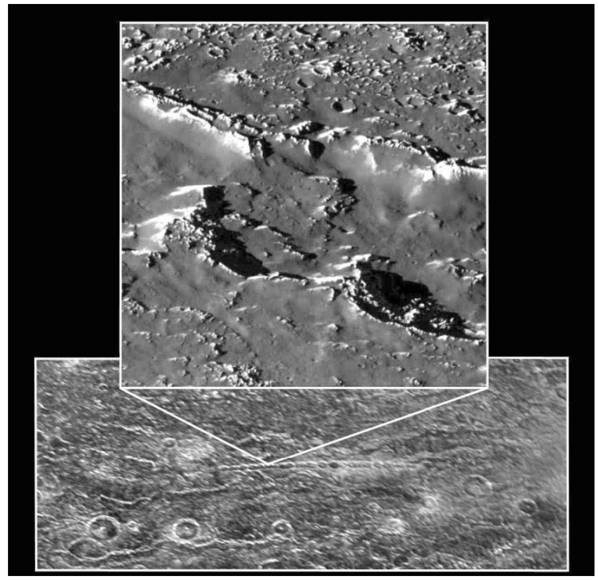

Figure 2.3-14. *Galileo images of a catena (crater chain) on Callisto. Note the dearth of small craters in the inset, which shows an area 8 km across.*

The process of sublimation degradation is recognized as a key surface modification process on Callisto (**Figure 2.3-14**).

The primary surface composition of Callisto is bimodal (water ice and an unidentified non-ice material), with trace constituents detected in the non-ice material. The visible color of the non-ice material is similar to C-type asteroids and carbonaceous chondrites. The trace materials detected in the non-ice material include: CO_2, C-H, CN, SO_2, and possibly SH [*Carlson et al. 1999, McCord et al. 1998*]. They may be present in the ice as well although they would remain undetected by remote sensing because of the low reflectance of large-grained ice at the wavelengths where these materials are spectrally distinct. Carbon dioxide is detected as an atmosphere and is nonuniformly dispersed over the surface, but concentrated on the trailing hemisphere and more abundant in fresh impact craters [*Hibbitts et al. 2002*]. This hemispheric asymmetry is similar to that for sulfate hydrates on Europa and is also suggestive of externally induced effects by corotating magnetospheric plasma [*Cooper et al. 2001*].

Outstanding questions remaining in Callisto studies include: What is the actual configuration of its interior and is there a rock core? What is the composition and structure of the upper "crust?" What controls impactor populations, and what are the retention ages represented by crater counts? What does Callisto reveal about Galilean satellite formation and evolution? Is the reason Callisto and Ganymede had divergent histories is solely the consequence of the role of tidal heating, or are there viable alternative explanations (such as accretion dynamics)?

2.3.6.2 Satellite Atmospheres

The interface between Jupiter's magnetosphere and Europa's surface is Europa's tenuous atmosphere (**Figure 2.3-15**), composed principally of O_2, and with a surface pressure of just ~2×10^{-12} bar [*McGrath et al. 2004*]. There is no widely accepted explanation for the non-uniform nature of the atmospheric emissions, and only a single modeling attempt has been made to address this issue [*Cassidy et al. 2007, 2008*]. The atmosphere is principally maintained by ion sputtering of Europa's surface. Atmospheric molecules are subsequently dissociated and ionized by electron impact, charge exchange, and solar photons. The abundance and distribution of the atmospheric constituents provide important clues to Europa surface processes and provide a link to surface composition. Once released from the surface, some atmospheric constituents such as Na and K are more readily observed in their gas phase. Their abundance relative to that on Io provides a strong discriminator between endogenic and exogenic origin for these species, which has been used to argue for the presence of an ocean on Europa [*Johnson et al. 2002*]. Europa's atmosphere could be in part supplied by active geysers [*Nimmo et al. 2007b*], the discovery of which would provide clues to subsurface processes and interior structure.

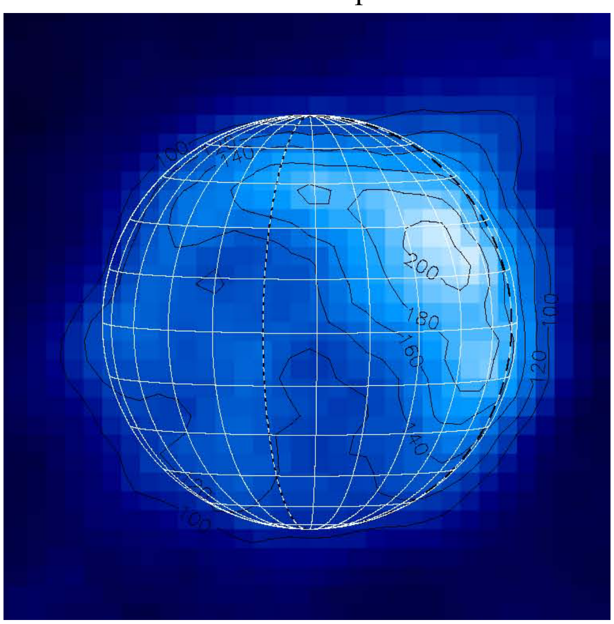

***Figure 2.3-15**. Oxygen emission from Europa's atmosphere, observed in ultraviolet wavelengths (1356 angstroms) with the Hubble Space Telescope [*McGrath et al. 2004*]. This image shows emissions to be bright in the anti-Jovian hemisphere, suggesting significant heterogeneity and complexity.*

Because material from Io is transported to and implanted in the surface of Europa, it is important to understand the nature of the Io atmosphere, the ultimate source of the exogenic material that contaminates Europa. Ganymede and Callisto also have tenuous atmospheres, which shed light on the evolutionary paths these satellites have followed. The atmospheric emissions of Ganymede, for example, are reminiscent of classic polar auroral emissions, very different than the case for Europa. Callisto is thought—like Europa and Ganymede—to have a predominantly O_2 atmosphere, but lacks oxygen emissions like those detected from Europa, Io, and Ganymede [*Strobel et al. 2002*]. Instead, Callisto has CO_2 emission above the limb, detected by the Galileo NIMS [*Carlson 1999*]. IR limb scans at Europa were not performed by NIMS. Small amounts of CO_2 may well be present in Europa's atmosphere, by analogy with Callisto. Callisto's atmosphere may be thicker than either Europa's or Ganymede's [*McGrath et al. 2004, Liang et al. 2005*], which is reflected by its relatively dense ionosphere [*Kliore et al. 2002*].

Stellar occultations are a powerful technique for studying tenuous atmospheres and performing plume searches, yet Galileo was not able to perform such observations at the Galilean satellites. Because stellar occultations directly measure atmospheric absorption, interpretation is not subject to assumptions about the local plasma environment. The Cassini UVIS observations of stellar occultations by Enceladus have proven the power of this method in probing not only atmospheric density [*Hansen et al. 2006*], but small variations in density (i.e., Enceladus "jets" contributing to the overall plume [*Hansen et al. 2008*].

2.3.6.3 Plasma and Magnetospheres

The plasma of Jupiter's rapidly rotating magnetosphere overtakes the Galilean satellites in their orbits. Charged particles flow predominantly onto the trailing hemispheres of satellites, where they weather the satellite surfaces. Energetic ions sputter neutral particles from the surfaces. Many of the newly liberated particles immediately return to the surface, but some become part of the satellite atmosphere, and some escape to space. A fraction of the neutrals that are no longer bound to a moon, either because of surface or atmospheric sputtering or another process, can form a circumplanetary neutral torus, such as at Europa's orbit [*Mauk et al. 2003*]. The neutral torus plasma density at Jupiter is typically small, which is the opposite of the case for Saturn's magnetosphere.

Io is the dominant source of particles in Jupiter's magnetosphere [*Broadfoot et al. 1979*], but other moons contribute water products and minor species through atmospheric and surface interactions [*Johnson et al. 2004*]; for example, Europa is a source of sodium [*Brown 2001, Leblanc et al. 2005*].

Perturbations of the magnetospheric plasma and electromagnetic fields in the vicinity of the satellites provide diagnostics of the satellites themselves. Through such analysis, satellite induced magnetic fields were detected [e.g., *Kivelson et al. 2004*], and these fields are a key line of evidence for subsurface oceans (§2.3.2.4). In turn, magnetospheric particle interactions produce changes in surface chemistry [*Johnson et al. 2004*].

2.3.6.4 Jupiter Atmosphere

With a mass of 318 Earth masses, Jupiter contains two-thirds of the planetary material in the Solar System. Its present-day atmospheric composition reflects the initial nebula conditions, albeit with significant reprocessing, from which Europa and the other satellites formed and evolved. Furthermore, the formation and evolution of the Jovian system from the protosolar nebula provides the best analogue currently available for the formation of both our own solar system and the hundreds of exoplanetary systems being discovered around other stars.

The plethora of dynamical and chemical phenomena of Jupiter's "visible" upper atmosphere (the "weather-layer") are thought to be governed by a balance between radiative-forcing due to the deposition of solar energy and forcing from deeper internal processes. The Juno mission will begin microwave remote sensing and gravitational mapping of Jupiter's internal structure in 2016. JEO will complement this mission by investigating the vertical coupling of the deep interior to the overlying atmospheric levels, from the troposphere to the ionosphere.

In the troposphere, important questions exist regarding the weather-layer manifestations of deep internal processes, such as storms, lightning, cloud formation, belt-zone contrasts, convection, jet streams, and wave propagation. In particular, one of the greatest unresolved mysteries for the tropospheric meteorology of Jovian planets is the formation mechanisms for the multiple east-west (zonal) jet streams, the structure of the banded system (**Figure 2.3-16**) and the redistribution of energy and angular momentum among different atmospheric layers [*Vasavada and Showman 2005*]. Some models suggest that the jets form by deep convection within the molecular envelope, whereas others suggest that shallow cloud-layer processes (e.g., thunderstorms or baroclinic instabilities) pump the jets [*Vasavada and Showman 2005, Salyk et al. 2006, Del Genio et al. 2007*]. It will be possible to distinguish between these models with remote sensing of the atmosphere over long temporal baselines (several months), combined with spectroscopic characterisation of the global physical and chemical environment (thermodynamic variables, abundances of aerosols, water and ammonia, energy flux deposition and redistribution measurements) at the cloud-tops. Measurements of lightning in individual convective cells will also constrain the energetics of the atmosphere at depth [*Borucki and Williams 1986, Little et al. 1999*].

Jupiter exhibits a wealth of time-variable phenomena, ranging from short-lived thunder-storms, lightning, and atmospheric waves to multi-year-long, quasiperiodic variations in the banded cloud patterns. Global upheavals of the banded structure occurred throughout 2007

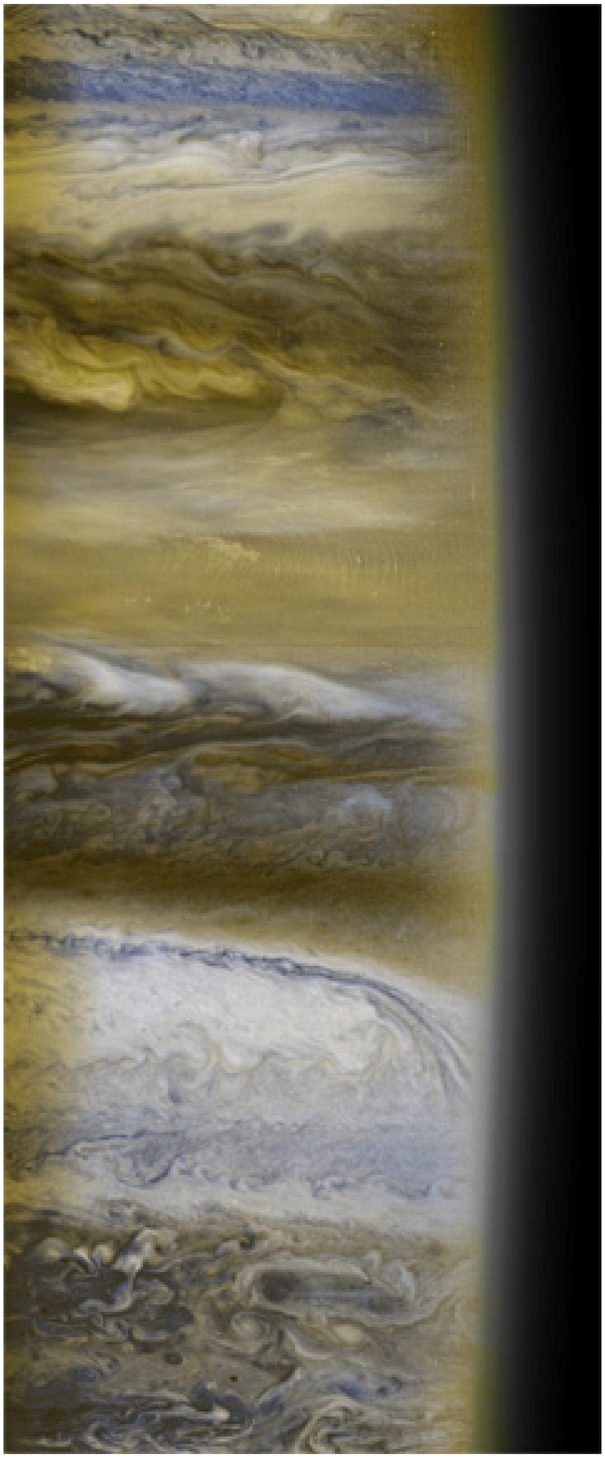

*Figure 2.3-16. New Horizons high resolution imaging (Ralph/MVIC) showing both the small-scale turbulence and the large-scale banded structure of the Jovian troposphere. The spatial resolution of 45 km/pixel is three times better than HST and will be surpassed by the JEO imaging capabilities [*Reuter et al. 2008*].*

[*Sanchez-Lavega et al. 2008*], also observed were the formation and reddening of new anticyclonic ovals in 2006 and 2008 (**Figure 2.3-17**) [*Simon-Miller et al. 2006, Cheng et al. 2008*]. Jovian compact vortices were seen to merge, split, eject filaments, orbit other vortices, oscillate in shape and position, migrate in longitude and latitude, change color and albedo, and interact with jets in a variety of ways. Lifetimes range from >100 years for the Great Red Spot (dimensions 20,000 km x 10,000 km) to only days for some of the smaller structures (hundreds of km or less). These behaviours provide clues to vortex dynamics and the background atmosphere in which the vortices reside. Jupiter also exhibits a 4-year cycle of low- and mid-latitude stratospheric variability known as the Quasi-Quadrennial Oscillation (QQO [*Leovy et al. 1991*]). The role of these phenomena in Jupiter's general circulation remain poorly understood, and there is a need for a high-resolution Jovian climate database that will have global coverage and continuous monitoring of these phenomena over a long temporal baseline. Temporal studies of the small-scale turbulent processes that transport momentum, heat, and tracers are crucial in understanding the basic structures of the jets, clouds, belts, zones, and vortices. Furthermore, temporal analysis of wave propagation and dissipation in the thermosphere (which is hotter than radiative equilibrium models can account for) will be used to elucidate their role in thermospheric heating.

The upper troposphere and stratosphere contain a wealth of trace chemical species and haze material that results from upward transport from the interior, meteoritic influx from above (e.g., HCN and CO from the Shoemaker-Levy 9 impact), condensation and photochemistry. The spatial distributions of ammonia, phosphine (PH_3), water vapor, germane (GeH_4), and tropospheric hazes can be used as passive tracers of the zonal, meridional and vertical transport within the upper troposphere. Mapping their horizontal and vertical distribution will yield insight into tropospheric chemistry (e.g., haze production from methane, phosphine, ammonia and hydrocarbon photolysis) and inferences of deep dynamic processes. The 3D distribution of stratospheric hydrocarbons and photo-

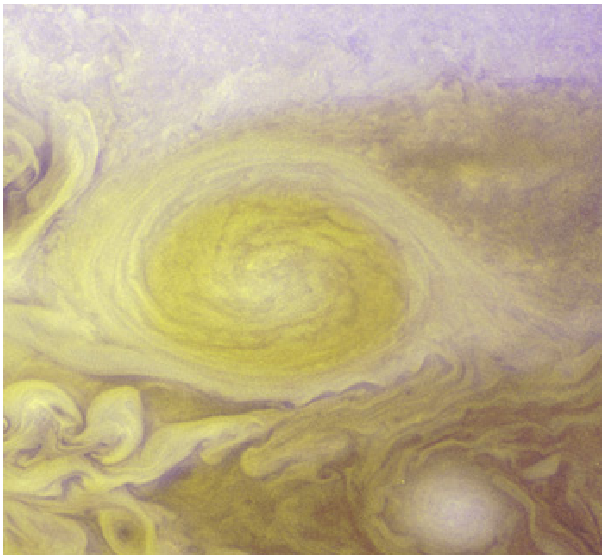

Figure 2.3-17. *Image of Jupiter's "Little Red Spot" (LRS) from the LORRI instrument on the New Horizons spacecraft in February 2007, colorized using Hubble Space Telescope images [*Cheng et al. 2008*]. The spot formed from the merger of three white ovals in 1998–2000, and visibly reddened in late 2005. The LRS is approximately 4000 km in width (half the size of the Great Red Spot). Image resolution is about 15 km/pixel, 10 times better than Hubble's. Images such as these permit an understanding of the development and dynamics of Jupiter's atmospheric storms.*

chemical hazes may yield insight into stratospheric chemistry and transport, and the presence of exogenic material (e.g., from comets) in the stratosphere allows further investigation of the processes at work in the redistribution of mass and energy during the formation of Jupiter and its satellites.

Moving to even higher altitudes above the stratosphere, there is presently poor understanding of the coupling between the neutral-atmospheric and charged-magnetospheric environments by the poorly studied Jovian ionosphere. Important issues include: the nature of energy-deposition processes and precipitating particles in the upper atmosphere, the evolution of the ion distribution with time, and the electrodynamic coupling between sources in the magnetodisk and the detailed three-dimensional structure of the Jovian aurorae.

2.3.6.5 Rings, Dust, and Small Moons

A system of small moons and faint rings encircles Jupiter (**Figure 2.3-18**), within Io's orbit. Although Saturn's ring system is more familiar, faint and dusty rings are much more common in the outer solar system, encircling all four of the giant planets, and may represent the end result of the evolution of a much denser ring system such as Saturn's. Dusty rings are of interest because they reveal a variety of non-gravitational processes that are masked within more massive disks. For example, fine dust grains become electrically charged by solar photons and by interactions with Jupiter's plasma. Their orbits are perturbed by solar radiation pressure and by Jupiter's magnetic field [e.g., *Burns et al. 2004*]. Therefore, a better description of dust's dynamics and properties has the potential to provide valuable information about Jupiter's plasma and magnetic field within regions that cannot be easily probed by spacecraft.

Jupiter's dusty rings may serve as a source of exogenic material on the surfaces of the Galilean satellites. Most ring dust evolves inward, but Galileo images show a very faint stream of material moving outward from Thebe [*Burns et al. 1999*, *Showalter et al. 2008*]. Little is known about this material, but *Hamilton and Krueger* [*2008*] attribute it to grains trapped in a particular orbital resonance with Jupiter's shadow. Furthermore, *Horanyi et al.* [*1993*] have investigated mechanisms whereby ring dust can contribute to dust streams emanating outward from Jupiter (although they regard Io as the dominant source).

Over relatively brief time scales, dust grains are swept from the system by drag forces or destroyed in place by impacts. They must therefore be continuously replenished from some reservoir. The inner moons clearly play a role—Amalthea and Thebe bound the especially faint "gossamer" rings [*Burns et al. 1999*], and these moons orbit near the edge of Jupiter's main ring. However, images indicate a family of additional bodies inside the main ring, which could contribute most of the main ring's dust [*Showalter 2007*]. However, New Horizons searched for kilometer-sized moons and found none, indicating a peculiar break in the size distribution below 8 km, the radius of Adrastea. Perhaps this is the result of a balance

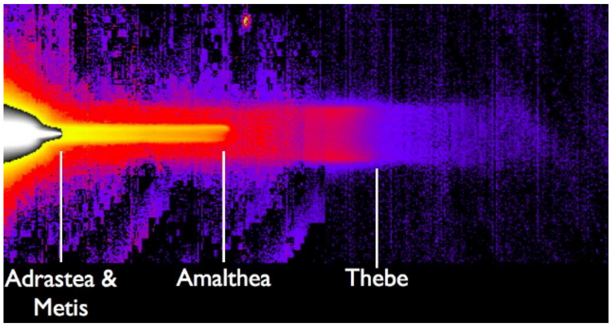

Figure 2.3-18. *This edge-on color-coded mosaic of the ring system from Galileo shows the connection between the dust and inner satellites. Adrastea and Metis bound the main ring and its thick interior halo (white, left). Amalthea and Thebe each produce fainter rings (yellow and red), which are shaped like "tuna cans." The very faint outward extension to Thebe's ring (blue) is unexplained.*

between accretion and disruption for small bodies orbiting at the edge of Jupiter's Roche zone.

With typical optical depths of 10^{-6} to 10^{-8}, small injections of new dust can produce noticeable changes in the ring. Recent impacts might explain a variety of changes observed in the ring system over the years, including the appearances of arcs, clumps and other asymmetries. With regular monitoring over a long time baseline than currently possible, one could potentially use the rings to place new constraints on the present flux of meteoroids into the Jovian system. This result would have implications for the ages of all satellite surfaces.

Jupiter's rings share many of their properties with protoplanetary disks. In both systems, dust and larger bodies commingle and interact through a variety of processes: gravitational, collisional and other. Thus, the ring system provides a dynamical laboratory for understanding the formation of the broader Jovian system.

2.3.6.6 Jupiter System Summary

Many important questions remain about the different components of the Jupiter system and how they interact, including how they may relate to better understanding Europa and its potential habitability.Some of these are:

- What factors control the different styles of eruptive activity on Io?
- Are plasma processes responsible for Ganymede's bright polar caps, and if so, how?
- Has Ganymede experienced cryovolcanism, or does intense tectonism create smooth terrains; and what is the distribution and thickness of Callisto's dark component?
- Is Europa's sputter-produced atmosphere patchy, and how does it vary spatially and temporally?
- Are Ganymede's and Callisto's atmospheres produced mainly by sputtering or sublimation?
- How do the sources and dynamics of the fields and plasma in the Jovian magnetosphere vary over time, especially as correlated with Io's activity?
- How does Jovian small-scale atmospheric convection contribute to development and maintenance of larger-scale storms?

Section 2.4.6 discusses how these and many other questions about the Jupiter System can be addressed by EJSM.

2.4 JEO Science Goal, Objectives, and Investigations

Galileo revealed Europa as a dynamic—and potentially habitable—world. However, many fundamental questions remain unanswered. Key issues on the production, presence and transport of materials among the surface, ice shell, and ocean is unknown; the thickness of the ice shell is uncertain by more than an order of magnitude; and the origins of most surface landforms remain mysterious. The influence of the Jovian environment is poorly understood, including complex systems such as the interplay among magnetospheres, plasma sources, and surface chemistry. In this section these open science issues are placed within the overall context of JEO, and how they will be addressed is detailed.

The Joint Jupiter Science Definition Team (JJSDT) consists of an international group of 27 US, 15 European, and 5 Japanese scientists. The JJSDT held 7 meetings over 6 months. During this time, it evaluated science goals from the US National Research Council's Planetary Science Decadal Survey, the ESA Cosmic Vision, the NASA 2007 Europa Explorer and Jupiter System Observer studies, and the 2007 ESA Laplace Proposal. These documents and previous committee reports were culled and honed to determine the goals, objectives, and investigations for studying Europa and the Jupiter system with the JEO and JGO elements of EJSM. **Table 2.4-1** summarizes the previous reports and recommendations, from which the JJSDT recommendations were built. Next is described the resultant JEO science traceability from goal to objectives to investigations.

2.4.1 JEO Science Goal and Traceability Matrix

The Planetary Decadal Survey summarizes the inherent motivation for Europa exploration as fundamental science question: "Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?" Understanding both processes and habitability are key drivers for Europa exploration, as are the focus areas of origin, evolution, and life. Thus, the goal adopted for the Jupiter Europa Obiter element of EJSM is:

Explore Europa
to investigate its habitability.

This goal implies understanding processes, origin, and evolution. This includes testing the numerous scientific issues described in §2.3. It also allows for "discovery" science—unpredicted findings of the type that have often reshaped the very foundations of planetary science, especially in the surprises uncovered in the outer solar system by the Voyagers, Galileo, and Cassini missions. "Investigate its habitability" recognizes the significance of Europa's astrobiological potential. "Habitability" includes confirming the existence and determining the characteristics of water below Europa's icy surface, understanding the possible sources and cycling of chemical and thermal energy, investigating the evolution and chemical composition of the surface and ocean, and evaluating the processes that have affected Europa through time.

The traceability from the JEO goal to objectives to investigations is summarized in **Table 2.4-2**. The complete traceability to measurements and generic instruments is compiled in the JEO Traceability Matrix and shown in **Foldout 1** (**FO-1**).

The JEO objectives are categorized in priority order as:

A. Europa's Ocean
B. Europa's Ice Shell
C. Europa's Chemistry
D. Europa's Geology
E. Jupiter System Science.

Table 2.4-1. *Heritage of Europa Science Objectives and Investigations.*

Committee	Report Title	Reference
Europa Orbiter Science Definition Team	Europa Orbiter Mission and Project Description	NASA AO: 99-OSS-04
Committee on Planetary and Lunar Exploration (COMPLEX)	A Science Strategy for the Exploration of Europa	COMPLEX [1999]
NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System	Europa and Titan: Preliminary Recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System	Chyba et al. [1999]
Solar System Exploration ("Decadal") Survey	New Frontiers in the Solar System: An Integrated Exploration Strategy	SSB [2003]
Jupiter Icy Moons Orbiter (JIMO) Science Definition Team	Report of the NASA Science Definition Team for the JIMO	JIMO SDT [2004]
Europa Focus Group of the NASA Astrobiology Institute	Europa Science Objectives	Pappalardo [2006]
Outer Planets Assessment Group (OPAG)	Scientific Goals and Pathways for Exploration of the Outer Solar System	OPAG [2006]
NASA Solar System Exploration Strategic Roadmap Committee	2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate	NASA [2006]
Europa Science Definition Team	2007 Europa Explorer Mission Study: Final Report	Clark et al. [2007]
Jupiter System Observer Science Definition Team	Jupiter System Observer Mission Study: Final Report	Kwok et al. [2007]
The Laplace Team	Laplace: A Mission to Europa and the Jupiter System for ESA's Cosmic Vision Programme	Blanc et al. [2007]

***Table 2.4-2**. Traceability from the JEO Goal to Science Objectives to Science Investigations*

Goal	Science Objective			Science Investigation	
Explore Europa to investigate its habitability	A. Ocean	Characterize the extent of the ocean and its relation to the deeper interior.		A1.	Determine the amplitude and phase of the gravitational tides.
				A2.	Characterize the magnetic environment (including plasma) to determine the induction response from the ocean over multiple frequencies.
				A3.	Characterize surface motion over the tidal cycle.
				A4.	Determine the satellite's dynamical rotation state.
				A5.	Investigate the core, rocky mantle, and rock-ocean interface.
	B. Ice	Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.		B1.	Characterize the distribution of any shallow subsurface water.
				B2.	Search for an ice-ocean interface.
				B3.	Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.
				B4.	Characterize regional and global heat flow variations.
	C. Chemistry	Determine global surface compositions and chemistry, especially as related to habitability.		C1.	Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability and potential biosignatures.
				C2.	Relate compositions to geological processes, especially material exchange with the interior.
				C3.	Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.
				C4.	Characterize the nature of exogenic materials.
	D. Geology	Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.		D1.	Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.
				D2.	Determine sites of most recent geological activity, and evaluate future landing sites.
				D3.	Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris.
	E. Jupiter system science	Understand Europa in the context of the Jupiter system.	Satellite surfaces and interiors	E1.	Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io
				E2.	Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust)
				E3.	Investigate the presence and location of water within Ganymede and Callisto.
				E4.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Ganymede.
				E5.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Callisto.
				E6.	Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.
			Satellite Atms.	E7.	Characterize the composition, variability and dynamics of Europa's atmosphere and ionosphere
				E8.	Understand the sources and sinks of Io's crustal volatiles and atmosphere.
				E9.	Determine the sources and sinks of the Ganymede and Callisto atmospheres.
			Plasma and magnetospheres	E10.	Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.
				E11.	Characterize the composition of and transport in Io's plasma torus.
				E12.	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.
				E13.	Study the interactions between Jupiter's magnetosphere and Io, Ganymede and Callisto (incl. characterize Ganymede's magnetic field)
				E14.	Understand the structure, composition and stress balance of Jupiter's magnetosphere.
				E15.	Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.
			Jupiter atm.	E16.	Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa.
				E17.	Characterize Jovian atmospheric dynamics and structure.
			Rings	E18.	Characterize the properites of the small moons, ring source bodies and dust
				E19.	Identify the dynamical processes that define the origin and dynamics of ring dust.

Origins	Evolution	Processes	Habitability	Life

The first four objectives (A-D) relate exclusively to Europa, while Objective E is tied to Jupiter system science. Investigations in **Table 2.4-2** and **FO-1** are listed in priority order within each objective. In **FO-1**, the measurements (and corresponding instruments) to address each investigation of the first four objectives (A–D) are also in priority order within each investigation. Investigations are listed in priority order within each category of Objective E, but there is no intended relative priority of the categories. Each objective and its corresponding investigations are described in the following sections (§2.4.2 through §2.4.6), along with the corresponding measurements needed to address them.

The right-hand colored columns of the Traceability Matrix (**FO-1**) comprise the JEO Science Value matrix, which is discussed in §2.5.5.

As stated in the 2006 Solar System Exploration Roadmap [*NASA 2006*], "By studying the Jupiter system as a whole, we can better understand the 'type example' for habitable planetary systems within and beyond our Solar System." The top priority objectives in the JEO Traceability Matrix relate directly to Europa and its potential habitability. Moreover, many aspects of Jupiter System science do relate closely to understanding Europa and its potential habitability. For example: Ganymede and Callisto are believed to possess subsurface oceans which would provide a comparisons to Europa's; Io holds clues to the fundamentals of tidal heating and interactions with the Jovian magnetospheric environment; and Jupiter's composition sheds light on the initial conditions of the Galilean satellite system.

The JJSDT also recognizes the importance of Jupiter System science in its own right, as it relates to the overall theme of ESJM: "The emergence of habitable worlds around gas giants." Jupiter system science presents important synergistic and complementary science opportunities, in combination with observations by the ESA JGO spacecraft. In the JEO Traceability Matrix (**FO-1**), marked with a "EJSM" icon are those observations that are not directly related to Europa's habitability but which are still important to the overall synergistic theme of EJSM.

The Decadal Survey builds a hierarchical flow-down from "Motivational Questions," to "Scientific Goals," to "Scientific Themes," to "Fundamental Science Questions." The Decadal Survey's scientific goals were subsequently modified to become the science questions highlighted in the 2006 Solar System Exploration Roadmap and the 2007 NASA Science Plan. **Table 2.4-3** maps the scientific goals of the Decadal Survey and the science questions of the Roadmap to five common

Table 2.4-3. *Jupiter Europa Orbiter Focus Areas, Based on Guiding Documents.*

Solar System Exploration ("Decadal") Survey	2006 SSE Roadmap and 2007 NASA Science Plan	Jupiter Europa Orbiter Mission
• Learn how the Sun's retinue of planets originated and evolved	• How did the Sun's family of planets and minor bodies originate?	Origins
• Discover how the basic laws of physics and chemistry, acting over aeons, can lead to the diverse phenomena observed in complex systems, such as planets	• How did the solar system evolve to its current diverse state?	Evolution
• Understand how physical and chemical processes determine the main characteristics of the planets, and their environments, thereby illuminating the workings of the Earth		Processes
• Determine how life developed in the solar system, where it may have existed, whether extant life forms exist beyond Earth, and in what ways life modifies planetary environments	• What are the characteristics of the solar system that led to the origin of life?	Habitability
	• How did life begin and evolve on Earth and has it evolved elsewhere in the solar system?	Life

FOLDOUT 1
SCIENCE TRACEABILITY MATRIX

JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective		Science Investigation		Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1B	2 Regional Proc. 2A	2B	3 Targ. Proc.
Explore Europa to investigate its habitability	A. Ocean	**Characterize the extent of the ocean and its relation to the deeper interior.**	A1.	Determine the amplitude and phase of the gravitational tides.	A1a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A1a. Telecom system		3	4	4	5	5
					A1b. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1-m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A1b. Laser altimeter		3	4	5	5	5
			A2.	Characterize the magnetic environment (including plasma), to determine the induction response from the ocean, over multiple frequencies.	A2a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for at least one month.	A2a. Magnetometer		2	3	4	4	5
					A2b. Determine the plasma distribution function with 1 min resolution continuously for several months; detect electrons in the few keV to hundreds of keV with angular and time resolution	A2b. Particle and plasma instrument		1	1	2	2	3
			A3.	Characterize surface motion over the tidal cycle.	A3a. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1 m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A3a. Laser altimeter		4	5	5	5	5
					A3b. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A3b. Telecom system		3	4	4	5	5
			A4.	Determine the satellite's dynamical rotation state.	A4a. Doppler shift from spacecraft tracking via two-way Doppler, to determine mean spin pole direction. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A4a. Telecom system		2	2	3	4	4
					A4b. Topographic differences at cross-over points from globally distributed topographic profiles to determine spin pole direction and libration amplitudes, with better than or equal to 1 m vertical accuracy.	A4b. Laser altimeter		2	2	3	4	5
			A5.	Investigate the core, rocky mantle, and rock-ocean interface.	A5a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve high degree gravity field. Doppler velocity of 0.1 mm/s over 60s accuracy. Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A5a. Telecom system		2	2	3	3	4
					A5b. Topographic profiles to resolve coherence with gravity, with better than or equal to 1 m vertical accuracy.	A5b. Laser altimeter		2	2	3	3	4
					A5c. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for several months.	A5c. Magnetometer		1	1	2	2	4
					A5d. Determine the distribution function of the plasma ions and electrons with continuous observations over several months	A5d. Particle and plasma instrument		1	1	1	2	3
	B. Ice	**Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.**	B1.	Characterize the distribution of any shallow subsurface water.	B1a. Identify and locally characterize subsurface thermal or compositional horizons and structures related to the current or recent presence of water or brine, by obtaining sounding profiles of subsurface dielectric horizons and structures, with better than 50 km profile spacing over more than 80% of the surface, at depths of 100 m to 3 km at 10 m vertical resolution, and performing targeted subsurface characterization of selected sites at least 30 km in length.	B1a. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth)		3	3	4	4	5
					B1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over more than 80% of the surface, co-located with sounding profiles.	B1b. Wide-angle camera (stereo) and laser altimeter		1	2	3	4	4
			B2.	Search for an ice-ocean interface.	B2a. Identify deep thermal, compositional, or structural horizons by obtaining sounding profiles of subsurface dielectric horizons, with better than 50 km profile spacing over more than 80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution.	B2a. Radar sounder (nominally ~5 or 50 MHz, with ~1 MHz bandwidth)		1	2	2	3	4
					B2b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over more than 80% of the surface, co-located with sounding data.	B2b. Wide-angle camera (stereo) and laser altimeter		1	2	3	4	4
			B3.	Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	B3a. Global identification and local characterization of subsurface dielectric horizons and structures, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with better than 50 km spacing over more than 80% of the surface, plus targeted characterization of selected sites at least 30 km in length.	B3a. Radar sounder (dual-frequency, nominally ~5 & ~50 MHz, with ~1 and ~10 MHz bandwidth)		3	3	4	4	5

Europa Explorer Themes:

Origins	Evolution	Processes	Habitability	Life

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective		Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1B	2 Regional Proc. 2A	2B	3 Targ. Proc.
Explore Europa to investigate its habitability	B. Ice	**Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.**	B3. Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	B3b. Map thermal emission from the surface by measuring the albedo over more than 80% of the surface at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, and make targeted thermal observations at better than 250 m/pixel spatial resolution and temperature accuracy better than 2 K.	B3b. Thermal imager		2	2	3	3	4
				B3c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable), and better than 12 nm through a spectral range of at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	B3c. Vis-IR imaging spectrometer		1	2	3	4	5
				B3d. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over more than 80% of the surface, co-located with sounding data.	B3d. Wide-angle camera (stereo) and laser altimeter		1	2	3	4	4
				B3e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel, and topographic sampling of targeted sites with better than 1 m vertical accuracy.	B3e. Narrow-angle camera and laser altimeter		1	1	1	1	1
				B3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over more than 80% of the surface.	B3f. Wide-angle camera, color		3	4	4	4	4
				B3g. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at better than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	B3g. UV imaging spectrometer		1	1	1	1	1
				B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	B3h. Medium-angle camera		2	2	3	3	4
				B3i. Doppler velocity of 0.1 mm/s over 60 s accuracy, to identify regions of density contrast within the ice crust. Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	B3i. Telecom system		1	2	3	3	4
			B4. Characterize regional and global heat flow variations.	B4a. Identify and map subsurface thermal horizons, by obtaining sounding profiles of subsurface dielectric horizons, with better than 50 km profile spacing over more than 80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution.	B4a. Radar sounder		1	2	2	3	4
				B4b. Map thermal emission from the surface by measuring the albedo over more than 80% of the surface at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy.	B4b. Thermal imager		2	2	3	3	4
	C. Chemistry	**Determine global surface compositions and chemistry, especially as related to habitability.**	C1. Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability and potential biosignatures.	C1a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm spectral resolution (20 nm floor) through a spectral range of at least 2.5–5 microns, along profiles with less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C1a. Vis-IR imaging spectrometer		2	2	3	4	5
				C1b. Characterize the composition of sputtered products from energetic particle bombardment of the surface, using ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C1b. Ion and neutral mass spectrometer		1	1	3	3	4
				C1c. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C1c. UV imaging spectrometer		1	1	1	1	1
			C2. Relate compositions to geological processes, especially material exchange with the interior.	C2a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 5 nm (10 nm floor) spectral resolution through a spectral range of at least 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm (20 nm floor) through a spectral range of at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C2a. Vis-IR imaging spectrometer		2	3	3	4	5
				C2b. Global identification and local characterization of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with better than 50 km spacing, plus targeted characterization of selected sites.	C2b. Radar sounder		2	2	3	3	4

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective		Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	C. Chemistry	**Determine global surface compositions and chemistry, especially as related to habitability.**	**C2.** Relate compositions to geological processes, especially material exchange with the interior.	C2c. Surface reflectance measurements by ultraviolet spectroscopy of targeted features at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns.	C2c. UV imaging spectrometer		1	1	1	1	1
				C2d. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	C2d. Medium-angle camera (stereo)		2	2	2	3	4
				C2e. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at better than or equal to 250 m/pixel spatial resolution, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy better than 2 K, over more than 80% of the surface.	C2e. Thermal imager		3	4	4	5	5
				C2f. Detailed morphological characterization of targeted features through imaging at better than or equal to 1 m/pixel.	C2f. Narrow-angle camera		3	3	4	4	5
				C2g. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution over >80% of the surface, and topographic characterization at better than 10 m/pixel spatial scale and better than or equal to 1 m vertical resolution and accuracy for targeted features, co-located with sounding data.	C2g. Wide-angle camera (stereo), medium-angle camera (stereo), and laser altimeter		2	2	2	3	3
			C3. Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.	C3a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm spectral resolution (20 nm floor) through a spectral range at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C3a. Vis-IR imaging spectrometer		1	2	3	4	5
				C3b. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal to 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C3b. UV imaging spectrometer		1	1	1	1	1
				C3c. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm through a spectral range of at least 2.5–5 microns with SNR greater than 32, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	C3c. Vis-IR imaging spectrometer and UV imaging spectrometer		2	2	3	4	4
				C3d. Characterize the composition of sputtered products from energetic particle bombardment of the surface, through ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of more than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C3d. Ion and neutral mass spectrometer		1	1	3	3	4
				C3e. Characterize the structure of the sputter-produced atmosphere using ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emissions, at equal to or better than 0.5 nm spectral resolution and 100 m/pixel scale through a spectral range of at least 0.1–0.20 microns.	C3e. UV imaging spectrometer		3	3	4	4	5
			C3. Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.	C3f. Determine the flux of trapped and precipitating ions (with composition) and electrons in the energy range 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute.	C3f. Particle and plasma instrument		1	1	2	3	3
				C3g. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over more than 80% of the surface.	C3g. Wide-angle camera, color		3	4	4	4	4
				C3h. Measure the surface albedo at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, over more than 80% of the surface.	C3h. Thermal imager		3	4	4	5	5
				C3i. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	C3i. Narrow-angle camera		3	3	4	4	5
			C4. Characterize the nature of exogenic materials.	C4a. Determine the ion (with composition) and electron precipitation flux at energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute.	C4a. Particle and plasma instrument		1	1	2	3	3

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

					SCIENCE VALUE					
					Jupiter System Science	EUROPA CAMPAIGNS				
						1 Global Framewrk		2 Regional Proc.		3 Targ. Proc.
Goal	Science Objective	Science Investigation	Measurement	Instrument		1A	1B	2A	2B	
Explore Europa to investigate its habitability	C. Chemistry: **Determine global surface compositions and chemistry, especially as related to habitability.**	C4. Characterize the nature of exogenic materials.	C4b. Ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of more than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C4b. Ion and neutral mass spectrometer		1	1	2	2	2
			C4c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor) with SNR better than 128, and better than 10 nm resolution (20 nm floor) through a spectral range of at least 2.5–5 microns (SNR better than 32), along profiles with less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C4c. Vis-IR imaging spectrometer		1	2	3	4	5
			C4d. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C4d. UV imaging spectrometer		1	1	1	1	1
			C4e. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over more than 80% of the surface.	C4e. Wide-angle camera, color		3	4	4	4	4
	D. Geology: **Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	D1. Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.	D1a. Determine the distributions and morphologies of surface landforms at regional and local scales, and the regional and global stratigraphic relationships among them, by determining surface color characteristics at ~100 m/pixel scale in at least 3 colors with near-uniform lighting conditions and solar phase angles less than or equal to 45 degrees, over more than 80% of the surface.	D1a. Wide-angle camera (color) and medium-angle camera		3	3	4	4	5
			D1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over more than 80% of the surface, co-located with sounding profiles.	D1b. Wide-angle camera (stereo)		1	3	3	5	5
			D1c. Topographic characterization at better than 10 m/pixel scale and better than or equal to 1 m vertical resolution and accuracy for targeted features, co-located with sounding profiles.	D1c. Medium-angle camera (stereo) and laser altimeter		2	2	2	2	3
			D1d. Global identification and local characterization of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with better than 50 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	D1d. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth)		3	3	4	4	5
			D1e. Characterize small-scale surface morphology, with stereo imaging at ~1 to 10 m/pixel over targeted high-priority sites, with vertical resolution of better than or equal to 1 m.	D1e. Medium-angle camera or narrow-angle camera		0	0	2	2	2
			D1f. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm resolution through a spectral range of at least 2.5–5 microns with SNR better than 32, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	D1f. Vis-IR spectrometer and UV imaging spectrometer		1	2	2	3	3
			D1g. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at spatial resolution better than or equal to 250 m/pixel, and by making daytime and nighttime thermal observations at spatial resolution better than or equal to 250 m/pixel and temperature accuracy better than 2 K, over more than 80% of the surface.	D1g. Thermal imager		2	3	3	4	5
			D1h. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D1h. Narrow-angle camera		1	2	3	3	4
		D2. Determine sites of most recent geological activity and evaluate future landing sites.	D2a. Thermal mapping better than or equal to 250 m/pixel spatial resolution and temperature accuracy better than 2 K, over more than 80% of the surface, with the same regions observed in both the day and night.	D2a. Thermal imager		2	2	4	4	5
			D2b. Search for and identify any regions of outgassing using ultraviolet stellar occultations, and ultraviolet imaging of the surface and atmosphere, at better than or equal to 0.5 nm spectral resolution through a range of at least 0.1–0.2 microns.	D2b. UV imaging spectrometer		2	3	4	5	5
			D2c. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	D2c. Medium-angle camera (stereo)		1	1	2	2	3

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective	Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	D. Geology: **Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	**D2.** Determine sites of most recent geological activity and evaluate future landing sites.	D2d. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D2d. Narrow-angle camera		1	2	3	3	4
			D2e. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm through a spectral range of at least 2.5–5 microns with SNR better than 32, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	D2e. Vis-IR spectrometer and UV imaging spectrometer		1	2	2	3	3
			D2f. Characterize the interaction between the surface and plasma to evaluate surface aging processes. Measure depth and temperature of the 1.65 micron water band (deeper for colder temperatures of crystalline (young) ice and nearly absent for pure amorphous (older) ice in addition to measurements at 3.1 and 4.53 microns. Determine the ion and electron precipitation flux with ion composition for energies of 1 eV to 1 MeV.	D2f. Particle and plasma instrument and Vis-IR imaging spectrometer		2	2	2	2	2
		D3. Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris.	D3a. Determine thermal inertia of surface materials, by thermal mapping, to better than or equal to 250 m/pixel spatial resolution and better than 2 K absolute temperature over >80% of the surface, with the same regions observed in both the day and night.	D3a. Thermal imager		2	2	3	3	4
			D3b. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D3b. Narrow-angle camera		1	2	3	3	4
			D3c. Characterize the interaction between the surface and plasma to evaluate surface aging processes. Measure depth and temperature of the 1.65 micron water band (deeper for colder temperatures of crystalline (young) ice and nearly absent for pure amorphous (older) ice in addition to measurements at 3.1 and 4.53 microns. Determine the precipitation flux of electrons and ions (with composition) in the eV to few MeV energy range.	D3c. Particle and plasma instrument and Vis-IR imaging spectrometer		2	2	2	2	2
			D3d. Measure ion-cyclotron waves and relate to plasma-pickup and erosion by magnetic field sampling at 32 vectors/s and a sensitivity of 0.1 nT, to constrain sputtering rates.	D3d. Magnetometer		1	1	2	2	4
	E. Jupiter System: **Understand Europa in the context of the Jupiter system.** Satellite surfaces and interiors	**E1.** Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io.	E1a. Determine regional and global heat flow by 1) measuring global surface thermal emission at spatial resolution of 5 km/pixel to 10% radiometric accuracy at at least two wavelengths; 2) identifying thermally-controlled subsurface horizons within the ice shell by radar sounding at depths of 1 to 30 km at 100 m vertical resolution.	E1a. Thermal imager and radar sounder	3					
			E1b. Thermal Mapping with 2K absolute accuracy, from ~80K to >160K, spatial resolution better than 10 km/pixel, preferably better than 500 m/pixel, within 30 degrees of the noon meridian and at night.	E1b. Thermal imager	2					
			E1c. Determine regional and global time-varying gravity and topography/shape of Io. Topographic differences at cross-over points with better than or equal to 10 m vertical accuracy. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy.	E1c. Telecom system and laser altimeter	3					
		E2. Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust).	E2a. Repeated (daily to monthly) monochromatic imaging of selected active volcanic features at ~1 km/pixel spatial resolution.	E2a. Narrow angle camera	1					
			E2b. IR imaging of volcanic thermal emission at better than 100 km/pixel spatial scale, absolute accuracy 2K, at silicate melt temperatures, over a range of temporal scales (e.g., hourly, daily, weekly, monthly). Desire better than 20 km/pixel spatial resolution.	E2b. IR imaging spectrometer	4					
			E2c. Frequent multispectral global mapping (minimum 3 colors) at better than or equal to 10 km/pix. Violet, green, NIR over a range of temporal scales (e.g., hourly, daily, weekly, monthly).	E2c. Narrow-angle camera	4					
			E2d. High-resolution visible imaging (better than 100 m spatial resolution) of selected volcanic features for change detection (e.g., with Galileo and Voyager data).	E2d. Narrow-angle camera	2					
			E2e. Global (>80%) monochromatic imaging at ~1 km/pixel spatial resolution at available opportunities.	E2e. Narrow-angle camera	1					
			E2f. IR imaging of volcanic thermal emission at better than 100 km/pixel spatial scale, absolute accuracy 2K, at silicate melt temperatures, over a range of temporal scales (e.g., hourly, daily, weekly, monthly). Desire better than 20 km/pixel spatial resolution.	E2f. IR imaging spectrometer	1					

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Goal	Science Objective			Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Satellite surfaces and interiors	**E2.** Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust).	E2g. UV - VIS plume imaging: high phase angle plume monitoring (for dust and gas emissions) and low phase angle observations (for gas absorptions) over a range of temporal scales. Visible spatial resolution better than 20 km/pixel; UV spatial resolution better than 50 km/pixel.	E2g. UV imaging spectrometer and narrow-angle camera	1					
					E2h. Long-distance visible and thermal characterization (e.g., from Ganymede or Jupiter orbit) over a period of years. Desire close flybys of Io to characterize terrains/active features/change at high resolution.	E2h. Narrow-angle camera and thermal imager	1					
				E3. Investigate the presence and location of water within Ganymede and Callisto.	E3a. Determine Degree-2 dynamic gravity field and spin pole orientation. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency preferred. Many flybys.	E3a. Telecom system	2					
					E3b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT with multiple flybys at different orbital phases and closest approach of < 0.5 moon radii.	E3b. Magnetometer	3					
					E3c. Characterize the extent and location of water (including brines) in 3D by obtaining profiles at depths of 1 to 30 km at 100 m vertical resolution, and obtain simultaneous topography at better than or equal to 1 km/pixel spatial scale and better than or equal to 10 m range accuracy.	E3c. Radar sounder and laser altimeter	3					
				E4. Determine the composition, physical characteristics, distribution, and evolution of surface materials on Ganymede.	E4a. Identify globally distributed bulk material compositions, grain size, porosity, crystallinity, and physical state from the IR (0.8–2.5 microns) with a spectral resolution of 4 nm and an IFOV smaller than 100 m, to the thermal with 2K absolute accuracy, from ~80K to >160K and spatial resolution better than 10 km/pixel.	E4a. Vis-IR imaging spectrometer and thermal imager	2					
					E4b. Map global distribution of different materials, including radiolytic materials (e.g., SO_x, O_3, H_2O_2, OH, O_2), and document variability over a range of timescales in the IR (0.8–5 microns) with a spectral resolution better than 10 nm (4 nm in the 1–2.5 micron range) and IFOV less than 1 km, along with UV observations (0.1 to 0.4 microns) with spectral resolution of better than 2 nm and spatial resolution better than 1 km/pixel.	E4b. Vis-IR imaging spectrometer and UV imaging spectrometer	2					
					E4c. Determine origin and evolution of non-ice materials, including the role of geologic processes in the IR (0.8–5 microns; spectral resolution of better than 10 nm and IFOV smaller than 1 km) of representative features. Co-registered with higher-resolution panchromatic images.	E4c. Vis-IR imaging spectrometer and narrow-angle camera	2					
					E4d. Document composition, physical state, distribution, and transport of surface volatiles, e.g., sublimation, over the UV wavelength range of 0.1 to 0.4 microns with spectral resolution of 2 nm and spatial resolution better than 1 km/pixel. Spatial coverage of 50% to search for short-lived or mobile species and repeated coverage to look for changes. Visible wavelength mapping at 0.55–0.75 microns, spectral resolution of 1 nm. 50% global coverage with spatial resolution better than 1 km/pixel; repeated coverage to look for changes. IR coverage from 0.8–5 microns with spectral resolution better than 10 nm, IFOV smaller than 1 km. 50% global coverage with spatial resolution better than 1 km/pixel; repeated coverage to look for changes.	E4d. UV imaging spectrometer and Vis-IR imaging spectrometer	2					
				E5. Determine the composition, physical characteristics, distribution, and evolution of surface materials on Callisto.	E5a. Identify bulk material compositions, grain size, porosity, crystallinity, and physical state using globally-distributed hyperspectral IR imaging (0.8–2.5 microns). Spectral resolution of 4 nm, IFOV smaller than 100 m.	E5a. Vis-IR imaging spectrometer	2					
					E5b. Identify globally distributed bulk material compositions, grain size, porosity, crystallinity, and physical state from the IR (0.8–2.5 microns) with spectral resolution of 4 nm and IFOV smaller than 100 m, to the thermal with 2K absolute accuracy, from ~80K to >160K and spatial resolution better than 10 km/pixel.	E5b. Vis-IR imaging spectrometer and thermal imager	2					
					E5c. Map global distributions of different materials, including radiolytic materials (e.g., SO_x, O_3, H_2O_2, OH, O_2), and document variability over a range of timescales using global IR imaging (0.8–5 microns). Spectral resolution better than 10nm (4 nm in the 1–2.5 micron range), IFOV smaller than 1 km, along with UV observations (0.1 to 0.4 microns) with spectral resolution of better than 2 nm and spatial resolution better than 1 km/pixel.	E5c. Vis-IR imaging spectrometer and UV imaging spectrometer	2					
					E5d. Determine origin and evolution of non-ice materials, including the role of geologic processes in the IR (0.8–5 microns; spectral resolution of better than 10 nm and IFOV smaller than 1 km) of representative features. Co-registered with higher-resolution panchromatic images.	E5d. Vis-IR imaging spectrometer and narrow-angle camera	2					

Europa Explorer Themes:

Origins	Evolution	Processes	Habitability	Life

SI = Science Investigation

0	1	2	3	4	5
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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective			Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	EUROPA CAMPAIGNS: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Satellite surfaces and interiors	E6. Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.	E6a. Measure the low order static gravity (J_2 and C_{22}) at 10^{-7} accuracy for the non-dimensional gravitational harmonics of both moons, via Doppler tracking.	E6a. Telecom system	5					
					E6b. Measure higher-order gravity to evaluate non-hydrostatic effects, via Doppler tracking.	E6b. Telecom system	4					
					E6c. Measure the dynamic degree-2 gravity signal to determine tidal k_2 to within 0.1, via Doppler tracking.	E6c. Telecom system	2					
					E6d. Measure the pole position to 0.1 deg accuracy to determine the obliquity of the spin axis.	E6d. Medium-angle camera	2					
					E6e. Globally distributed altimetry to 1 m vertical resolution and better than 1 km horizontal resolution (100 m horizontal resolution preferable, at least along specific spacecraft tracks if not globally)	E6e. Laser altimeter	1					
					E6f. Global (more than 80% coverage) visible imaging at 100 m/pixel spatial resolution. Additionally, desire ~10–20% coverage at 10 m/pixel.	E6f. Narrow-angle camera	1					
					E6g. Globally distributed profiling of thermal, compositional and structural horizons for Ganymede and Callisto's icy shells to depths from 1 up to 30 km at 100 m vertical resolution.	E6g. Radar sounder	3					
					E6h. Measurement of, or upper limit on, heat flow using thermal measurements in the 8 to 100 micron range with a spectral resolution of 2K and spatial resolution better than 30 km/pixel; observation collected several times of day and at night.	E6h. Thermal imager	4					
					E6i. Magnetic field. Determination of induction response at orbital (as well as Jupiter rotation) time scales to an accuracy of 0.1 nT but with the emphasis on looking for secular variation of the "steady" field or variation in the induction signal since Galileo.	E6i. Magnetometer	3					
			Satellite atmospheres	E7. Characterize the composition, variability, and dynamics of Europa's atmosphere and ionosphere.	E7a. Perform UV imaging of Europa over the spectral range 100–200 nm at better than 0.5 nm resolution, better than 1 km spatial resolution, and better than 48 hr temporal resolution, including through the synodic cycle.	E7a. UV imaging spectrometer	4					
					E7b. Perform stellar occultations of Europa at UV wavelengths to search for water absorption and oxygen emission signatures. Cover 100–200 nm at better than 0.5 nm resolution, and latitude/longitude resolution of less than 30 deg.	E7b. UV imaging spectrometer	3	3	4	4	5	5
					E7c. Scan perpendicular to the limb from ~5 km above the surface to the surface of the satellite at IR wavelengths to measure or search for emission from O_2 (1.27 microns), H_2O, CO_2 (4.26 microns) and other species in the Europa atmosphere.	E7c. IR imaging spectrometer	3					
					E7d. Perform radio occultations of Europa to measure its ionosphere.	E7d. Two-band radio communication system with USO	3					
					E7e. Determine the fluxes of positive ions and neutral particles, by ion mass spectrometry over a mass range of 300 Daltons, mass resolution of better than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	E7e. Ion and neutral mass spectrometer	4					
					E7f. Understand how sputtering generates an exosphere. Determine the flux and composition of the impacting charged particles (ions and electrons) between energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute.	E7f. Particle and plasma instrument	3	1	1	2	3	3
				E8. Understand the sources and sinks of Io's crustal volatiles and atmosphere.	E8a. Characterize volatile cycle, including composition, physical state, distribution, and transport of surface volatiles by global mapping of the surface at UV-IR wavelengths (e.g., for SO_2 frost variations) on a range of temporal scales (~days). IR (1–5 microns) at 20 nm spectral resolution and ~10–500 km/pixel; VNIR (0.35–1 microns) at 2 nm resolution; NUV (0.2–0.35 microns) with better than 20 nm spectral resolution and better than 100 km spatial resolution.	E8a. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
					E8b. Dayside, nightside and eclipse coverage at UV wavelengths, 0.1–0.35 microns (for SO_2 and other gas density) at 0.5 nm spectral resolution, better than 500 km/pixel spatial resolution	E8b. UV imaging spectrometer	2					
					E8c. Determine roles and rates of sublimation, sputtering, and radiation darkening by global mapping of surface at UV-IR wavelengths at ~10–500 km/pix at better than 10 nm spectral resolution for 1–5 microns, and at ~2 nm for 0.1–1 microns, over a wide range of longitudes (i.e. to facilitate comparisons between leading and trailing hemispheres, especially in non-plume regions) and with thermal IR mapping with regional spatial resolution better than 10 km, including polar coverage.	E8c. Thermal instrument	1					

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

SCIENCE VALUE — EUROPA CAMPAIGNS

Goal	Science Objective			Science Investigation		Measurement	Instrument	Jupiter System Science	1 Global Framewrk		2 Regional Proc.		3 Targ. Proc.
									1A	1B	2A	2B	
Explore Europa to investigate its habitability	E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Satellite atmospheres	E8.	Understand the sources and sinks of Io's crustal volatiles and atmosphere.	E8d. Determine column densities of atmospheric/plume species across the globe and document correlations with plumes, geologic features and local albedo variations by global EUV - NIR (0.06–5 microns) surface and limb spectroscopy at better than 50 km resolution. UV spectral resolution of 0.3 nm. UV spatial resolution of better than 500 km/pixel. Visible imaging in eclipse.	E8d. UV imaging spectrometer, Vis-IR imaging spectrometer, and narrow-angle camera	2					
						E8e. UV stellar occultations (FUV-NUV) over a range of latitude/longitude space and a range of temporal scales/periodically throughout the mission. UV spectral resolution of 0.5 nm, 0.1–0.25 microns.	E8e. UV imaging spectrometer	3					
						E8f. Perform long-term and high-temporal-resolution monitoring of atmosphere, plumes, limb-glow, and equatorial spots via EUV - VNIR (0.06–1 microns) imaging limb observations of plumes, atmosphere, neutral clouds over a range of temporal scales (e.g., hourly, daily, weekly, monthly). UV spectral resolution of 0.5 nm, spatial resolution of <500 km/pixel. VNIR spatial resolution better than 10 km/pixel.	E8f. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
						E8g. Determine the composition, distribution and physical characteristics (grain-size, crystallinity) of volatile materials on the surface, including SO_2 frost by vis-IR (0.4–5 micron) imaging on a global scale (better than 10 km/pixel for yellow and white-gray units), and at higher resolution for green and red units (~1 km/pixel).	E8g. Vis-IR imaging spectrometer	3					
						E8h. In situ neutral mass spectroscopy measurements of Io's atmosphere.	E8h. Ion and neutral mass spectrometer	3					
				E9.	Determine the sources and sinks of the Ganymede and Callisto atmospheres.	E9a. Determine column densities of atmospheric species across the globe at better than 1 km spatial resolution using IR limb scans, UV spectroscopy, and UV and visible-IR stellar occultations. UV spectral coverage 100–320 nm at 0.5 nm resolution. Perform long-term and high-temporal-resolution monitoring in context of magnetospheric variations.	E9a. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
						E9b. Determine the composition, distribution and physical characteristics (grain-size, crystallinity, physical state) of volatile materials on the surface, including UV measurements of O_3, H_2O_2 and other species (100–320 nm at 2 nm resolution).	E9b. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
						E9c. Investigate sputtering processes at high latitudes as compared with lower latitudes by measuring water ice grain sizes and products such as O_3, H_2O_2 and other species (UV observations over 100–320 nm at 2 nm resolution); measure flux of precipitating ions to representative satellite regions.	E9c. UV imaging spectrometer and particle and plasma instrument	2					
						E9d. Global FUV - IR (0.1–5 microns) spectroscopy at better than 50 km spatial resolution to measure SO_2, SO, S, O, Cl and other species in absorption and/or emission. UV spectral resolution of 0.5 nm; IR spectral resolution better than 10 nm.	E9d. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
						E9e. Perform stellar occultations at IR and UV wavelengths to search for water absorption and oxygen emission signatures. For UV, cover 100–200 nm at better than or equal to 0.5 nm resolution, and latitude/longitude resolution of better than 30 deg.	E9e. UV imaging spectrometer and Vis-IR imaging spectrometer	3					
						E9f. Scan perpendicular to the limb from ~5 km above the surface to the surface of the satellite at IR wavelengths to measure or search for emission from O_2 (1.27 microns), H_2O, CO_2 (4.26 microns) and other species in the Ganymede and Callisto atmospheres.	E9f. Vis-IR imaging spectrometer	4					
						E9g. Perform radio occultations of Ganymede and Callisto to measure the ionospheres.	E9g. Two-band radio communication system with USO	3					
			Plasma and magnetospheres	E10.	Characterize the neutral atoms and molecules escaping Europa's gravity.	E10a. Detect neutrals coming off Europa with a mass range up to 300 Daltons and a mass resolution of up to 500.	E10a. Ion and neutral mass spectrometer	2	2	3	3	4	4
						E10b. Measure the flux of pickup ions in the tens to hundreds of eV energy range.	E10b. Plasma instrument	2	2	3	3	4	4
						E10c. Determine the cold plasma temperature of the electrons to estimate ionization rates near Europa.	E10c. Plasma instrument	2	2	3	3	4	4

Europa Explorer Themes:	Origins	Evolution	Processes	Habitability	Life

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective			Science Investigation	Measurement	Instrument	SCIENCE VALUE: Jupiter System Science	Europa Campaigns: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	E. Jupiter System	Understand Europa in the context of the Jupiter system.	Plasma and magnetospheres	E11. Characterize the composition of and transport in Io's plasma torus.	E11a. Perform EUV imaging spectroscopy (30–110 nm) of the Io plasma torus at 0.1 Rj/px and <0.5 nm spectral resolution over a range of timescales (e.g., hourly, daily, weekly, monthly) with emphasis on daily monitoring for > 30 days.	E11a. UV imaging spectrometer	3					
					E11b. Measure the flux and composition of charged particles (ions and electrons) between energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E$ = 0.1 and a time resolution of at least 1 minute during passes of Io's torus. Magnetometer provides pitch angle distribution information. 8 vectors/s cadence is adequate. 0.1 nT resolution and 0.1 degree orientation knowledge.	E11b. Particle and plasma instrument and magnetometer	3					
				E12. Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.	E12a. Measure pickup ions in the tens to hundreds of eV energy range and energetic ions in the tens to few hundred keV/nuc energy range.	E12a. Ion and neutral mass spectrometer and particle and plasma instrument	3					
					E12b. Image neutral tori (e.g., H, O, S) at the orbits of Io, Europa, Ganymede, and Callisto.	E12b. UV imaging spectrometer	4					
				E13. Study the interactions between Jupiter's magnetosphere and Io, Ganymede, and Callisto (including characterize Ganymede's magnetic field).	E13a. Determine the trapped and precipitating fluxes of ions and electrons with energies between 10 eV and 10 MeV, 15° angular resolution or higher, $\Delta E/E$=0.1, and time resolution of 1 minute or higher.	E13a. Magnetometer and particle and plasma instrument	3					
					E13b. Investigate the generation of Ganymede's aurora with UV imaging (0.1–0.35 microns) of Ganymede (at 0.3 nm spectral resolution) at 1 km spatial resolution and at cadences of a minute or longer.	E13b. UV imaging spectrometer	3					
					E13c. Investigate the modification of surface composition and structure on open vs. closed field line regions by imaging of Ganymede at FUV-NIR wavelengths (100–350 nm and 0.8–2.5 microns) at 1 km spatial resolution.	E13c. UV imaging spectrometer and Vis-IR imaging spectrometer	4					
					E13d. Determine the flux and composition of precipitating ions and electrons between energies of 10 eV and 10 MeV and 15° angular resolution, $\Delta E/E$=0.1, and time resolution of at least 1 minute.	E13d. Magnetometer and particle and plasma instrument	3					
					E13e. UV and visible measurements at 1 min resolution of emission from moon magnetic footpoints in the Jovian auroral region.	E13e. UV imaging spectrometer and narrow-angle camera	2					
					E13f. Investigate effects of direct magnetospheric plasma, energetic particle, solar UV, and interplanetary dust interactions with the moon surfaces & atmospheres, search for hemispherical differences, and associated temporal variations with global UV-NIR measurements (0.1–3 microns) of hemispherical distributions of radiation products (sulfates, H_2O_2, O_2, CO_2) at 10 km resolution, and via repeated observations (timescale of months).	E13f. Particle and plasma instrument, UV imaging spectrometer, and Vis-IR imaging spectrometer	2					
				E14 Understand the structure, composition, and stress balance of Jupiter's magnetosphere.	E14a. Make continuous measurements of vector magnetic field (1 s resolution)	E14a. Magnetometer	3					
					E14b. Make continuous measurements of plasma and energetic charged particles (10 eV to 10 MeV), with full sky coverage and an angular resolution of 15°, $\Delta E/E$=0.1, and 10 s time resolution or higher.	E14b. Particle and plasma instrument	3					

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal	Science Objective		Science Investigation	Measurement	Instrument	Science Value: Jupiter System Science	Europa Campaigns: 1 Global Framewrk 1A	1 Global Framewrk 1B	2 Regional Proc. 2A	2 Regional Proc. 2B	3 Targ. Proc.
Explore Europa to investigate its habitability	E. Jupiter System: **Understand Europa in the context of the Jupiter system.**	Plasma and magnetospheres	E15. Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.	E15a. Make continuous measurements of vector magnetic field (1 s resolution).	E15a. Magnetometer	2					
				E15b. Make continuous measurements of plasma and energetic charged particles (10 eV to 10 MeV), with full sky coverage and an angular resolution of 15°, ΔE/E=0.1, and 10 s time resolution or higher.	E15b. Particle and plasma instrument	2					
		Jupiter atmosphere	Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa.	E16a. Measure the global distribution of water vapor humidity in the 2–8 bar region with 100 km spatial resolution. Use 5-micron imaging spectroscopy with spectral resolution R > 400.	E16a. Vis-IR imaging spectrometer	4					
				E16b. Measure the global distribution of gaseous ammonia with 100 km horizontal spatial resolution at 2–6 bars (5 micron spectroscopy, R>400) and 200 km resolution at 0.1–0.4 bars (10 micron spectroscopy, R>400).	E16b. Vis-IR imaging spectrometer	4					
				E16c. Measure the vertical distribution of stratospheric water, 1–300 mbar (sub-mm sounding from 100–3000 GHz), 1–20 mbar with far-IR (R>400) spectroscopy.	E16c. Sub-mm wave sounder	0					
				E16d. Measure the global distribution of gaseous water and ammonia in the 10–100 bar region using passive microwave radiometry at 1–5 cm wavelength, possibly using the telecom antenna as a receiver for 1–5-bar region.	E16d. Microwave radiometer	0					
				E16e. Measure the 3-D distribution of disequilibrium species in the 0.1–4.0 bar region: measure PH_3, CO, AsH_3, GeH_4 at 100 km resolution using 5 micron spectroscopy at R>400. Measure PH_3, NH_3 in 100–600 mbar region at 200 km resolution at 10 microns with R>400 or at 1.0–4.0 microns with R>400. Measure at p<250 mbar in UV spectra.	E16e. Vis-IR imaging spectrometer, thermal imager, and UV imaging spectrometer	3					
				E16f. Determine the distribution of aerosols with altitude, latitude and longitude; investigate single scattering albedos, column abundances, topography of upper cloud layers, particles size distributions, IR opacities. Monitor changes in aerosol distribution associated with variations in atmospheric state (temperature, composition). Perform observations at multiple phase angles.	E16f. Vis-IR imaging spectrometer, wide- and medium-angle camera, and UV imaging spectrometer	4					
			E17. Characterize Jovian atmospheric dynamics and structure.	E17a. Global visible/near-IR dayside imaging at 30 km/pixel to characterize dynamics. Imaging should include repeated coverage of the same regions at ~2 hour intervals for cloud tracking (necessary to obtain winds). Wavelengths should include visible and/or near-IR continuum as well as one or more methane absorption band (e.g., 889 nm and other) to obtain vertical structure of winds and clouds. Imaging strategy must characterize behavior over a range of timescales, including short (1–3 days), medium (~1 month), and long (~1 year) timescale variability. Strategy ideally should involve global or near-global daily coverage for periods of weeks-to-months.	E17a. Wide/medium-angle camera and Vis-IR imaging spectrometer	4					
				E17b. Obtain global temperature maps (100 km resolution) for vertical temperature structure and horizontal gradients (for deriving thermal wind shears). Pressure ranges 1–10 mbar and 100–500 mbar for 7–250 micron spectroscopy, 5–300 mbar for sub-mm spectroscopy. Limb spectroscopy with 20–40 km vertical spatial resolution for vertical distribution.	E17b. Thermal imager and sub-mm spectrometer	1					
				E17c. Make repeated radio occultations to obtain vertical temperature profiles closely spaced in space and time (e.g., at the same latitude ±10 degrees, once every 2 weeks) to investigate wave propagation in the stratosphere and upper troposphere, in addition to investigating the temporal behavior of the Jovian ionosphere.	E17c. Two-band radio communication system with USO	4					
				E17d. Perform stellar and solar occultations over a wide range of latitudes to obtain high vertical resolution temperature structure and composition in the upper stratosphere (1 km at 20 K per measurement).	E17d. Vis-IR imaging spectrometer, thermal imager, and UV imaging spectrometer	2					
				E17e. Measure the 3-D distribution of stratospheric hydrocarbons and other molecules in the stratosphere, at 100 km spatial resolution with global coverage and spectral resolution R > 2000 in the mid-IR (8–16 microns) and FUV (110–200 nm). Limb spectroscopy with 20–40 km vertical spatial resolution for vertical distribution.	E17e. Mid-IR spectrometer and UV imaging spectrometer	3					
				E17f. Measure Jovian aurora on timescales of minutes, hours, and days at IR (0.8–2.5 microns) and UV (0.1–0.2 microns) wavelengths.	E17f. Vis-IR imaging spectrometer and UV imaging spectrometer	2					

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JUPITER EUROPA ORBITER: TRACEABILITY MATRIX

Goal		Science Objective		Science Investigation	Measurement	Instrument	Jupiter System Science	1A	1B	2A	2B	3 Targ. Proc.
							SCIENCE VALUE	EUROPA CAMPAIGNS				
								1 Global Framewrk		2 Regional Proc.		
Explore Europa to investigate its habitability	E. Jupiter System	Understand Europa in the context of the Jupiter system.	Rings	E18. Characterize the properties of the small moons, ring source bodies, and dust.	E18a. Conduct a comprehensive search for embedded moons within the ring system, down to a limiting size of ~100 m (~14th magnitude). Conduct multiple surveys of the ring region at low phase angles to ensure completeness of coverage. Each object should be detected at least ~20 times over a time frame of ~1 year to enable a precise determination of its orbit; astrometric precision of better than 30 km is required.	E18a. Narrow-angle camera with a clear or very broad-band filter	3					
					E18b. Search for km-sized moons throughout the Jovian system (from the rings to beyond the orbit of Callisto) with a detection threshold of ~1 km (~10th magnitude). This requires repeated, complete mosaics of the system taken at low phase angles and using a medium- or a wide-angle camera. After discovery, each previously unknown object should be targeted with a narrow-angle camera ~ 20 times over a time frame of ~1 year to provide a precise determination of its orbit. Astrometric precision of better than 30 km is required.	E18b. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter	3					
					E18c. Search for dust belts throughout the Jovian system (from the rings to beyond the orbit of Callisto) down to optical depths of ~10^{-9} (or reflectivities of ~10^{-8}). Emphasize high phase angles and edge-on viewing geometry to achieve the most stringent detection limits. Study any belts detected from at least 10 phase angles, ranging from less than 10 degrees to greater than 170 degrees, to constrain particle sizes. At a few phase angles, measure the color in the visual and near-IR for additional limits on size and composition.	E18c. Wide-, medium- and/or narrow-angle cameras with several very broad-band filters	3					
					E18d. Profile the radial structure of the entire ring system (from the inner halo to beyond the orbit of Thebe) down to a spatial resolution of ~10 km and a sensitivity to reflectivities of 10^{-8}. Obtain at least 10 phase angles from less than 10 degrees to greater than 170 degrees, and use several visual and near-IR broad-band filters. Requires a viewpoints at least a few degrees out of the ring plane.	E18d. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter (especially CH_4)	3					
					E18e. Determine ring and inner moon surface composition with a sensitivity to reflectivities of ~10^{-7}. Obtain this level of sensitivity in each of more than 200 spectral bands from the visual to beyond ~ 3 microns. Observe near backscatter to emphasize the surface composition of the larger embedded bodies in the system.	E18e. Vis-IR imaging spectrometer	2					
				E19. Identify the dynamical processes that define the origin and dynamics of ring dust.	E19a. Determine the ring's 3-D structure, including the vertical structure of the halo and gossamer rings, via imaging from a variety of viewing geometries. Requires complete mosaics of the system from Jupiter out to beyond the orbit of Thebe, with resolution of better than 100 km/pixel. Images of the faintest ring components must be sensitive to reflectivities below 10^{-8}. Images must be obtained at a variety of opening angles and phase angles in order to decouple the ring's variations depending on radius, vertical distance from the ring plane, and phase angle. Note that imaging of the halo along the boundary of Jupiter's shadow provides optimal vertical resolution.	E19a. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter (especially CH_4)	3					
					E19b. Identify and characterize time-variable phenomena, including clump formation and evolution, via repeated, complete rotational profiles of the main ring with a resolution of better than 100 km/pixel. Obtain at least 20 complete profiles, sampling a wide variety of time scales from ~ days to ~ 1 year.	E19b. Narrow-angle camera with a clear or very broad-band filter	3					
					E19c. Search for warps and asymmetries on scales of 10–30 km via imaging of the system from nearly and exactly edge-on perspectives. Encompass the entire region from the halo out to beyond the orbit of Thebe, using cameras that are matched to the spatial scales of each region.	E19c. Wide-, medium- and/or narrow-angle cameras with appropriate filters (especially CH_4)	3					

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focus areas: Origins, Evolution, Processes, Habitability, and Life. Although the mapping is not one-to-one, similar themes are crosscutting. These color-coded focus areas are applied to the goal, objectives, and investigations of the JEO Traceability Matrix **(FO-1)**. Color-coding to the goal, each objective, and each investigation corresponds to the guiding focus area of **Table 2.4-3** to which it most closely pertains.

2.4.2 Objective A: Europa's Ocean

Characterize the ocean and deeper interior.

Galileo observations, in particular the magnetometer data (§2.3.2.4), make the presence of a sub-surface ocean very likely. Given the critical importance of such an ocean to Europa's astrobiological potential, it is important to first confirm its existence.

In the likely instance that an ocean exists, several geophysical measurements (**FO-2**) will place constraints on its depth, extent, and physical state (e.g., salinity).Several of these techniques will also help characterize the deeper interior structure of Europa (the mantle and core). Doing so is important because of the coupling that takes place between the near-surface and deeper layers: for instance, an Io-like mantle implies a vigorously convecting ocean, and a relatively thin ice shell. In priority order, the investigations and corresponding techniques are as follows.

2.4.2.1 Investigation A1: Determine the amplitude and phase of the gravitational tides.

Perhaps the most direct way of confirming the presence of an ocean is to measure the time-variable gravity and topography due to the tides raised by Jupiter. In the absence of an ocean, Europa's ice shell will be coupled directly to the rocky core, and the time-dependent tidal surface displacement will be a few meters [*Moore and Schubert 2000*]. On the other hand, if Europa has a liquid water ocean beneath a relatively thin ice shell, the displacement amplitude will be 30 m over one orbit (**Figure 2.4-1**). The surface displacement will also cause a measurable periodic gravity signal. Thus, measurement of the tidally driven time-variable topography or gravity (described by the Love numbers h_2 and k_2, respectively) will provide a simple and definitive test of the existence of a sub-ice ocean.

The Love number k_2 is estimated from the time-variable gravitational field of Europa. Simulations show that measurements of the

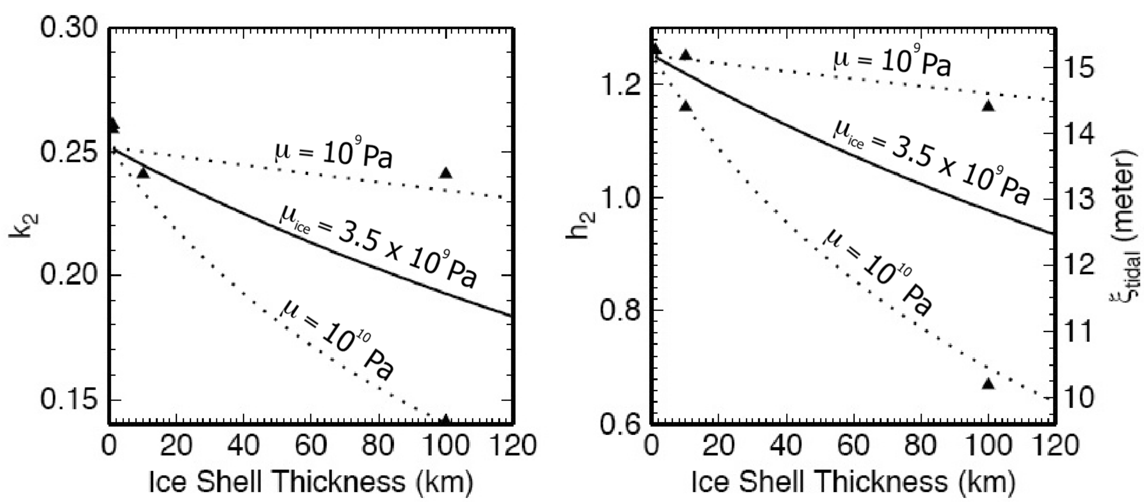


Figure 2.4-1. *Sensitivity of Love numbers* k_2 *(left) and* h_2 *(right) to ice shell thickness and rigidity, with the assumption of a subsurface ocean. For the same curves which depict* h_2*, the right-hand axis shows the amplitude* ζ_{tidal} *(which is half of the total measurable tide) as a function of ice shell thickness. For a relatively thin ice shell above an ocean, the tidal amplitude is* ζ_{tidal} *~ 15 m (total measureable tide ~30 m), while in the absence of an ocean* ζ_{tidal} *~1 m [*Moore and Schubert *2000]. Solid curves show the* h_2 *and corresponding* ζ_{tidal} *for an ice shell rigidity of* $\mu_{ice} = 3.5 \times 10^9$ *Pa, while the dotted lines bound a plausible range for ice rigidity). A rocky core is assumed, with a radius 1449 km and rigidity* $\mu_{rock} = 10^{11}$ *Pa, and the assumed ice + ocean thickness = 120 km. Triangles show the reported values from* Moore and Schubert *[2000], which did not include a core. [*Figure courtesy Amy Barr.*]*

Doppler shift of the spacecraft radio signal can be used to estimate k_2, the mantle and ice shell libration amplitudes and phase lag angle, and the static gravitational field parameters, which are estimated along with the spacecraft trajectory information [*Wu et al. 2001*]. Simulations adding altimetry measurements shows that the tidal Love number h_2 can also be estimated [*Wahr et al. 2006,* §2.4.2.3].

Multiple orbits are required to estimate the body gravity field, including the tidal response, because the spacecraft orbit has to be determined at the same time. Orbit determination is improved by crossover analysis using the laser altimeter. If the spacecraft measures different distances to the same spot on the surface during different orbits, then (neglecting tides) the change must be due to the changing spacecraft altitude. In this manner, the spacecraft position can be accurately determined as at Mars [*Neumann et al. 2001*]. This approach can also take into account the fact that the surface undergoes periodic displacements, due to tides and librations (see §2.4.2.3).

To detect the radio Doppler shift caused by the spacecraft motion in the line-of-sight to Earth, two frequency bands have been considered. X-band (near 8 GHz) is used for spacecraft commanding and Ka-band (near 32 GHz) is used for transmission of spacecraft data to Earth. With the X-band uplink, Doppler measurement accuracy is limited by fluctuations in the solar plasma. An accuracy of 0.1 mm/s for 60 s integration times is typical but varies as a function of solar elongation. To reduce the effect of solar plasma, an auxiliary Ka-band receiver is included in the baseline payload. By using Ka-band on both Earth-to-spacecraft and vice versa, the Doppler measurement accuracy is improved by a factor of 10 except for times near solar conjunction. At Ka-band the dominant noise for most observing times is due to Earth troposphere calibration accuracy.

Doppler-only simulations [*Wu et al. 2001*] show that the Love number k_2 can be determined with an accuracy of about 0.0005, or 0.25%, using either X/X or X/Ka Doppler tracking over 15 days when fit simultaneously with the Europa gravity field, librations, and spacecraft trajectory. In the same estimation the radial position of the spacecraft can be determined with accuracy 2 m, close to the desired orbit reconstruction accuracy, but about 10 times worse than currently being achieved with Mars orbiting spacecraft using much longer data arcs [*Konopliv et al. 2006*]. The expected accuracy in determining k_2 is easily sufficient to distinguish between an ocean-bearing and ocean-free Europa. The addition of Ka/Ka tracking reduces the radial orbit error below 1 m and would permit definitive testing of the ocean hypothesis based on the tidal response as measured by h_2.

In addition to testing the ocean hypothesis, h_2 and k_2 can be used to investigate the ice shell thickness **(FO-2)**. **Figure 2.4-1** shows how these quantities vary with ice shell thickness and rigidity. Based on simulations of plausible internal structures, measurement uncertainties of ±0.0005 for k_2 and ±0.01 for h_2 will permit the actual k_2 and h_2 of Europa to be inferred with sufficient accuracy such that the combination places bounds on the depth of the ocean and the thickness of the ice shell [*Wu et al. 2001, Wahr et al. 2006*].

2.4.2.2 Investigation A2: Characterize the magnetic environment (including plasma), to determine the induction response from the ocean, over multiple frequencies.

The strongest current evidence for Europa's ocean is the induction signature apparently generated by Jupiter's time-dependent magnetic field interacting with a shallow conductive layer, presumably a salty ocean (§2.3.2.4). However, because they were effectively measuring the induction response at a single frequency, the Galileo flybys were only able to establish the product of the layer thickness and conductivity. By contrast, an orbiter can determine both thickness and conductivity by measuring the induction response at multiple frequencies.

Europa is immersed in various low-frequency waves that could be used for magnetic sounding, some of which arise from Io's torus at the outer edge of Europa's orbit. Waves of different frequencies penetrate to different depths within the satellite, and exhibit different induction responses. Dominant frequencies occur at the synodic rotation period of Jupiter (period ~ 11 hr) and the orbital period of Europa (period = 3.55 days = 85.2 hr). Over a broad range of parameter space, the induction curves at two frequencies

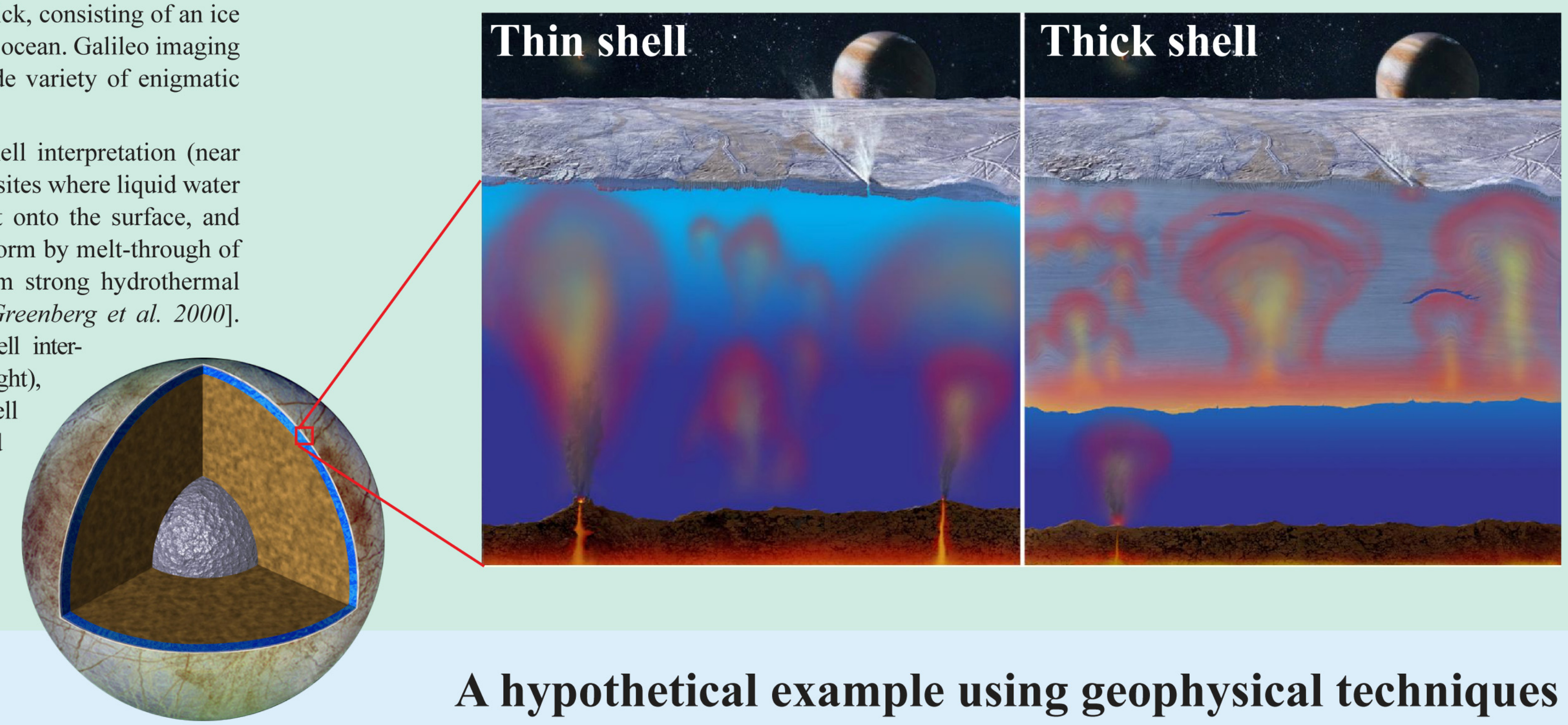
Can JEO determine the thickness of Europa's ice shell?

On Thick or Thin Ice?

Despite more than a decade of study of the Galileo data, the fundamental issues of the thickness of Europa's ice shell remain uncertain to over an order in magnitude [*Kattenhorn and Billings 2005*]. Estimates range from just a few kilometers [*e.g. Greenberg et al. 2000*] to several tens of kilometers, or more [*Pappalardo et al. 1999*]. The thickness of the ice shell is important to understanding Europa's potential habitability, for example, in controlling the types of geological processes that affect material exchange between the ice shell and ocean.

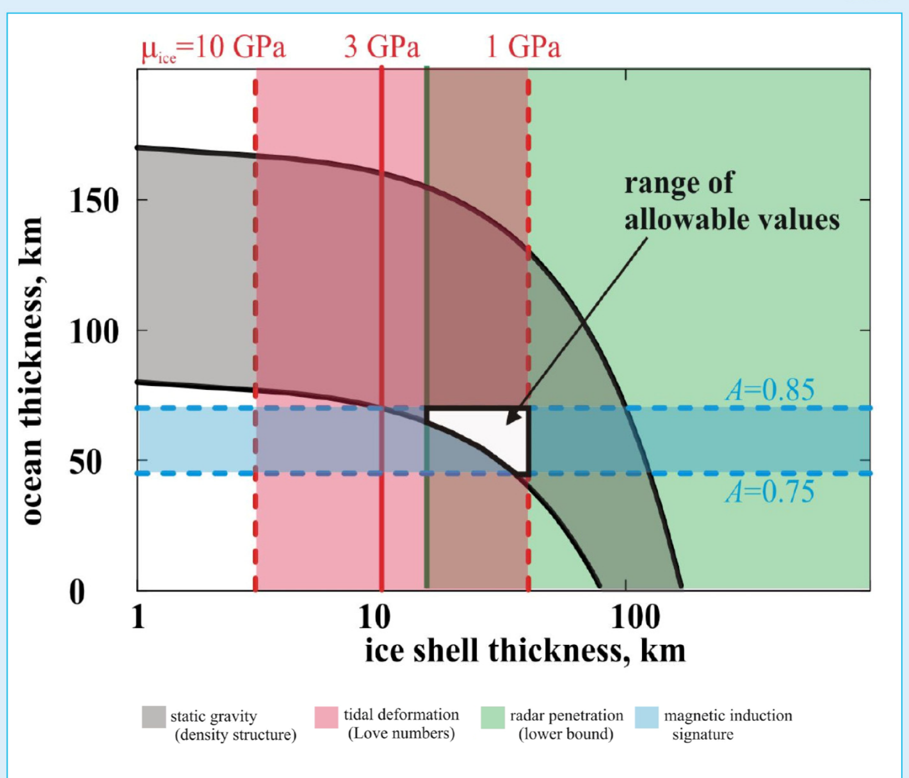
Galileo gravity data suggest that Europa is differentiated into an iron core, rocky mantle, and an H_2O-rich outer shell ~100 km thick, consisting of an ice shell and a liquid ocean. Galileo imaging data reveal a wide variety of enigmatic surface features.

In a thin ice shell interpretation (near right), ridges are sites where liquid water has squeezed out onto the surface, and chaotic terrains form by melt-through of the ice shell from strong hydrothermal plumes below [*Greenberg et al. 2000*]. In a thick ice shell interpretation (far right), Europa's ice shell is convecting and localized partial melting can occur [*Pappalardo et al. 1999*].



A hypothetical example using geophysical techniques

Geophysical measurements are non-unique. Nevertheless, using a combination of carefully planned geophysical techniques, JEO can constrain the thickness of Europa's ice shell.



Here is presented an example of how a combination of (hypothetical) JEO measurements can be used to constrain the ice shell thickness. Based on the bulk density and moment of inertia of the satellite (derived from flybys by JEO and previous spacecraft), the thickness of the water + ice layer may be obtained (gray shading) [*Anderson et al. 1997*]. The uncertainties arise mainly from our lack of knowledge of the density of the rocky interior (the bulk density is already well known).

Gravity and topography measurements

Measuring the time-variable gravity and topography gives the k_2 and h_2 Love numbers, respectively. Hypothetical Love number constraints here (red shading) assume observed h_2 and k_2 of 1.202 and 0.245, respectively, and constrain shell thickness as a function of rigidity μ_{ice} [*Moore and Schubert 2000*]. The hypothetical values assumed here are characteristic of a moderately thick ice shell.

In the example shown, the ice shell deformation is sufficiently large that a shell thickness in excess of 40 km is prohibited. Determining both k_2 and h_2 constrains the thickness significantly more than either value can alone. The ratio of h_2/k_2 is quite different depending on whether a subsurface ocean exists or not, and provides an additional test of the ocean's existence.

Radar Sounding

A lower bound on the ice shell thickness may be derived using ice-penetrating radar observations. The base of the ice shell is hard to image because warm ice is radar absorptive; however, even a non-detection of the ice-water interface allows a lower bound to be placed on the shell thickness. Here, a tectonic model of ice shell properties is assumed [*Moore 2000*], resulting in a radar penetration depth (and lower bound on shell thickness) of 15 km (green shading).

Magnetometer data

Multiple-frequency magnetic induction signatures (blue shading) constrain ocean thickness [*Khurana et al. 2002*]; here a hypothetical dimensionless induction signal A = 0.75–0.85 and an ocean conductivity of 2 S/m are assumed, resulting in an ocean thickness in the range 45-70 km.

This particular (hypothetical) set of observations results in a range of acceptable ice shell thicknesses (15 to 40 km) and a range of acceptable ocean thicknesses (45-70 km). A different set of observations would result in different constraints, but the main point is that the combined constraints are more rigorous than could be achieved by any one technique alone. JEO will provide the measurements needed to constrain the thickness of Europa's ice shell.

intersect (**FO-2**). In this range, the ocean thickness and conductivity (which constrains the salinity) can be determined uniquely.

In order to sound the ocean at these two frequencies, continuous data are required from low altitude over times of at least one month. Further constraints on the ocean, mantle, and core would be provided by the broad-band (but weak) signal excited by Io's torus for which continuous observations of at least months are desirable.

This latter requirement drives the required sensitivity of the magnetometery measurements to 0.1 nT. Magnetometry requires near-continuous observations from Europa orbit, for at least 8–10 eurosols, i.e., at least one month. A high cadence of 8 vectors/s is required to remove the effects of moon-plasma interactions from the data, and knowledge of spacecraft orientation is required to 0.1°. In addition, measurements of plasma density, temperature, and flows are required to quantify the currents generated in Europa's vicinity by the moon-plasma interaction and remove their contribution from the measured magnetic field. Near the surface of Europa, at the synodic rotational period of Jupiter, the interaction currents contribute to the internal and external harmonics of first degree (uniform external field and dipolar internal field) at a level of 10–20 nT [*Schilling et al 2007*]. The requirement to determine interaction currents can be met by measuring fluxes of charged particles (ions and electrons) over a broad energy range (tens of eV to several MeV) over a solid angle of 2π. Because the energies of the sputtering particles is very high ($E \geq 100$ keV) and the energies of the recently picked-up ions is quite low (a few keV), measurements over a broad energy range are desired to quantify the plasma interaction.

2.4.2.3 Investigation A3: Characterize surface motion over the tidal cycle.

The time-dependent tidal deformation of Europa's surface, characterized by the Love number h_2, provides a strong test for the existence of an ocean (§2.4.2.1). It can also be used in conjunction with the k_2 Love number to constrain the ice shell thickness (**FO-2**).

The Love number h_2 is derived by measuring the time-variable topography of Europa, specifically by measuring topography, with the laser altimeter, at cross-over points (**Figure 2.4-2**), a technique which has been demonstrated for Earth [*Luthcke et al. 2002, 2005*] and Mars [*Rowlands et al. 1999, Neumann et al. 2001*]. After ~60 days in orbit about Europa the sub-spacecraft track will form a reasonably dense grid, comprised of a number N (~700) great circle segments over the surface of Europa. Each of the N arcs intersects each of the remaining N-1 arcs at two roughly antipodal locations, and at these cross-over locations, the static components of gravity and topography should agree. As illustrated in **Figure 2.4-2**, differences in the measured values at cross-over points are equal to a sum of actual change in radius caused by tides and libration, combined with the difference in orbital altitude, along with any errors in range to the center of the body or orbital position. The errors are dominated by long wavelength effects and can be represented by 4 sine and cosine terms in each orbital component (radial, along track, and cross track). The tidal effects in gravity and topography have known spatial and temporal patterns and can each be represented globally by two parameters, an amplitude and phase. The librations are effectively periodic rigid rotations with specified axes and periods, and again an amplitude and phase parameter

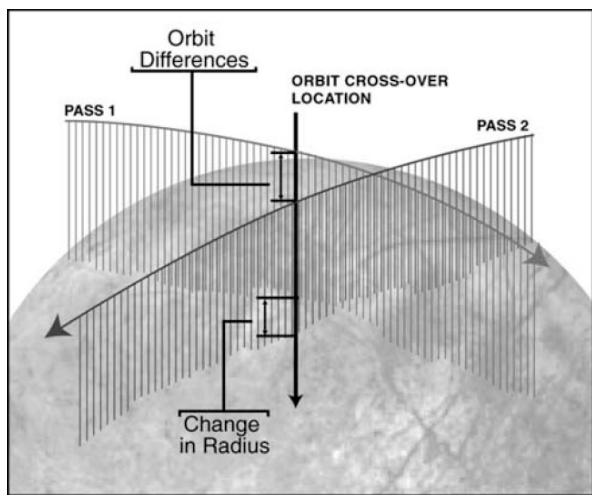


Figure 2.4-2. *Illustration of the cross-over technique. Actual change in radius of Europa due to tidal and librational motions is determined by measuring altitude from the spacecraft to the surface, and by accounting for the distance of the spacecraft from the center of mass by means of Doppler tracking [*Wahr et al. 2006*].*

suffices to describe each axis. Thus, there are 12 N + 10 parameters to be estimated (12 N orbital, 4 tidal, and 6 librational), from 2 N*(N-1) cross-over points. The accuracy with which the altimetric profiles can be interpolated to the cross-over locations depends on range accuracy, surface spot size over which altitude is sampled, and along-track sampling rate. In an ideal case, the surface spots would be small (to minimize topographic variation within spots), and near-contiguous or even overlapping. Those considerations need to be assessed against power and data-rate constraints of an instrument, and the desire to interrogate topography for as much of the surface as possible.

2.4.2.4 Investigation A4: Determine the satellite's dynamical rotation state.

As part of the orbit determination and crossover analysis necessary to determine h_2 and k_2 (§2.4.2.1, §2.4.2.3), Europa's rotation pole position and its librations in both longitude and latitude will be determined. These quantities all depend on Europa's internal structure, and thus provide additional, largely independent, constraints on the presence or absence of an ocean, and the polar moment of inertia C. This latter quantity contains information about the distribution of mass within the satellite.

Librations in longitude and latitude are driven by the non-zero eccentricity and obliquity of the satellite, respectively. The amplitude of forced librations in longitude gives the combination (B-A)/C for the principal moments of inertia A < B < C, as has been done for Earth's Moon [*Newhall and Williams 1997*]. The quantity (B-A) depends on the degree-two static gravity coefficients, which will be determined to high accuracy, and thus the polar moment of inertia C may be determined. If the ice shell is decoupled from the interior by an ocean, the libration amplitude will be a factor of three larger than for a solid Europa [*Comstock and Bills 2003*]. Similar constraints will be provided by determination of the latitudinal libration amplitude.

If there is an ocean, there may be two librational signals, one from the ice shell, and another from the deeper interior. The shell's signal would be revealed in both gravity and topography data, whereas the deeper signal would appear only in the gravity.

Europa's obliquity—the angular separation between its spin and orbit poles—provides another constraint on its polar moment of inertia C. If its spin state is tidally damped, the obliquity is expected to be ~0.1° [*Bills 2005*], with the exact amplitude depending on C [*Ward 1975, Bills and Nimmo 2008*].

The dynamical rotational state (spin rate and orientation, libration amplitudes) of Europa will be determined using Doppler tracking data and laser altimetry crossover technique (§2.4.2.3). Initially assuming both steady rotation and zero obliquity, the cross-over analysis described above will be used to adjust the spacecraft orbit estimate and to determine the dynamical rotation as well as the tidal flexing of Europa.

2.4.2.5 Investigation A5: Investigate the core, rocky mantle, and rock-ocean interface.

Whether Europa's silicate interior is Io-like and dissipative, or cold and inactive, has important consequences for the likely thickness of the shell, and for silicate-ocean interchange. Clues to the nature of the deeper interior can be obtained from gravity, topographic and magnetic observations.

Static gravity observations, made using the same techniques as outlined in §2.4.2.1, may be used to investigate the topography at the silicate-ocean interface. **Figure 2.4-3** illustrates the estimated gravitational spectrum for Europa, with separate contributions from an ice shell and a silicate interior, along with simulated error spectra for 30 days of tracking at each of three representative orbital altitudes [cf. *Wu et al. 2001*]. To be conservative, only the X-band error estimate has been used. The recovered gravity errors are smaller at lower altitudes because the spacecraft is closer to the anomalies, and thus experiences larger perturbations.

At long wavelengths, the gravity signal is dominated by the silicates. Since the water-silicate density contrast likely greatly exceeds density variations within the mantle, long-wavelength gravity anomalies will provide evidence for seafloor topography and may point to the existence of seamounts or volcanic rises. Such long-wavelength gravity anomalies may also result in potentially measurable

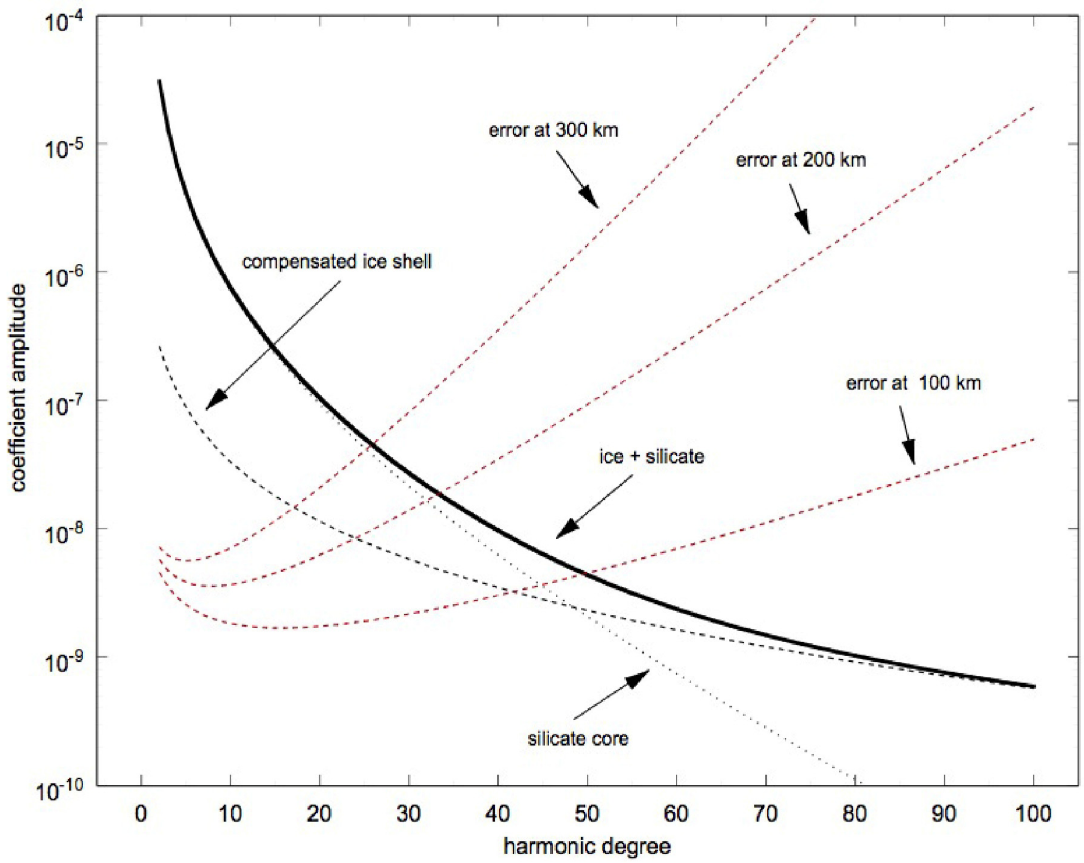


Figure 2.4-3. *Models of Europa's gravity spectrum, assuming an ice shell 10 km thick with isostatically compensated topography above an ocean, and a silicate interior with a mean surface 100 km below the ice surface. The variance spectra of the ice topography and silicate gravity are assumed similar to those seen on terrestrial planets [*Bills and Lemoine 1995*]. The signal has contributions from the silicate mantle and ice shell. The error spectra represent 30 days at fixed altitude, and reflect variations in sensitivity with altitude. The error spectra at different orbital altitudes do not have the same shape because the longer wavelength anomalies are attenuated less at higher altitudes. During a few days at these altitudes, the improvement is linear with time; for longer times, repeat sampling leads to improvement proportional to square root of time.*

surface topographic variations (as with the sea surface on Earth).

At shorter wavelengths, the signal is dominated by the shallower ice-shell contributions, and the topography and gravity should be spatially coherent [*Luttrell and Sandwell 2006*]. If the wavelength at which the transition from silicate-dominated to ice-dominated signals can be determined, this will provide a constraint on the thickness of the ice shell (assuming isostatic compensation). Such a transition is potentially detectable at 100 km orbit altitude.

Time-dependent gravity measurements may also provide constraints on Europa's deep interior: for instance, a fluid-like Love number ($k_2 \approx 2.5$) would imply a low-rigidity mantle and core, as well as a subsurface ocean.

Magnetometer measurements of very low-frequency magnetic variations (periods of several weeks) will shed light on the magnetic properties of the deep interior, including the core. For instance, a partially molten, Io-like mantle is expected to have a higher conductivity than a cold, inactive interior. Such measurements need to be taken over a period of several months. Simultaneous

Table 2.4-4. *Hypothesis Tests to Address Selected Key Questions Regarding Europa's Ocean and Interior.*

	Example Hypothesis Questions	Example Hypothesis Tests
A1.	Does Europa undoubtedly have a subsurface ocean?	Measure the gravity field at Europa over the diurnal cycle.
A2.	What are the salinity and thickness of Europa's ocean?	Determine the magnetic induction signal over multiple frequencies to derive ocean salinity and thickness.
A3	What is the internal structure of Europa's outermost H_2O-rich layers?	Use measurements of the time-variable topography to derive the Love number h_2, to relate the ice shell and ocean layer thicknesses.
A4.	Does Europa have a non-zero obliquity and if so, what controls it?	Use gravitational and topographic measurements of the tides to infer obliquity, which in turn constrains moments of inertia especially in combination with libration amplitude(s).
A5.	Does Europa possess an Io-like mantle?	Radar, magnetic and/or gravitational inferences of the ice shell thickness constrain how much heat the silicate interior is producing; magnetometer inferences of ocean salinity constrain the rate of chemical exchange between silicates and water, and the conductivity structure of the deep interior; local thinning of the ice shell (identified by radar) can be linked to hydrothermal plumes; time-variable gravity place bounds on the rigidity of the silicate interior.

plasma measurements are necessary to remove the effects of moon-plasma interactions from the data.

The key outstanding questions relating to Europa's ocean (§2.3.2) can be linked to and addressed by the Objective A investigations described above, as summarized in **Table 2.4-4**.

2.4.3 Objective B: Europa's Ice Shell

Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.

There are strong scientific reasons for studying the subsurface structure of Europa's shell, especially as related to subsurface water and the nature of surface-ice-ocean exchange (see §2.2). The dielectric losses in very cold ice are low, yet highly sensitive to increasing temperature, water, and impurity content; therefore, much can be learned through orbital electromagnetic sounding of the ice shell. This is especially true when subsurface profiling is coupled to observations of both the topography and morphology of surface landforms and placed in the context of both surface composition and subsurface density distribution. Because of Jupiter's strong radio emissions and the unknown size of volume scatterers within Europa's ice shell, the range of sounding frequencies must be carefully matched to the science objectives.

The thickness of Europa's ice shell is perhaps the most important question left unanswered by Galileo. Determining the ice shell thickness is of fundamental astrobiological significance: it constrains the tidal heat the satellite is generating, whether the silicate interior is Io-like or not, and the extent to which the ocean and near-surface are likely to exchange material.

2.4.3.1 Investigation B1: Characterize the distribution of any shallow subsurface water

The subsurface signatures from near-global ice-penetrating radar surveys at high depth resolution combined with surface topography of similar vertical resolution would identify regions of possible ongoing or relatively recent upwelling of liquid water or brines. Orbital subsurface profiling of the top 3 km of Europa's ice shell should be feasible [*Chyba 1998, Moore 2000*] and is recommended at frequencies slightly above the upper end of Jupiter's radio noise spectrum (i.e., about 50 MHz), to establish the geometry of various thermal, compositional, and structural horizons to a depth resolution of about 10 m (requiring a bandwidth of about 10 MHz). This high-resolution search for shallow water will produce data analogous to that of the Shallow Subsurface Radar (SHARAD) instrument onboard the Mars Reconnaissance Orbiter (**Figure 2.4-4**).

This profiling should be done in conjunction with co-located stereo imaging and laser altimetry which can be used to register photogrammetric topography to vertical resolution of better than 10 m, permitting surface clutter effects to be removed from the radar data. Stereo imaging is susceptible to relative errors, and stereo

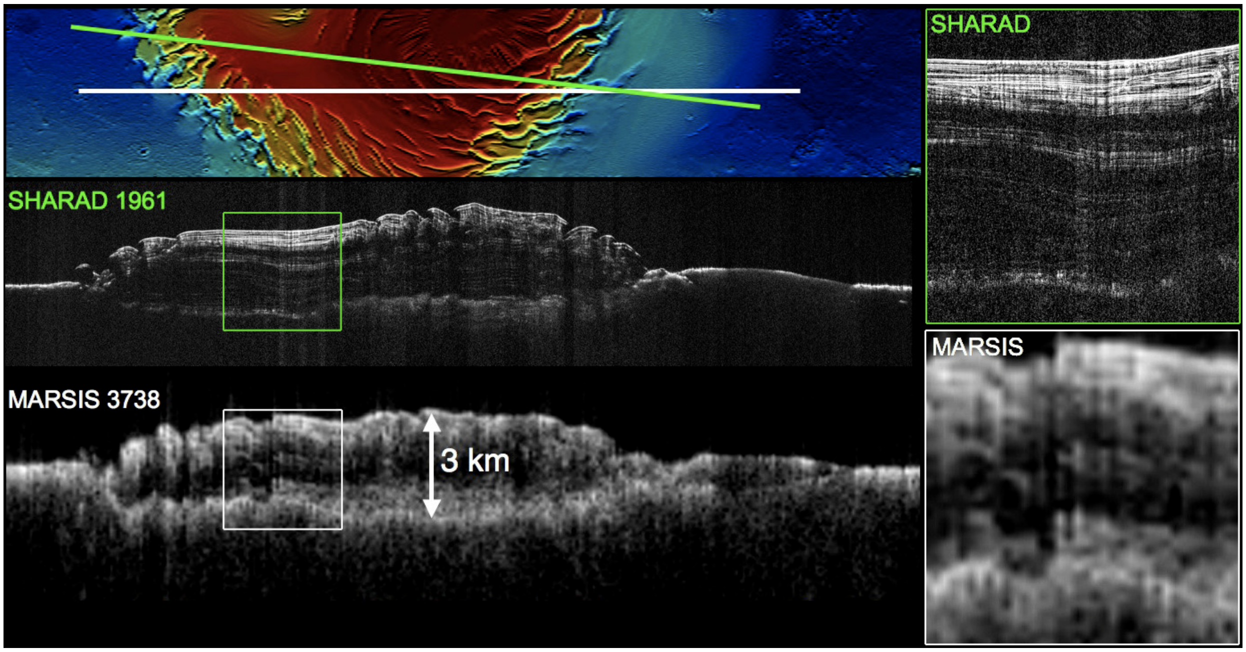


Figure 2.4-4. *Orbital Subsurface Profiling of Mars North Polar Cap. These nearly co-linear profiles across the Mars North Polar Cap (MOLA data at top left) demonstrate the value of the complementary perspectives provided by the high-center frequency and high bandwidth profiling of the SHARAD instrument (20 MHz and 10 MHz, respectively), and the low-center frequency and low bandwidth profiling of MARSIS (5 MHz and 1 MHz, respectively). In particular, note the clarity of shallow horizons revealed by SHARAD (detail at top right) and the prominence of deep interfaces revealed in the MARSIS results (detail at bottom right). The value of a multi-frequency approach to subsurface profiling on Europa would be significantly enhanced in the presence of strong volume scattering. (MARSIS data courtesy of Picardi, Plaut and the MARSIS Team; SHARAD data courtesy of Seu, Phillips, and the SHARAD Team.)*

vertical accuracy may vary across a scene. However, significantly higher vertical resolutions can be extracted using photoclinometrythat is controlled by stereo imaging and laser altimetry profiles. By tying this high horizontal-resolution relief to the high absolute vertical resolution of a laser altimeter, substantially improved digital elevation models with vertical resolution <10 meters can be generated, which can be used to attribute radar clutter. Ultimately, shallow subsurface profiling should extend over at least 80% of Europa's surface utilizing profiles with spacings no more than twice the hypothesized maximum ice shell thicknesses (i.e., about 50 km).

2.4.3.2 Investigation B2: Search for an ice-ocean interface.

Subsurface signatures from lower resolution but more deeply penetrating radar surveys might reveal a shallow ice-ocean interface, which could be validated over a region by carefully correlating ice thickness and surface topography. An unequivocally thin ice shell, even within a limited region, would have significant implications for understanding direct exchange between the ocean and the overlying ice. Similarly, the detection of deep subsurface interfaces in these surveys and the presence or absence of shallower interfaces above them could validate hypotheses regarding the convective upwelling of deep ductile ice into the cold brittle shell implying indirect exchange with any ocean. Additional orbital profiling of the subsurface of Europa to depths of 30 km with a vertical resolution of about 100 m would establish the geometry of any deeper geophysical interfaces such as an ice-ocean interface. Although warm ice is very attenuating [*Chyba et al. 1998*], thick ice in a regime of steady-state thermal conduction could be soundable on Europa to depths of 25 to 40 km if it is essentially "free" of impurities [*Moore, 2000*]. Although impurities are almost certainly present, the non-steady-state convective thermal regime could generate "windows" of very cold downwelling material within the ice shell, allowing local penetration to great depth [*McKinnon 2005*]. Moreover, while the presence of meter-scale voids within the ice shell would confound sounding efforts at higher frequencies (> 15 MHz) [*Eluszkiewicz 2004*], the presence of such large voids is probably unrealistic [*Lee et al. 2005*].

Deep ocean searches will produce data analogous to those of the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on the Mars Express spacecraft (**Figure 2.4-4)**. This profiling should establish the geometry of any deeper geophysical interfaces that may correspond to an ice-ocean boundary, to a vertical resolution of about 100 m (requiring a bandwidth of about 1 MHz).

Frequencies significantly less sensitive to any volume scattering that may be present in the shallow subsurface profiling detailed above (i.e., about 5 MHz) should be used on the anti-Jovian side of Europa, which is substantially shadowed from Jupiter's radio emissions. This low-frequency low-resolution profiling should be complemented by high-frequency low-resolution profiling over Europa's sub-Jovian surface (where Jupiter's radio noise is an issue for low-frequency sounding). Combined, the deep low-resolution profiling should also cover at least 80% of Europa's surface with a minimum profile separation of about 50 km. Profiling should be performed along with co-located stereo imaging and laser altimetry of better than 100 m topographic resolution, permitting surface clutter effects to be removed from the radar data.

2.4.3.3 Investigation B3: Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.

Targeted radar observations will lead to understanding the processes controlling the distribution of any shallow subsurface water and either the direct or indirect exchange of materials between the ice shell and its underlying ocean. Fractures, topographic and compositional data correlated with subsurface structures can provide information on tidal response and its role in subsurface fluid migration. Similarly, differences in the physical and compositional properties of the near-surface ice may arise due to age differences, tectonic deformation, mass wasting, or impact gardening. Knowledge of surface properties gained from spectroscopy and high resolution topographic data will be essential for integrated interpretation of subsurface structure, as well as understanding liquid water or ductile ice migration within Europa's ice shell.

Because of the complex geometries expected for subsurface structures, subsurface imaging should be obtained along profiles ~30 km long in targeted regions, either to a depth of 3 km for high resolution imaging of shallow targets or to a depth of 30 km for lower resolution imaging of deeper features, in conjunction with co-located topographic data. These targeted subsurface studies should be considered a necessary prerequisite for any future *in situ* astrobiological exploration.

2.4.3.4 Investigation B4: Characterize regional and global heat flow variations.

The thermal structure of the shell (apart from local heat sources) is set by the transport of heat from the interior. Regardless of the properties of the shell or the overall mechanism of heat transport, the uppermost few kilometers at least are thermally conductive, cold, and stiff. The thickness of this conductive "lid" is set by the total amount of heat that must be transported; thus, a measurement of the thickness of the cold and brittle part of the shell will provide a constraint on the heat production in the interior. For a thin ice shell, the ice-ocean interface forms a significant dielectric horizon at the base of the thermally conductive layer. However, when warm pure-ice diapirs from the interior of a thicker convective shell approach the surface, they may be different from the pure-ice melting point and above the eutectic of many substances and may create regions of melting within the rigid shell above them as the temperature increases above the flattening diapir. Any dielectric horizon associated with these melt regions would also provide a good measurement of the thickness of the conductive layer. Global radar profiling of the subsurface thermal horizons to depths of 30 km at a vertical resolution of 100 m

Table 2.4-5. *Hypothesis Tests to Address Selected Key Questions Regarding Europa's Ice Shell*

	Example Hypothesis Questions	Example Hypothesis Tests
B1.	Is Europa's ice shell very thin and conductive or thick and convecting?	Sound Europa's ice shell for a strong water reflector at shallow depth, or to observe a gradual absorption of the signal with depth which may reveal diapiric structures.
B2.	Is there fluid transport from the ocean to the near-surface or surface, and vice versa?	Sound Europa's ice at shallow and greater depths for liquid water, and correlate to surface morphology, compositional and thermal data.
B3.	What are the three-dimensional characteristics of Europa's geological structures?	Combine ice-penetrating radar and topographic measurements, with high-resolution imaging to investigate the 3D structure of geological features.
B4.	Are there regional variations in the thickness of Europa's thermally conductive layer?	Sound Europa's ice shell to map dielectric horizons near-globally.

combined with global maps of thermal emissions at the surface enable characterization of regional and global heat flow variations in Europa's ice shell.

The key outstanding questions relating to Europa's iceshell (§2.3.3) can be related to and addressed by the Objective B investigations described above, as summarized in **Table 2.4-5**.

2.4.4 Objective C: Europa's Chemistry

Determine global surface compositions and chemistry, especially as related to habitability.

Composition forms the linkages that enable understanding Europa's potential habitability in the context of geologic processes. Composition is also a probe of the interior and records the evolution of the surface under the influence of internal and external processes. Investigations regarding Europa's chemistry and composition require synergistic, coordinated observations of targeted geological features, along with synoptic near-global remote-sensing data, including multi-spectral imaging, stereo imaging, radar sounding, and thermal mapping.

There are two basic approaches to determining the composition of Europa's surface; materials can be measured on the surface using remote optical (ultraviolet through infrared) spectroscopy, or the surface composition can be inferred by measuring materials sputtered or ejected from the surface into an atmosphere using both direct sampling and remote observations. Optical measurements of the surface can determine the composition and distribution of materials at geologically relevant scales (10 s to 100 s of meters). However, the spectroscopy of solids is complicated by the physical properties of the material (i.e., grain size, temperature, etc.) and by material mixing, and high-quality spectra of specific surface units are required to identify minor components. Materials with strong, narrow, isolated absorption features can be accurately identified with detection limits of ~1%, and much greater sensitivity (~0.1%) can be achieved for strongly absorbing components intimately mixed with a less-absorbing component such as water ice. Materials with broad, shallow features may have detection limits of ≥10%, and their identification may be limited to the mineral or functional group of material present (e.g., phyllosilicates). Some materials (e.g., NaCl) are optically inactive through much of the visible and infrared and are difficult to detect remotely. Detection and identification of atmospheric components can be very precise using mass spectroscopy or UV through millimeter wavelength spectroscopy, with detection limits that can be several orders of magnitude more sensitive than surface spectroscopy. However, materials in an atmosphere will be derived from an area approximately equal to the height at which the measurement is made [e.g., *Hartle and Killen 2006*], so only regional surface compositions can be inferred. In addition, the surface composition must be inferred from measurements of daughter products that have been derived from the surface by sputtering and radiation-induced chemistry.

Various measurement techniques are appropriate for the investigation of Europa's composition and were considered by the JJSDT during its deliberations, including UV, visible, infrared, microwave, and mass spectroscopy. Examples of the capabilities of these techniques are summarized in **Table 2.4-6**.

Ultraviolet through infrared imaging spectroscopy could detect a broad suite of surface ices, hydrates, organics, and mineral compounds and map these globally at a spatial scale of tens of meters. UV through microwave spectroscopy would investigate the

Table 2.4-6. *Composition Measurements and Candidate Instruments*

	VIS/NIR Imaging Spectrometer	UV Spectrometer	INMS	IR or Millimeter Spectrometer
Europa science measurements (From Traceability Matrix, **FO-1**)	• Composition of organic and inorganic materials (C1a) • Relationship of surface materials to geologic processes (B3c; C2a, C3c) • Effects of radiation environment (C3a) • Nature of exogenic materials (C4c) • Exposure age (D1f) • Recent activity (D2e)	• Plume composition and regional mapping to surface vents (C1c) • Current activity through spatial and temporal variability of venting (D2b) • Effects of radiation, sputtering (C3b, C3e) • Relationship of surface materials to geologic processes (Imager; B3g; C2c; C3c, D2e) • Exposure age (Imager; D1f) • Nature of exogenic materials (Imager; C4d)	• Composition of organic and inorganic surface materials (C1b) • Effects of radiation, sputtering (C3d) • Nature of exogenic materials (C4b)	• Composition of organic and inorganic surface materials (C1b) • Effects of radiation, sputtering (C3d) • Nature of exogenic materials (C4b) • Recent activity (D2e)
Species of interest				
Identified	H_2O; CO_2, SO_2, H_2O_2, sulfate hydrates, CH compounds, CN compounds, O_2	• H, O (gas emission) • H_2O_2, SO_2 (solids)	• O_2 (~10^6 cm^{-3}); H_2; Na (~300 cm^{-3}); K; Cl+ (Atmosphere) • SO_2 (~1600 cm^{-3}); CO_2 (~700 cm^{-3}); H_2O (~10^5 cm^{-3}) (Surface)	• H_2O
Expected	HC, SH, SO, Fe^{2+}, S_8, HCHO, H_2S, $MgSO_4$, H_2SO_4, H_3O^+, $NaSO_4$, Na_2MgSO_4, CH_3OH, CH_3COOH	• OH, C, CO (gas emission) • H_2O (gas absorption)		• OH, C, CO (atmosphere) • H_2O (atmosphere)
Possible	$NaHCO$, $NaCO_3$, H_2CO_3, $MgCO_3$, $MgCl_2$, NaCl, OCS, HCN, OCN-, KOH, K_2O, SO_3, CH_2CO	• S, Cl, N (gas emission) • CO_2, SO_2, SO, O_3, hydrocarbons (gas absorption) • Water ice, salts, sulfates, acids, Tholins (solids)	• H_2O_2 (~200 cm^{-3}); sulfur, sulfate, carbon, carbonate, CN, organics, minerals	• CO_2, SO_2, SO, O_3, hydrocarbons salts, sulfates, acids, tholins • Sputtered species: e.g., Mg-sulfate $\Rightarrow$ $MgSO_3$, MgO_2, MgS, MgO, Mg
Detection Limits	Surface: 0.1 to 10% abundance, varying with species and environmental conditions	Atmosphere: 1×10^{15} cm^{-2} H_2O column	~ 200 cm^{-3}	Atmosphere: Column abundance 10^{-3} to 30% relative to H_2O vapor for many possible species
Measurement requirements				
Spectral/mass range	0.4 - >5 µm (desired) ~1.2 - 4.8 µm (floor)	EUV (60-110 nm); FUV (110-200 nm); NUV (200-350 nm) (desired); FUV (110-200) (floor)	1 to ≥300 amu	IR: 5-50 µm mm: 110 ±20 GHz; 560 ±30 GHz,
Spectral/mass resolution	(Grating) 0.4-2.5 µm: 5 nm; 2.5-≥5 µm: 10 nm (desired) 1.2-4.8 µm: 10 nm (floor)	0.5 nm EUV, FUV; 3 nm NUV	• Mass resolution: Dm/m ≥500 • Pressure range: 10^{-6}-10^{-17} mbar • Sensitivity: 10^{-5} A/mbar	IR: 1-5 cm^{-1} mm: 100-250 kHz
Spatial resolution	25 m/pixel from 100 km (0.25 mrad) (desired) 100 m/pixel (1 mrad) (floor)	1 mrad/pixel (imager)	100-200 km (comparable to orbital altitude)	100-500 m
SNR	≥128 (0.4-2.6 microns), ≥32 (2.6-5 microns)	≥5	N/A	>50
Coverage	Global	Occultation profiles at ≤25 km spacing over >80% of surface	Regional	Regional
Heritage	(Grating) NIMS, VIMS, Hyperion, CRISM, ARTEMIS, M3, Rosetta VIRTIS, Mars Express OMEGA, Dawn VIR	Cassini UVIS; New Horizons ALICE	Cassini INMS; Rosetta ROSINA	CloudSat, EOS-MLS, MIRO, and Herschel-HIFI

composition and temporal and spatial variability of atmospheric components such as oxygen, hydrogen, organics and sulfur-bearing compounds. An ion and neutral mass spectrometer (INMS) can detect ions and neutrals that are sputtered, outgassed, and sublimated from the surface, with a significant fraction of these molecules reaching 100 km altitude [*Johnson et al. 1998, Paranicas et al. 2007*]. Both remote UV and long-wavelength observations and *in situ* INMS sampling could provide sensitive detection of gaseous plumes, if present, as demonstrated by the Cassini UVIS and INMS instruments at Enceladus [*Hansen et al. 2006, Waite et al. 2006*].

Surface spectroscopy. The best means to map the surface composition at the spatial scales relevant to geologic processes is through near-UV to infrared imaging spectroscopy. Data obtained by the Galileo NIMS of Europa and observations by the Cassini VIMS of the Saturnian system demonstrate the existence of a wealth of spectral features throughout this spectral range [e.g., *McCord et al. 1998, Carlson et al. 1999a, b, Clark et al. 2005, Cruikshank et al. 2007*]. Of the materials studied thus far in thelaboratory, the hydrated sulfates appear to most closely reproduce the asymmetric and distorted H_2O spectral features observed at Europa. In these compounds, hydration shells around anions and/or cations contain water molecules in various configurations, held in place by hydrogen bonds. Each configuration corresponds to a particular vibrational state, resulting in complex spectral behavior that is diagnostic of composition. These bands become particularly pronounced at temperatures below 150 K as the reduced intermolecular coupling causes the individual absorptions that make up these spectral features to become more discrete [*Crowley 1991, Dalton and Clark 1998, Carlson et al. 1999b, 2005, McCord et al. 2001, 2002, Orlando et al. 2005, Dalton et al. 2003, 2005, Dalton 2000, 2007*]. As a result, the spectra of low-temperature materials provide highly diagnostic, narrow features ranging from 10 to 50 nm wide (**Figure 2.4-5**).

Cryogenic spectra for all of the hydrated sulfates and brines in **Figure 2.4-6** display the diagnostic absorption features near 1.0, 1.25, 1.5, and 2.0 µm that are endemic to water-bearing compounds. These features generally align with those in water ice and with the features observed in the Europa spectrum. Other spectral features arising from the presence of water occur in many of the spectra, including features of moderate strength near 1.65, 1.8, and 2.2 µm (**Figure 2.4-7**). An additional absorption common to the hydrates at 1.35 µm arises from the combination of low frequency lattice modes with the asymmetric O-H stretching mode [*Hunt et al. 1971a,b, Crowley 1991, Dalton and Clark 1999*]. Although weak, this feature is usually present in hydrates and has been used to place upper limits on abundances of hydrates in prior studies [*Dalton and Clark 1999, Dalton 2000, 2003*].

Cassini Visual and Infrared Mapping Spectrometer (VIMS) observations of Phoebe provide additional examples of the wealth of information available in infrared spectra. In 2005 [*Clark et al. 2005*] reported 27 individual spectral features (**Table 2.4-7)** indicating a

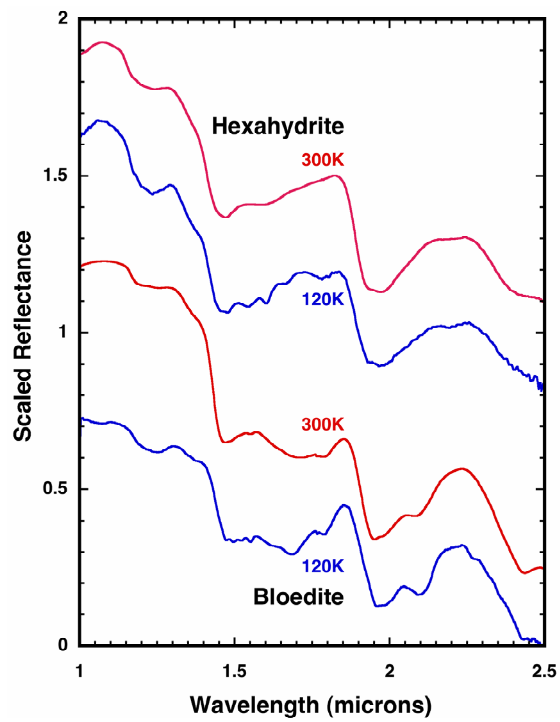


Figure 2.4-5. *Reflectance spectra of two hydrated salts at room temperature and at 120 K, as expected at the surface of Europa. The fine spectral structure apparent at high (~5 nm) spectral resolution can be exploited to discriminate between hydrates (from Dalton [2003]).*

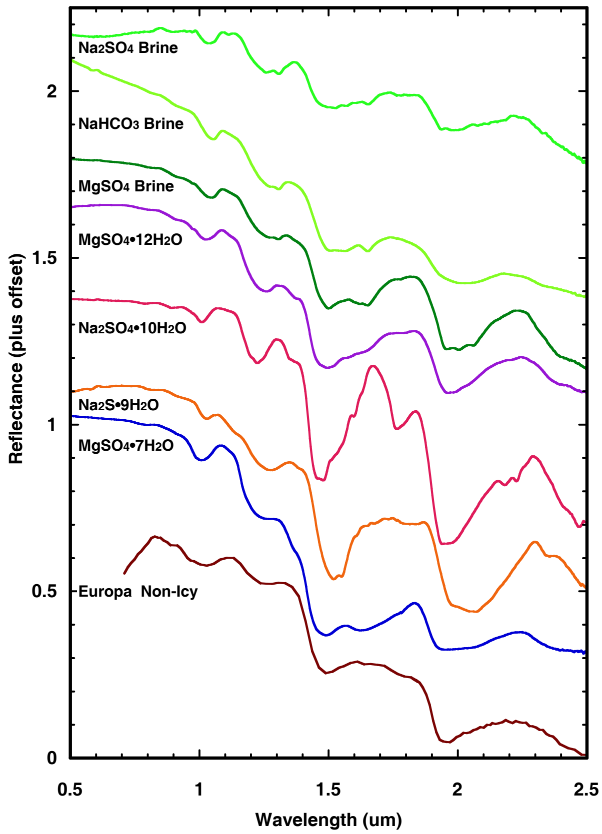


***Figure 2.4-6**. Cryogenic reflectance spectra of hydrated sulfates and brines, compared to Europa. Spectra of epsomite ($MgSO_4$•$7H_2O$), hexahydrite ($MgSO_4$•$6H_2O$) and bloedite ($Na_2Mg(SO_4)_2$•$4H_2O$ were measured at 100, 120, and 120 K, respectively [Dalton 2000, 2003]. Spectra of sodium sulfide nonahydrate (Na_2S•$9H_2O$), mirabilite (Na_2SO_4•$10H_2O$) magnesium sulfate dodecahydrate ($MgSO_4$•$12H_2O$) and $MgSO_4$, $NaHCO_3$, and Na_2SO_4 brines were measured at 100 K [Dalton et al. 2005].*

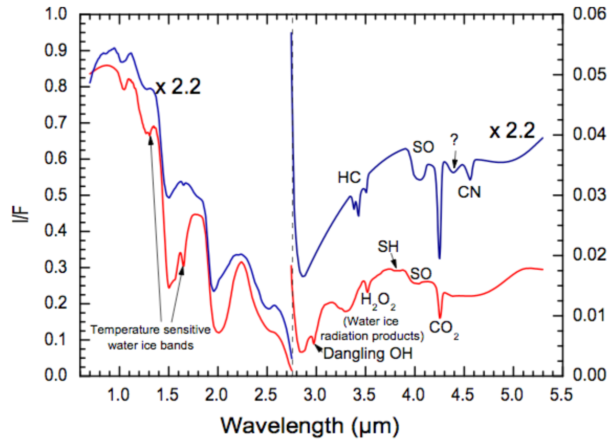


***Figure 2.4-7.** Notional reflectance spectra for icy (lower) and non-ice (upper) regions on Europa (based on observations of compounds observed on other Jovian and Saturnian satellites) at 6 nm spectral resolution in the 1–5 µm spectral range. A variety of materials and molecules have been identified or inferred from the Galileo results. The spectra shown here are composites to illustrate the types and variety of features found or expected. The detailed spectral structure observed in hydrates at high spectral resolution (e.g., **Figures 2.4-5–6**) is not fully represented here. The non-ice spectrum is scaled by 2.2 from the ice spectrum, and the 2.8–5 µm range spectra are scaled by 10 over the shorter wavelength range. [Figure courtesy Tom McCord.]*

complex surface containing a rich array of ices including H_2O and CO_2, and organic species including CN-bearing ices. The 3–5 µm portion of the Phoebe spectrum include absorptions tentatively interpreted as nitrile and hydrocarbon compounds. This spectral range is useful for detecting numerous organic and inorganic species anticipated at Europa.

Unexpectedly, the diagnostic spectral features of hydrated minerals are not seen in high spectral resolution 1.45–1.75 µm Keck telescopic spectra collected from regions of dark terrain that are several 100 km in extent, suggesting that hydrated materials may be non-crystalline (glassy) because of radiation damage or flash freezing [*Spencer et al. 2006*]. Although these regions are dominated by dark materials, ice-rich materials probably occur within the observed area, and significant spatial mixing and dilution of the spectra of the optically active species may occur. It is also possible that the various hydrated species are mixed in such proportions that their diagnostic features overlap. It is expected that there will be smaller regions (perhaps the youngest ones) on Europa in which diagnostic spectral features can be found if observed at high spatial resolution. An excellent example of the importance of spatial resolution is observed for Martian dark region spectra, in which telescopic spectra in both the thermal and short-wave infrared [e.g., *Bell 1992, Moersch et al. 1997*] did not reveal the mineralogic components that have been detected once high spatial resolution spectra were acquired from orbit [e.g., *Christensen et*

Table 2.4-7. *Carbon and Nitrogen Compound Absorption Bands Observed at Saturn's Moon Phoebe by Cassini VIMS*

Feature	Wavelength (μm)	Width (μm)	Origin
f1	1.0	1.1	Probable Fe^{2+}
f2	1.04	~0.05	H_2O ice overtone
f3	1.2	~0.02	OH stretch, CH combination, or artifact
f4	1.3	~0.02	OH stretch, CH combination, or artifact
f5	1.4	~0.02	OH stretch, CH combination, or artifact
f6	1.5	~0.2	H_2O ice overtone
f7	1.7	Variable	CH stretch overtone
f8	1.95	~0.1	Bound H_2O
f9	2.02	~0.2	H_2O ice combination
f10	2.16	~0.03	Probable metal-OH combination
f11	2.42	~0.07	Probable CN combination
f12	2.95	~0.7	H_2O ice and/or bound H_2O
f13	3.1	~0.05	H_2O ice Fresnel peak
f14	3.2–3.3	Variable	CH stretch fundamentals
f15	3.55	~0.06	Probable CH
f16	3.9	~0.2	Perhaps CH, CN or H_2O
f17	4.26	~0.03	Trapped CO_2 (gaseous / fluid inclusion)
f18	4.50	~0.03	CN in a nitrile
f19	4.8–5.0	~0.05	Probable CN fundamental
f20	5.1	??	not determined
f21	4.3	0.7	H_2O ice and/or bound water
f22	2.05	0.17	H_2O ice
f23	2.3	~0.08	Probable metal-OH combination
f24	2.72	~0.05	OH stretch fundamental
f25	1.25	~0.1	H_2O ice
f26	3.62	~0.07	Probable CH or CN
f27	2.54	~0.016	Probable CH

al. 2001, *Bibring et al. 2005, Ehlmann et al. 2008, Mustard et al. 2008*].

Laboratory studies have shown that at Europa's surface temperature, anticipated materials, in particular hydrates, exhibit fine structure, with the full width at half maximum (FWHM) of spectral features ranging from 7–50 μm [*Carlson et al. 1999b, 2005, Dalton 2000, 2003, Orlando et al. 2005*]. Analysis shows that to detect materials in relatively low abundance, or in mixtures with dark materials, signal-to-noise ratio (S/N) > 128 is desirable in the wavelength range 0.4–2.6 μm, and S/N > 32 is desirable in the wavelength range 2.6–5.0 μm (**Figure 2.4-8**). An ideal spectral resolution of 2 nm per channel would be sufficient to identify all of the features observed in the laboratory hydrates thus far [*Dalton 2003, Dalton et al. 2005*]. This would ensure multiple channels across each known feature of interest. However, at Jupiter's distance from the Sun, the reflected near-infrared radiance limits the achievable spectral resolution for high spatial resolution mapping. The signal-to-noise performance is further complicated by the severe radiation noise effects at Europa's orbit.

Obtaining infrared spectra at wavelengths beyond 5 μm might enhance the capability to map and characterize organic chemistry and potential biosignatures. In particular, carbon and nitrogen compounds, which are essential to the chemistry of known life, have numerous absorption bands associated with C-O, C-C and C-N bonds in the 5–7 μm region. The strong carbonyl and amide bands at ~5.9 μm might be detected at concentrations of tens of ppm using sufficiently long integration times and large spatial averages. However, **Figure 2.4-9** shows that the flux of reflected sunlight decreases markedly as wavelength increases through this spectral region, while thermal emission simultaneously increases. Therefore, the interpretation of spectra in this region is hindered by both low SNR resulting from the low fluxes, and by the complex and variable intermingling of reflected and thermal emission. Nevertheless, it is plausible that the blackbody thermal radiation of Europa in warmer regions at ~130 K might be detected using a combination of spectral integration made possible by being in orbit around Europa, spectroscopic techniques such as Fourier transform spectroscopy that significantly enhance signal throughput, and reduced spatial resolution "point spectroscopy" approaches.

In summary, the multiple spectral features and fine (10–50 nm) structure of materials of interest in the 1 to ≥5 μm range in low temperature spectra are sufficiently unique to allow these materials to be identified even in mixtures of only 5–10 weight percent [*Dalton 2007, Hand 2007*]. The ability to fully resolve these features through high-spectral, high-spatial resolution observations will permit determination of the relative abundances of the

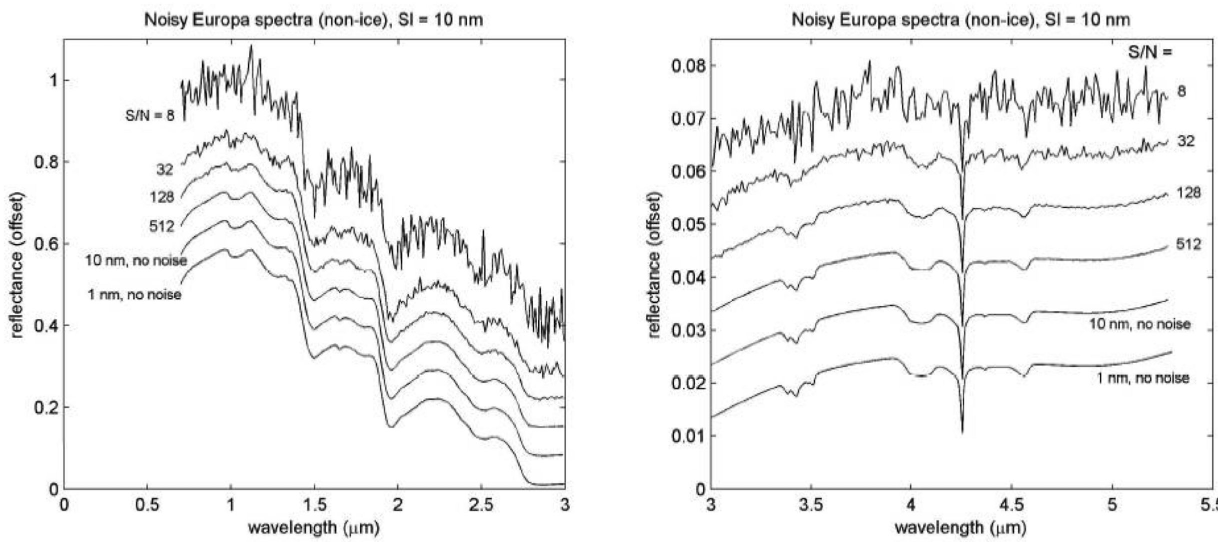


***Figure 2.4-8**. Infrared reflectance spectra for a range of signal-to-noise ratios (S/N) show that to detect absorption bands of materials in relatively low abundance, or in mixtures with dark materials, S/N > 128 is desirable in the shorter wavelength range 0.4-2.6 µm, and S/N > 32 is desirable in the longer wavelength range 2.6-5.0 µm. [*Tom McCord, personal communication.*]*

astrobiologically relevant molecules at the surface of Europa (**Figure 2.4-7**).

Atmospheric spectroscopy. Remote UV through millimeter spectroscopy of the atmosphere would enhance the study of surface composition and the search for current activity at Europa, with ties to the subsurface ocean and habitability.

Venting or transient gaseous activity on Europa could arise from present-day activity. UV measurements would provide high sensitivity to very low column gas abundances using stellar occultations, as demonstrated in the detection of the Enceladus gas plume [*Spencer et al. 2006, Hansen et al. 2006*]. UV imaging of Europa could measure atmospheric density, distribution, and temporal and spatial variations of the atmosphere that could be related to surface composition on regional scales. A stellar occultation instrument operating in the FUV could provide information on the derived atmospheric constituents.

Long wavelength (IR through millimeter) observations could detect, definitively identify, and determine the abundance of atmospheric species. The rotational-vibrational absorption lines of gases are extremely diagnostic of specific composition, and can provide total column abundances at ppm levels *[Fink and Sill, 1982*]. These observations would provide sensitive detection of plumes at low opacities. They would also have the capability to determine the isotopic composition and abundance of the major components (e.g., C, O, and N). Millimeter/sub-millimeter observations have been modeled to have

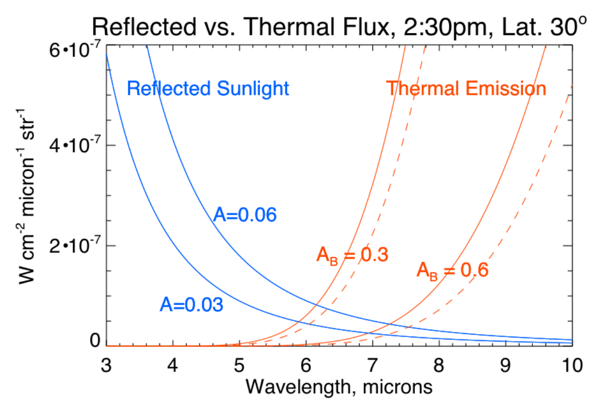


***Figure 2.4-9.** Expected reflected and thermal flux from Europa for an example mid-afternoon, mid-latitude location. The relative proportions of reflected and thermal emission in the 5–7 µm region depend very strongly on both the surface albedo at the wavelength of interest, A, and the surface temperature, which is controlled by the bolometric albedo A_B and the thermal inertia. Solid and dashed thermal emission curves are for plausible thermal inertias of 40 and 80 W m^{-2} $s^{-1/2}$ K^{-1} respectively.*

detection sensitivities of 2%, 3%, 12%, and 36% for NaCl, MgS, NaO, and CH_3CN relative to water vapor for an assumed water column abundance of 5×10^{13} molecules/cm^3 in nadir observations [*Herzberg, 1991*]. Improvements by factors of several hundred are possible for limb emission and solar occultation observations respectively.

Long wavelength observations could provide insight into the physical processes that have led to the creation of the atmospheres of Europa and the other icy satellites and the processes that underlie the formation of any plumes. These observations could also provide measurements of the temperature of the solid surfaces of the moons. As with the UV measurements, an IR or millimeter instrument operating remotely would be less sensitive to

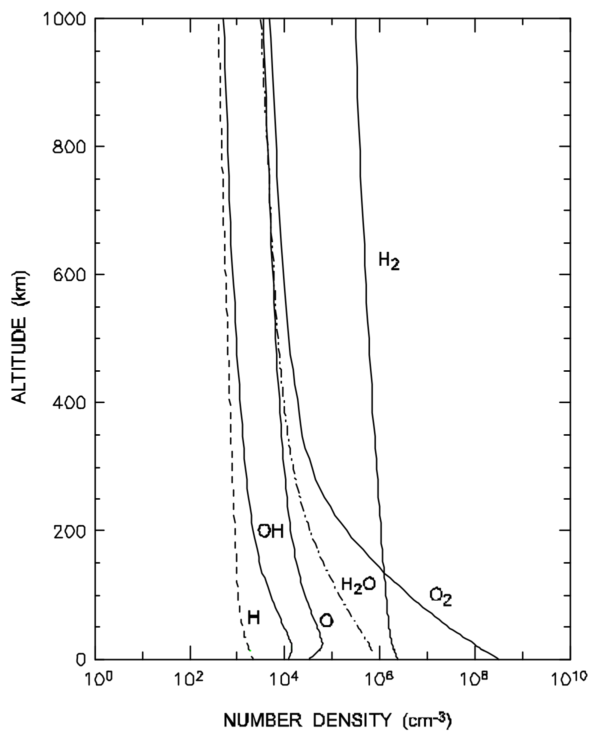


Figure 2.4-10. *Vertical distribution of the modeled abundance, globally averaged density of potential atmospheric components. The O_2 rate was set to reproduce the 135.6 nm O brightness of 37 ± 15 Rayleigh observation of* Hall et al. *[*1995*]. Sublimation was taken into account but is unimportant except in the sub-solar region. In both simulations, the ejecta energy distributions discussed in the text were used for H_2O and O_2 and thermalization of returning H_2 and O_2 in the regolith is assumed. From* Smyth and Marconi *[*2006*].*

distance from target, and would be effective at making composition measurements for all targets within the Jovian system.

Europa's tenuous atmosphere, first postulated to exist in the 1970s, has four observed components: O [*Hall et al. 1995, Hall et al. 1998*] near the surface, Na and K in the region from ~3.5 to 50 R_E [*Brown and Hill 1996, Brown 2001, Leblanc et al. 2002, Leblanc et al. 2005*] and H_2 in Europa's co-orbiting gas torus [*Smyth and Marconi 2006*]. The robust plasma bombardment of Europa's surface is expected to produce many other components [e.g., *Johnson et al. 1998]*. To date there have been so few measurements of the Europan atmosphere that models must be relied upon to draw inferences about the its vertical structure, and especially the abundances of species other than those already detected (O, Na, and K). **Figure 2.4-10** shows one such model [*Smyth and Marconi 2006*] of Europa's atmosphere.

An INMS would provide a highly-sensitive means to measure ions and neutrals present in Europa's atmosphere that are derived from the surface by sputtering, outgassing, and sublimation. Most of the postulated atmospheric constituents could be detected by an orbiting instrument at 100 km based on the proposed detection limit of 200 cm^{-3} from the ROSINA reflectron type time-of-flight (RTOF) mass spectrometer, which is flying on the Rosetta mission.

An important contribution from an INMS would be the capability of measuring isotopic ratios. As a key example, the stable isotopes of oxygen in water could be determined, as shown in **Table 2.4-8**. The variations in the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios in water vapor are

Table 2.4-8. *Water Vapor Components, Including Isotopes, in Europa's Atmosphere Expected To Be Measurable by INMS*

Species	Mass	Expected partial pressure (mbar) at 200 km
H_2	2.01	$>10^{-10}$
O_2	31.99	10^{-10}
O	15.9	10^{-12}
H_2O	18.0	5×10^{-13}
$^{18}O^{16}O$	33.9	2×10^{-13}
$^{17}O^{16}O$	32.9	7×10^{-14}
HD	3.02	$>10^{-14}$?
HDO	19.0	2×10^{-16}

the most useful system for distinguishing different planetary materials. For example, it has been argued that two gaseous reservoirs, one terrestrial and one ^{16}O rich, are required to explain O-isotopic variations in meteorites. The terrestrial fractionation line is due to mass fractionation of the O isotopes in terrestrial materials and the carbonaceous chondrite fractionation line represents mixing between different components. Obtaining similar isotope information for Europa would provide important constraints on the origin of water ice in the Galilean satellites.

The sensitivity for ions is much higher than for neutrals, and based on experience at Enceladus and Titan [*Waite et al. 2006*], ionization will occur by electron impact, photo-ionization, charge exchange, and electron attachment. Predicted ionization rates for several of these molecules are: O_2: 2×10^{-6}/s; H_2O: 3×10^{-6}/s; O: 2×10^{-7}/s; Na: 5×10^{-6}/s; CO_2: 5×10^{-6}/s; and SO_2: 10^{-5}/s.

The trace materials detected from surface spectroscopy (SO_2, CO_2) should be readily detected using INMS [*Johnson et al. 2007*]. Further characterization of the hydrate and associated dark materials could also be accomplished. For example Mg should be present in the atmosphere if $MgSO_4$ is present at the surface. Atmospheric emission measurements have confirmed a surface source for Na and K [*Johnson et al. 2002, LeBlanc et al. 2002*], with some evidence that the Na and K originate in dark regions [*LeBlanc et al. 2005, Potter et al. 2005, Cassidy et al. 2008*]. However, these have not yet been detected in surface spectral measurements. Vented material or materials from flows that are emplaced on the surface are rapidly degraded by the incident radiation. However, this degradation process also produces sputtered products that could be detected and interpreted. Trace organics would also be sputtered with the ice from the surface. Some calculated densities for these various classes of compounds at an orbital altitude of 100 km are shown in **Table 2.4-9**. The range of values indicates various assumptions about the interaction with the regolith.

Using a modeled atmosphere and some assumptions about trace surface salts and organics and the Monte Carlo sputtering model of *Cassidy,* [*2008*] predicted atmospheric composition models at 100 km can be generated. These models can be used to generate simulated mass spectra, shown in **Figure 2.4-11**. Predicited isotopic abundances are shown in the blow-out figure. Ratios of $^{13}C/^{12}C$ could be infered over the course of the mission given sufficiently long integration times.

Table 2.4-9. *Calculated Densities of Sputtered Europa Surface Materials at 100 km*

Species	Predicted Densities @ 100 km
Na	60–1600 cm^{-3}
CO_2	170–580 cm^{-3}
SO_2	290–1800 cm^{-3}
H_2O_2	150–3000 cm^{-3}
L-Leucine (Mass 131)	$3 \times 10^6 F$ cm^{-3} where F is number fraction at surface

Ionospheric model results are shown in **Figure 2.4-12** and are expected to be within INMS detection limits. From this analysis it is apparent that an INMS could detect vapor from an active vent, sublimation from a warm region, the sputter products during the degradation process, and ions that are in all of these processes.

2.4.4.1 Investigation C1: Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability and potential biosignatures

The first priority investigation for Europa's surface composition and chemistry is to identify the surface organic and inorganic constituents, with emphasis on materials relevant to Europa's habitability, and to map their distribution and association with geologic features. The search for organic materials, including compounds with CH, CO, CC, and CN, is especially relevant to understanding Europa's potential habitability.

Moreover, identifying specific salts and/or acids may constrain the composition, physical environment, and origin of Europa's ocean [*Kargel et al. 2000, McKinnon and Zolensky 2003, Zolotov and Kargel 2008*]. Additional compounds of interest include species that can be detected at UV wavelengths, such as water ice (crystalline and amorphous phases), products of irradiation (e.g., H_2O_2), compounds formed by implantation of sulfur and other ions, and other as yet unknown materials.

A spectral sampling of ~5 nm through the visible and near-IR wavelengths of 0.4 to ~2.5 µm, and ~10 nm from ~2.5 to ≥5 µm would provide the required SNR while maximizing spectral separability (**Figures 2.4-5, -6, and -7)** [*Dalton 2003, 2007*]. Observations should sample across at least 80% of the globe, with targeted imaging observations having better than 100 m/pixel spatial resolution in order to resolve small geologic features, map compositional variations, and search for locations with distinctive compositions. By comparison, the Galileo NIMS observations of Europa had a spectral sampling of 26 nm, a spatial resolution of 2 to >40 km, and an SNR which varied from 5 to 50 in individual spectra. Linear spectral modeling using Galileo NIMS data with cryogenic measurements of hydrate spectra displayed sensitivities to abundances at

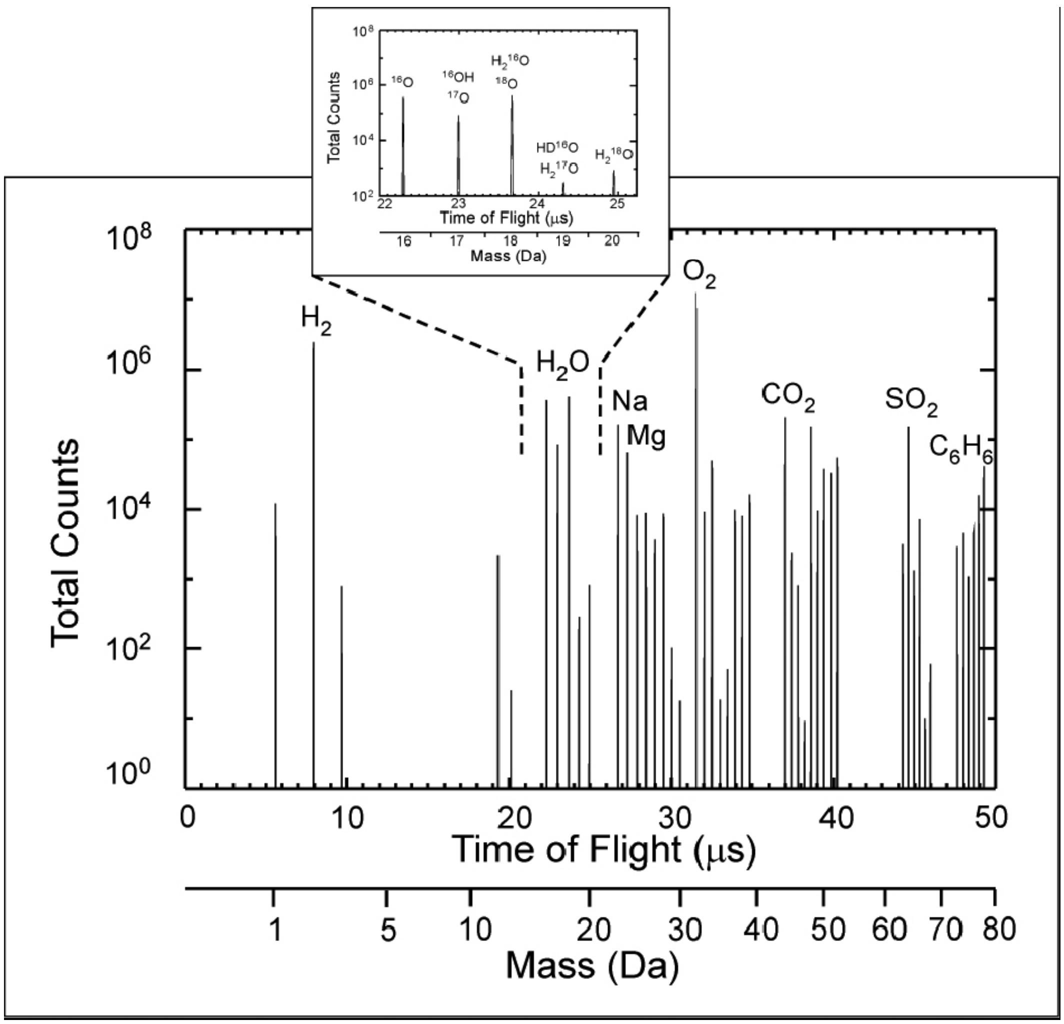


Figure 2.4-11. *Simulated mass spectrum of the anticipated Europa Ion Neutral Mass Spectrometer (INMS) results for neutral species at an orbit altitude of 100 km. The simulation is based on a surface composition given by 60% sulfuric acid hydrate: $H_2SO_4 \cdot 8H_2O$, 20% mirabilite: $Na_2SO_4 \cdot 10H_2O$, 10% hexahydrite: $MgSO_4 \cdot 6H_2O$, 5% epsomite: $MgSO_4 \cdot 7H_2O$, and 4% CO_2 combined with the modeled atmospheric composition and 1% heavy organic represented in this case by benzene (but similar for any heavy organic that may be present). This surface composition has been used as an input into a Monte Carlo ion sputtering/thermal desorbtion model based on the work of* Cassidy et al. *[2008] the output of which was then introduced into an instrument model of the ROSINA Reflectron Time-of-Flight (RTOF) mass spectrometer to produce the simulated spectrum. The plot assumes a background noise of 1.*

the 10% level [*Dalton 2007*]. High spectral resolution, coupled with high spatial resolution that can permit sampling of distinct compositional units at 25–100 m scales, will allow identification and quantification of the contributions of hydrated salts, sulfuric acid, sulfur polymers, CO_2, organics, and other compounds anticipated at the surface of Europa.

Ultraviolet measurements should be made in the 0.1-0.35 µm range, with at least 3 nm spectral resolution, to measure water ice abundances and radiolytic products such as H_2O_2 and SO_2.

INMS observations should be performed to determine the composition of sputtered products. Such measurements should be made in the mass range from 1 to > 300 amu, with a mass resolution (m/Δm) of ≥ 500, and pressure range of 10^{-6} to 10^{-17} mbar.

2.4.4.2 Investigation C2: Relate compositions to geologic processes, especially material exchange with the interior

The spatial resolution required for compositional mapping is determined by the scale of critical landforms such as bands, lenticulae, chaos, and craters. Europa displays albedo and morphological heterogeneity at scales of 25–100 m, suggesting that compositional variations also exist at this scale. However, the composition of these features remains unknown because Galileo NIMS observations are averages of light reflected from large areas containing both icy and "non-icy" terrain units [e.g., *McCord et al. 1999a, Fanale et al. 1999*] (**Figure 2.3-6**). Spectra of adjacent regions within an instrument field of view combine to produce an average spectrum, with spectral features from all the materials. However, these composite spectra have potential overlap of spectral features and reduced spectral contrast relative to the spectra of the individual surface units. This spectral mixing and reduced contrast results in an attendant decrease in detectability, and eventually a given material can no longer be distinguished from its surroundings. For this reason it is desirable to resolve regions of uniform composition in order to map distinct surface units. While these in turn may be mixtures, spatially resolving dark terrains that have fewer components and are free of the strong and complex absorption features of water ice will greatly facilitate identification of the non-ice materials. For reasonable statistical sampling, it is also desirable to have multiple pixels within a given surface unit. Adjacent measurements can then be compared with each other and averaged together to improve the signal and reduce noise.

An example illustrating the importance of spatial resolution is shown in **Figure 2.4-13.** This image has a nominal resolution of 12 m/pixel and shows a variety of small-scale features, including linea with

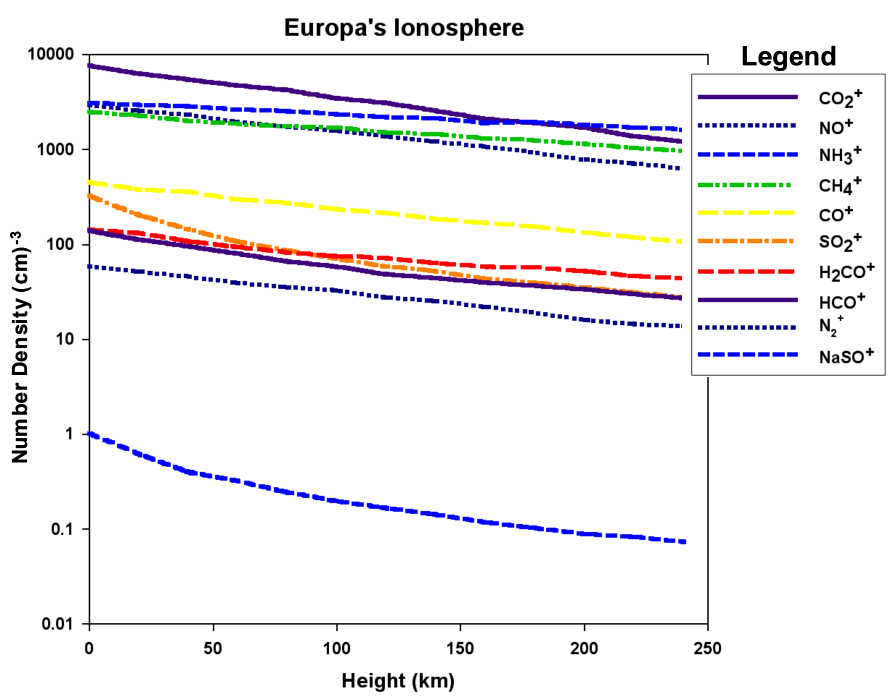


Figure 2.4-12. *Ionospheric densities vs. altitude, determined as discussed in* Johnson et al. [1998] *for molecules sputtered from the Europa's surface based on suggested surface materials. All densities exceed the detection limit (10^{-3} cm^{-3}; Y-axis) of a modern time-of-flight mass spectrometer, such as the Cassini INMS instrument.*

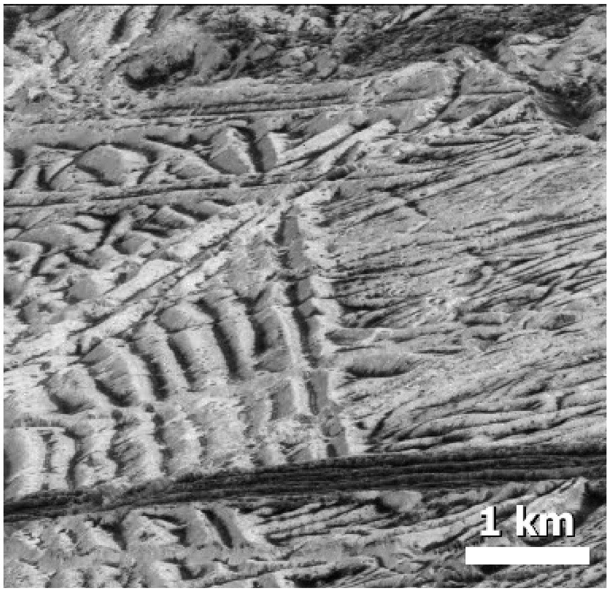


Figure 2.4-13. *Galileo SSI image of ridged plains on Europa at 6 m/pixel horizontal resolution. The lineae in the central portion of the image have central troughs with deposits of dark material ~100 m wide, but with bright, presumably icy ridges and walls close by. Spectral observations with at least 100 m spatial resolution would be needed to independently measure the bright and dark materials. Such measurements would address outstanding questions regarding the composition and origins of the dark material.*

central troughs filled with dark material. The troughs are ~100 m wide and present an opportunity for spectral measurements of contiguous deposits of dark material. Dark material may be linked to interior processes, or may result from radiolytic processing, or a combination of both, while the bright icy material may be water frost. Spectral imaging of these units at a spatial resolution of ≤ 100 m/pixel would allow the composition of the bright and dark materials to be independently determined.

Galileo images of Europa suggest geologically recent formation ages for ridges, chaos, and other features. The images also show abundant evidence for much younger materials exposed by mass-wasting of faces and scarps [*Sullivan et al. 1999*]. These post-formational modification processes have likely affected many surfaces, potentially exposing fresh materials that are less altered than their surroundings. Spectroscopy at a resolution better than 100 m would isolate these surfaces and provide an opportunity to determine the composition of primary materials. Such spectroscopic measurements should be made in the 0.4–2.5 μm region with a resolution of 5 nm, and in the 2.5–5 μm regions at 10 nm resolution, in addition to the UV range of 0.1–0.35 μm with of spectral resolution better than 3 nm.

2.4.4.3 Investigation C3: Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry

In order to understand the surface, it is important to separately determine the effects of weathering (by photons, neutral and charged particles, and micrometeoroids). In particular, radiolytic processes may alter the chemical signature over time, complicating efforts to understand the original composition of the surface. Assessing these relationships requires a detailed sampling of the surface with ultraviolet through infrared spectroscopy, using global and targeted observations. Ultraviolet measurements of the surface should cover the 0.1–0.35 μm spectral range, with spectral resolution of better than 3 nm. Visible-near IR measurements should cover the 0.4–2.5 μm spectral range with better than 5 nm spectral resolution, and the 2.5–5 μm range at better than 10 nm spectral resolution. It is also critical to populate, to the greatest extent possible, a precipitation map of ion and electron flux into the surface as a function of species and energy. Efforts to separate the primary and alteration surface composition will be aided by the acquisition of high spatial resolution spectra on both leading and trailing hemispheres, in which younger, less altered materials may be exposed by magmatic, tectonic, or mass-wasting processes.

Characterization of the sputter-produced atmosphere with UV observations of Europa's atmosphere would allow for the measurement of species, abundances, and ion implantation rates. Atmospheric measurements could be accomplished with far-ultraviolet stellar occultations and ultraviolet imaging of atmospheric emissions. These UV measurements should cover the 0.1–0.2 μm range with a spectral resolution of better than 0.5 nm.

An INMS would provide a highly sensitive means to directly measure species sputtered off the surface, which may include organic fragments. An INMS should operate in the mass range from 1 to > 300 amu, with a mass resolution (m/Δm) of ≥ 500, and pressure range of 10^{-6} to 10^{-17} mbar. For sputtering sources, it is important to measure ions from the plasma energies to about 10 MeV. The number of sputtered molecules is the product of the precipitating ion flux and the neutral yield per ion. For heavy ions, the yield peaks in the few MeV energy range, so it is important to measure ion fluxes into the MeV. Combined with imaging data and geological stratigraphic maps, these synergistic observations will allow determination of how Europa's surface materials evolve in the radiation environment.

2.4.4.4 Investigation C4: Characterize the nature of exogenic materials

The nature of exogenically implanted materials can be elucidated by measuring ions. Each ion energy and species has a specific penetration depth in ice. If they do have access to the surface, cold plasma ions are deposited in the most processed layer. Energetic charged particles can penetrate more deeply into surfaces and therefore will not be removed as readily by processes such as sublimation. A 1 MeV proton has a range of 24 µm depth and 1 MeV electron has a range of 4.2 mm in water. In addition to sputtering by ions, which adds molecules to the atmosphere of a satellite, electron radiolysis can also create neutral species in the material (e.g., H_2O_2). Such molecules can dissociate in the ice and the lighter byproducts can escape from the surface and enter the atmosphere with a small amount of energy. To properly constrain the exogenic materials, the flux of the precipitating charged particles over the entire surface should be determined for the energy range between the eV and few MeV, with resolutions ΔE/E ~ 0.1, 15° angular resolution, and basic ion mass discrimination. This is accomplished with a plasma sensor and an energetic charged particle sensor, both with the capacity to measure the upstream flux at the satellite orbits and to view in the precipitating direction at all points in Europa orbit. These measurements should be synthesized with globally distributed infrared and ultraviolet measurements as described above, along with global multi-spectral visible images. These data will allow materials to be traced from their magnetospheric sources, to the surface, and into the sputter-produced atmosphere. The atmosphere is then measured directly (e.g., with the INMS as described above) and remotely.

The key outstanding questions relating to Europa chemistry (§2.3.4) can be related to and addressed by the Objective C investigations described above, as summarized in **Table 2.4-10**.

2.4.5 Objective D: Europa's Geology

Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ *exploration.*

Europa's landforms are enigmatic and have a wide variety of hypotheses for formation. The search for geologic activity is especially significant for understanding Europa's potential for habitability. Identification and characterization of astrobiologically promising sites will guide future *in situ* exploration.

Table 2.4-10. *Hypothesis Tests to Address Selected Key Questions Regarding Europa's Chemistry and Composition*

	Example Hypothesis Questions	Example Hypothesis Tests
C1.	Are there endogenic organic materials on Europa's surface?	Examine surface and sputtered materials for absorptions and masses consistent with organic materials, especially in regions most protected from radiation, and correlate distributions to likely endogenic materials.
C2.	Is chemical material from depth carried to the surface?	Determine whether hydrates and other minerals that may be indicative of a subsurface ocean are concentrated in specific geologic features, and correlate with evidence for subsurface liquid water at these locations.
C3.	Is irradiation the principal cause of alteration of Europa's surface materials through time?	Determine the suite of compounds observable on Europa's surface, correlating to the local radiation environment and to the relative age of associated surface features.
C4.	Do materials formed from ion implantation play a major role in Europa's surface chemistry?	Determine the distribution of sulfur-rich and other compounds and correlate to inferred implantation rates and the chemistry of material escaping from Io.

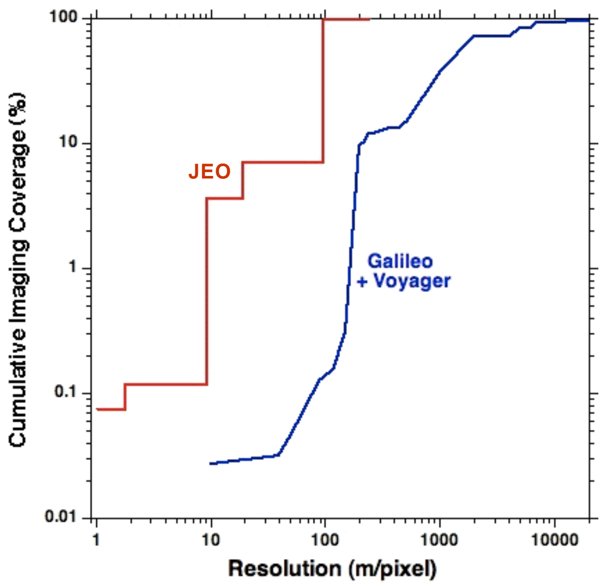


Figure 2.4-14. Cumulative imaging coverage of Europa's surface as a function of imaging resolution, illustrating the 1–2 orders of magnitude improvement of planned JEO imaging coverage relative to that from Voyager and Galileo combined. Unlike the opportunistic coverage obtained from earlier flybys, JEO's deliberate imaging coverage from orbit will be in discrete resolution steps.

2.4.5.1 Investigation D1: Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms

Of first order importance is characterization of surface features—their distribution, morphologies, and topography—at regional and local scales, to understand the processes by which they formed. Galileo images demonstrate that regional-scale data (~100 m/pixel especially as aided by 3-color coverage), is excellent for geologic study of Europa, yet less than 10% of the surface was imaged at better than 250 m/pixel (**Figure 2.4-14**). Near-global coverage (> 80% of the surface) in at least 3 colors at 100 m/pixel will ensure characterization of landforms across the satellite. Galileo images (e.g., **Figure 2.4-13**) also show the great value of targeted high-resolution (~10 m/pixel) monochromatic imaging for detailed characterization of selected landforms.

Topographic mapping through stereo images at regional scale, provide vertical resolutions of ~20 m, which will greatly aid morphologic characterization and geologic interpretation. Stereo imaging can be achieved through horizontal overlap of adjacent medium-angle camera image tracks, resulting in approximately 20 m vertical height accuracy with 100 m/pixel images (see §4.2.2.9 and **Figure 4.2-17**). Height accuracy further improves by $\approx\sqrt{N}$ by averaging of N overlapping stereo pairs. For example, each equatorial patch of Europa could be imaged about 12 times in 9 months, improving height accuracy by ~3 times. High latitudes are sampled much more, so height accuracy improves even further by approximately the cosine of latitude.

It is also important to determine topographic signatures at high resolution through stereo imaging and altimetric profiling across targeted representative features, with vertical accuracy of 1 m or better. Subsurface profiling (discussed above) will greatly illuminate subsurface structure and the role of liquid water. Europa's surface is quite heterogeneous and rough at the decameter scale (**Figure 2.4-13**), and the same may be true at smaller scales. Very high resolution monochromatic imaging (1 m/pixel; <0.1% of the satellite) will reveal the detailed character of landforms, the properties of the regolith, and erosion and deposition processes. Moreover, imaging at this scale will be critical in characterizing future landing sites.

2.4.5.2 Investigation D2: Determine sites of most recent geological activity, and evaluate future landing sites

Geologically active sites are the most promising for astrobiology, and will be important to identify and characterize in preparation for future landers. Active processes typically involve elevated heat flow and may involve plumes detectable by imaging, laser altimetry, or UV occultations. These would also be the most likely locations for near-surface liquid water. Recently or currently active regions also best illustrate the processes involved in the formation of some surface structures, showing pristine morphologies and geologic relations and perhaps associated thermal and/or plume activity (as seen on Enceladus).

Modeling shows that liquid water brought to the surface of Europa can maintain >5 K nighttime thermal anomaly over hundreds of years, with younger spots being warmer [*van Cleve et al. 1999*, *Abramov and Spencer 2008*]. Regions of anomalously high heat flow should be identified through thermal mapping, with a 2 K measurement temperature accuracy to permit a robust search for elevated temperatures due to thermal anomalies when combined with albedo information. Such requires observing the same features in the day and at night, ideally near maximum and minimum temperatures, but with no strict requirement on the relative times between the measurements. A resolution of 250 m/pixel is sufficient to resolve Europa's larger cracks and ridge axial valleys, and observations should be made over at least 80% of the surface.

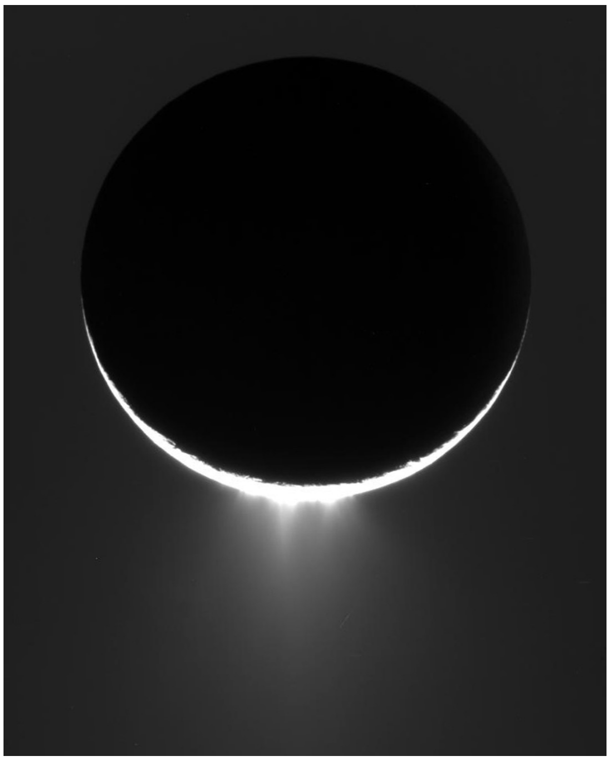


Figure 2.4-15. *The plumes of Enceladus dramatically illustrate that satellite to be geologically active today, as revealed by a combination of Cassini high-phase imaging (shown here), plus thermal, UV, and fields and particles observations [*Porco et al. 2006*]. Analogous plumes would be ~70 km tall when scaled to Europa's gravity [*Nimmo et al. 2007b*], so similar activity could be plentiful yet undiscovered on Europa, and might contribute to Europa's recently discovered torus [*Mauk et al. 2003*]. A combination of thermal and UV observations would permit a thorough search and characterization of active regions on Europa.*

Searching for regions of outgassing is a powerful method of locating currently active regions, best accomplished by observing stellar occultations in the ultraviolet, since vented water vapor and other gases will absorb starlight. Ultraviolet stellar occultation experiments were fundamental to discovery of plumes on Enceladus [*Hansen et al. 2006*] (**Figure 2.4-15**). Moreover, observing the surface and the tenuous atmosphere at ultraviolet wavelengths could reveal patchy regions of absorption that might be related to recent venting or other internal activity. An ultraviolet wavelength range of 0.1–0.35 µm and spatial resolution of better than 100 m/pixel are recommended, with capability to observe the sunlit surface, stellar occultations over Europa's limb, and atmospheric emissions.

Discoveries of any active regions would be followed by visible and other remote sensing of the inferred source. It may be possible to observe surface changes within the orbital lifetime of JEO; moreover, the most recently active landforms are expected to show the freshest morphologies and display the least superposed impact craters. Imaging at high resolution (10 m/pixel) in stereo, coupled with very high resolution (~1 m/pixel) images, and thermal and compositional measurements, will be used to characterize features that are suspected candidates for recent activity. If age-sensitive chemical or physical indicators can be identified, such as H_2O frost, ice crystallinity, sulfate hydrates, SO_2, or H_2O_2, then mapping their distribution may reveal currently or recently active regions.

Constraining the global and local heat flow of Europa is of great importance. High heat fluxes (~1 W/m^2) would be necessary for detection of uniform conductive heat flow [*Spencer et al. 1999*], but lower levels of endogenic heat flow can be detected if locally concentrated, as on Enceladus [*Spencer et al. 2006*]. A high heat flow could indicate that significant tidal heating and likely volcanic activity is occurring in the mantle. This would have important implications for astrobiology, as on Earth it is hypothesized that life may have developed at hot hydrothermal vents on the ocean floor. Thermal emission from the surface can be appropriately mapped by measuring albedo to 10% radiometric accuracy at spatial resolution of ~250 m/pixel in two thermal wavelength bands with temperature accuracy <2 K, over > 80% of the surface.

Constraints on global heat flow will also come from subsurface ice temperatures derived from ice penetrating radar, and estimates of ice shell thickness derived from gravity or radar data **(FO-2)**.

Determining the relative ages of Europa's surface features allows the evolution of the surface to be unraveled. Indication of relative age comes from the stratigraphy, derived from cross-cutting and embayment relationships, and the relative density of small primary impact craters. These relationships enable a time history to be assembled within regions, for global extrapolation. Galileo 3-color imaging at low phase angle showed the great advantage of color in stratigraphic studies, because features generally brighten and become less red with age [*Geissler et al. 1998*]. Without a global map, the relative ages of different regions cannot be determined, because they cannot be linked; this is the current problem in understanding Europa's stratigraphy based on Galileo imaging. Global color imaging (> 80% of the surface) at resolution better than ~100 m/pixel, with near-uniform lighting conditions and phase angle ≤ 45°, will allow Europa's global stratigraphic sequence to be derived. Similar to searching for recent or currently active regions, relative surface ages also can be derived by identifying regions of anomalously high heat flow, by assessing surface morphology and topography, and by mapping age-sensitive chemical and physical indicators.

2.4.5.3 Investigation D3: Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris

Europa's regolith provides information about modification processes occurring on very small scales. Modification occurs by mass wasting, sputtering, impact gardening, and thermal redistribution of material. Investigation of regolith characteristics and processes will be important in characterizing high-priority sites for future landed missions, and in understanding means of material exchange between the oxidant-rich upper meter of the surface and the subsurface. Regolith processes can be investigated by imaging at ~1 m/pixel resolution, which will reveal the small-scale morphology of targeted sites, shedding light on erosional processes and material deposition. Meter-scale imaging is critical to understanding the nature and safety of potential future landing sites.

Variations in daytime temperatures seen by the Galileo Photopolarimeter Radiometer (PPR) show 5 K temperature variations that could have been caused by variations in thermal inertia when corrected for albedo [*Spencer et al. 1999*]. Thermal measurements will investigate the regolith by mapping surface thermal inertia, with the same measurement requirements as for investigation of possible thermal anomalies (§2.4.5.2). This will follow up on the mysterious nighttime thermal anomalies identified by Galileo.

Magnetometry data are important for understanding sputtering and its effects on regolith evolution; thus, it is valuable to measure ion-cyclotron waves, which can be related to plasma-pickup and erosion processes. Measuring these high-frequency waves requires magnetic field sampling at 32 vectors/s at a sensitivity of 0.1 nT, knowledge of spacecraft orientation to 0.1°.

The key outstanding questions relating to Europa's geology (§2.3.5) can be related to and addressed by the Objective D investigations described above, as summarized in **Table 2.4-11**.

2.4.6 Objective E: Jupiter System

Understand Europa in the context of the Jupiter system.

Aside from its intrinsic value, understanding the Jupiter system as a whole is critical for placing Europa in its context as a member of the Jovian system. However, Jupiter system science is the lowest priority objective for JEO because these investigations are less directly related to the overall goal of "Explore Europa to investigate its habitability." However, JEO embraces additional Jupiter system science in assuring inherent linkage to the overall EJSM theme, and synergistic science with JGO. Consequently, Jupiter system science is not a strong driver for the instrumentation, and it will be performed on a best effort basis.

Table 2.4-11. Hypothesis Tests to Address Selected Key Questions Regarding Europa's Geology

	Example Hypothesis Questions	Example Hypothesis Tests
D1.	Do Europa's ridges, bands, chaos, and multi-ringed structures require the presence of near-surface liquid water to form?	Combine high-resolution imaging, compositional, subsurface, and thermal data sets to determine the style of surface deformation and the links to interior structure and water.
D2.	Where are the youngest regions on Europa and how old are they?	Use repeat imaging, sputtering measurements, vapor transport observations and thermal data to determine absolute age ranges.
D3.	What is the roughness and thickness of the regolith?	Use thermal measurements and imaging, combined with plasma measurements, to characterize the uppermost surface.

Jupiter system science investigations fall into five categories: satellite surfaces and interiors, satellite atmospheres, plasma and magnetosphere, Jupiter atmosphere, rings, dust and small moons. The investigations and measurements are prioritized within each of these categories, with the lower priorities generally having less relevance to the Europa habitability goal of JEO, yet allow application to the overarching theme of EJSM. The Jupiter system science will be the principal focus of the Jovian Tour phase of the JEO mission, which has a duration of about 2.5 years prior to Europa Orbit Insertion.

Given the large number of Jupiter system science investigations, the following subsections are described in less detail and slightly different format from the Europa-specific objectives and investigations.

JEO Jupiter system science complements that of the Juno mission, to be launched in 2011. Juno will be in a close polar orbit, with objectives focused on the interior structure of Jupiter, its magnetosphere and aurora, and the polar atmosphere. Juno performs no direct satellite science. By contrast, satellite science is a high priority for JEO. For its study of Jupiter's atmosphere, Juno will not have sufficient spatial resolution, wavelength coverage, or temporal coverage to constrain small-scale turbulent processes that transport momentum, heat, and tracers that are crucial for understanding the basic structures of the jets, clouds, belts, zones, and vortices. JEO has the potential to provide the first high-resolution climate database with global coverage over a long temporal baseline (many months). Jupiter science to be conducted by JEO relates fundamentally to understanding the evolution of icy lithospheres of Jupiter's large satellites, Europa's ocean, and Io's volcanism.

2.4.6.1 Satellite Surfaces and Interiors

All four major satellites probably formed in a similar environment, while the inner three affected each other as their orbits and interiors evolved. The outer three satellites share similar surface materials, altered to differing extents by external and internal processes. Clues to Europa's origin, evolution and present-day state may also be found elsewhere in the Jovian system.

In the Jupiter system science category of satellite surfaces and interiors, prioritized investigations are:

- E1. *Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io.*
- E2. *Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust).*
- E3. *Investigate the presence and location of water within Ganymede and Callisto.*
- E4. *Determine the composition, physical characteristics, distribution and evolution of surface materials on Ganymede.*
- E5. *Determine the composition, physical characteristics, distribution and evolution of surface materials on Callisto.*
- E6. *Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.*

Tidal heating has shaped the evolution of all four Galilean satellites, but the details remain poorly understood. Tidal heating is most readily studied on Io, where the spatially and temporally variable surface temperature and heat flow can be measured using a thermal mapper. Combined with high-resolution images, stereo- or altimeter-derived topography, and visible/NIR observations of high-temperature volcanic thermal emissions, these measurements will characterize the different styles of volcanic activity and their controlling factors. For the icy satellites, recent activity is potentially detectable with a thermal mapper. Otherwise, the strongly temperature-dependent radar absorption of ice allows subsurface radar profiling to determine an approximate temperature gradient, and thus the heat flux. Predicted long-wavelength variations in stress and heating—due to tides or other processes—can be investigated using either the thermal or the radar approach, and correlated with spatial variations in surface features.

Ganymede and Callisto are both thought to possess oceans sandwiched between two layers of ice. The presence of such oceans can in principle be confirmed by measuring the time-dependent (tidally-driven) gravity field or surface topography; these measurements will also help determine the amount of tidal heating (see below). Magnetometer observations will place bounds on the depth, thickness, and salinity of the oceans. The deeper structure of these satellites, and in particular the extent to which Callisto is differentiated, may be determined by Doppler-tracking during equatorial and polar flybys. Combining regional images taken at different times will establish the spin pole orientation, and potentially detect librations (both of which depend on the internal structure). For Ganymede, characterization of the spatial and temporal variability of its internal magnetic field will constrain dynamo models.

Characterizing surface materials on Ganymede and Callisto will help disentangle the origin of similar materials on Europa. IR and UV spectroscopy will identify individual compounds and map their distribution (e.g., hydrated non-ice material and trace constituents such as CO_2). Combined with high-resolution color images, correlations between particular species and geologic features may be tested. Repeat measurements will allow characterization of any surface changes. (e.g., mass wasting or sublimation). Similarly, visible and IR mapping may be used to determine the compositional variability, spatial and temporal distribution, and geologic associations of both silicates and volatiles at Io.

2.4.6.2 Satellite Atmospheres

The tenuous atmospheres of the four Galilean satellites vary dramatically from one another, and they provide insights into the chemistry of the satellite surfaces and interactions with the external magnetospheric environment. Io's atmosphere is patchy and supported by volcanic activity, sublimation of surface SO_2 frost, and sputtering by charged particles. The atmospheres of Europa and Ganymede have sputtering as their primary sources, with Europa receiving the greater amount of charged particle bombardment, and Ganymede's magnetosphere partially shielding the surface. Plumes could plausibly contribute to Europa's atmosphere **(Figure 2.4-16)**. At Callisto, sublimation may be more significant than charged particle sputtering. Current knowledge of the atmospheres is largely based on isolated observations, derived largely from observations of spectral emission features that are reliant on the local plasma environment, and which provide little information on minor species chemistry and temporal variations.

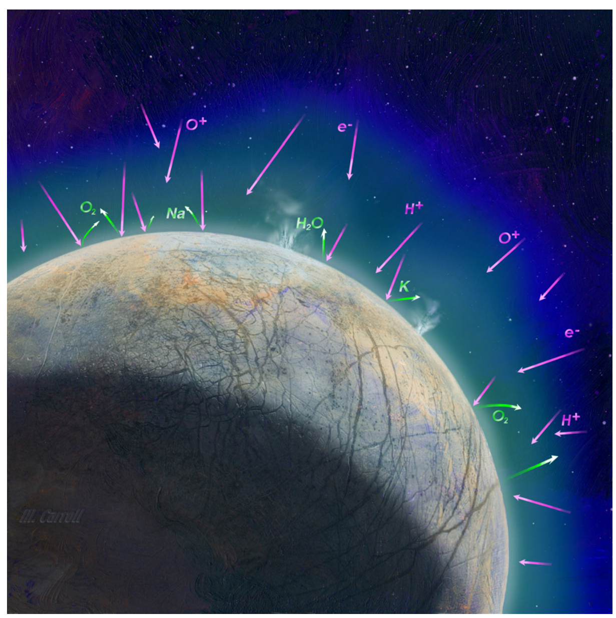


Figure 2.4-16. *Artist's rendition of Europa's tenuous atmosphere, supplied chiefly by charged particle bombardment of the surface. If Europa is currently geologically active, plumes may also contribute.*

In the Jupiter system science category of satellite atmospheres, prioritized investigations are:

E7. *Characterize the composition, variability and dynamics of Europa's atmosphere and ionosphere*.

E8. *Understand the sources and sinks of Io's crustal volatiles and atmosphere*.

E9. *Characterize the sources and sinks of the Ganymede and Callisto atmospheres*.

The surfaces of the Galilean satellites continuously exchange material with the atmospheres, so it is important to make direct measurements of the atmospheres and ionospheres an important goal of the Jupiter system science. The measurement of major and minor constituents of the neutral atmospheres would greatly aid geological, compositional, and exospheric studies. In addition to water ice, heavy molecules and molecular fragments can be sputtered and subsequently detected by UV spectroscopy, IR spectroscopy (including limb scans such as those used to detect the CO_2 atmosphere of Callisto [*Carlson 1999*]), and *in situ* by an INMS. UV stellar occultations provide stringent constraints on the extent and structure of the satellites' atmospheres. The JEO mission implementation currently includes a Callisto polar flyby, which would provide useful new information about the sources and sinks at Callisto.

Non-uniform atmospheres are anticipated and can be examined with *in situ* INMS measurements. Measurements of the Ganymede and Callisto atmospheres will reveal a wealth of information about the auroral processes at work on Ganymede, as well as the sources and sinks of both atmospheres.

Understanding the ionosphere of Europa is critical to disentangling the higher order magnetic moments for interpretation of Europa's induced magnetic field. Radio occultations provide a proven technique with which to sound the ionospheres of all the Galilean satellites during the tour phase of the mission [*Kliore et al. 1997, 2001a, 2001b, 2002*]. During the Europa orbital phase of the mission, in situ measurements of the ionosphere can be made by both an INMS and the plasma and particle instrument (PPI).

A variety of techniques are required to understand Io's unusual atmosphere, produced by a combination of sources. Its reservoir of surface volatiles, especially SO_2, has a major impact on the Jovian system. The Io plasma torus is a key link in the transfer of material from Io to Europa. The JEO Io campaign includes multiple Io flybys, allowing direct sampling of the upper atmosphere with the INMS, and perhaps also large plumes (**Fig. 2.4-17**). Whether plumes can be flown through safely would require further study, but it is worth noting that Galileo flew through the large Thor plume without incident in late 2001, and Cassini is making multiple passes through the Enceladus plume. Understanding the sources and sinks of the volatiles, both on the surface and in the atmosphere, that contaminate Europa is a key undertaking of the Jupiter system science program. Eclipse imaging, plume monitoring, far- and mid-UV and IR spectroscopy of the surface and atmosphere with high spatial and temporal resolution, as well as stellar occultations, will provide critical constraints on the flux of materials escaping Io. Monitoring the neutral clouds and plasma torus, together with measurements of dust and neutral and charged particles, will help determine how these materials are dispersed throughout the Jovian system and beyond.

2.4.6.3 Plasma and Magnetospheres

Europa resides in Jupiter's magnetosphere near the outer edge of Io's plasma torus. Its surface is influenced by Iogenic material that is largely energized in the co-rotating magnetosphere of Jupiter. Surface weathering includes sputtering, in which, neutrals are liberated and contribute to the satellite atmosphere and neutral torus. This section considers the physics of processes such as pickup and charge exchange. As they relate to the magnetosphere more generally, the plasma and charged particles are responsible for the basic structure of the system (e.g., the stretched magnetodisk), auroral signatures, dynamics in the form of injections and other plasma transport, and the stress balance between magnetic and particle pressures.

***Figure 2.4-17**. Artist's conception of a JEO flyby of Io, performing in situ atmospheric, plume, and torus measurements. (Io background graphic by John Kaufmann.)*

In the Jupiter system science category of plasma and magnetospheres, prioritized investigations are:

- E10. *Measure the dust, plasma, and neutral ejecta from Europa.*
- E11. *Characterize the composition of and transport in Io's plasma torus.*
- E12. *Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.*
- E13. *Study the interactions between Jupiter's magnetosphere and Io, Ganymede and Callisto. (incl. characterize Ganymede's magnetic field).*
- E14. *Understand the structure, composition and stress balance of Jupiter's magnetosphere.*
- E15. *Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.*

Investigation of Jupiter's magnetosphere requires near-continuous temporal observations, with spatial sampling throughout the magnetosphere, especially in special regions including boundaries and near satellites. For instance, Jupiter's magnetopause separates regions of high intensities of electrons from the solar wind. Furthermore, JEO will investigate the consequences of reconnection on the populations closer to the planet, e.g., in sporadic plasma flux enhancements. The question of stress balance in the Jovian plasma sheet has not been successfully resolved. From the satellites outward, current systems and electron beams link the equatorial and polar regions of the magnetosphere and are responsible for auroral signatures. Closer to the planet, the radiation belts contribute to the weathering of the satellite surfaces.

It is important to understand how Jupiter spins up its space environment. In addition to the source at Io, neutrals are being added to the magnetosphere from surface sputtering and possibly from plumes. These neutrals become ionized quickly at Jupiter and must be accelerated to the corotation speed of the local plasma. By measuring the plasma flow field over a wide range of radial distances and latitudes and the current systems (through magnetometer measurements), it will be possible to understand the addition of new material to the magnetosphere.

Close spacecraft encounters with all four Galilean satellites will reveal ways in which magnetosphere interactions depend on the properties of a moon and its local magnetospheric environment. The resulting knowledge will provide a useful basis for interpretation when the JEO focus shifts primarily to Europa. Whereas the JEO tour will characterize the orbital environments of the moons, the close flybys will reveal the perturbed magnetosphere, the near-surface environments in the immediate vicinity of each moon, and in some cases the precipitation flux.

Plasma observations near satellites should be made at various altitudes and orientations and will be designed to probe different parts of the region in which the flowing plasma is modified by the presence of the moon, including the upstream, flank, wake and polar regions. Satellites interact with the magnetosphere over a large distance (e.g., the so-called "Alfven wing") and this interaction provides information about the conductivity of the body and the electrodynamics of the satellite ionosphere and atmosphere [*Neubauer 1998*]. In addition to magnetometer measurements near the satellites (to constrain the fields and current systems), it is also important to detect modifications to the plasma flow field near the satellite and particle signatures of the interaction. For the icy moons these flybys expand the coverage of the induced and intrinsic magnetic field perturbations from the initial measurements from Galileo.

Because of its critical role in the transfer of material from Io to Europa, the Io plasma torus will be an important target of Jupiter system science observations during the Jovian Tour phase of the JEO mission. The UV spectrometer on JEO should cover the EUV–FUV wavelength range (~70–200 nm), similar to the Cassini UVIS instrument. During the Jupiter approach and flyby, Cassini UVIS obtained perhaps the most illuminating series of synoptic observations (over a period of 45 days) of the Io torus ever obtained [*Delamere et al. 2004, Steffl et al. 2004, 2006, 2008*], from which a transport rate of 100–200 days was derived. Because the torus energy loss is primarily by EUV line radiation from multiple sulfur and oxygen ions, these measurements cannot be made from Earth. The JEO mission promises to provide a much longer, and hence even more enlightening, set of synoptic observations during which multiple Io volcanic eruptions are likely to occur, leading to plasma injections into the torus, followed by transport of material to Europa in ~100–200 days. During the approach and Jupiter tour phase of JEO, covering a period of over two years, a similar series of synoptic observations will be obtained covering a substantially longer time period than the highly successful Cassini UVIS observations.

For studies of Ganymede's internal field and its magnetosphere, trajectories that complement the latitude/longitude coverage of Ganymede by Galileo should be favored. Ganymede's surface is weathered differently on open and closed magnetic field lines [*Khurana et al. 2007*], and it is critical to measure the charged particle populations on those field lines.

Elucidating the links between Io's volcanic activity and the dynamics of the Jovian magnetosphere requires UV and visible observations of the Io torus, Jovian auroral oval, and the satellite auroral footprints at high time and spectral resolution, combined with monitoring of Io activity in the visible and infrared.

2.4.6.4 Jupiter Atmosphere

Following the Juno mission's exploration of the interior structure of Jupiter in 2016, many questions will probably remain regarding the dynamics, chemistry, vertical structure and temporal evolution of Jupiter's neutral and charged atmosphere. Juno will greatly boost understanding of the depth of the jet streams, the small-scale structure of Jupiter's magnetic field, and the deep abundances of water vapor and ammonia. However, Juno will not have sufficient spatial resolution, wavelength coverage, or temporal coverage to constrain the small-scale processes and their long term variations governing the basic structures of the jets, clouds, belts, zones, and vortices in the troposphere.

JEO will observe weather-layer manifestations of the deep water and ammonia contrasts revealed by Juno, such as storms, lightning, cloud formation, belt/zone contrasts, convection, jet streams and wave propagation. These models can be extended, by comparison with Juno, to provide an understanding of how Jupiter's composition varies with depth and how the planet radiates away its internal heat, thereby generating insights into the internal reprocessing of material since the time of Jupiter's formation. Furthermore, JEO's suite of instrumentation provides information on altitudes above the troposphere which will be inaccessible to Juno. Jupiter science from JEO will surpass previous investigations in terms of continuous high-resolution global coverage over many months, with the goal of producing the first comprehensive climate database with visible imaging and spectroscopic characterization for Jupiter's atmosphere.

In the Jupiter system science category of Jupiter's atmosphere, prioritized investigations are:

E16. *Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa*.

E17. *Characterize Jovian atmospheric dynamics and structure*.

JEO can make specific measurements to address some of the puzzles unresolved after Juno mission. These will aid in understanding the relation among the upper troposphere, lower troposphere, and internal structure, thereby elucidating Jupiter's bulk composition and the evolution of the system as a whole.

Jet Stream Meteorology. High resolution long-term cloud tracking at visible and near-IR wavelengths at 30 km resolution allows the zonal (east–west) and meridional (north–south) velocities to be obtained, and could allow measurement of the mean-meridional velocity at the cloud level for the first time. High spectral-resolution sub-millimeter investigations of the 1-500 mbar region could allow direct measurements of wind velocities without the need for cloud-tracking. Observations of any correlation between zonal and meridional velocities will determine whether small eddies are pumping the jets at cloud level [*Salyk et al. 2006*] and how this process varies with latitude and time. Observations at different wavelengths from the visible through the sub-millimeter would permit studies of the vertical wind shear in the tropospheric jets, which could then be related to the deep structures observed by Juno to determine the vertical coupling between the upper and lower atmospheres. Spectroscopic studies will constrain the thermal and chemical environments in the vicinity of these cloud tracers.

Tropospheric Hazes and Clouds. The characterization of the altitude and global distribution of photochemical hazes and condensation clouds will provide fundamental clues to their origin and the meridional transport in the troposphere. The haze distribution is vital to understanding the details of solar energy deposition in the atmosphere and its role in hemispherical asymmetries. Correlation between temporal variations of cloud properties (size, optical properties, vertical distribution, color and albedo) with changes of environmental temperatures and composition will be used to determine what is responsible for major changes in Jupiter's cloud properties. These may provide a fundamental clue for the origin of their various colors. The detection of condensed ammonia, ammonium hydrosulfate and water ice will provide significant clues to the size and strength of updraft regions in the atmosphere [e.g., *Baines et al. 2002*].

Evolution of Discrete Cloud Features. Weather-layer phenomena such as thermal hotspots, large anticyclonic vortices, turbulent regions, convective plumes, and thunderclouds can be monitored using visible and IR imaging over a long temporal baseline. Spatial resolutions of ~30 km provide the capability to examine the cloud properties, energetics, and angular momentum of individual storm systems [*Porco et al. 2003*] and their relation to the global atmospheric circulation.

Measurements of thunderstorms on the dayside and lightning on the night side will constrain the energetics of the atmosphere at depth.

Atmospheric Waves and the Thermosphere and Ionosphere. Radio science investigations will characterize the detailed vertical temperature structure in the stratosphere and upper troposphere, thus providing a window into stratospheric dynamics. This will allow a characterization of the vertical propagation of a variety of atmospheric waves, including small-scale gravity, larger-scale Rossby waves, and the altitude dependence of slowly moving thermal waves that are uncorrelated with cloud structures. A characterization of such waves would also prove invaluable in understanding the dynamics of the quasi-periodic stratospheric oscillation (QQO), which is a time-evolving stratospheric phenomenon, much like the Earth's quasi-biennial oscillation (QBO), and thought to be driven by atmospheric wave absorption. Radio and stellar occultations can also be used to characterize the thermosphere and determine the extent to which wave absorption can cause the high thermospheric temperatures.

Tropospheric Dynamical Tracers. To complement the Juno investigation of the lower troposphere, near-IR spectroscopy will measure H_2O and NH_3 in the upper troposphere, in addition to disequilibrium species such as PH_3, GeH_4 and CO as diagnostics of the dynamics associated with the jet stream meteorology and discrete cloud features. In particular, high-inclination orbits will be able to map these species and tropospheric aerosols at polar latitudes to determine the relative roles of dynamics and seasonally forced radiation in maintaining Jupiter's cold and hazy polar vortices [cf. *Vincent et al. 2000, Porco et al. 2003*]. High spectral resolution long-wavelength observations could also provide three-dimensional information on the vertical distribution of trace gaseous species, as well as providing vertical temperature structure and wind velocities in regions of the atmosphere inaccessible to nadir-sounding thermal-IR spectroscopy.

Stratospheric Temperature and Composition. Spectroscopic studies of Jupiter's stratosphere (at UV, visible, near-IR, and sub-millimeter wavelengths) will shed light on the photochemistry and atmospheric motion responsible for the distribution of hydrocarbons and hazes. Thermal monitoring could allow the first detection of tides raised by the Galilean satellites. Detection of material from exogenic sources (HCN, CO, CO_2, H_2O) will permit studies of the changing environment surrounding the satellites and rings.

Electrodynamic Phenomena. The diverse Jovian tour phase of the JEO mission offers the prospect of measuring the time variability of the Jovian ionosphere for the first time. The temporal evolution of the distribution of ions within the ionosphere will be probed at a range of latitudes through radio occultations at multiple frequencies, accomplished using precisely time-referenced Ka- and X-band transmissions. The coupling between Jupiter's three dimensional auroral spatial structure and source regions within the magnetosphere will be studied using imaging of H_3^+ emission in the near-IR, as well as in the visible and UV.

2.4.6.5 Rings, Dust and Small Moons

The "skeleton" that holds together the Jovian ring system is its collection of source bodies. Four inner moons are known, but it is clear that the ring also contains a large number of embedded meter- to kilometer-sized bodies. Learning the nature and properties of these bodies is critical to understanding origin, evolution and the long-term stability of the system.

In the Jupiter system science category of rings, dust, and small moons, prioritized investigations are:

E18. *Characterize the properties of the small moons, ring source bodies and dust.*

E19. *Identify the dynamical processes that define the origin and dynamics of ring dust.*

At a certain point, the distinction between a "moon" and a "ring body" should become moot, because the ring contains a continuum of sizes. However, imaging at low phase angles is needed to characterize the radial distribution of the bodies and to identify its largest members. A detection threshold of 500 meters in radius was achieved by New Horizons; future imaging should reduced this threshold to ~100 m (assuming albedos comparable to Adrastea and Metis) in order to ensure detection of the largest bodies. The camera should also be sensitive to reflectivities in the range of 10^{-8} for high-quality ring detections. Searches for the source bodies must be conducted primarily at low phase angles, which means that the camera must be capable of targeting just off the planet with minimal interference from light scattered inside the optics. Little is known about the composition of the Jovian ring or its ring-moons, beyond the fact that they are very dark and red. Spectrophotometry in visible and near-IR wavelengths is needed for precise information about the molecular makeup of their surfaces.

The dust component of the system should also be characterized. The size distribution of ring dust probably varies with location, and can be derived from light phase curves and spectra. Sensitive images of all the ring components should be carried out at a full range of phase angles, up to and including within a few degrees of exact forward-scatter. This is where diffraction by the dust particles dominates, yielding the most precise size constraints. Such imaging can only be obtained when passing through the Jovian shadow. Measurements should be sensitive to rings with optical depths as low as $\sim 10^{-9}$, the approximate value for a faint outward extension to Thebe's "gossamer" ring.

To assess the role of ring dust in contributing to the surfaces of the Galilean satellites, more information is required about the composition of the dust. This can be accomplished via IR spectroscopy of the dust grains and their parent bodies, particularly Amalthea and Thebe. A match of specific spectral signatures between the rings and the Galilean surfaces would provide strong circumstantial evidence that this process is occurring. It is also important to understand better the dynamics of the faint outward stream of ring dust, which requires imaging the outermost ring components with fine sensitivity. This is most readily accomplished using the NAC at very high phase angles, where diffraction by the fine dust grains makes the rings much easier to observe.

The search for Jovian dust and moons should not end at the ring boundary. Trojan moons are a commonplace feature of the Saturnian system, but a deep, systematic search for small moons orbiting among the Galilean satellites has never been conducted. Any bodies that are found would surely have interesting dynamical histories and place new constraints on how the entire system formed. The detection threshold should be less than 1 km. The camera should also be used to conduct precision astrometry of any bodies that are found. At higher phase angles, the system should be searched for faint dust belts, which might be indicators of unseen small bodies in the system.

In addition to precise measurements of the particle properties, a better understanding is needed of the dust grains' motion. The grains are known respond to solar radiation pressure and magnetic forces. These produce the "Lorentz resonances" that distribute so much of the dust well out of the ring plane. However, the three-dimensional structure of the system's faint inner "halo" and its outer gossamer rings have never been mapped out in detail. This requires imaging at a large variety of viewing and lighting geometries, with sensitivity to I/F $\sim 10^{-8}$ and resolution of finer than 100 km. Such observations may illuminate the dynamics behind some of system's more peculiar features, such as vertical ripples found in some Galileo images [*Ockert-Bell et al. 1999*].

Because the system has shown clumps and other time-variable phenomena, repeated observations of the system throughout the tour are required. The most rapid phenomena are likely to change in periods of days to months. To understand the phenomena at work, it is critical to obtain reliable constraints on their time scales.

The sampling of key outstanding questions relating to the Jupiter System (§2.3.6) can be related to and addressed by the Objective E investigations described above, as summarized in **Table 2.4-12.** This table includes only a few representative hypothesis questions pertinent to Jupiter system science.

***Table 2.4-12.** Hypothesis Tests to Address Selected Key Questions Regarding Jupiter System Science*

Example Hypothesis Questions		Example Hypothesis Tests
E2.	What factors control the different styles of eruptive activity on Io?	Thermal and spectral imaging of surface deposits will identify composition and temperature; morphology of individual volcanic centers, spatial and temporal variations in these characteristics may be compared with theoretical predictions, e.g., spatial variations in tidal heating rate.
E6.	Has Ganymede experienced cryovolcanism, or does intense tectonism create smooth terrains; and what is the distribution and thickness of Callisto's dark component?	Sound and image regions of smooth/dark materials to determine the subsurface structure, including the nature of any layering and/or related tectonic structure.
E7.	Is Europa's sputter-produced atmosphere patchy, and how does it vary spatially and temporally?	Observe the external field and particle environment over the globe through time, while also observing variability of the atmospheric emissions.
E9.	Are Ganymede's and Callisto's atmospheres produced mainly by sputtering or sublimation?	Determine temperature and composition of surface ices to assess sublimation, local plasma environment to assess sputtering, and the atmospheric spatial distribution inferred from in situ data.
E13.	How do the sources and dynamics of the fields and plasma in the Jovian magnetosphere vary over time, especially as correlated with Io's activity?	Monitor the magnetic and plasma environment of Jupiter's magnetosphere spatially and temporally, while also monitoring Io's activity and plasma environment.
E17.	How does Jovian small-scale atmospheric convection contribute to development and maintenance of larger-scale storms?	Observe Jupiter's atmosphere at small scales while monitoring larger-scale patterns, both over time.

2.5 Science Implementation

2.5.1 Payload Considerations

The Galileo spacecraft, developed in the mid-1970s, made an outstanding survey of the Jovian system, including the Galilean satellites. However, data acquisition was greatly hampered by the failure of Galileo's high gain antenna to deploy, forcing reliance instead on data downlink through its low-gain antenna at only ~50 bits/s. Moreover, Galileo was not specifically equipped with the instrumentation necessary to characterize subsurface oceans. The former Europa Orbiter mission concept was developed in the late 1990s, when the focus was on basic aspects of Europa science (Appendix C). Since then, the Decadal Survey explicitly endorsed expansion of the science scope of a Europa mission (§2.2.2 and §2.7). Through the adoption of a Venus-Earth-Earth Gravity Assist trajectory, dry mass delivery capability for JEO has increased greatly relative to the Europa Orbiter, enabling a full suite of high priority scientific investigations to be addressed.

Developing the mission payload concept requires consideration of two approaches: (1) identifying payloads that are designed to test specific hypotheses, and (2) identifying payloads that have the potential for serendipitous discovery (i.e., pure exploration). Solar system exploration is replete with examples of the latter consideration. The JEO model payload addresses specific measurements to test known hypotheses, while providing a broad and highly capable instrument suite that allows the flexibility to respond to new discoveries.

Europa's very tenuous atmosphere (2 picobar) is a boon to orbital investigations of the surface and interior. Low orbital altitudes (~100 km) can be maintained, and atmospheric absorption and scattering are not issues, allowing for optimal spatial resolution of remote sensing instruments. A low altitude greatly increases the sensitivity of radar sounding and magnetometry. The absence of atmospheric drag improves orbit and pointing knowledge, enabling measurements of higher order and time-dependent gravity field components accurately and quickly. Sputter-production of the tenuous atmosphere is useful in bringing material from the surface to the spacecraft. The benefits of exploring bodies with very tenuous atmospheres are also applicable to flybys of the other Galilean satellites.

JEO's instruments have to be designed with Europa's harsh radiation environment in mind. The Galileo experience of making scientific measurements in the vicinity of Europa combined with an improved understanding of the effects of radiation on sensor performance were brought to bear to better understand the limitations and, in some cases, the opportunities. This has significantly influenced the design and detailed characteristics of JEO's model payload, discussed below. Risk mitigation relative to the radiation environment also greatly influences the data acquisition strategy (§4.5).

2.5.2 Model Payload and Science Management

2.5.2.1 Model Payload

The JEO model payload (**Table 2.5-1**) comprises 11 instruments including radio science. **Table 2.5-1** illustrates the trace from the measurement requirements and the generic instruments of the Traceability Matrix (**FO-1**) to the specific instruments adopted for the JEO model payload. This suite of instruments enables the development of the mission concept that addresses the identified science objectives within reasonable resources requirements and constraints. The actual payload for JEO would ultimately be the result of an Announcement of Opportunity (AO) selection process carried out by NASA, and might or might not include the instruments of the JEO model payload.

For nearly all instruments, the model payload instrument meets or exceeds the Traceability Matrix measurement envelope. In some cases (e.g., the UVS and the PPI), the required measurement envelope is larger than the measurement capability provided by the model payload instrument. The JJSDT took a conservative approach to instrument definition and selection and chose not to preclude the inclusion of instruments with broader capabilities that are not yet available in the public domain.

Foldout 3 (**FO-3**) describes the relationship between the model payload instruments and Traceability Matrix investigations. This table rates each instrument as primary or secondary to achieving each investigation. **FO-3** also describes the constraints placed on the mission architecture and orbit by science investigations (see §2.5-3).

Should descoping of some instruments or instrument capabilities become necessary, **Table 2.5-2** indicates the prioritized order in which science desopes might occur, and the resultant science lost. The order in which JEO capabilities are descoped was decided by the JJSDT based on prioritization of the scientific objectives that are met by those capabilities This leaves the "core" (floor) payload listed in **Table 2.5-3**.

The resultant JEO performance floor mission is similar to the 2007 Europa Explorer (EE) floor mission, where all science objectives are partially but satisfactory addressed. The JEO core payload has several differences from the 2007 EE floor payload. The specific differences are that the JEO core payload: 1) retains dual magnetometer capability; 2) retains robust plasma capability of the PPI (recognized as critical to the magnetometry measurements); 3) does not retain the energetic particle capability of the PPI; 4) does not retain a thermal instrument.

2.5.2.2 Science Management

A Project Scientist will be appointed who is responsible for the scientific integrity and overall scientific success of the project. The Project Scientist will represent science interests to the Project and reports to the JPL Director. The Project Scientist is a peer of the Project Manager in all matters impacting science and in science-engineering design trades and is collocated with the Project Manager as a member of the project staff.

The Project Scientist will have three major responsibilities in his/her project science management role: 1) is responsible for the scientific integrity and overall scientific success of the mission, 2) represents the Scientific Investigators of the mission to the Project and to NASA, and 3) is the scientific spokesperson for the Project.

During Pre-Phase A, the Project Scientist will define, with project management, and systems engineers, key elements of the operations concept and mission operations architecture for the mission. This includes optimization of the division of responsibility between a centralized Science Operations Center (SOC) and remote sites, roles and responsibilities of the science teams in the development and integration of flight and ground hardware and software (including models, simulations and planning tools), and test and operations planning and execution. After the instruments are selected through the AO process, the team structure, roles and responsibilities may be adjusted to incorporate the capabilities and experience of the selected team members.

Table 2.5-1. *Measurement Requirements Envelope and Model Payload Instruments.*

Generic Instrument	Measurement Requirement Envelope	Model Payload Instrument Characteristics	Model Payload Instrument
telecom system	**Doppler Velocity:** 0.1 mm/s over 60 s accuracy; **Multi-frequency** communication (e.g., Ka & X) is best, but X is sufficient; **USO**	**Ka-band Transponder** **Doppler Accuracy:** 0.01 mm/s **Integration Time:** 60 seconds for stated accuracy **Ultra Stable Oscillator** **Stability:** 2 x 10-13 **Timescales:** 1 to 100 seconds for stated stability	Radio Science (RS)
laser altimeter	**Vertical Accuracy:** better than 1 m at Europa	**Time-of-Flight Laser Rangefinder** **Transmitter:** 1.064 µm laser **Detector:** Avalanche Photodiode **Resolution:** better than 1 m vertical **Spatial:** 50 m laser spot size, 26 Hz pulse rate	Laser Altimeter (LA)
radar sounder	**Dual Frequency:** ~50 MHz with ~10 MHz bandwidth to sound as deep as 3 km with 10 m vertical resolution; ~5 MHz with ~1 MHz bandwidth to sound as deep as 30 km with 100 m vertical resolution	**Dual-Mode Radar Sounder** **Shallow Mode**: 50 MHz with 10 MHz bandwidth **Vertical Depth:** ~3 km **Vertical Resolution:** 10 m **Deep Mode**: 5 or 50 MHz with 1 MHz bandwidth **Vertical Depth:** ~30 km **Vertical Resolution:** 100 m	Ice Penetrating Radar (IPR)
Vis-IR imaging spectrometer	**Spectral Range:** 400 - 2500 nm with better than 5 nm spectral resolution **Spectral Range:** 2500 - >5000 nm with better than 10 nm spectral resolution **Spatial Resolution:** better than 50 m/pix at Europa **SNR:** >32 from 2600 to 5200nm	**Pushbroom Imaging Spectrometer** **Detector:** two HgCdTe arrays **Spectral Range**: 400 to > 5200 nm **Spectral Resolution:** 5 nm from 400 to 2600 nm **Spectral Resolution:** 10 nm from 2600 to 5200 nm **Spatial Resolution:** 25 m from 100 km orbit **FOV:** 9.2 deg cross-track **IFOV:** 0.25 mrad **Articulation:** Along-track scan mirrorscan mirror	Vis-IR Imaging Spectrometer (VIRIS)
UV imaging spectrometer	**Spectral Range:** 30-350 nm **Spectral Resolution**: better than or equal to 0.5 nm **Spatial Resolution**: 100 m/pix at Europa	**Grating Spectrometer + High-Speed Photometer** **Detector:** MCP + position sensitive anode **Format:** 1024 spectral x 64 spatial pixels **Spectral range:** 70 – 200 nm **Spectral Resolution:** 0.5 nm **Spatial Resolution:** 100 m from 100 km orbit **FOV: 3**.7 deg cross-track **IFOV:** 1 mrad **Articulation:** 1-D scan system for stellar occultations	Ultraviolet Spectrometer (UVS)
ion & neutral mass spectrometer	**Mass Range**: 1 - 300 Daltons **Mass Resolution**: M/ΔM ≥500 **Pressure Range**: 10e-6 to 10e-17 mbar **Energy Resolution:** 10%	**Reflectron Time-of-Flight Mass Spectrometer** **Mass Range:** 1 to > 300 Daltons **Mass Resolution:** > 500 **Pressure Range:** 10-6 to 10-7 mbar **Sensitivity:** 10-4 A/torr **FOV:** 10 x 40 deg	Ion and Neutral Mass Spectrometer (INMS)
thermal imager	**Spatial Resolution:** 250 m/pix, **Temperature Resolution**: 2 K **Radiometric Accuracy**: 10%	**Temperature Sensing Thermopile Array** **Detector:** Thermopile array with filters **Detector Configuration:** 21 pixels cross-track, 6 bands **Spectral Bands:** 8-20µ, 20-100µ, 21µ, 28µ, 40µ, 17µ **Temperature Range:** >160K to 80K **Spatial Resolution:** 250 m **Resolution:** 2K **IFOV: 2**.5 mrad	Thermal Instrument (TI)

Generic Instrument	Measurement Requirement Envelope	Model Payload Instrument Characteristics	Model Payload Instrument
narrow-angle camera	**Color Bands:** at least 3, plus panchromatic **Spatial Resolution**: 1 m/pix from Europa orbit	**Pushbroom and Framing Imager** Panchromatic Pushbroom Imager + Color Framing Imager **Detector**: CMOS array or CCD array + line array **Detector Size**: 2048 pixels wide **Color Bands**: 9 plus panchromatic **Spatial Resolution**: 1 m from 100 km orbit **FOV**: 1.2° **IFOV**: 0.01 mrad IFOV **Mechanism**: Filter wheel	Narrow-Angle Camera (NAC)
wide-angle camera and medium-angle camera	**WAC:** **Color Bands**: at least 3, plus panchromatic **Stereo Spatial Resolution**: 100 m/pix at Europa **Vertical Resolution**: ~20 m **MAC:** **Spatial Resolution:** 10 m/pix at Europa	**WAC:** Color Pushbroom Imager **FOV: 58°** IFOV: 1 mrad **Spatial Resolution:** 100 m from 100 km orbit **Detector:** CMOS or CCD line arrays (4) **Detector size**: 1024 pixel line arrays (4) **Color Bands:** violet, green, near-IR, and panchromatic **MAC - Panchromatic Pushbroom Imager** **Detector:** CMOS or CCD line array **Detector Size:** 2048 pixels **Spatial Resolution:** 10 m from 100 km orbit **FOV:** 11.7 deg line scan **IFOV:** 0.1 mrad	Camera Package (WAC + MAC)
magnetometer	**Sensitivity**: 0.1 nT **Maximum Sampling Rate**: 32 vectors/sec **Knowledge of spacecraft orientation**: to 0.1°	**Dual 3-axis fluxgate magnetometer** **Boom:** 10 m **Sensor Location:** 5 m and 10 m from s/c **Dynamic Range:** 3000 nT **Sensitivity:** 0.1 nT **Sampling Resolution**: 0.01 nT **Maximum sampling rate:** 32 Hz	Magnetometer (MAG)
particle and plasma instrument	**Energy Ranges**: 1 eV to 10 MeV **Angular Resolution**: 15° **ΔE/E**: 0.1 **Spatial Coverage**: 4p coverage desirable	**Plasma:** Top Hat Analyzer **Energy Range:** 10 eV to 30 KeV electrons **Energy Range:** 10 eV to 30 KeV ions with composition **FOV:** 360° x 90° **Particles:** Puck Analyzer **Energy Range:** 30 KeV to 1 MeV electrons **Energy Range:** 30 KeV to 10s of MeV ions **FOV:** 120° x 20° **High Energy Electrons: Omnidirectional SSDs** **Energy Ranges**: >2 MeV, >4 MeV, >8 MeV, >16 MeV	Particle and Plasma Instrument (PPI)

Much has been learned on past missions but thorough, well-disciplined assessments are needed to understand how operations are best performed 15 years from now. Analyses of lessons learned from current missions similar to JEO have been performed (Appendix K) and recommendations from those analyses have been incorporated into the JEO mission concept. Tour operations are influenced by experience from the Cassini and MESSENGER missions, and Europa orbital operations are influenced by the MRO mission. A general plan for development and operations has been described in §4 and will be refined throughout Pre-Phase A and Phase A. Because of the long mission development and flight time, all operations system concepts and designs will be flexible and ready to incorporate advances in tools, capabilities, communications, and organization methods.

It is anticipated that much of the advance science planning and the majority of data analysis will be performed at facilities provided by the science investigations. Operations systems will provide rapid coordination and delivery of planning and sequencing products and mission data among the science and mission operations facilities. Plans for data delivery, analysis and archiving are typical and standard, and they are detailed in §4.6 and Appendix G.

Table 2.5-2. *Science Descope Order*

Descope Order	Descope Item	Science Impact
1	Ka-band Up (Ka transponder req.)	Poorer gravity data for high-order gravity terms.
2	Color on the NAC	Significant losses in Jupiter and Io science
3	Energetic particle capability	Significant loss of information regarding surface weathering of Europa and other moons by particles, including source of sputtering and radiolysis; total loss of information about penetrating radiation, radiation belts of Jupiter and their variations; degradation of magnetospheric science including beams and auroral processes.
4	USO	Reduced opportunities for ionospheric and upper atmosphere studies
5	INMS	No *in situ* characterization of Europa's atmospheric species, including any sputtered organics; loss of *in situ* sensing of Io's atmosphere and torus
6	OpNav Functionality	Reduced delivery accuracy to the satellite aimpoints results in a minimum flyby altitude of 500 km imposed for safety
7	Reduce Europa Science Phase by 5.5 month	Loss of Campaign 4
8	6 Interdisciplinary scientists	
9	Thermal Instrument	Loss of thermal emission maps of Europa's surface, which are key in investigating current activity.
10	UVS	Loss of sensitive Europa atmospheric measurement and plume searches, in addition to unique Ganymede/Jupiter auroral and Io torus investigations.
11	ATLAS V 551 to 541	
12	Tour Phase reduced by 10mo	Loss of high latitude Ganymede and Callisto flybys results in significant degradation of interior and magnetospheric studies.
13	Hybrid SSR	Loss of data storage and return capabilities during Io and System Campaigns
14	Descope IR Capability (Reduce to 0.9 - 5 µm, with decreased spatial and spectral resolution)	Decreased spectral sensitivity hinders identification of Europa surface impurities, especially organics, and poorer spatial resolution mapping reduces correlations with geological processes and decreases the chance of identifying unique compositional endmembers.
15	NAC	One order of magnitude degradation in imaging resolution means loss of detailed surface charaxteriztion, including recent Europan activity and relative ages, and significant degradation of Jupiter system imaging.

Table 2.5-3. *JEO "Core" (Floor) Payload*

Core Payload	Capability
Radio Science	**X-band up and Down, Ka- band Down**
Laser Altimeter	**Single spot**
Near-IR Spectrometer	**0.9 - 5 µm, with limited spatial and spectral resolution**
Ice Penetrating Radar	**2 band, 5Mhz and 50 Mhz**
Wide and Medium Angle Camera	**Wide: Color, Medium: panchromatic**
Dual Magnetometer	**Dual 3-axis fluxgate sensors, 10 m Boom**

2.5.3 Mission Constraints

Measurements identified for JEO objectives and investigations place constraints on JEO **(FO-3)**. Optimizing among the envelope of constraints in **FO-3** has shaped the Europa Campaign. The nominal JEO mission would be 9 months at Europa. As a risk mitigation strategy, and to ensure sufficient time to follow up on discoveries, the primary science hypotheses would be addressed in the first 100 days in Europa orbit (≈ 28 eurosols ≈ 3 months). The desired orbit is near-circular, with an orbital inclination of 80–85° (or the retrograde equivalent of ~95–100°). The optical remote sensing instruments are nadir-pointed and mutually boresighted. The initial orbital altitude is 200 km, which is reduced to 100 km altitude after several eurosols to meet the requirements of gravity, altimetry, magnetometry, and radar. The orbit is not quite sun-synchronous but precesses slowly, such that the orbit does not exactly repeat the same ground track but allows instrument fields of view to overlap with previous tracks. Thus, the orbit is near-repeating after several eurosols, within about 1° of longitude at the equator. The solar incidence angle is nominally 45° (2:30 p.m. orbit) on average, as the best compromise to the requirements of imaging and spectroscopic optical remote sensing measurements.

FOLDOUT 3
INSTRUMENTATION TRACEABILITY

Objective			Science Investigation	RS	LA	IPR	VIRIS	UVS	INMS	WAC +MAC	NAC	TI	MAG	PPI	Architecture and Orbit Constraints	Additional Mission Constraints
A. OCEAN: Characterize the extent of the ocean and its relationship to the deeper interior.		A1.	Determine the amplitude and phase of the gravitational tides.	P	S										Gravity and Altimetry: Orbiter required, low altitude (~100-300 km), orbital inclination of ~40–85° (or retrograde equivalent) for broad coverage and cross-overs. Ground-tracks should not exactly repeat (while near-repeat is acceptable), so that different regions are measured. Requires a mission duration of at least several eurosols to sample the time-variability of Europa's tidal cycle. Magnetometry, Particles and Plasma: Near-continuous measurements near Europa, globally distributed, at altitudes ≤500 km, for a duration of at least 1–3 months.	Gravity and Altimetry: Knowledge of the spacecraft's orbital position to high accuracy and precision (~meters radially) via two-way Doppler. Gravity: Long undisturbed data arcs are required (>12 hr periods without spacecraft thrusting), and momentum wheels to maintain spacecraft stability Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month.
		A2.	Characterize the magnetic environment (including plasma), to determine the induction response from the ocean, over multiple frequencies.										P	S		
		A3.	Characterize surface motion over the tidal cycle.	S	P											
		A4.	Determine the satellite's dynamical rotation state.	P	S											
		A5.	Investigate the core, rocky mantle, and rock-ocean interface.	P	P								S	S		
B. ICE: Characterize the ice shell and any subsurface water, including heterogeneity, and the nature of surface-ice-ocean exchange.		B1.	Characterize the distribution of any shallow subsurface water.		S	P				S					Radar Sounding: Low orbit (≤ 200 km) considering likely instrument power constraints. Near-repeat groundtracks are required to permit targeting of full-resolution observations of previous survey-mode locations. Close spacing of profiles requires a mission duration of months, and near-global coverage implies orbital inclination ≥80°.	Radar Sounding and Altimetry: Data sets need to be co-aligned, and highly desirable to be time-referenced to 10–30 ms accuracy. Radar Sounding: Raw full-resolution targeted radar data requires ≥900 Mb solid-state recorder. Early flyby of Europa for radar signal processing assessment.
		B2.	Search for an ice-ocean interface.		S	P				S						
		B3.	Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	S	P	P	P	S		P	S	P				
		B4.	Characterize regional and global heat flow variations.			P						S				
C. CHEMISTRY: Determine global surface compositions and chemistry, especially as related to habitability.		C1.	Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability and potential biosignatures.				P	S	P						Infrared Spectroscopy: Solar phase angles of ≤45°, with orbital inclination ≥80° for near-global coverage. Near-circular orbit is desirable. Close spacing of profile-mode data implies a mission duration on the order of months. A near-repeat orbit is desired, to permit targeted observations to overlap previous profiling-mode observations. INMS: As low an orbit as feasible is desired, for direct detection of sputtered particles.	Optical remote sensing: Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable.
		C2.	Relate compositions to geological processes, especially material exchange with the interior.		S	P	P	P		P	S	S				
		C3.	Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.				P	P	P		S	S		S		
		C4.	Characterize the nature of exogenic materials.				P	S	P	S				P		
D. GEOLOGY: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.		D1.	Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.		P	P	S	S		P	S	S			Optical Remote Sensing: Near-repeating orbits required to permit regional-scale coverage overlap, follow-up targeting, and stereo; close spacing of profile data implies a mission duration on the order of months; ≥80° orbital inclination to provide near-global coverage. Imaging: Solar incidence angles of 45–60° are best for morphological imaging, while a solar phase angle ≤45° is best for visible color imaging. Near sun-synchronous and near-circular orbit is highly desired to permit global coverage to be as uniform as practical. Beginning at a higher orbital altitude and reducing to a lower altitude will allow rapid initial areal coverage, followed by improved resolution coverage at low altitude. Thermal Mapping: Day-night repeat coverage required: afternoon orbit is desireable.	Optical Remote Sensing: Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable, and also highly desirable to be time-referenced to 10–30 ms accuracy. Radar Sounding and Altimetry: Data sets need to be co-aligned, and highly desirable to be time-referenced to 10–30 ms accuracy. Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month. Ultraviolet Spectroscopy: Atmospheric emissions observations and stellar occultations, require a view to the satellite's limb.
		D2.	Determine sites of most recent geological activity, and evaluate future landing sites.				S	P		P	S	P		S		
		D3.	Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris.				S				P	P	S	S		
E. JUPITER SYSTEM: Understand Europa in the context of the Jupiter system.	**Satellite Surfaces and Interiors**	E1.	Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io.	S	S	P						P			Optical Remote Sensing: Up to three flybys of Io with one at low altitude over an active volcanic region; at least five flybys of Ganymede (altitudes of < 1000 km with at least four with altitude < 200 km); at least five Callisto flybys including 1 polar; all with altitudes <1000 km); closest approach distributed globally in latitude and longitude. Imaging: Solar incidence angles of 45–60° are best for morphological imaging, while a solar phase angle ≤45° is best for visible color imaging.	Optical Remote Sensing: Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable.
		E2.	Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust).				P	S			P	S				
		E3.	Investigate the presence and location of water within Ganymede and Callisto.	P	S	S							P			
		E4.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Ganymede.				P	P			S	P				
		E5.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Callisto.				P	S			S	P				
		E6.	Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.	P	P	S				P	S	S	S			
	Satellite Atmospheres	E7.	Characterize the composition, variability and dynamics of Europa's atmosphere and ionosphere.	S			P	P	S					S	Radio Science: ≥10 radio occultation observations of the Galilean Satellites. INMS: Very close Io fly-bys (≤75 km altitude) strongly desired.	Radio Subsystem: Inclusion of an ultra-stable oscillator (USO) is desirable INMS: Requires observing in the ram direction.
		E8.	Understand the sources and sinks of Io's crustal volatiles and atmosphere.				P	P	S		S	P				
		E9.	Determine the sources and sinks of the Ganymede and Callisto atmospheres.	S			P	P						P		
		E10.	Measure the dust, plasma and neutral ejecta from Europa.						P					P		
	Plasma and Magnetospheres	E11.	Characterize the composition of and transport in Io's plasma torus.					P					S	S	Magnetometry, Particles and Plasma, INMS: Near-continuous measurements throughout the tour; dedicated campaign to observe the Io torus; Broad distribution of Ganymede-magnetic latitude sampled on both leading and trailing hemispheres; near-continuous measurements near Europa during flybys, globally distributed, at altitudes ≤500 km.	Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month. Particles and plasma, and INMS: Require observing in the ram direction.
		E12.	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.					S	P					P		
		E13.	Study the interactions between Jupiter's magnetosphere and Io, Ganymede and Callisto (including characterizing Ganymede's magnetic field).				P	P			S		P	P		
		E14	Understand the structure, composition and stress balance of Jupiter's magnetosphere.										P	S		
		E15.	Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.										P	S		
	Jupiter Atmosphere	E16.	Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa.				P	S		S		S			Optical Remote Sensing: Coordinated feature-track observations using the entire suite of remote sensing instruments; sufficient time and resources for dedicated campaigns covering at least 2 full Jupiter rotations; solar, stellar and radio occultations covering as wide a range of latitudes as possible.	Optical Remote Sensing: Boresight co-alignment of all imaging instruments is highly desirable. Radio Subsystem: Inclusion of an ultra-stable oscillator (USO).
		E17.	Characterize Jovian atmospheric dynamics and structure.	S			P	S		P		P				
	Rings	E18.	Characterize the properties of the small moons, ring source bodies and dust.				S			P	P				Optical Remote Sensing: At least one shadow passage from long range; ≥3° inclination off of the ring plane.	Optical Remote Sensing: Boresight co-alignment of all imaging instruments is highly desirable.
		E19.	Identify the dynamical processes that define the origin and dynamics of ring dust.							P	P					

P Primary S Secondary

Significant Jupiter system science is enabled by the Jovian tour, which lasts approximately two and a half years prior to Europa Orbit Insertion. Requirements and desires on the tour to accomplish Jupiter system science are also listed in **FO-4**. The model payload will provide the capability for meeting Jupiter system science objectives, tracking Jupiter and the other Galilean satellites to accomplish observations during the Jovian tour phase (§4.3, §4.6, and Appendix G). However, as the lowest priority objective, Jupiter system science generally does not impose strong constraints on the spacecraft itself, with the exception of the addition of an Ultra-Stable Oscillator (USO) to derive the properties of the satellites' atmospheres and ionospheres from radio occultations.

2.5.4 Data Acquisition Strategy

The data acquisition strategies for the JEO mission are organized by phase and campaign. The Jovian Tour phase is divided into the Io Campaign and the System Campaign. The Europa Science phase is organized into four campaigns: Europa Campaign 1 – Global Framework, Europa Campaign 2 – Regional Processes, Europa Campaign 3 – Targeted Processes, and Europa Campaign 4 – Focused Science.

Table 2.5-4 provides a brief description of the science-based campaign strategy and its key aspects. A complete description of the mission profile is provided in §4.3, while §4.6 fully describes the operations plan and data acquisition strategy.

2.5.4.1 Jovian Tour Data Acquisition

Jupiter system science will be the principal focus of the Jovian Tour phase of the JEO mission. The Jupiter system science investigations fall into five categories: satellite surfaces and interiors, satellite atmospheres, plasma and magnetosphere, rings, and Jupiter atmosphere and divide into two distinct science campaigns: the Io Campaign and the System Campaign. Monitoring and measurement of the system plasma environment and magnetosphere, Io's volcanism and torus, and the Jupiter atmosphere will be accomplished through routine periodic measurements each week. Daily DSN coverage will provide more than 1 Gbit per day of science data and the articulated HGA antenna will allow a large variety of orbiter observing attitudes even during downlink activities.

Many of the measurements that support satellite-specific objectives will be accomplished during the satellite flyby encounters. Flyby geometries are highly varied for latitude and lighting but are opportunistic as the trajectory is optimized for meeting the science requirements along with duration, ΔV,and radiation dose. Using the requirements in **FO-3** and working with the science team, tour optimization studies will look for science optimum mixes of flyby conditions that answer the highest priority objectives. A description of the current nominal tour flyby conditions is included in §4.3.

The orbiter capabilities are optimized for Europa operations, and this constrains, to some degree, the observing capabilities during satellite encounters. The solid state recorder (SSR has been augmented with and additional 16 Gbit of memory for use during the Jovian Tour phase of the mission. This memory is less radiation hardened, and is not required to survive past orbit insertion at Europa. Using a combination of the SSR and real time data downlink with the Ka-band radio system, the orbiter will be able to collect and return about 16 Gbit of science data during the 1–2 hours around closest approach for each satellite encounter. This will enable constant data collection from the magnetometer and the plasma instrument along with an IPR full resolution profile (>30 s), and many observations with the TI, UVS, WAC, MAC, NAC, and VIRIS. The INMS will operate during low-altitude satellite fly-bys of several hundred kilometers of less, notably at Io. The gimbaled high gain antenna will enable imaging of a satellite with limited slews for mosaics or motion compensation while Earth pointing for real-time downlink. An example timeline of observing activities for an early Io encounter is shown in **Figure 2.5-2**. Assuming the nominal satellite tour of §4.3, **Table 2.5-5** summarizes the imaging resolution improvement expected for each Galilean satellite over the existing resolution coverage from Galileo and Voyager, along with nominal profile lengths that are expected to be obtained (see also §4).

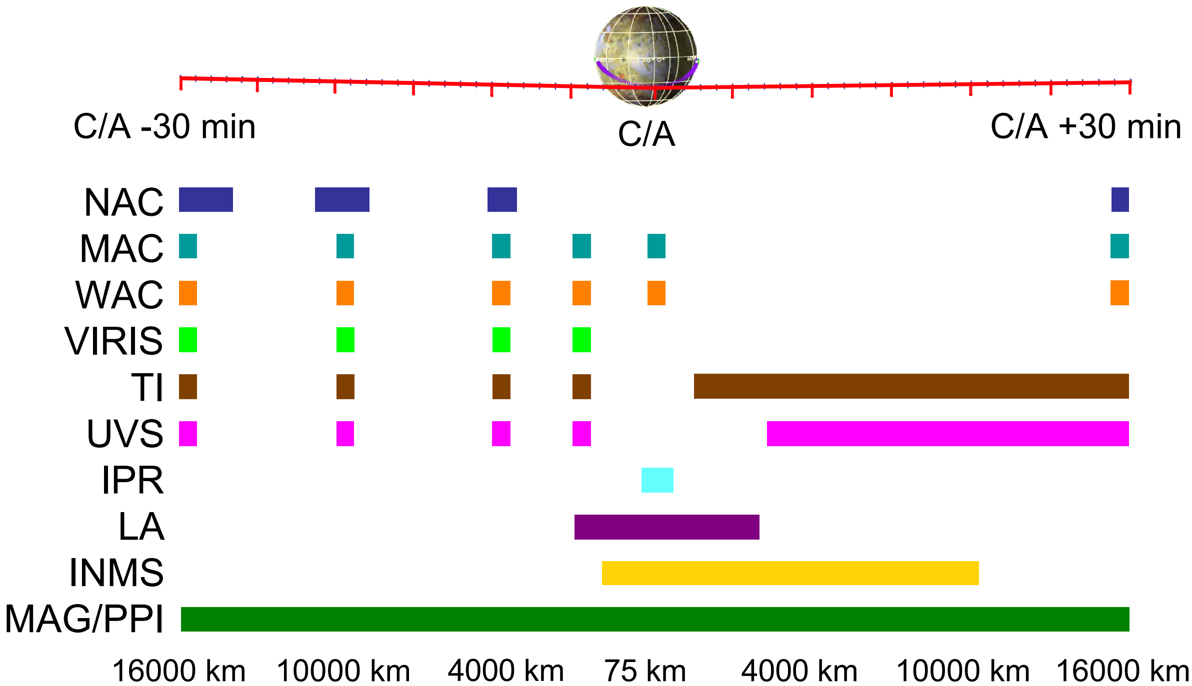


Figure 2.5-2. *Example flyby observation timing for a 10 km/s, 75 km closest approach encounter with Io early in the Io Campaign of the Jovian Tour science phase.*

In addition to the encounter observations, periodic distant monitoring observations of Io, its plasma torus, Jupiter, and its ring system are planned. **Figure 2.5-3** shows an overview of the opportunistic science observations (numerous non-targeted and distant viewing observations of major and minor satellites, dust, rings, and auroras) for the Jovian Tour phase. Additional details of the geometric flybys, motion compensation, monitoring opportunities, and data return can be found in §4.6 and **Table G.4-5** in Appendix G.

2.5.4.2 Europa Orbital Data Acquisition

The data acquisition strategy during the Europa Science phase of the mission is designed to obtain the highest-priority observations first and quickly. Following a brief check-out period, data taking proceeds through 4 campaigns, beginning with Global Framework campaign, then focusing on Regional Processes, next concentrating on Targeted Processes to address local-scale science questions and follow-up on discoveries made during the earlier campaigns, and finishing with the Focused Science campaign.

Throughout the Europa Campaigns, several instruments collect data continuously, both on the day and night sides of Europa (**Table 2.5-4**). Specifically, these are: Radio science-gravity (RS, via the telecom subsystem, continuous for Europa Campaigns 1–3 only), Thermal Instrument (TI), Magnetometer (MAG), Laser Altimeter (LA), and Particle and Plasma Instrument (PPI). The INMS operates for a 50% duty cycle because of power constraints. The UVS is operated for a few minutes every other orbit to collect stellar occultation observations of selected UV source stars.

For other remote sensing instruments, a 2-orbit repeating scenario is planned, which permits power and data rate equalization. Even orbits emphasize optical remote sensing by the Wide-Angle Camera (WAC), Medium-Angle Camera (MAC), and Vis-IR Imaging Spectrometer (VIRIS), while odd orbits emphasize data collection by the Ice-Penetrating Radar (IPR). The IPR and VIRIS typically operate in low-data-rate profiling modes, permitting a high degree of areal sampling across the globe, given the limited downlink rate. These instruments also operate in higher data-rate targeted modes, obtaining higher resolution data of high-priority features.

Targeted observations are implemented by orbital timing, when passing over a feature of interest with the nadir-pointed remote sensing

Table 2.5-5. *JEO Resolution Improvement Over Galileo and Voyager, and Profiling Coverage*

Galilean satellite	VGR+GLL Imaging ≤1 km	JEO Imaging ≤1 km	VGR+GLL Imaging ≤200m	JEO Imaging ≤200 m	VGR+GLL Imaging ≤50 m	JEO Imaging ≤50 m	VGR+GLL Imaging ≤10 m	JEO Imaging ≤10 m	JEO IPR Length (km)	JEO LA Length (km)
Io	~25%	**30%**	~3%	**20%**	~1%	**5%**	0%	**tbd**	**1000**	**7400**
Europa	13%	**60%**	0.4%	**60%**	~0.4%	**15%**	~0%	**0.01%**	**6600**	**19000**
Ganymede	25%	**50%**	0.3%	**50%**	~0.3%	**10%**	0%	**0.02%**	**17000**	**28000**
Callisto	30%	**85%**	0.3%	**75%**	~0.3%	**5%**	~0%	**0.01%**	**15000**	**30000**

instruments. These observations are coordinated (**Figure 2.5-4**) among the several optical remote sensing instruments (MAC, NAC, and VIRIS), along with the profiling IPR mode, and the continuously operating TI and LA. Targets of ~450 Mb each comprised of IPR full resolution profiles (30 seconds, 900 Mb, with MAC context) will also be collected. Over 1900 targeted observations, including both types, are obtained during the Europa Science phase. Each remote sensing instrument has additional non-coordinated targeted opportunities during the Europa orbital phase of the mission.

A brief description of the science-based campaign strategy is provided herein, with the key aspects summarized in **Table 2.5-4**. Section 4.3 provides a complete description of the mission profile, while §4.6 fully describes the operations plan and data acquisition strategy.

Europa Campaign 1, Global Framework: During the first campaign of the Europa Science phase, the flight system orbits at 200 km altitude. While the whole Global Framework Campaign lasts 8 eurosols (≈ 28 days), the mission's highest priority data is acquired during the 4 eurosols (≈ 2 weeks) of Europa Campaign 1A, then data acquisition continues through the 4 additional eurosols of Europa Campaign 1B. During Europa Campaign 1A, gravity, altimetry, and magnetometry provide a first-order characterization of the ocean and ice shell. The WAC obtains a global color map, and the IPR searches for shallow water. The VIRIS operates primarily in profiling mode, with additional targeted observations along with the NAC and MAC. During Campaign 1B, the WAC acquires another global map to be processed into an early global stereo map. The IPR performs a deep ocean search, and other remote sensing instruments continue to acquire profiling and targeted data. Targets for Europa Campaign 1 are chosen using existing Galileo data. Through this and subsequent campaigns, the Laser Altimeter, thermal, plasma, and magnetic field instruments operate continuously.

Europa Campaign 2, Regional Processes: The science emphasis of Europa Campaign 2 is on regional scale processes. Characterization of the gravity field during Europa Campaign 1 allows a relatively stable orbit to be selected for Europa Campaign 2, for which the flight system moves to a 100 km altitude orbit for 12 eurosols (≈43 days). Gravity, altimetry, and magnetometry improve their characterization of the ocean and ice shell. Europa Campaign 2A again emphasizes production of a global color map by the WAC, and a shallow water search by the IPR, and Europa Campaign 2B emphasizes stereo mapping by the WAC and a deep ocean search by the IPR. At lower altitude, these are now at two times better spatial resolution than obtained during Europa Campaign 1. Stereo processing is an additive process where improved vertical resolution is obtained by both improved horizontal resolution and number of observations. Optical remote sensing observations continue in profile mode to obtain a denser grid, now at higher spatial resolution. The expanded 12 eurosol (≈ 43 days) length of this campaign allows for the necessary areal coverage from this altitude relative to Europa Campaign 1, and the number of targeted observations increases. The most interesting findings of Europa Campaign 1 will be followed up by targeted observations in Europa Campaign 2.

Europa Campaign 3, Targeted Processes: The third campaign emphasizes coordinated targeted observations and high data-rate radar observations, homing in on specific features at a local scale. Observations during this campaign bring the total number of coordinated,

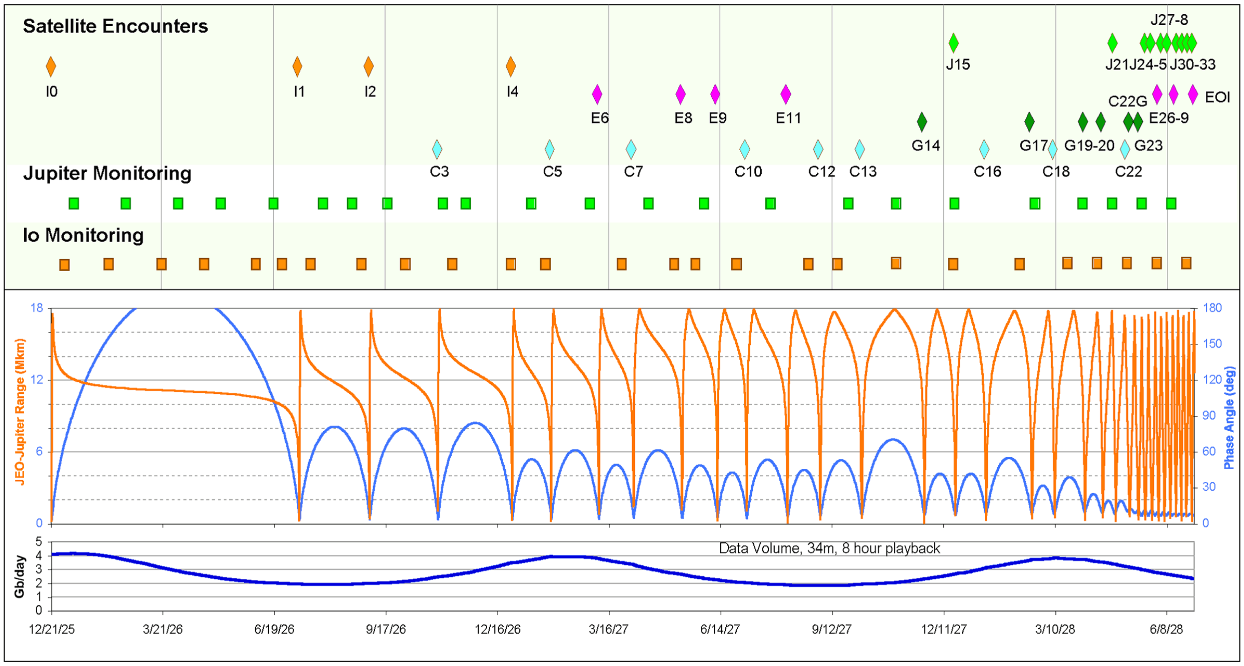


Figure 2.5-3. *Example overview of the observation opportunities for the Tour Phase. The tour range and solar phase angle, daily data volumes, and observing opportunities are shown. (This version is from trajectory T08-007. T08-008, the current trajectory, is similar to this.)*

multi-instrument observations to nearly 700, each of the type illustrated in **Figure 2.5-4**. Profiling observations achieve a grid spacing of < 25 km for the optical remote sensing observations, and < 50 km for each of the shallow water search and deep ocean search modes of the IPR. The Project Science Group (PSG), described in §2.2, will maintain a prioritized list of coordinated targets to be acquired by the remote sensing instruments. Targets can be added and priorities modified at any time. Targets will be selected on a weekly basis by the ground system based on priority and opportunity, depending upon the overflight geometry and the available data volume (see §4.6).

Europa Campaign 4, Focused Science: The emphasis of the fourth campaign is to focus in on science discoveries achieved earlier in the mission. Thus, its principal priority is to obtain targeted observations that probe these new discoveries. The specific science priorities and orbit characteristics are open to discussion, but a candidate list of science strategies has been developed by the SDT:

- Establish a finer topographic grid using remote sensing profiling observations.
- Infill profiling grids on IPR shallow subsurface observations, especially in discovery areas.
- Obtain higher-order gravity results (potentially including mantle topography).
- Measure secular changes in rotational parameters with gravity and altimetry.
- Address the properties of the core with magnetometry.
- Achieve narrow-angle camera stereo observations, using off-nadir flight system pointing.
- Investigate the time-variability of the charged particle environment.
- Improve coverage and characterization of candidate future landing sites with the remote sensing instruments.
- Dip to low altitude for improved gravity, INMS, optical remote sensing, and radar observations.
- Monitor activity on Io and Jupiter with the optical remote sensing instruments.
- Attempt to use Jupiter radio emission as a source to sound the ocean using the IPR.

The Focused Science Campaign will be implemented similarly to the Targeted Processes Campaign, with the PSG maintaining a prioritized list of coordinated targets to be acquired. The ~46 eurosol (~ 6 months) duration of Campaign 4 brings the total length of the Europa orbital phase to a milestone of ~76 eurosols, the total number of coordinated targeted remote sensing observations (**Figure 2.5-4**) to >1700, and the total number of targeted IPR observations to >200. This mission duration will permit extremely robust gravity, fields and particles, and remote sensing to be accomplished at Europa, ensuring that the science objectives and goal are fully achieved.

2.5.4.3 Paving the Way for a Future Landed Mission

To prepare for a future landed mission on Europa, several measurements from orbit are of critical importance. For astrobiology, identification of regions both rich in surface chemistry (e.g., C-H, C-C, and C-N bonds) and young in surface age are likely to yield the most information about the potential habitability of the subsurface. Such regions will be key science targets for a future lander.

From an engineering and technical standpoint, a better understanding must be gained of the meter-scale topography and surface heterogeneity of Europa. Furthermore, the depth and porosity of the surface regolith should be understood in order to ensure that the safety of a future lander. The combination of these measurements will drive the future design of entry, descent, and landing scenarios, and help determine sampling and communication protocols.

The JEO instruments that can best serve the science preparations for a landed mission are the VIRIS, IPR, and high-resolution imagery. Thermal imagery would also be of great utility for identification of sites of recent activity. For the engineering and technical constraints, the most useful dataset will be images provided by a high-resolution, narrow-angle camera. Experience with landed spacecraft on the surface of Mars has shown that such imagery is crucial to landing site selection and ultimately mission success. Second to imagery, data from the Laser Altimeter provides much need topographic information. The combination of imagery and spectroscopy also yields much needed information about regolith composition and depth. Imagery provides an understanding of surface deposits, while spectroscopy provides complementary compositional information. The above-mentioned instruments and observation types would provide a solid foundation for a future landed mission to Europa.

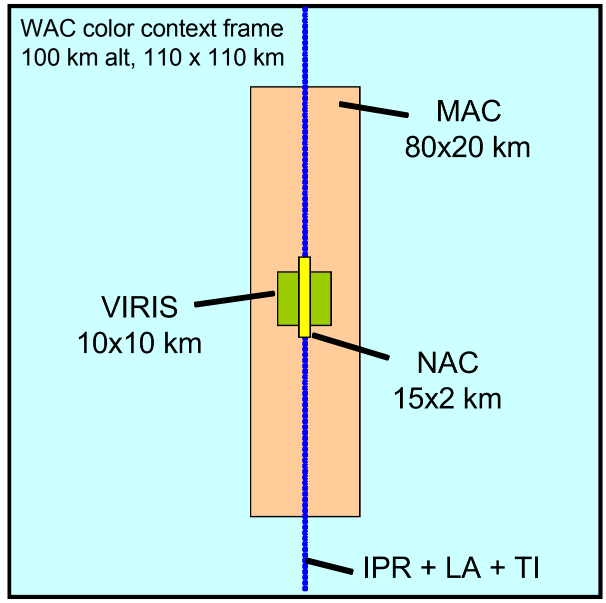


Figure 2.5-4. *Coordinated Targeted Remote Sensing Observations, with scales based on a 100 km altitude. Targeted observations are set within WAC color context (100 m/pixel panchromatic, plus 3-colors at 200 m/pixel). Coordinated targeted observations consist of: MAC monochromatic imaging (orange, 10 m/pixel), VIRIS imaging (green, 25 m/pixel, 700 wavelengths), and a low-data rate IPR profile (blue), and a TI profile (blue, 250 m/pixel). The laser altimeter operates continuously, as do the fields and particles instruments (MAG and PPI). Nearly 700 such targeted observations are obtained through Europa Campaign 3, and over 1700 through Europa Campaign 4.*

2.5.5 Science Value

Science value is necessarily subjective, and impossible to accurately quantify. Nonetheless, the JJSDT has worked to estimate science value rating for each measurement in the JEO Traceability Matrix (**FO-1**). The science value ratings are shown in the colored columns at the right of the Traceability Matrix. Rating criteria are:

5 Definitely addresses full science investigation.
4 May address full science investigation.
3 Definitely addresses partial science investigation.
2 May address partial investigation.
1 Touches on science investigation.
0 Does not address science investigation.

For measurements made principally during the orbital Europa Campaign, science value ratings are included for Campaigns 1A, 1B, 2A, 2B, and 3, demonstrating how the cumulative science value increases rapidly through the first 100 days in Europa orbit. As a risk mitigation strategy, higher priority measurements within each investigation are accomplished first, so these tend to receive a higher science value rating sooner than lower priority measurements.

Most measurements for investigations pertinent to Objective E (Jupiter System science) are principally obtained during the Io and System Campaigns, which occur during the Jovian tour, i.e., prior to EOI. The associated science value ratings are provided in the single "Jupiter System" column of the Traceability Matrix (**FO-1**).

In constructing the Traceability Matrix (**FO-1**), the JJSDT has identified measurements which the group believes would fully address the objectives and investigations. The approach has been vetted with the science community and is intentionally very inclusive. The model payload presented uses only publicly available information and was selected to address the highest priority measurements, without overly stressing the resources (cost, mass, power, and risk). By taking this approach, the JJSDT acknowledges that not all measurements are fully addressed by the model payload—in fact, a few measurements are not at all addressed. This conservative strategy was taken intentionally, for several reasons: 1) it allows those with innovative or proprietary ideas to propose more capable instruments; 2) it balances the development risk and science value given publicly available information; 3) it demonstrates that the targets and mission are scientifically rich, leaving room for innovative concepts; 4) it highlights how JEO also provides direct benefit to the complementary and synergistic JGO science objectives; and 5) it provides NASA Headquarters with information to best evaluate the cost vs. risk posture for JEO once the instruments are actually proposed via the Announcement of Opportunity process.

2.6 Complementary and Synergistic Science between JEO and JGO

Comparative planetology is key to the deep-rooted understanding of fundamental processes in the Solar System. To understand the processes that control the habitability of icy worlds, EJSM will conduct in-depth exploration of both Europa and Ganymede, the two active ocean-bearing worlds of the Jovian system. EJSM will also address fundamental processes that shape the Jovian system as a whole.

The JEO and JGO elements of EJSM will perform investigations that are both complementary and synergistic. Complementary science implies that the two mission elements make measurements, at either similar or different times, with each contributing to the greater picture of the whole, such that "1 + 1 = 2." For example, two spacecraft may make independent spectroscopic observations of the northern and southern hemispheres of a satellite, to build up a more complete scientific picture of the whole. Synergistic science, in contrast, implies that measurements are made near-simultaneously, with the sum of the measurements being greater than the parts, such that "1 + 1 = 3." For example, two spacecraft might make simultaneous observations of an eruptive plume from different vantage points near-simultaneously, e.g., from the inside making *in situ,* measurements and from the outside with remote sensing instruments, conveying a greater degree of information than had the observations been made at different times.

This section first discusses the science goals and mission plan for JGO, and then addresses synergistic and complementary observations between JEO and JGO.

2.6.1 ESA Jupiter Ganymede Orbiter (JGO) Science Goals, Objectives, and implementation

2.6.1.1 Science Background of JGO within the EJSM concept

The Galilean satellites are extremely diverse with respect to geology, internal structure, evolution and degree of their past and present activity. In order to place Europa in the right context, as well as to fully understand the Galilean satellites as a system, the two ocean-bearing bodies, Europa and Ganymede, as well as the giant planet itself will be investigated in detail by the Europa-Jupiter System Mission (EJSM).

A key element of the scientific strategy is that the satellite system must be considered as a strongly coupled system rather than an arbitrary collection of objects (**Figure 2.6-1**). Emphasis must be placed on the two key coupling processes within that system: (1) gravitational coupling and tidal interaction, which are responsible for internal heating of the satellites and for the continuous exchange of momentum and energy between Jupiter and the Io/Europa/Ganymede triad locked in the Laplace resonance, and (2) electrodynamical coupling, which is responsible for the plasma feeding and fast rotation of the magnetosphere of Jupiter, and for the formation of its unique magnetodisk and radiation belts. In both cases, Jupiter itself plays a key role in the coupling and will therefore be studied as the central element of the system.

Whereas JEO will focus on the inner part of the Galilean Satellite system—Io and mainly Europa—the ESA-led JGO component will investigate the large icy satellites—Ganymede and Callisto—in the outer part of the system. JEO and JGO combined will carry out a systematic synergistic in-depth study of the Jupiter system to address the EJSM overarching theme: *"The emergence of habitable worlds around gas giants."*

Whereas Europa's ocean is in contact with the satellite's silicate mantle, the oceans in Ganymede and Callisto are located between ice at the top and high-pressure ice phases at the ocean floor. Ganymede's interior is fully differentiated; however, the process of separating the chemical constituents in Callisto has been incomplete. How these different states came to be and how the oceans are affected by the different internal structure, e.g., higher abundance of rocky material in Callisto's ice shell, is an open question which will be addressed by JGO.

2.6.1.2 Science Goals of JGO

In order to achieve the overarching EJSM goal, the targets of JGO are the Jupiter atmosphere and magnetosphere, the satellites Ganymede and Callisto, and the Jupiter system as a whole (Appendix L). The global characteristics of Ganymede and Callisto, their shapes and rotational states and orientations in space will be determined with laser altimetry and imaging combined. Geodetic networks as reference systems will be the basis for all other remote sensing measurements.

The presence and location of an ocean within Ganymede will be inferred with JGO by recording the satellite's tidal response during the orbital phase. Determination of the gravity fields by Doppler tracking will constrain the deep interior structure. The flybys of JEO at Ganymede and Callisto will be used in a complementary way to further constrain the internal states of the two icy moons. The inferred oceans at Ganymede and Callisto are expected to be located at a depth of ~100 km and will not be detected as a liquid-solid interface. However, radar

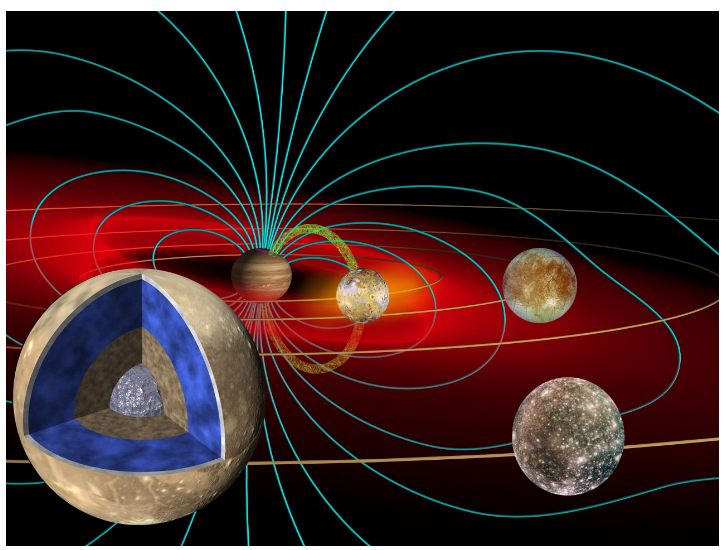


***Figure 2.6-1**. Individual objects and processes are uniquely coupled in the Jovian System.*

observations will give insight into the dynamics of the near-surface ice-layers, showing compositional or phase boundaries. The relation between tectonic features at Ganymede's surface, precisely measured with laser altimetry and stereo imaging, and the dynamics in the ice shell inferred by radar will provide information on how ocean, ice and surface have interacted.

Because of the limited coverage and resolution data returned by Galileo, current image and compositional coverage of Ganymede and Callisto is sparse. Mapping by JGO will significantly increase knowledge of the composition and physical characteristics of the surface, especially for Ganymede, which will be mapped at high resolution from orbit. Stereo imaging and altimetry data will characterize the tectonic features on Ganymede and the craters on the two icy moons. From the cratering record, the surface ages can be derived globally, regionally and locally, using corresponding degrees of image resolution. This will be most important to characterize the different types of terrain on Ganymede and to identify certain epochs of the satellite's activity. JGO will investigate the different evolutionary paths of Ganymede and Callisto with respect to their interiors and degrees of geologic activity.

A unique characteristic of Ganymede is its intrinsic magnetic field. The interplay between self-sustained field, induced magnetic fields generated in the ocean, and the Jovian magnetosphere will be characterized during JGO's dedicated elliptical orbit phase. In addition, JGO will study the magnetosphere and magnetodisk of Jupiter considering the giant planet as a fast magnetic rotator and giant particle accelerator. Comparing Ganymede and Europa, which—although it has a metallic core—is lacking a magnetic field, will give further insight in the different evolutionary paths of the Galilean satellites.

JGO will also study the unique interaction of particles inside Ganymede's tenuous atmosphere with the magnetosphere, and the consequences for surface processes. Callisto's atmosphere and surface processes will also be investigated.

Io, Europa, the small inner and the outer irregular satellites and the Jovian ring system will not be specific targets of JGO. However, these objects will be studied remotely during the mission.

2.6.1.3 Science Implementation

After a 6-year cruise phase the JGO main science campaign will begin (the entire mission timeline can be found in Appendix J. The science campaign can be divided into four phases:

1. Jupiter science phase: main focus: Jupiter's atmosphere and magnetosphere; Ganymede and Callisto science (gravity and mag. fields, remote sensing) at flybys.
2. Callisto Science phase (383 days using resonance orbits): detailed investigation of Callisto's surface, interior (including the putative subsurface ocean) and exosphere; additional Jupiter science.
3. Ganymede elliptical orbit (80 days): detailed investigation of Ganymede's magnetosphere and its interaction with the Jovian magnetosphere; targeted remote sensing campaigns; high-precision determination of the gravity field to prepare for the next phase
4. Ganymede circular orbit (180 days): main science phase (**Figure 2.6-2**) to investigate Ganymede's surface and interior including the ocean and the satellite's tidal response; coordinated

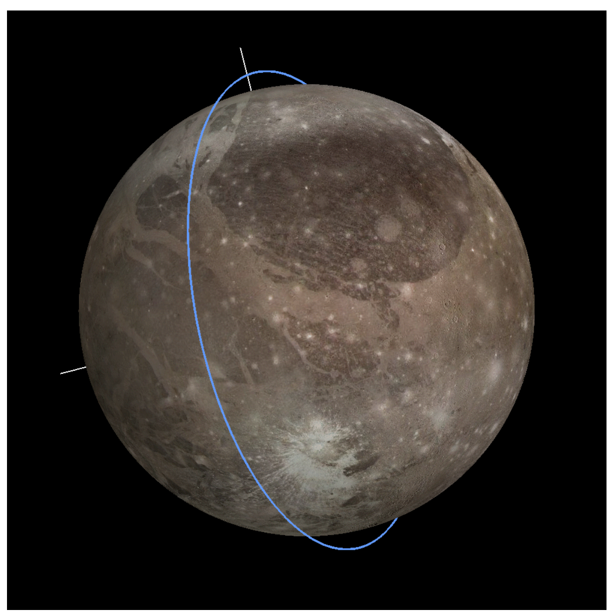


Figure 2.6-2. *JGO's near-polar orbit of Ganymede, inclined at ~75°.*

targeted observations; sub-surface sounding of the ice shell; and studies of Ganymede's exosphere.

2.6.1.4 Model Payload

A 77 kg model payload includes the instruments shown in **Table 2.6-1**, to accomplish the JGO science goals.

Table 2.6-1. JGO Model payload

Micro Laser Altimeter
Radio Science Package
Radar Sounder
V/NIR Imaging Spectrometer
UV Imaging Spectrometer
Thermal IR Imaging Spectrometer
Wide and Medium Angle Cameras
Magnetometer
Plasma Package
Sub-mm wave sounder

2.6.2 Concepts for Complementary and Synergistic Investigations

The presence of two spacecraft in the Jupiter system at the same time (**Figure 2.6-3**) opens up many opportunities for rich synergistic science. The details of this science will depend on the precise mission profiles and instrument complement of the respective spacecraft, but here some of the numerous possibilities are highlighted.

2.6.2.1 Magnetospheric Synergies

In the Jupiter system, a wealth of opportunities exists for exciting synergistic observations in the field of magnetospheric science. A major problem in understanding the structure and dynamics of the Jovian magnetosphere is a general lack of simultaneous field and plasma measurements from multiple spacecraft. With observations from a single spacecraft, it is not possible to distinguish between temporal and spatial gradients in the magnetosphere. The temporal changes in the structure, shape and size of the magnetosphere occur in response to the variable buffeting by the solar wind and variable input of mass from interior sources such as Io's torus maintained by its volcanic activity and small but appreciable mass-loading near Europa from surface/plasma interaction. The magnetospheric spatial gradients are known to occur naturally in plasma density, current sheet thickness and electrical current density over local time and radial distance.

Simultaneous measurements from two (JEO and JGO) spacecraft would help in distinguishing between spatial and temporal changes. Here several different synergistic strategies are discussed for improved understanding of the structure and dynamics of Jupiter's magnetosphere.

One synergistic opportunity is to investigate how disturbances in the solar wind impact the Jovian magnetosphere. For example, shock passage over the Jovian magnetosphere will affect plasma flow, boundaries, and aurora. A synergistic scenario exists whereby one spacecraft in the solar wind (on approach to Jupiter) would detect the shock and its properties, while the other spacecraft, in orbit about the planet, measures the Jovian aurora and the effects of the IMF and solar wind dynamic pressure changes on the middle and outer magnetosphere.

The presence of two spacecraft in the Jovian system enables observations of the dynamic coupling between different magnetospheric regions (e.g., injections, reconnection) and can provide a global perspective on 3-day and other system periodicities. Simultaneous two point monitoring of reconnection in Jupiter's magnetotail by two spacecraft, one located in the pre-midnight sector and the other located in the post-midnight sector, would help in understanding whether the magnetotail reconnection process is global or local in scope and if the reconnection line is slanted in such a way that it occurs close to Jupiter in the dawn sector but recedes away from the planet in the dusk sector, as some theoretical models predict.

In another potential scenario, JEO monitors volcanic activity on Io (perhaps during Io flybys) and images Io's torus to quantify plasma input to Jupiter's magnetosphere, while JGO measures the perturbations to the system from such an event.

Having two spacecraft in the system simultaneously also allows for stereoscopic UV imaging of the Io torus—observations that would revolutionize understanding of the three

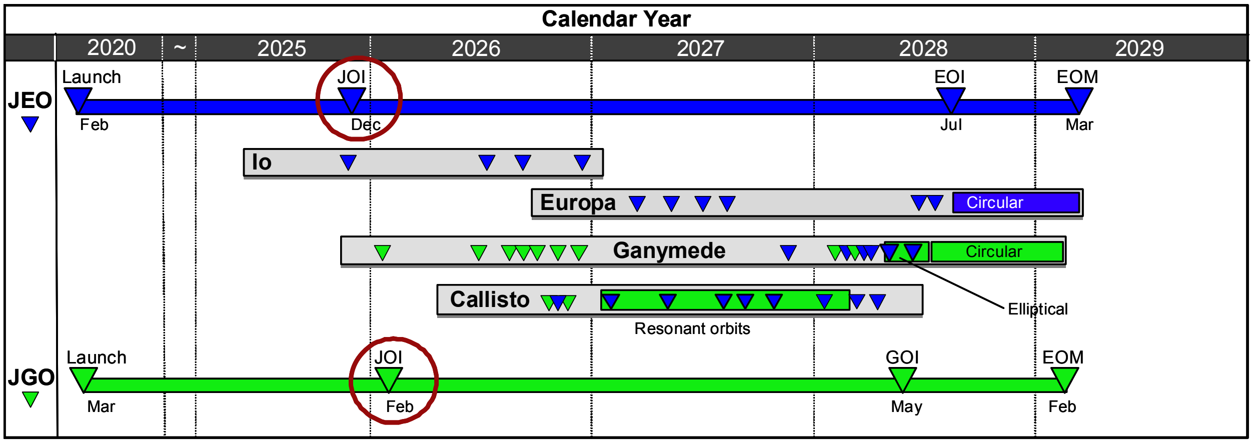


Figure 2.6-3. Notional timeline for the EJSM, assuming launches one month apart in 2020. The resulting synergistic observations of magnetospheric and other dynamic phenomena is unprecedented in planetary exploration. The red circles highlight the opportunity for closely occurring JOI provided by the current EJSM concept.

dimensional structure and dynamics of Io's torus.

Ganymede magnetospheric synergistic opportunities are enabled in the situation where JGO is in Ganymede orbit and JEO performs Ganymede flybys (**Figure 2.6-4**). Such a scenario would allow simultaneous internal and external observations of Ganymede's magnetosphere (e.g., boundaries, convection, reconnection conditions). Furthermore, in this scenario, connections between in-situ observations of the plasma environment and changes in the Ganymede aurora can be investigated.

2.6.2.2 Jupiter Atmosphere

With differing instrument packages, the two spacecraft will obtain synergistic and complementary data that will increase knowledge of Jupiter's atmosphere. JEO will obtain medium-to-high resolution visible-wavelength imaging of the planet, which will allow definition of the zonal jets and, importantly, the eddies that appear to be pumping these jets at cloud level [*Salyk et al. 2006*]. JGO, in contrast, will emphasize the acquisition of thermal observations and possibly, with microwave sounding, could provide the first direct measure of the stratospheric jet pattern by measuring the Doppler shift associated with stratospheric spectral lines. This direct characterization of the stratospheric temperature and wind pattern with JGO will complement the cloud-level tropospheric information obtained from JEO. Because the troposphere and stratosphere are a tightly coupled system, having these observations together will greatly increase the science return relative to either dataset alone. Furthermore, because the atmospheric state changes in time, there is great benefit to performing the above tropospheric and stratospheric observations simultaneously or near simultaneously.

A second possible synergy would be performing JEO-to-JGO (or JGO-to-JEO) radio occultations of Jupiter's atmosphere. Though the model payloads for JEO and JGO do not yet include the necessary capabilities to exercise this experiment, it is mentioned here as a potential synergistic measurement that could be considered. To date, radio occultations in the Jupiter system have occurred only with a radio signal transmitted from a spacecraft (e.g., Voyager) and received at Earth. Having spacecraft-to-spacecraft radio occultations allows for geometries that are unattainable from Earth. Furthermore, spacecraft-to-Earth occultations must deal with the perturbing effects of Earth's atmosphere on the radio signal, a problem that disappears with spacecraft-to-spacecraft communication.

2.6.2.3 Satellite Atmospheres

Measurements that achieve satellite atmospheric science are enabled by the simultaneous operation of remote sensing instruments on both JEO and JGO in the Jupiter system.

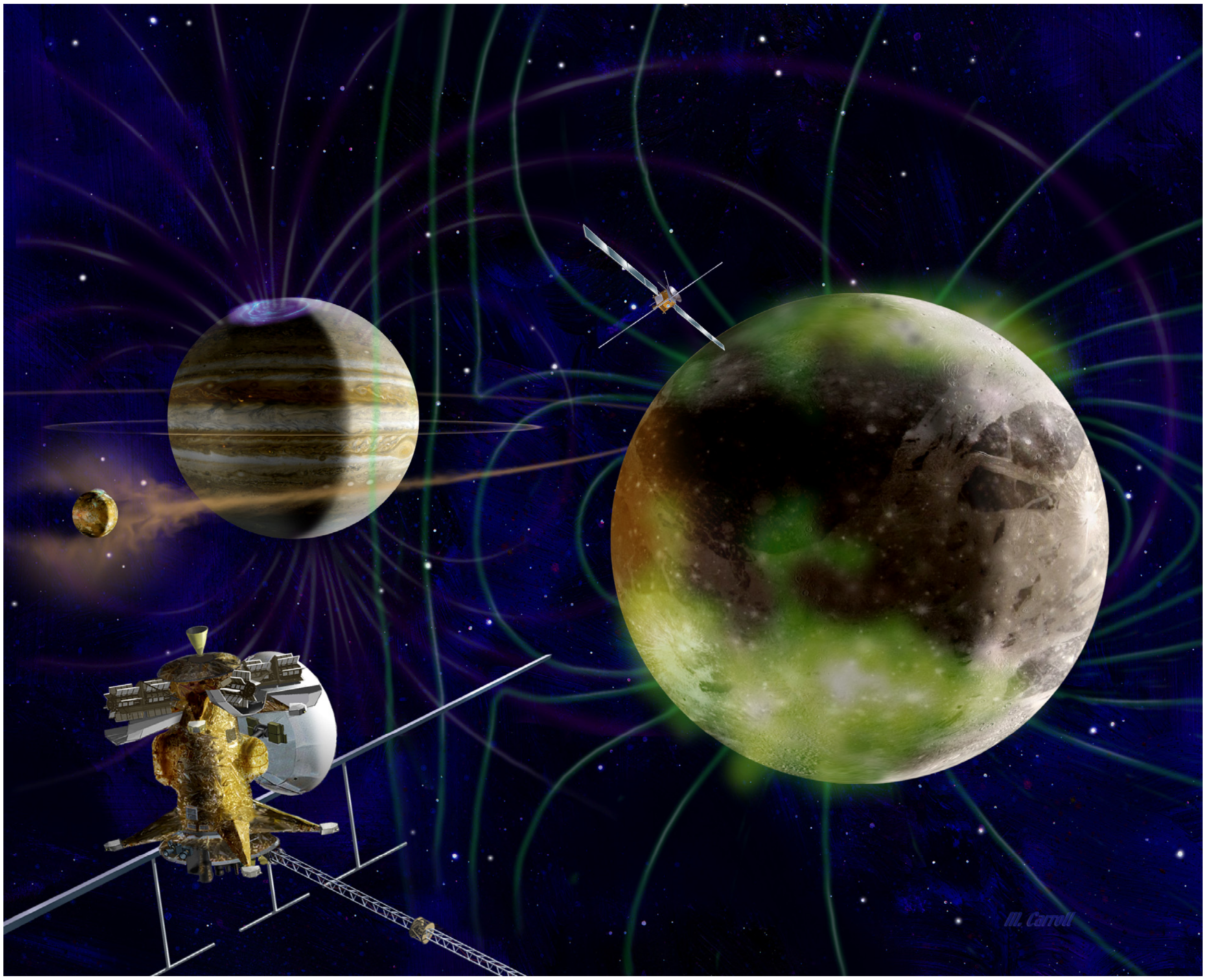


Figure 2.6-4 *Synergistic measurements of Ganymede's magnetic field and aurora are enabled by the two EJSM flight systems: JGO can acquire data while within the magnetosphere of Ganymede, as JEO measures the influence of the Jovian magnetic field.*

The combined suite of instruments on JEO and JGO can potentially enhance the spatial and spectral coverage of atmospheric measurements. Many diagnostic gaseous emission and absorption features are present in the UV, but several important features are present in the visible and IR as well. Synergistic measurements from the two spacecraft would allow for simultaneous observations in different wavelength regimes; such measurements would provide unprecedented spectral coverage of the satellite atmospheres. Furthermore, because isolated flybys of the moons will likely not provide full spatial coverage of the atmosphere, observations using the two spacecraft will enable greater coverage to understand atmospheric asymmetries.

Io monitoring to investigate correlations between volcanic activity and atmospheric species, coverage and density are critical. Io is an ever-changing world, so the overall duration of the combined JEO-JGO mission allows for increased temporal coverage in monitoring this volcanic world. Simultaneous imaging of Io in eclipse from the two spacecraft could provide unique information on the three-dimensional plasma interaction.

Temporal resolution is also important at Ganymede, whose auroral emissions vary spatially and temporally; shared observations of this unique phenomenon by JEO and JGO will probe both the atmospheric and the magnetic characteristics of Ganymede.

The presence of two spacecraft in the Jovian system allows for the unprecedented opportunity to do dual-spacecraft radio occultation experiments of the satellite ionospheres, to infer atmospheric conditions and study plasma interactions at a wide range of local times. Radio occultations involving the Earth are, in contrast, restricted to local times near 6 a.m. and 6 p.m., limiting study of the diurnal variability of the satellite atmospheres. As discussed in §2.6.2.2, such dual-spacecraft occultation experiments are mentioned here in an effort to discuss many potential synergistic opportunities, though this is not currently enabled with the planned payloads of JEO and JGO.

An additional complementary use of two spacecraft in the Jupiter system simultaneously is simply the ability to respond to discoveries by one spacecraft, with additional observations by the second spacecraft. For instance, if JEO were to discover outbursts in activity at Europa or Io, JGO could provide backup support with additional observational coverage, perhaps using a complementary set of instruments.

2.6.2.4 Geophysics

There are several geophysical investigations that are enhanced by the presence of multiple spacecraft. These have the potential to address the interior properties and dynamics of the satellites, as well as rotational and potentially orbital dynamics. These investigations will be particularly valuable for Ganymede and Callisto, which will have multiple flybys from both JEO and JGO. The most direct application is to the determination of gravity fields by Doppler tracking of flybys. Multiple spacecraft can improve coverage by distributing closest approach positions more widely over the satellite and by altering the geometry of flybys, depending on the orbit geometries of the spacecraft. This can help to break degeneracies in the inversion process, potentially allowing the determination of gravity coefficients at degrees larger than 2. Multiple flybys of satellites at different orbital phases may also potentially measure the tidal response, thereby constraining the internal rheological structure and possibly identifying oceans. Tracking and geodetic (control network) measurements through observations of the same locations on the surface multiple times also lead to the accurate determination of the rotational state and potentially to measurement of the rotational dynamics.

Multi-point magnetic field measurements between a Europa orbiter and a Jupiter orbiter can help to separate the influence of Jovian magnetospheric dynamics from the magnetic response of Europa. Phase coverage of induced magnetic field measurements in the other satellites can also be increased by multiple spacecraft encountering the satellite at different phases of Jupiter's magnetic field, potentially allowing the determination of the induced response at multiple periods. Similarly, JEO flybys of Ganymede while JGO is in orbit will aid in assessing the interaction of the Jovian field with the intrinsic Ganymede field.

Another synergy that can be achieved from the presence of multiple spacecraft in the system is the potential for extremely accurate spacecraft-to-spacecraft positioning by single-beam interferometry. This technique has the potential to improve satellite ephemerides, though it requires significant antenna resources on the ground.

2.6.2.5 Io and Europa from JGO

JGO will obtain only distant observations of Europa and Io, but these may be valuable for enhancing JEO science. For instance, low-spatial-resolution photometric and solar phase angle coverage of both bodies may improve knowledge of the bolometric albedos of Io and Europa and thus improve understanding of their internal heat flow. Depending on instrumentation, JGO may be able to improve the temporal resolution and temporal coverage of monitoring of Io volcanism: large hot spots and plumes can be seen even with very low spatial resolution. Stereo imaging of plumes would also provide a valuable constraint on plume dynamics. Outbursts on Io can be monitored by both spacecraft for increased coverage.

2.7 Summary

A comprehensive set of science objectives has been developed by an international team of over 50 scientists in response to the NASA Decadal Survey science questions. This set of objectives has evolved over the past 12 years and has been scrutinized and modified by input from over 200 individual scientists. A two flight element mission concept has been developed which addresses these objectives and can now be executed without new technology. The JEO and JGO mission concepts each address the objectives from different perspectives. JEO spends significant time meeting the objectives from the inner regions of Jupiter's system (Io and Europa) while JGO focuses on meeting the objectives from the outer regions (nearer Callisto and Ganymede). This approach provides a unique opportunity to observe and investigate phenomena from two vantage points simultaneously.

A key figure of merit to assess the ability of JEO and the combined JEO/JGO mission to achieve groundbreaking science is to evaluate the degree to which the major science objectives and questions outlined by the Decadal Survey can be addressed. A rating has been created using a six level scale (0 = Does not address science, to 5 = Definitely addresses full science) as defined previously (§2.5.5). The JJSDT evaluated both the NASA-only JEO and the full EJSM (JEO + JGO) against the Decadal Survey questions for Europa shown in **Table 2.7-1**. The matrix for the Giant Planets panel portion of the Decadal Survey is shown in Appendix L.

Steering Group Recommendations: Given that the highest priority of JEO will be to provide a comprehensive study of Europa, the baseline mission will fully or nearly-fully address all of the Decadal Survey Europa Geophysical Explorer science objectives as defined by the Decadal Survey's Steering Group recommendations. In comparison, the focus of JGO will be on Ganymede science, so its contribution to exploring Europa will be limited.

Large Satellites Panel Recommendations: Questions from the Decadal Survey's Large Satellites panel imply the need to study multiple outer planet satellites in detail. Both JEO and JGO will perform flybys of multiple satellites and each goes into orbit around a key large icy moon for in-depth study. Because the Galilean satellites cover the spectrum from primitive (Callisto) to relatively evolved (Io), investigations related to the moons' physical properties, structure and composition benefit greatly from the combination of JEO and JGO.

Giant Planets Panel Recommendations: Decadal Survey investigations that emphasize understanding Jupiter, its atmosphere, and its environment (Appendix L) are not achieved to the same degree as those for the satellites, but such is not expected of JEO. This is mainly because the Decadal Survey recommended *in situ* or close-in measurements of Jupiter, as will be done by Juno.

Both the NASA-only JEO and the full EJSM JEO/JGO approaches to Jupiter system and Europa/Ganymede exploration make the next leap in solar system understanding possible. The individual JEO and JGO spacecraft will provide significant and revolutionary science in the Jupiter system. Observations by both spacecraft, in concert and independently, will greatly enhance the ability to address key science questions outlined by the Decadal Survey.

Table 2.7-1. *Summary of Decadal Survey Steering Committee and Large Satellites Panel Recommended Objectives Achieved by JEO and JGO.*

Science Value Scoring			
5	Definitely addresses full	2	May address partial science
4	May address full science	1	Touches on science
3	Definitely addresses partial	0	Does not address science

	JEO	JEO + JGO	Comments	JEO Science Objective
DECADAL SURVEY STEERING GROUP RECOMMENDATIONS:				
"EUROPA GEOPHYSICAL EXPLORER" SCIENCE OBJECTIVES				
Group 1:				
Determine the presence or absence of an ocean.	5	5		A. Ocean
Characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layer.	5	5		B. Ice
Understand the formation of surface features, including sites of recent or current activity, and identify candidate landing sites for future lander missions.	5	5		D. Geology
Group 2:				
Characterize the surface composition, especially compounds of interest to prebiotic chemistry.	4	4	An *in situ* surface element would be required to achieve full science.	C. Chemistry
Map the distribution of important constituents on the surface.	5	5		C. Chemistry
Characterize the radiation environment in order to reduce the uncertainty for future missions, especially landers.	5	5		C. Chemistry D. Geology
LARGE SATELLITES PANEL THEMES AND KEY QUESTIONS:				
Theme 1. Origin and Evolution of Satellite Systems				
1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO	C. Chemistry E. Jupiter System
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)	4	5	Scoring does not reflect the emphasis on Titan. Detailed investigations of Ganymede and Callisto are facilitated by JGO	E. Jupiter System
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?	5	5		A. Ocean B. Ice C. Chemistry D. Geology E. Jupiter System
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?	5	5		D. Geology E. Jupiter System
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and is Ganymede unique?	3	5	Detailed investigation of Ganymede's magnetic field is accomplished by JGO, and synergies with JEO.	E. Jupiter System
Theme 2. Origin and Evolution of Water-Rich Environments in Icy Satellites				
1. What is the chemical composition of the water-rich phase?	4	4		C. Chemistry E. Jupiter System

	JEO	JEO + JGO	Comments	JEO Science Objective
2. What is the distribution of internal water, in space and in time?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO.	A. Ocean B. Ice E. Jupiter System
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?	5	5	Emphasis on investigations in orbit around Europa. The JEO and JGO satellite tours places Europa in context with the other satellites. JGO orbital science increases the rating beyond that anticipated by the Decadal Survey.	A. Ocean C. Chemistry D. Geology E. Jupiter System
4. Can and does life exist in the internal ocean of an icy satellite?	3	3	Scoring emphasizes focus on assessing potential for habitability rather than direct search for life.	A. Ocean C. Chemistry E. Jupiter System
Theme 3. Exploring Organic-Rich Environments				
1. What is the nature of organics on large satellites?	4	5	Inclusion INMS as part of the payload facilitates direct sampling of materials, especially at Ganymede & Callisto.	C. Chemistry E. Jupiter System
2. What are the processes currently affecting organic-rich surfaces?	4	5	Direct monitoring of the radiation environment provides insight into processes at Europa (JEO); JGO will examine the impact of the radiation environment on organic materials at Ganymede.	C. Chemistry E. Jupiter System
3. How does organic chemistry evolve in a hydrocarbon solvent?	0	0		N/A
4. How do atmospheric processes affect organic chemistry?	3	3	JEO investigates sputtering processes and the effects on chemistry.	C. Chemistry E. Jupiter System
Theme 4. Understanding Dynamic Planetary Processes				
1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?	4	4	Scoring reflects that JEO is not optimized for Io science.	A. Ocean E. Jupiter System
2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?	5	5	Scoring reflects emphasis on Europa science by JEO.	C. Chemistry D. Geology E. Jupiter System
3. What are the complex processes and interactions on the surfaces and in volcanic or geyser-like plumes, atmospheres, exospheres, and magnetospheres?	4	5		C. Chemistry D. Geology E. Jupiter System
LARGE SATELLITES PANEL OVERALL HIGH-PRIORITY QUESTIONS:				
1. Is there extant life in the outer solar system?	3	3	Scoring emphasizes focus on assessing potential for habitability rather than direct search for life.	A. Ocean C. Chemistry E. Jupiter System
2. How far toward life does organic chemistry proceed in extreme environments?	3	3		C. Chemistry E. Jupiter System
3. How common are liquid-water layers within icy satellites?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO.	A. Ocean B. Ice E. Jupiter System
4. How does tidal heating affect the evolution of worlds?	4	5	Scoring reflects that JEO is not optimized for Io science. Detailed investigations of Ganymede and Callisto are facilitated by JGO	A. Ocean E. Jupiter System

3. EJSM MISSION ARCHITECTURE ASSESSMENT

An international team of scientists and engineers have developed a multi-flight element architecture to explore the vast scientific richness of the Jupiter System. The tremendous advantages of exploring a system with multiple flight systems in close proximity can be seen by the cooperative and synergistic science achieved at Mars. Independent, yet coordinated, developments and capabilities ensure maximum utilization of scarce resources to achieve extraordinary science well beyond what Galileo's glimpse into this system was able to provide.

The Galileo mission's spectacular, though limited, science data has been analyzed for over a decade. The added value of continued analysis is reaching the point of diminishing return as most of the data has been sifted through and very little additional data is expected from the Jupiter System until Juno enters the system in 2016. Juno will conduct focused science relative to Jupiter's deep interior and magnetosphere; little additional information regarding the jovian satellites or ring system will be enabled by Juno.

Extensive architectural studies building on and expanding Jupiter System and Europa science have been performed over the past decade, which have, each time, resulted in a Europa orbiting element as the primary science solution (Appendix C). The Galilean satellites are very diverse with respect to their geology, internal structure, evolution and degree of past and present activity. In order to place Europa and its putative habitability in the right context, as well as to fully understand the Galilean satellites as a system, Europa and Ganymede must be investigated in detail. Studies of the Jovian system including the giant planet itself, its atmosphere and magnetosphere and the other two Galilean satellites, Io and Callisto will additionally add to the rich understanding of how Gas Giant systems evolve.

In 2007, ESA issued a call for mission concepts for its Cosmic Vision Programme. The Jupiter mission concept, *Laplace*, was selected for further study in 2008. The *Laplace* concept was for three separate flight elements to explore the Jupiter system, one a Jupiter orbiter, one a Europa orbiter and a one small drop-off flight element in Jupiter orbit to study the magnetosphere.

Starting in 1996, and continuing every year, NASA studies have matured concepts to reach Europa and study its secrets within the context of the technology capability to survive within the challenging radiation environment. Most recently, in 2006 and 2007, NASA performed two extensive Europa studies where current technologies were evaluated to achieve the science defined by Science Definition Teams.

The 2007 NASA study was documented in *Clark et al.* [*2007*] while the ESA 2007 study effort is reported in *Blanc et al.* [*2007*]. In 2008, the NASA Study and the ESA *Laplace* Study teams began working very closely to merge the concepts and to align the goals of a single integrated mission concept. The Science Teams were merged and began the discussion of the total system science. The resulting Europa Jupiter System Mission (EJSM) allows organizational strengths, budgets and timelines to be exploited to carry out a systematic in-depth study of the Jupiter system aiming at one unique overarching theme:

The emergence of habitable worlds around gas giants

The EJSM complement of model payload, trajectory and data downlink capabilities provides a dramatic increase in data volume to explore the dynamic worlds over a 3 to 4 year period. This 3-order of magnitude increase in data volume promises to enable an extensive investigation of the overall theme.

3.1 Baseline EJSM Architecture

The baseline mission architecture for the EJSM mission consists of two separate elements operating in the Jovian system at or near the same time. The NASA-led JEO would be launched on a NASA launch vehicle in February 2020. ESA would launch the Jupiter Ganymede Orbiter (JGO) on a separate launch vehicle also in 2020. A potential JAXA-led Jupiter Magnetospheric Orbiter (JMO) could be added as either an add-on to JGO or as a separate launch in 2020. The JMO concept is in the very early stages of development within JAXA and thus, is not touched upon much in this report. If it were to materialize, the addition of a third flight element in the Jupiter system focusing on magnetospheric measurements would be a boon for studying and understanding the immense magnetosphere of Jupiter and its interactions with its satellites. By launching in the same year, the overlapping time spent in the Jupiter system by the two (or three) flight elements is maximized without altering their optimized trajectories. A summary of the EJSM mission concept is shown in **Foldout 4** (**FO-4**).

It's important to note that the launches of JEO and JGO are *not* dependent on each other. If one were to reach Jupiter earlier than the other, some of the science performed simultaneously while in the Jupiter system may be lost. There are two ways to regain that synergistic science: 1) adjusting the interplanetary trajectory and 2) lengthening the tour portion of the mission. There would most likely be some natural overlap unless the launch years become very far apart.

Both JEO and JGO provide significant science return as stand alone mission elements. The synergistic science available by operating both flight element in the Jupiter system at the same time is significant (§2.6 and §3.4). By decoupling the launch dates, options become available to resolve potential development issues, including delaying the launch of one element. The final down-select by ESA for the Cosmic Vision Mission is currently scheduled for 2012. In the unfortunate case that NASA chooses to support the EJSM mission and ESA chooses a competitor (LISA or XEUS) in 2012, the JEO mission element could proceed with no flight system or launch system impact. This flexibility could also be crucial as cost, schedule and risk issues evolve over the next decade at each agency.

3.2 The Jupiter-Ganymede Orbiter (JGO): ESA's Contribution to the EJSM

3.2.1 Science Goals

Jupiter and the two outer icy moons, Ganymede and Callisto, will be the main targets of the JGO. Besides the Jupiter orbit tour, the science phase will include a dedicated science campaign at Callisto and an elliptical and final 200 km near-polar circular orbit campaign around Ganymede (**Figure 3.2-1**).

JGO's main focus will be complementary to the one of JEO, which will venture close to Io while exploring Ganymede and Callisto prior to settling into orbit around Europa. The targets and main scientific objectives to be investigated by JGO can briefly be summarized as follows:

- Characterize Ganymede as a planetary object including its potential habitability,
- Study the Jovian satellite system,
- Study the Jovian atmosphere,
- Study the Jovian magnetodisk/magnetosphere,
- Study the interactions occurring in the Jovian system.

3.2.2 JGO Mission Overview

JGO launches on an Ariane 5 ECA in March, 2020. Using a Venus–Earth–Earth Gravity Assist (VEEGA) trajectory to Jupiter, JGO gets to Jupiter in approximately 6 years. After a Ganymede gravity assist and Jupiter Orbit Insertion (JOI), JGO will find itself in a 13×245 R_J (Jupiter radii) elliptical orbit in February, 2026. The choice of a Ganymede gravity assist keeps JGO outside the worst part of Jupiter's radiation belts.

A sequence of swing-by's at Ganymede and Callisto over about 10 months allows ample time for Jupiter system science before starting an intensive study of Callisto. Over the course of 383 days, JGO makes 19 Callisto flybys at altitude of 200 km using 2:3 resonant orbits, allowing for significant global surface coverage.

Subsequent swing-by's at Ganymede and Callisto move the flight system to Ganymede where it inserts into 200×6000 km elliptical orbit. The Ganymede elliptical orbit science phase lasts for ~80 days. JGO will then maneuver to reach a low altitude (200 km), circular, near-polar orbit where it stays for a minimum of 180 days. The end of nominal mission after 3254 days, i.e., about 8.9 years on February 6, 2029. The end of mission disposal would be eventual impact on Ganymede's surface.

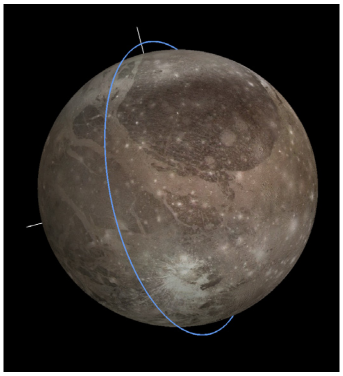


Figure 3.2-1. *JGO's final orbit*

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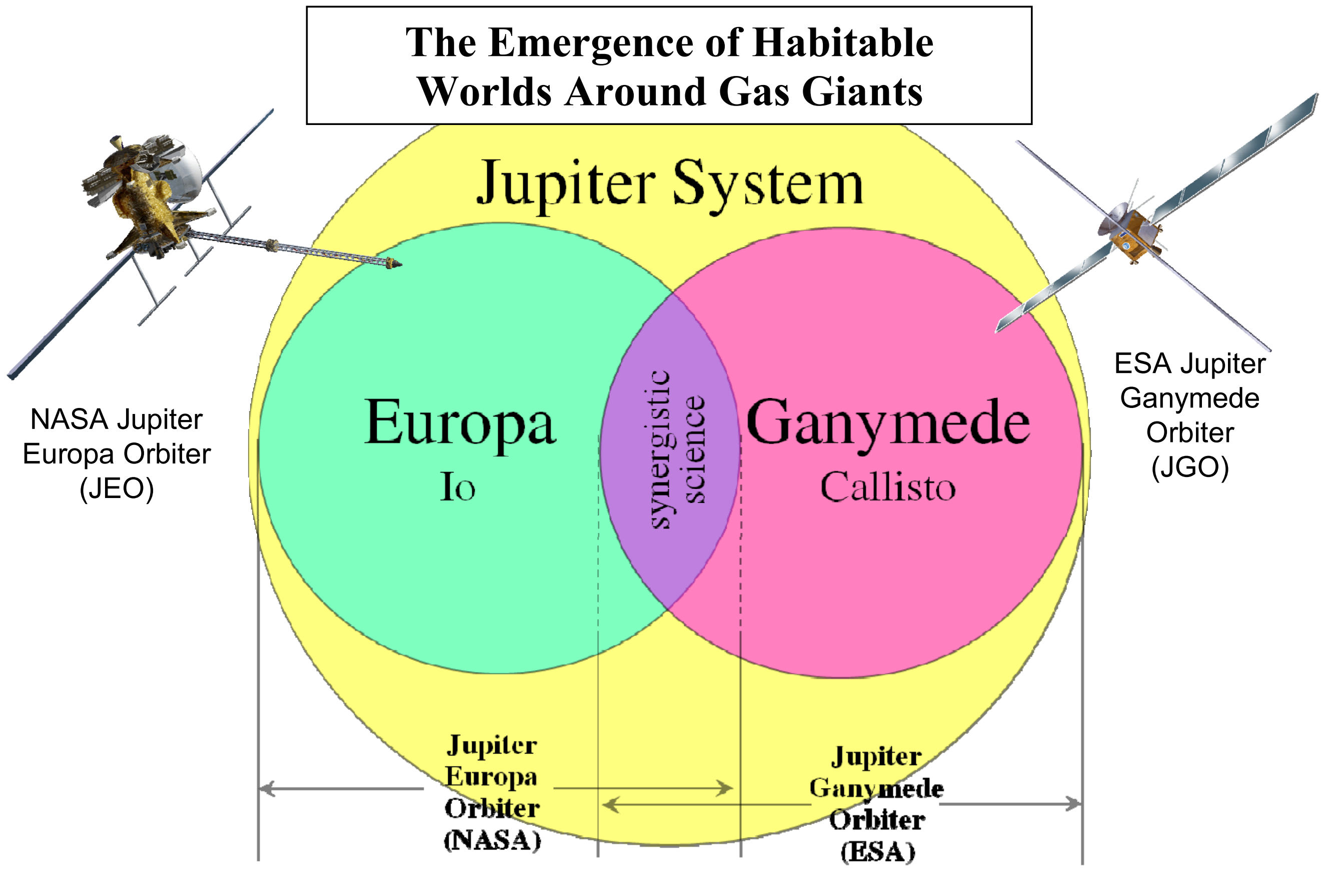
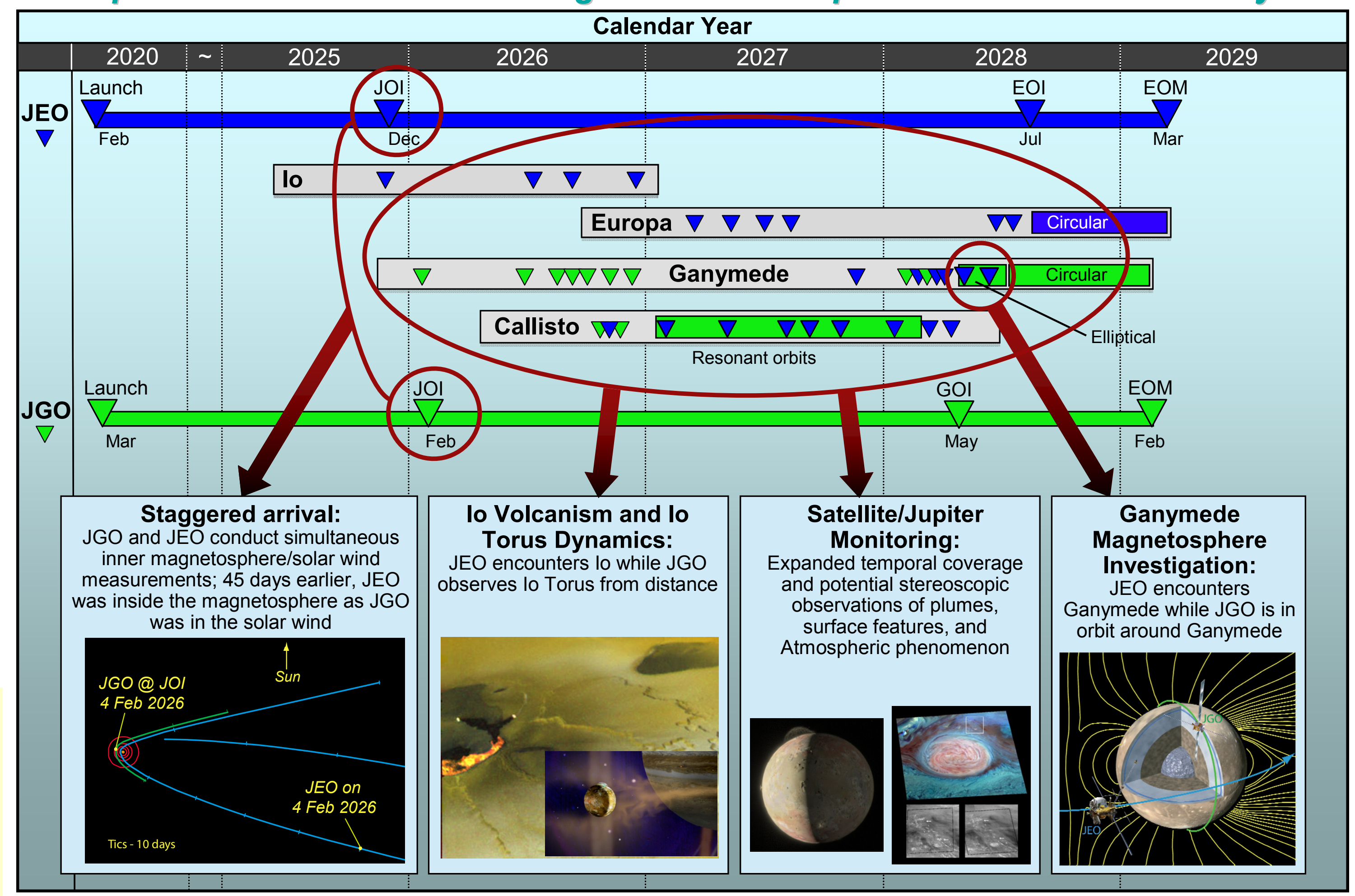
EJSM's Two Complementary Flight Systems Enable Unique Exploration of the Jovian System

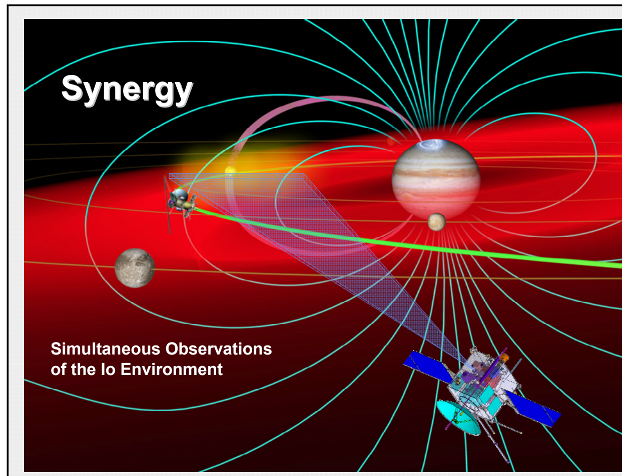


Observing the Jupiter system with two flight systems at the same time enables unprecedented science investigations of multiple bodies in the Jovian system



Model Payload		
Instrument	**Jupiter Europa Orbiter**	**Jupiter Ganymede Orbiter**
Laser Altimeter	Single-beam: 1.064 µm, 50 m spot	Single Beam: 1064 nm, 10 m spot
Radio Science	2-way Doppler with Ka translator; USO	2-way Doppler with Ka-Band transponder including SSPA & USO
Ice Penetrating Radar	Dual frequency: 50 Mhz and 500 Mhz, Vertical depths: 3 and 30 km, Dipole antenna: 30 m	Single frequency: 20-50 Mhz, Dipole antenna length: 10 m
Visible-IR Spectrometer	Pushbroom with along-track scan mirror, single channel, 2000-5200 nm	Pushbroom imaging spectrometer, two channels; 400-2200 & 2000-5200 nm
UltraViolet Spectrometer	FUV: 70-200 microns, scan system for stellar occultations	EUV: 50-110 nm FUV+MUV: 110-320 nm
Ion and Neutral Mass Spectrometer	1-300 daltons	N/A
Thermal Instrument	8-20 µm, and 20-100 µm	5 – 25 µm, 4 narrow filter bands
Narrow Angle Camera	Panchromatic pushbroom plus nine color framing mode	N/A
Wide and Medium Angle Camera	Wide-Angle: 3-color + panchromatic; IFOV of 1 mrad, pushbroom Medium-Angle: pushbroom, stereo, panchromatic	WAC: framing camera, spectral range: 350-1050 mm, FoV: 117° spatial resolution: 400 m/pix @200 km MRC: pushbroom, spectral range: 350-1050 nm, 4-color + panchromatic
Magnetometer	Dual sensors on 10 meter boom; 0–3000 nT	Dual tri-axial fluxgate sensors on 3 meter boom
Plasma and Particles	Electrons: 10 eV to 30 keV Ions: 10 eV to 30 keV	Cold plasma (Te < 10 eV) Electrons: 1 eV - 15 keV Ions: 1 eV - 5 MeV ENA: 10 eV – 10 keV
Submillimeter Wave Sounder	N/A	Spectral range: 550-230 µm, 2 channels
Mass	**106 kg**	**73 kg**

Complementary model payloads on the two flight systems provides unique capabilities to obtain simultaneous observations of a single phenomenon



The Europa Jupiter System Mission provides unique capabilities for investigating the Jovian system by using two complementary flight systems. Each flight system focuses on studying two of the four Galilean satellites while also gathering complementary and synergistic science data with the other flight system.

3.2.3 Science Operations

After a 6 year cruise the JGO main science phase start. It is divided into four campaigns:

- Jupiter science campaign main focus: Jupiter's atmosphere; Ganymede and Callisto science (gravity and mag. fields, remote sensing) at flybys.
- Callisto science campaign (383 days): detailed investigation of Callisto's surface, interior (including the putative subsurface ocean) and exosphere; additional Jupiter science.
- Ganymede elliptical orbit campaign (80 days): detailed investigation of Ganymede's magnetosphere and its interaction with the Jovian magnetosphere; targeted remote sensing campaigns; high-precision determination of the gravity field to prepare for the next phase.
- Ganymede circular orbit campaign (180 days): main science phase to investigate Ganymede's surface and interior including the ocean and the satellite's tidal response; coordinated targeted observations; subsurface sounding of the ice shell; studies of Ganymede's exosphere.

Throughout the mission Jupiter, Io, and Europa will be investigated by remote sensing. Possible mission extensions will include a lower Ganymede orbit (~100 km altitude) allowing for further coordinated targeted observations and better resolution.

3.2.4 JGO Flight Element

The JGO flight element is a redundant (key subsystems) 3-axis stabilized with a launch mass of 5070 kg including the launch adapter. The current estimated dry mass is 1275 kg (including 20% margin but excluding adapter). This includes a 77 kg model payload. The bi-propellant MON/MMH propulsion system provides 2920 m/s and is sized for 2060 kg of propellant which assumes all dry mass margin is utilized by launch. The total dry mass margin including contingency is 533 kg.

JGO stays in the outer regions of the radiation belts and uses deployable and rotating LILT solar arrays (area ~51 m^2) for main power and carries a Li-ion battery for power during eclipse science mode. The downlink communications is provided primarily using Ka-band through a 2.8 m high gain antenna. X-band is used for commanding and Ka-band up and down is used for radio science (includes a USO for radio science atmosphere investigations as well). The downlink data rates vary depending on the point in the mission. Data rates of 40–66 kb/sec are available to the ESA ground station network from 5 AU to 6.1 AU (max.). Data can be stored on-board using a 256 Gb solid state recorder until the opportunity exists to downlink it.

JGO is estimated to be exposed to 100 krad behind 8 mm (320 mils) Al-radiation shielding. This design point results in 80 kg of shielding assuming the current model payload.

The model payload includes: wide and medium angle cameras, thermal instrument, visible-IR spectrometer, ice penetrating radar ultraviolet spectrometer, submillimeter wave sounder, laser altimeter, magnetometer, plasma and particle instrument, and radio science. (**Figure 3.2-2**).

3.3 The Jupiter Europa Orbiter (JEO): NASA's Contribution to the EJSM

Building upon over a decade of study, NASA supplied a set of ground rules which are used to define the more detailed assessment of the JEO mission element for the 2008 Study. The ground rules were supplied to the study team to simplify the execution and review of the results of the studies. The original ground

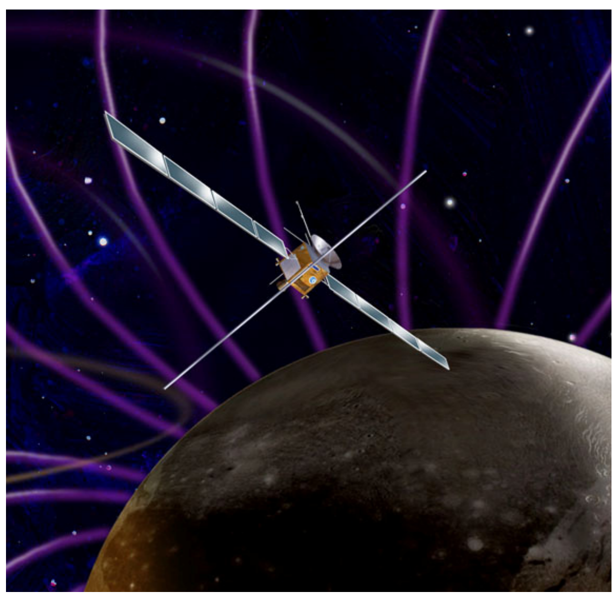


Figure 3.2-2. *JGO carries a model payload into a 100 km circular orbit around Ganymede allowing extensive detailed investigation of the surface, subsurface and exosphere.*

rules supplied in February 2008 placed hard constraints on the choice of power source (Multi-mission Radioisotope Thermoelectric Generator, MMRTG only), a Europa orbital lifetime of 60 days maximum and cost cap <$2.1B (FY07). During the course of the study, a presentation of this "core" mission concept was provided to the NASA Headquarters sponsor. Re-direction was given in June 2008 to modify the mission concept to increase the capability to address the Decadal Survey science and to find a "sweet spot" balance between science and cost. The ground rules were updated at that point to also include the option to incorporate a more advanced, but still developmental, power source (Advanced Stirling Radioisotope Generator, ASRG).

The final ground rules are summarized in **Table 3.3-1**. No Final Report outline or content instructions were provided except to follow the basic structure used in the 2007 studies.

3.3.1 Statement of Work

The broad statement of work for the JEO mission was 1) to focus on updating the 2007 mission concept to incorporate findings from the Science, Technical, Management and Cost Review of the 2007 EE mission concept along with any applicable findings from the Jupiter System Observer Study from 2007 and 2) to make progress on risk reduction activities related to radiation and planetary protection.

Additionally, specific 2008 JEO study instructions are summarized as:

Table 3.3-1. *NASA-provided ground rules provide framework for JEO study report.*

Power options	Solar, MMRTG or ASRG—costs and characteristics supplied for radioisotope power options
Planetary Protection	JEO: ≤10^{-4} of contaminating the Europan ocean
Launch Vehicle (LV)	Delta IV-H, Ares and Atlas family—costs given including launch services and nuclear processing
Technology Philosophy	Be conservative
Launch Dates	Nominally 2020 but investigate 2018–2022
DSN Capability	Ka band downlink available, current 70 m equivalent capability available, current 34 m available, DSN ground system throughput of 100 Mbits/s
International Contributions	<$1B (FY07) consistent with Cosmic Vision Proposals

- Abide by additional programmatic constraints including,
- The duration of the JEO mission in orbit around Europa should be based on trades examining science return, cost, and impact to the flight system,
- Include Jovian system science as a Level 1 requirement,
- Refine the tour trajectory address science objectives,
- Respond to the independent review findings from the TMC and Science panels, especially,
- Refine the Chemistry science objective, especially as it relates to habitability (Form A),
- Analyses concerning radiation-induced effects on measurement quality and mitigation strategies (Form B),
- Identify and investigate opportunities for international partnerships within the $1B limit for contributions, including but not limited to deploying and supporting a mission element(s) independent of the Europa orbiter and adjusting the tour design,
- Refine the radiation plan described in the 2007 report and endorsed by the TMC panel in response to the radiation findings on Forms B and C; and begin executing,
- Define the "sweet spot" JEO mission by augmenting the capabilities of the $2.1B (FY07) cost capped mission,
- Define a floor mission which may be the $2.1B (FY07) cost capped mission or closely derived from it,
- Assess the benefits of conducting simultaneous or sequential observations in the Jupiter with an ESA JGO and how this might impact the design of the sweet spot JEO. Assess the impact on the JEO sweet spot mission design of an ESA decision in 2011 not to proceed with a JGO mission,
- Provide a final report describing the JEO sweet spot mission, the JEO floor mission and focusing on the NASA-only option,
- Provide appendices to the final report which,
- Describe the ESA JGO and the contributions it makes to the EJSM mission,
- Conduct an assessment of the science value of NASA ESA and NASA only missions

with respect to the science goals in the 2003 NRC Decadal Survey.

3.3.2 JEO Architectural Options

The basic architectural elements were defined during the 2007 NASA and ESA studies. For JEO, the study team was directed to redesign the mission concept described in the 2007 EE study in accordance with revised ground rules. The 2007 design was based on the 2006 design. Both are summarized in **Table 3.3-2**. Appendix C provides a good roadmap to the alternatives which have been evaluated for exploring Europa over the past 12 years including solar alternatives.

In 2008, the Joint Jupiter Science Definition Team (JJSDT) again evaluated a landed element as an alternative architecture to meet the Europa science goal and objectives. Once again, the landed element was not selected as an element of the mission architecture.

Three architectural elements were open for exploration: launch vehicle, trajectory and power source. The options are described below.

3.3.2.1 Launch Vehicles

The Delta IV-H, Ares 1 and 5, and Atlas V class launch vehicles were available for consideration in this study. The Ares was not explored in depth as the cost and development uncertainty were much higher than for the Atlas and Delta class launch vehicles, and the potential increased performance was not required. The Atlas V launch vehicle has a significantly lower cost than the Delta IV-H launch vehicle. As shown in **Table 3.3-2**, the delivered mass capability of the Atlas V 551 is sufficient to accommodate the floor and baseline flight systems for the nominal launch date of February 2020.

Table 3.3-2. *The maturity of the Europa orbiter over the past 3 years has increased and has resulted in concepts with significant science capability.*

	2006 Reference	2007 Baseline	2008 Baseline	2008 Floor
Launch Vehicle	Atlas V 551	Delta IV-H	Atlas V 551	Atlas V 541
Launch Month/Year	6/2015	6/2015	2/2020	2/2020
Trajectory	VEEGA	VEEGA	VEEGA	VEEGA
Flight time to Jupiter (years)	6	6	6	6
Time in Jovian tour	18 months	23 months	30 months	20 months
Europa orbital lifetime	3 months	9-12 months	9 months	3.5 months
Number of Instruments including Radio science	10	12	11	7
Power source	8 MMRTG	8 MMRTG	5 MMRTG	5 MMRTG
Data volume	4.5 Tbit	5.4 Tbit	4.5 Tbir	3.0 Tbit
Cost ($BRY, $BFY07)	N/A	N/A, 3.3	3.8, 2.7	3.0, 2.1
Instruments:				
Wide-Angle Camera (WAC)	X	X	Combined	Combined
Medium-Angle Camera (MAC)	Stereo	Stereo		
Narrow Angle Camera (NAC)		X	X	
Vis-IR Spectrometer (VIRIS)	Line	Line	X	Partial
Laser Altimeter (LA)	X	X	X	X
Ice Penetrating Radar (IPR)	X	X	X	X
Thermal Instrument (TI)	X	X	X	
Ultraviolet Spectrometer (UVS)		X	X	
Magnetometer (MAG)	X	X	X	X
Ion and Neutral Mass Spectrometer (INMS)	X	X	X	
Particle and Plasma Instrument (PPI)	X	X	X	Partial
Radio Science (RS)	X both ways Ka both ways	X both ways Ka down only USO	X both ways Ka both ways USO	X both ways Ka down only
Instrument Mass CBE (kg): (include shielding)	*107*	*126*	*165*	*98*
Instrument Peak Power CBE (W):	*161*	*179*	*172*	*99*
2 Orbit Instrument Average Power CBE (W)	*99*	*102*	*71*	*44*

3.3.2.2 Trajectory

There are many different trajectory types and launch opportunities for transfers between Earth and Jupiter between 2018 and 2022, only some of which could be evaluated within the timeframe of the study. The maximum dry mass capability that can be delivered to Europa is based strictly on launch vehicle capability and required mission ΔV. In general, the VEEGA trajectory consistently provides the greatest amount of delivered dry mass capability for flight times up to ~7 years. The ground rules stipulated that the nominal launch year is 2020. As a part of the decision process, JEO was designed to be able to launch as early as October 2018 to provide flexibility. This has the side benefit that the mass margin for the nominal 2020 opportunity is even larger than what would otherwise be held for this design at this point in time. In addition, there are several launch opportunities which provide the required mass margin with reasonable flight times to Jupiter, **Table 3.3-3**. Options other than the baseline and those listed in **Table 3.3-3** are potentially available, and are discussed in §5.0.

3.3.2.3 Power Source

Two power sources were evaluated for this study: MMRTG and ASRG. A discussion of the characteristics and trade study is given in §4.4.5.1. Both of these systems are currently in development by NASA and Department of Energy (DOE). The MMRTG was selected over the ASRG for JEO because it is well understood and characterized (power source for the 2009 MSL mission). Five MMRTG units are required to power the baseline JEO mission concept, not including a ground spare.

The ASRG was evaluated for this study. On the surface, the ASRG looks to be a very good trade for mass and power. The Study Team felt uncomfortable with moving to the ASRG at this point as there are many open issues associated with the integration of a technology still under development without adequate time to understand its impacts. The team found no show-stoppers with using the ASRG, but felt that the MMRTG implementation was much better understood at this point in time and lower risk. Exploring ASRG implementation options in Pre-Phase-A along with working with technology developers would enable incorporation of ASRG into design within resources currently allocated to MMRTG implementation.

Table 3.3-3. *These selected trajectories and launch opportunities are only some of the ones available which provide the required mass margin and shorter flights times to Jupiter. The baseline trajectory is shown in blue.*

Launch Opportunity	Fly-bys	TOF to JOI	Atlas V 551 Capability	Addt'l Margin (beyond req'd 33%)	Total LV Margin (%)
August 2016	VE	5.1 yrs	4975 kg	15 kg	34%
October 2018	VVE	5.8 yrs	4560 kg	6 kg	33%
June 2019	VVE	7.9 yrs	4780 kg	111 kg	37%
February 2020	**VEE**	**5.8 yrs**	**5040 kg**	**295 kg**	**43%**
March 2020	VVE	6.2 yrs	4735 kg	132 kg	38%
November 2021	VEE	6.1 yrs	4725 kg	40 kg	35%

3.3.3 Architecture Summary

3.3.3.1 Floor JEO Architecture

The first half of this year's study was to identify a $2.1B (FY07) mission. In doing so, the JJSDT and engineering team worked very closely to evaluate the smallest payload, mission design and engineering capability which would meet the minimum science requirements. The JJSDT reached a point where deleting any more capability compromised the desire to continue with the mission. Thus, the "core" (floor) mission was defined.

- *Single orbiter:* lowest cost concept which meets science objectives,
- *7 instruments including radio science*
- *20-month Jovian tour:* allows use of a series of Io gravity assist to increase delivered mass to Europa. Significant system science will be achieved before entering Europa orbit,
- *Low-altitude, near-circular Europa orbit:* provides very close exploration of a near-airless body and required to meet science objectives,
- *3.5 months in Europa orbit:* addresses science hypotheses,
- *Atlas V 541:* enables the floor payload to be delivered to low-altitude, Europa orbit with margin,
- *VEEGA trajectory*: allows significant delivered mass to Europa orbit with flight times just under 6 years,

- *February 2020 launch opportunity*: Best alignment with ESA launch opportunity,
- *MMRTGs*: most mature technology and well understood implementation.

3.3.3.2 Baseline JEO Architecture

The baseline mission was determined by adding capability to the floor mission in science priority order to increase the science return until the point where the cost increase associated with an addition became very steep. This process is described in §4.1.The resulting baseline JEO mission is a comprehensive exploration of the Jupiter system with particular attention to monitoring the time varying phenomenon and exploring Europa close up.

A brief summary of the baseline architecture and associated implementation chosen for this mission concept is as follows:

- *Single orbiter:* lowest cost concept which meets science objectives,
- *11 instruments including radio science,*
- *30-month Jovian tour:* allows use of a series of Io gravity assist to increase delivered mass to Europa. Significant system science will be achieved before entering Europa orbit,
- *Low-altitude, near-circular Europa orbit:* provides very close exploration of a near-airless body and required to meet science objectives,
- *9 months in Europa orbit:* addresses science hypotheses in first 3.5 months, allowing for follow-on investigation of new discoveries,
- *Atlas V 551:* enables the baseline payload to be delivered to low-altitude, Europa orbit with margin,
- *VEEGA trajectory*: allows significant delivered mass to Europa orbit with flight times just under 6 years,
- *February 2020 launch opportunity*: Best alignment with ESA launch opportunity,
- *MMRTGs*: most mature technology and well understood implementation.

Table 3.3-2 summarizes the major differences between the baseline and floor mission concepts. Also included in this table are the mission concepts resulting from the 2006 and 2007 Europa orbiter concept studies. Only minor updates to the base implementation have been incorporated as the science and implementation options are fairly mature. The descope strategy for this mission would be to delete science instruments and engineering capabilities sequentially from the baseline mission until the floor mission is reached. This descope strategy is described further in §4.11.7.8.

3.3.3.3 NASA-Only Architecture

Due to the decoupled nature of the EJSM flight elements, the NASA-only mission architecture is identical to the baseline JEO architecture. Note that the descope strategy for the NASA-Only mission would be identical to the baseline mission.

3.4 Opportunities for Synergistic Operations

The presence of two flight elements simultaneously touring the Jovian system opens up exciting investigation possibilities that would not be possible with a single flight element. **FO-4** highlights several examples of collaborative investigations that would be possible if both JEO and JGO were to arrive in the jovian system in late 2025 or early 2026.

In this example (assuming the ESA August 2008 CDF study for JGO and JEO's 08-008 tour), collaborative investigations of the jovian magnetosphere's interaction with the solar wind would start months before JGO, in this example, got to Jupiter. As JEO entered the magnetosphere, it would measure the inner magnetosphere while JGO was outside the magnetosphere, as Galileo and Cassini successfully did in late 2000 and early 2001. Not long afterward JEO, now on its large initial orbit would be again outside of the jovian magnetosphere while JGO moved into the magnetosphere. Given the geometry of the early orbits, the flight elements would exchange places several more times, allowing extensive spatial and temporal measurements of the changing magnetosphere to be made.

Another exciting collaboration would have JGO monitoring the Io Plasma Torus as JEO encounters Io, potentially allowing the correlation of specific volcanic activity to changes in the Io Plasma Torus.

Lastly, there would be the possibility of JEO flying slowly (~2 km/s) past Ganymede while JGO was in orbit around Ganymede. These opportunities would allow for extensive simultaneous measurements of different portions of the Ganymede magnetosphere.

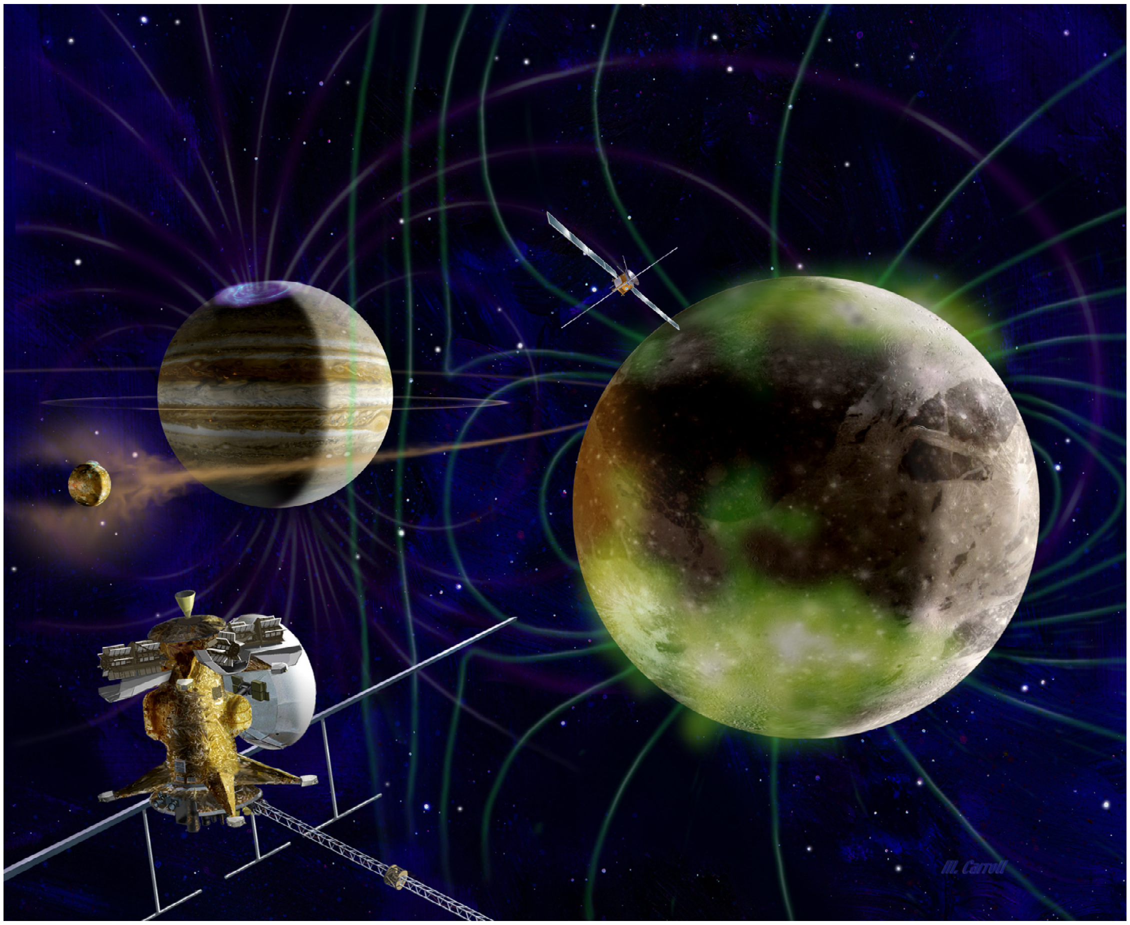


Figure 3.4-1. *Sister flight elements JEO and JGO provide synergistic science measurements as they soar through the Jupiter system enroute to their final destinations.*

The timelines for JEO and JGO shown in **FO-4,** weren't specifically developed with synergy in mind, suggesting that there would be dramatically more that could be accomplished were the two missions to be designed together for such synergistic measurements. Interestingly, such a design would not significantly compromise the measurements of either mission, and so even in the event that only one flight element made it to Jupiter, the other would still have a rich mission (**Figure 3.4-1**).

4. MISSION CONCEPT

JEO is the NASA element of the EJSM mission. Developed over years of critical scientific and engineering review, the baseline concept has leveraged the intellectual troves of 100s of scientists, engineers and operations personnel to provide a robust and resilient approach to achieving extraordinary science. It is designed to follow-up on the major discoveries of the Galileo and Voyager missions at Europa, especially its putative ocean. Great scientific strides were made when Galileo spent time in the Jupiter System. JEO would spend approximately the same time in it's prime mission but would return 3 orders of magnitude more data including >1 Tbit of data from the rooftops of Europa.

The remainder of the main body of this report will focus on the standalone JEO mission concept.

4.1 JEO Mission Architecture Overview and Context

The desire for an orbital mission to Europa was discussed in *Clark et al.* [*2007*] and is not reiterated herein. JEO launches on an interplanetary trajectory using Venus and Earth to gain energy and arrive at Jupiter 6 years later. After using Io's gravity to assist in capturing at Jupiter, JEO spends 2.5 years exploring the Jupiter system, making long term observations of the time-varying phenomenon and close-up encounters of the four Galilean satellites, **Figure 4.1-1**. Ending in a tight circular orbit at Europa, JEO takes advantage of Europa's very tenuous atmosphere (2 picobar) to perform over 9 months of extraordinary orbital investigations of the surface and interior. Low orbital altitudes (~100 km) can be maintained, and atmospheric absorption and scattering are not issues, allowing for optimal spatial resolution of remote sensing instruments. A low altitude greatly increases the sensitivity of radar sounding and magnetometry. The absence of atmospheric drag improves orbit and pointing knowledge, enabling measurements of higher order and time-dependent gravity field components accurately and quickly. Sputter-production of the tenuous atmosphere is useful in bringing material from the surface to the spacecraft. The benefits of exploring bodies with very tenuous atmospheres are also applicable to flybys of the other Galilean satellites. This JEO mission concept relies only on existing technologies and includes the payload capability to address both the Jupiter System and Europa science objectives.

An original cost cap of $2.1B (FY07) was directed for this study as documented in the study guidelines. In June 2008, that direction was changed to enable the study to focus on a mission concept which delivered a larger payload complement to more comprehensively address the science objectives. The Joint Jupiter Science definition team (JJSDT) originally produced the "core" payload which was the minimum set of instruments to address the science objectives. This "core" set of instrument was included in the original $2.1B (FY07) mission concept. An evaluation by the study JJSDT produced a prioritized set of instruments and capabilities which were added

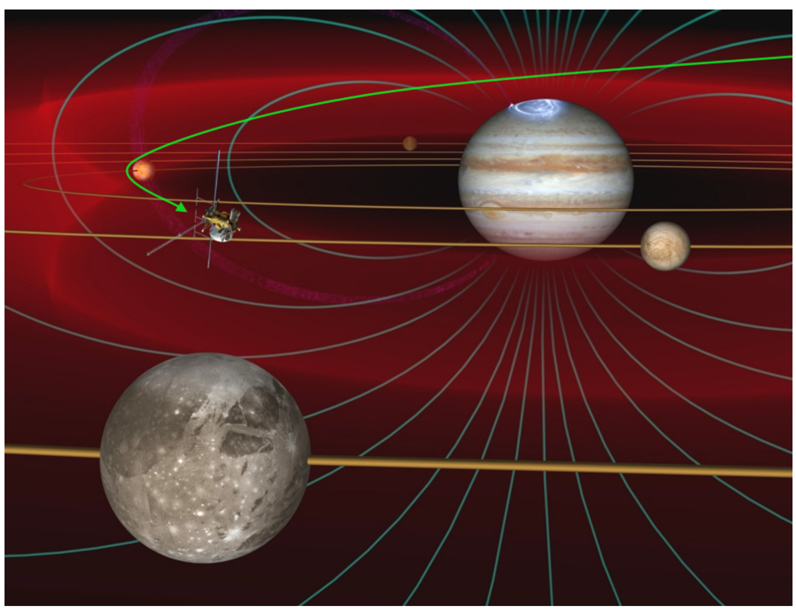


Figure 4.1-1. *JEO uses Io for a gravity assist prior to entering the JOI. For 2.5 years, JEO explores the Jupiter System making close flybys of the Galilean satellites including multiple flythroughs of Ganymede's magnetophere, observing Jupiter's smaller satellites, rings and dust and monitoring Io's volcanic activity and Jupiter's dynamic atmosphere.*

back to the "core" payload to produce a "sweet spot" mission as the best balance of science, cost and risk. This "sweet spot" mission has evolved slightly into the baseline the mission concept described within the remainder of this report. The "core" mission remains as the JJSDT's recommended floor mission concept.

4.1.1 Draft Level 1 Requirements

Level 1 requirements are negotiated between the NASA program office and the project after careful assessment of risk, allocated resources, and in consultation with JPL management, science representatives and key project staff. Preliminary level 1 requirements are required at end of Phase A with the final version approved by the end of Phase B. Notional level 1 requirements for this JEO mission study were developed to understand the driving interactions between science, implementation and risk. A draft of these requirements is outlined below.

4.1.1.1 Science Requirements

The JEO mission will achieve the science objectives of §2.0 by meeting the following requirements, which correspond to JEO science objectives A–E. [Brackets indicate specific values that are expected to be negotiated with NASA Headquarters.]

The Jupiter Europa Orbiter Project shall:

- Constrain the thickness of Europa's ocean and ice;
- Determine whether liquid water or thermal anomalies exist within Europa's ice shell;
- Identify key organic and inorganic chemical constituents on Europa's surface;
- Identify and characterize representative terrain types and landforms on Europa, including their topography;
- Quantify the Jovian radiation environment in both the spatial and temporal domains with emphasis on the region near Europa;
- Monitor and characterize the long-term [>2 years] volcanic activity of Io;
- Quantify the major constituents and determine the long-term [>2 years] dynamics of the Jupiter atmosphere;
- Quantify the long-term [>2 years] spatial and temporal structure of the Jupiter magnetosphere and its interaction with the Galilean satellites;
- Perform at least [two] close < [2000] km science encounters each of Io, Ganymede and Callisto during the mission tour phase.

4.1.1.2 JEO Mission Performance

- The JEO Mission shall utilize a launch period that opens in [February 2020],
- The JEO Mission shall achieve Jupiter and Europa orbits that supports the Science Requirements in §4.1.1.1.
- The JEO Mission shall characterize potential landing sites for future mission to the surface of Europa,
- The nominal end of the JEO mission operations shall be [9 months] after Europa Orbit Insertion and no later than [September 2030].

4.1.2 Key Challenges

The primary challenges of a mission to Europa are: Jupiter's radiation environment, planetary protection, high propulsive needs to get into Europa orbit and the large distance from the sun and Earth.

Radiation is the life limiting parameter for the flight system. Designing for the estimated radiation environment requires adequate knowledge of the environment, understanding of available hardware, conservative hardware and software design approaches and an approach to controlling the pervasive mission and system level impacts (including trajectory, configuration, fault protection, operational scenarios, and circuit design). Harnessing the experiences from NASA, academia, DoD, DoE, and industry is crucial to instilling the radiation-hardened-by-design concept at the mission concept level.

The high propulsive requirements to get into Jupiter orbit and subsequently into Europa orbit drives the large propellant load required and the dry mass of the propulsion subsystem to hold the propellant. Trajectory options, including gravity assists of Venus, Earth, and multiple Jupiter satellites lower the propellant requirements enough to enable this mission concept.

The solar insolation at Europa is 3 to 4% of that at Earth. This, combined with Jupiter's trapped radiation and the pointing and stability required to meet the identified science requirements, strongly favors the use of radioisotope power sources over solar array power systems. Juno manages to perform its mission by strictly avoiding the most severe radiation environments, avoiding eclipses, and using its battery for relatively short high-power periods.

The distance from Earth varies from 4 to 6.5 AU during the course of the orbital mission at Jupiter. This large distance requires a very capable telecommunications system to return the significant data required to meet the science objectives.

4.1.3 JEO Mission Description

The JEO mission concept encompasses three major components summarized in **Table 4.1-1**, while key mission parameters are shown in **Table 4.1-2**.

The baseline mission concept includes a single orbiter flight system which travels to Jupiter by means of a gravity assist trajectory and reaches Jupiter approximately 6 years after launch. The large main engine places the flight system into orbit around Jupiter followed by approximately 2.5 years of Jupiter System science while the flight system uses repeated satellite gravity assists to lower its orbit until a final burn inserts it into orbit around Europa.

Table 4.1-1. *JEO Mission Components*

Component	Description
Launch Vehicle	1. Atlas V 551 2. Support and procurement provided by Launch Planning Office at KSC 3. Launch mass capability of 5040 kg to C_3 of 12.8 km^2/s^2 for the February 2020 VEEGA opportunity
Flight System	4. Single Orbiter 5. Spacecraft (§4.4) • MMRTG Power Source supplied by the Department of Energy • Chemical Propulsion—dual mode Bi-propellant system • X up/down and Ka-Band down Telecommunications (Ka-Band up/down link for gravity science) 6. Launch Vehicle adapter 7. 5 individual Science Teams with Instruments selected via NASA Announcement of Opportunity
Ground System (Appendix G)	8. Ground Data System 9. Flight Operations Team (engineering and science) 10. Deep Space Network and related services

Table 4.1-2. *Key JEO Mission Parameters*

Parameter	Baseline Value	Notes
Instruments		
Number of instruments	11	Includes the on-board Ka-band uplink/downlink equipment for Radio Science in the baseline flight system. 5 Science Teams are identified with instruments solicited via AO being selected as a part of each Science Team.
Instrument mass	165 kg	Current Best Estimate. Includes 43 kg of radiation shielding for the detectors and 16.6 kg shielding for the instrument electronics which is carried by the spacecraft bus. Does not include Ka-band transponder (1.5 kg) and USO (1.5 kg) that are tracked in telecom.
Instrument power	71 W	Current Best Estimate, orbital average. This is the average power level over two consecutive Europa science orbits (one radar orbit and one optical remote sensing orbit). Does not include power for Ka-band transponder.
Science Accommodation		
Pointing accuracy	1 mrad (3 σ)	S/C body pointing control accuracy during nadir-oriented non-thrusting orbital period.
Pointing stability	10 µrad/s (3 σ)	For body-fixed instruments in science orbit during non-thrusting periods.
Minimum duration between reaction wheel orbit desaturations	24 hours	Minimum duration between desaturation thruster firings.
Science Data storage Tour/Europa Orbit	16 + 1 Gbits (tour), 1 Gbits (Europa orbit)	16 Gbits radiation tolerant SDRAM for tour. Radiation hardened, non-volatile, phase changing CRAM in baseline design for Europa orbit use.
Data volume	4.5 Tbits	Assumes 3 dB link margin, Ka band, 34 m stations, 90% weather, multiple data rates optimized for range, elevation, Jupiter presence, while in Europa orbit.
Spacecraft		
Available power at EOM	540 W	Power output from 5 MMRTGs at EOM
Delta V requirement	2260 m/s	Propellant mass is calculated assuming launch mass is equal to the launch vehicle capability (5040 kg).
Radiation design point	2.9 Mrad behind 100 mils of aluminum	Represents the reference design point without radiation design factor applied. Note that current trajectory. Results in a lower estimated dose.
Heliocentric operating range	0.7 to 5.5 AU	Minimum range defined by VEEGA trajectory.
Maximum Earth Range	6.5 AU	

The flight system uses a gravity assist of Io on approach to Jupiter just prior to Jupiter Orbit Insertion (JOI). Then using a series of Io, Ganymede, Europa, and Callisto flybys to lower its energy, most of the Jupiter System science objectives are achieved over a period of 2–3 years. Icy satellite flybys allow for focused science measurements while distant monitoring of Jupiter's atmosphere, Io's activity, Jupiter's ring system, the magnetosphere and other activities fill in critical pieces of information regarding how the system interacts and operates.

Once in Europa orbit and after initial 5-day engineering assessment period, the Europa Campaigns 1–3 span approximately 100 days (~28 eurosols) to address all identified Priority 1 science measurements meaning that data for preliminary assessment of key hypotheses will be available. These first 3 Europa Campaigns provide:

- 4 global maps: 2 at 200 m pixel resolution (1 color, 1 panchromatic), 2 at 100 km pixel resolution (both panchromatic which combine for stereo);
- LA and TI globally distributed profiles at an average of 18 km resolution;
- IPR (deep and shallow water search) and VIRIS globally distributed profiles at an average of 35 km resolution;
- 690 Imaging targets;
- 40 IPR targets;
- 550 UVS Stellar occultations.

Campaign 4 focuses on strengthening the initial data interpretation, filling in any holes from data outages and following up on discoveries. This Campaign is defined as 5.5 months to bring the total prime mission in orbit at Europa to 9 months. Extended missions past this Campaign would be anticipated.

At a starting altitude of 200 km at Europa (changing to 100 km after Europa Campaign 1), the flight system orbits Europa approximately 11 times in an Earth day. The planning payload is comprised of 11 instruments including radio science and is estimated at 165 kg (Current Best Estimate including shielding, CBE) with an 2-orbit average power of 71 watts (CBE). Over the course of Europa Campaigns 1–4 almost 4.5 Tbits of science data can be returned using a continuous Ka-band downlink strategy with the 34 m DSN capability. The Europa Campaign strategy is structured to address the science objectives in priority order. Global Europa science is addressed first, followed by more localized science as the orbital mission progresses.

4.1.4 Primary Mission Definition

The estimation of lifetime within the radiation environment at Europa is a challenging issue. The evolution of radiation lifetime estimation approaches from the traditional deterministic approach to the more modern statistical approach is the next step in efficiently using the typically hidden design margins within the system [*Clark et al. 2007*]. A 5.5-month Europa Campaign 4 was chosen as a balance between cost (~$8M [RY]/ month), radiation risk and science return (~3.2 Gbits/ day data volume). It would be natural to continue to operate the spacecraft for longer than the currently baselined Europa orbit of 9 months until it becomes inoperable.

For JEO, the baseline mission has adopted an Io gravity assist flyby prior to JOI to increase delivered mass to Europa. Including the Jupiter arrival, tour through the jovian system and the Europa orbital radiation dose, the flight system is designed to tolerate a Total Ionizing Dose environment of 2.9 Mrad behind 100 mils of aluminum.

The radiation design point required for designers to use known processes and procedures to design and analyze circuit performance. The chosen design point, 2.9 Mrad behind 100 mils of aluminum, corresponds to an allocation for the mission designers for 105 days in Europa orbit (the current trajectory results in a lower estimate than the allocation). By using a statistical approach to understanding mission lifetime, this design point results in a greater than 83% confidence of being fully functional at 9 months (see §4.5.2.2). Therefore, the primary mission is defined as tour plus 9 months in Europa orbit.

4.1.5 Floor Mission

The NASA Study ground rules for 2008 require that a NASA-only option and a floor option be investigated.

The process for defining the floor mission began with initial Ground Rules for the 2008 JEO study. The original Ground Rule was to define a mission to Europa, based on the 2007 study, which could be done for $2.1BFY07. This task was very difficult and included minimizing the payload, the flight time and the science operational time, to the point to where the JJSDT no longer felt the mission was worth the cost. Unfortunately, outer planet missions have costs which easily pass those of other types of missions. This is especially true of orbital missions which require significant propulsive capability and complexity.

The team worked very hard to define a mission that carried 7 very clearly defined Instruments (including radio science) a short flight time to Europa (small mass and short tour) and had a 100-day science mission at Europa. This, along with changes incorporated from the Operations Lessons Learned task (Appendix K), allowed the mission cost to reach just above the target value. The payload identified for that "core" mission is shown in **Table 4.1-3**.

Once this Ground Rule was lifted and the team was asked to provide a mission which balanced cost risk and science, the team went through a very methodical assessment of "plus-ups" defined by the JJSDT **Table 4.1-3**. The mass, power and cost were estimated for each potential addition. Then, the technical team sequentially "added" the capabilities to the "core" mission and a complete cost estimate for each step was estimated. The points where additional launch vehicle and power source capability was required was identified and those aspects were factored into the costs as well. The launch vehicle performance used was for the October 2018 opportunity to ensure that the mission could be launched early if desired. The results are

Table 4.1-3. *The identified "Plus Ups" were added to the core mission capability with estimated mass, power and cost. The results were evaluated and a final floor and baseline capability resulted.*

"Plus Up" Priority	"Plus Up"	Capability	Mission Accommodation
Core	Radio Science	X-band Up and Down, Ka-band Down	Floor
Core	Laser Altimeter	Single spot	Floor
Core	Near-IR Spectrometer	400–2600 nm	Floor
Core	Ice Penetrating Radar	2 band, 5 Mhz and 50 Mhz	Floor
Core	Wide and Medium Angle Camera	Wide: Color, Medium: panchromatic	Floor
Core	Dual Magnetometer	Dual 3-axis fluxgate sensors, 10 m Boom	Floor
Core	Plasma Instrument	10–30 KeV electrons and Ions	Floor
1	Narrow Angle Camera	Color	Baseline
2	Augmented IR	Expand to 400 – >5200 nm	Baseline
3	Hybrid Solid State Recorder	Add 16 Gbits storage for Tour Science	Baseline
4	Diverse Tour	10 additional months	Baseline
	ATLAS V 541 to 551		**Baseline**
5	Simple Ultraviolet Spectrometer (UVS)	Basic capability (70–190 nm)	Baseline
6	Simple Thermal Instrument	8–20 microns and 20–100 microns	Baseline
7	Interdisciplinary scientists	6 Interdisciplinary Teams	Baseline
8	Particle Instrument	Higher energy electrons and ions	Baseline
9	Op-Nav functionality	Add requirements on NAC	Baseline
10	Ultra Stable Oscillator (USO)	Add to Telecom Subsystem	Baseline
11	Multi-spot Laser Altimeter	Multi-spot	
12	Stereo to MAC	Stereo	
13	Ion and Neutral Mass Spectrometer (INMS)	1–300 Daltons	Baseline
	Add MMRTG and go to Delta IVH		
14	Dust Detector	Basic capability	
15	Augmented UV	Expand capability to 30–350 nm	
16	Ka-band Uplink	Requires Ka-band transponder	Baseline
17	Penetrator Demonstration	Assumed 50 kg contribution	
18	Extended Europa Science phase	5.5 additional months	Baseline
19	Cassini IR Spectrometer (CIRS)	Expanded thermal range and sensitivity	

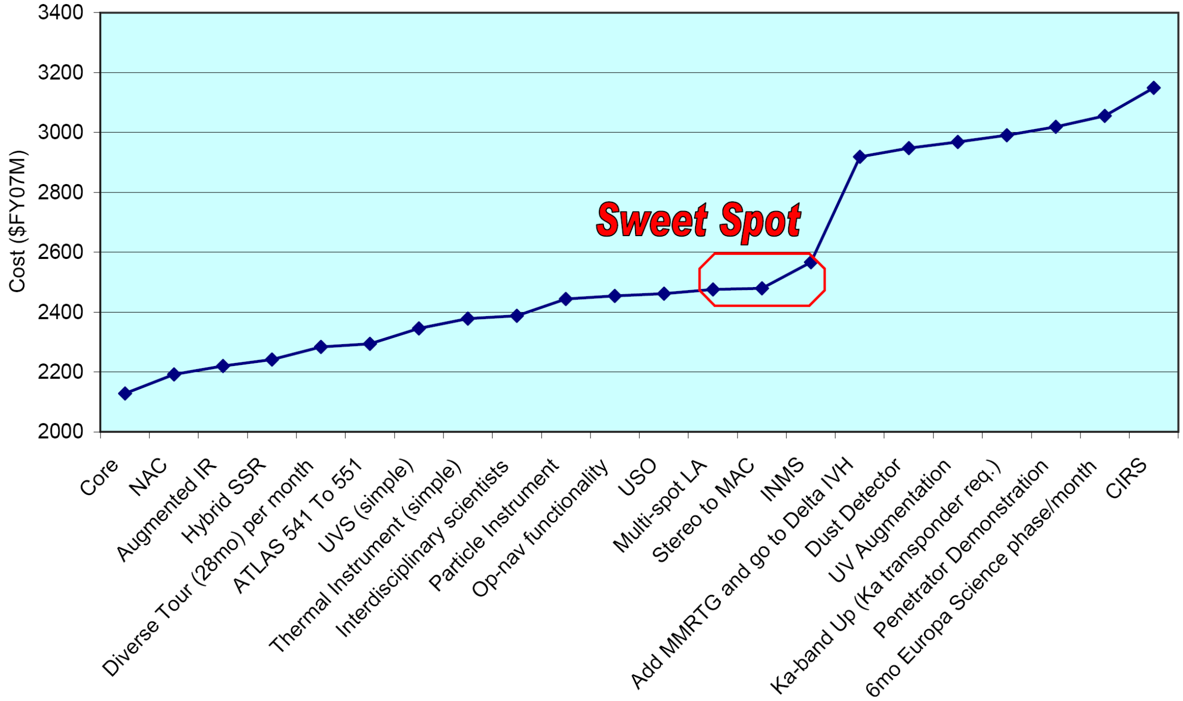


***Figure 4.1-1**. The "Sweet Spot" was defined to be the point just before the cost curve takes a significant steep turn*

shown in **Figure 4.1-1**. The "Sweet Spot" was determined to be the point just before the cost curve takes a significant steep turn.

After the "Sweet Spot" analysis some minor alterations were worked with the JJSDT including better estimates of resources required for the "plus-up". The longer time in Europa orbit was strictly a cost impact and was determined to be very valuable programmatically though the JJSDT did not originally include it in the sweet spot. The first 100 days of science answer the highest priority science objectives, but the extended time allows for follow-up on unanticipated discoveries and allows mission flexibility. The actual plus-ups which were incorporated into the baseline mission are indicated in **Table 4.1-3**.

Once the baseline mission was fully developed, the JJSDT re-assessed the order in which the descopes would be taken from a science perspective. The final descope order the JJSDT recommends from a science perspective is slightly different from the reverse "plus up" order and is shown in **Table 4.1-4**. A comparison of the major attributes of the baseline and floor mission concepts is shown in **Table 3.3-2**.

***Table 4.1-4.** Final descope order based on science priorities identified by the JJSDT*

Descope Order	Descope Item
1	Ka-band Up (Ka transponder req.)
2	Color on the NAC
3	Energetic particle capability
4	USO
5	INMS
6	OpNav Functionality
7	Reduce Europa Science Phase by 5.5 month
8	6 Interdisciplinary scientists
9	Thermal Instrument
10	UVS
11	ATLAS V 551 to 541
12	Tour Phase reduced by 10mo
13	Hybrid SSR
14	Descope IR Capability (Reduce to 0.9 – 5 μm, with decreased spatial and spectral resolution)
15	NAC

4.1.6 NASA-Only Mission

After discussion with the JJSDT, the consensus was that the NASA-only mission is identical to the baseline JEO mission and has the same descope path.

4.2 Science Instrumentation

4.2.1 Model Payload

The model payload presented here uses only publicly available information and was selected to address the highest-priority science measurements. By taking this approach, the JJSDT acknowledges that not all measurements are fully addressed by the model payload. This conservative strategy enables detailed analysis of the radiation mitigation techniques required to meet the science objectives and thus providing a conservative accountable estimate of resources (cost, mass, and power) versus performance.

The JEO model payload, while notional, is used to bound the engineering aspects of the mission and spacecraft design and to define operational scenarios required to obtain the data necessary to meet the science objectives. For the purposes of this study, instruments were defined to demonstrate a viable approach to meeting the measurement objectives, performing in the radiation environment, and meeting the planetary protection requirements. Therefore, instrument descriptions are provided here to show proof of concept; they are not final selections nor final implementations. Heritage or similarities discussed refer to instrument techniques and basic design approaches, and do not imply that specific implementations are fully viable in their detail. Physical and electrical modifications of previous designs will be required for all instruments to function within the context of the mission requirements, and these modifications are included in the mass and cost estimates. The instrument mass estimates assume only currently available detector performance. Advanced developments have been included in the cost estimates but their projected performance improvements have not been assumed in these performance calculations. Alternative instrument concepts and techniques that meet the mission objectives may be selected via NASA's Announcement of Opportunity (AO) process, and the instrument capabilities presented are not meant to prejudge AO solicitation outcome.

As introduced in §2.5.2, the model payload selected for the JEO study consists of a notional set of remote sensing instruments, *in situ* instruments, and both X-band and Ka-band telecommunications systems which provide Doppler and range data for accurate orbit reconstruction in support of geophysical objectives. Instrument representatives on the JJSDT (or identified by JJSDT members) were utilized extensively to understand the requirements for each instrument. **Table 4.2-1** presents the estimated resource requirements for each instrument and for the total model payload, while **Foldout 5 (FO-5)** summarizes the instruments and their capabilities. A more detailed mass estimate for each instrument is included in Appendix D and in the accompanying Instrument Data Package on the Report CD, as input for the NASA Instrument Cost Model (NICM).

4.2.1.1 Payload Accommodation

All remote sensing instruments in the model payload nominally view in the nadir direction when in orbit around Europa, as shown in **FO-5**. Because JJSDT analysis indicates that nominal nadir pointing of the remote sensing instruments meets the science objectives, spacecraft-provided scan platforms are not baselined. Individual instruments that require scan systems for target tracking or target motion compensation must provide such a system as an integral part of the instrument. Two notional instruments in the model payload, the UV Spectrometer (UVS) and the VIS-IR Spectrometer (VIRIS), assume such systems.

Adequate instrument mounting area for the science payload on the nadir-facing deck is available (see **FO-5**). *In situ* instruments with wide fields of view, such as particle and plasma sensors, are located to minimize obstructions in those fields of view. Note that the high-gain antenna (HGA) is deployed well clear of instrument fields of view and is 2-axis articulated to decouple instrument pointing from the telecom link to Earth. Instrument mounting and accommodation requirements are summarized in **Table 4.2-1**.

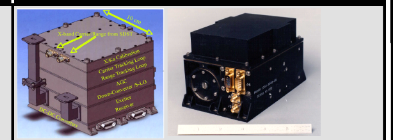
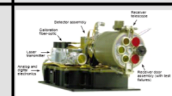
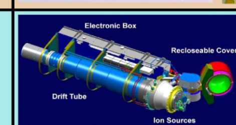
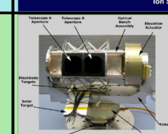
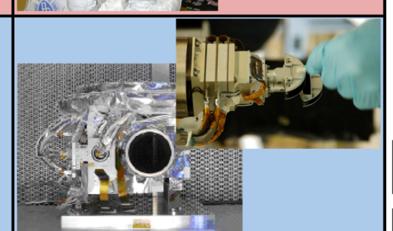
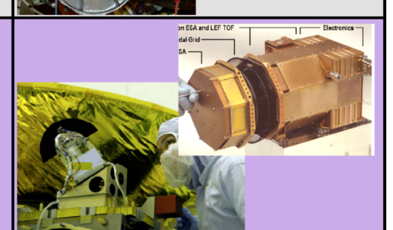
The JEO mission design calls for an orbit at Europa with 95° to 100° inclination and orbit plane orientation provides local time such that one side of the spacecraft is protected from the Sun and an ideal location for thermal radiators. The science payload is expected to contain instruments with detectors requiring cooling to as low as 80 K for proper operation while dissipating perhaps 300 mW of heat. Cooling to this level would be accomplished via

***Table 4.2-1**. JEO model payload resource requirements and accommodations.*

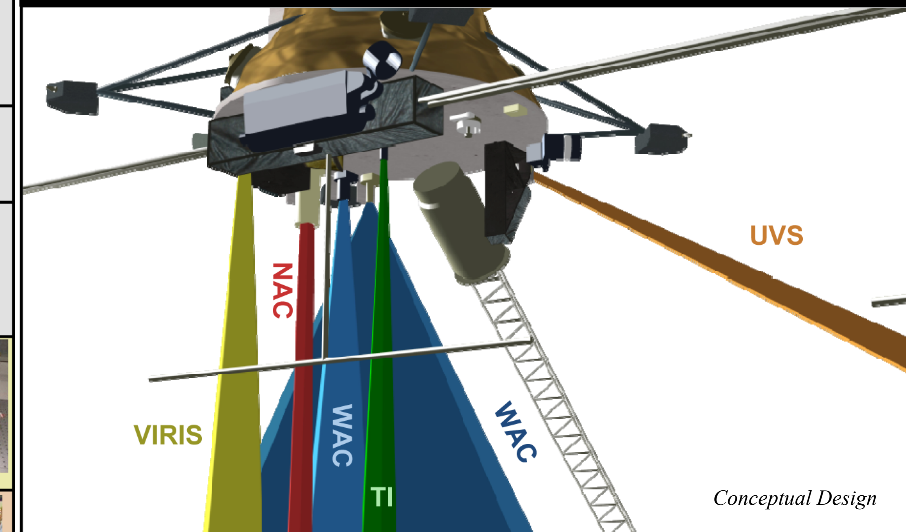
Instrument	Acronym	Unshielded Mass (kg)	Shielding Mass (kg)	Total Mass (kg)	Operating Power (W)	Instantaneous Telemetry Bandwidth (kbps)	Telemetry Interface	Science Electronics Chassis Board Count	Field of View	Pointing
Laser Altimeter	LA	5.0	4.7	9.7	15	2	Mil-Std-1553	2	0.029° diameter spot	Nadir
Ice Penetrating Radar	IPR	26.0	5.0	31.0	45	140	SpaceWire	6	5.7° swath width	Nadir
VIS-IR Spectrometer	VIRIS	15.7	11.8	27.5	25	11,400	SpaceWire	3	9.17° × 0.014°	Nadir ± 45°
UV Spectrometer	UVS	6.4	3.1	9.5	5	10	Mil-Std-1553	1	3.67° × 0.057°	Nadir to anti-ram
Ion and Neutral Mass Spectrometer	INMS	13.0	2.1	15.1	33	2	Mil-Std-1553	2	20° × 40°	Ram
Thermal Instrument	TI	3.7	1.3	5.0	5	15	Mil-Std-1553	1	3° × 0.14°	Nadir
Narrow-angle Camera	NAC	10.4	3.0	13.4	14	10,700	SpaceWire	2	1.17° × 0.00057° Pushbroom mode 1.17° × 1.17° Framing mode	Nadir
Wide-angle Camera and Medium-angle Camera	WAC	2.3	1.5	3.8	6	213	SpaceWire	1	58° × 0.057°	Nadir
	MAC	2.6	1.5	4.1	7	1,065	SpaceWire	1	11.7° × 0.0057°	Nadir
Magnetometer	MAG	3.2	0.0	3.2	4	4	Mil-Std-1553	1	N/A	
Particle and Plasma Instrument	PPI	7.6	8.8	16.4	13	2	Mil-Std-1553	2	Plasma: 360° × 90° torus Particles: 160° × 12° fanbeam Onmi Electrons: 4π	
Science Electronics Chassis		10.0	16.6							
TOTAL ALL INSTRUMENTS		**105.9**	**59.4**	**165.3**	**172**			**22**		
TOTAL ALL INSTRUMENTS + 30% contingency				**214.9**	**224**					

Note: Resource requirements for the Ultra-Stable Oscillator and Ka-band Translator used for Radio Science are carried as part of the spacecraft telecommunications system. See Section 4.4.

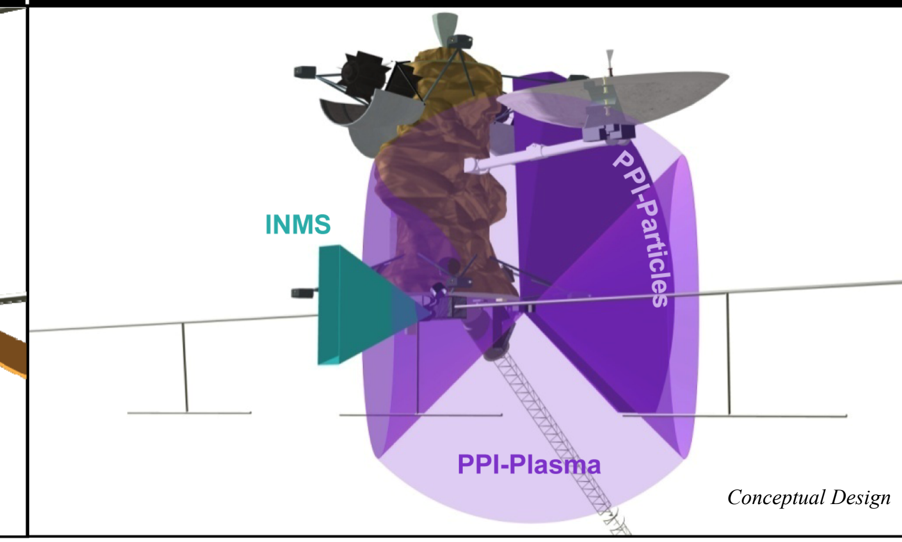
FOLDOUT 5
INSTRUMENT CAPABILITIES SUMMARY

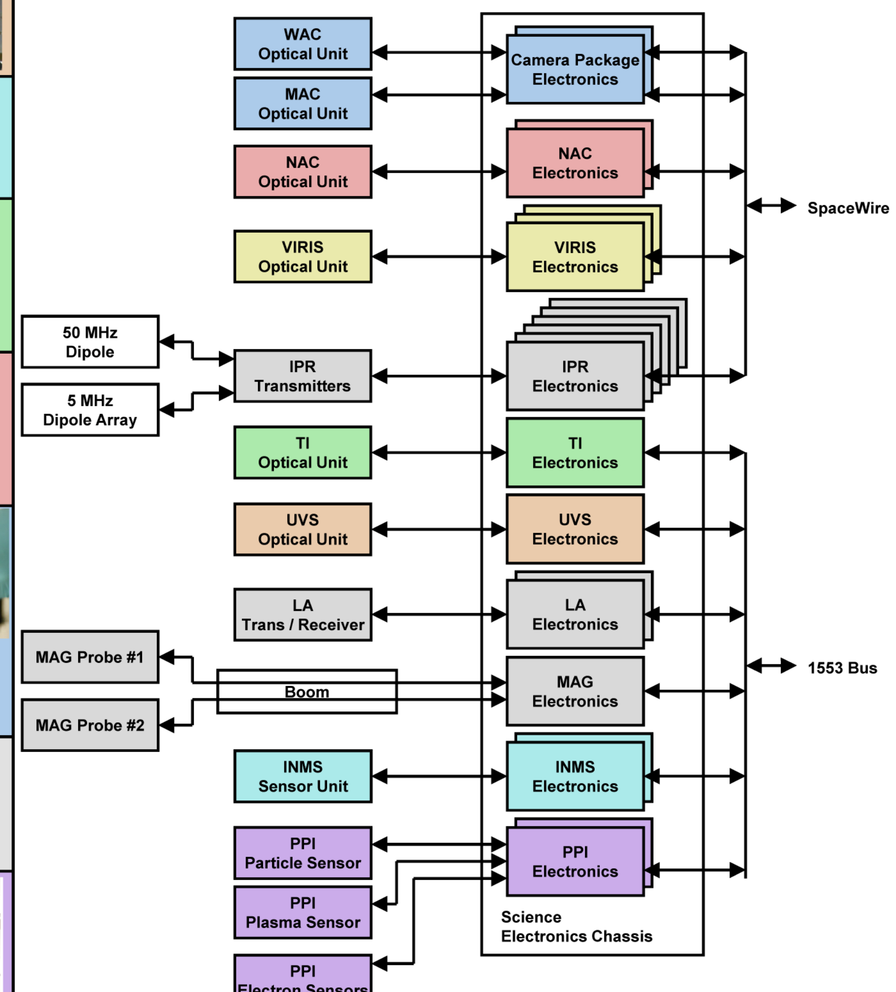
Team	Instrument	Characteristics	Similar Instruments	
Ocean Team	Radio Science (RS)	**Ka-band Transponder** **Doppler Accuracy:** 0.01 mm/s **Integration Time:** 60 seconds for stated accuracy **Ultra Stable Oscillator** **Stability:** 2 x 10^{-13} **Timescales:** 1 to 100 seconds for stated stability	Cassini Juno New Horizons GRAIL	
Ocean Team	Laser Altimeter (LA)	**Time-of-Flight Laser Rangefinder** **Transmitter:** 1.064 µm laser **Detector:** Avalanche Photodiode **Resolution:** better than 1 m vertical **Spatial:** 50 m laser spot size, 26 Hz pulse rate	NEAR NLR MESSENGER MLA LRO LOLA	
Ice Team	Ice Penetrating Radar (IPR)	**Dual-Mode Radar Sounder** **Shallow Mode:** 50 MHz with 10 MHz bandwidth **Vertical Depth:** ~3 km **Vertical Resolution:** 10 meters **Deep Mode:** 5 or 50 MHz with 1 MHz bandwidth **Vertical Depth:** ~30 km **Vertical Resolution:** 100 meters	Mar Express MARSIS MRO SHARAD	
Chemistry Team	Vis-IR Spectrometer (VIRIS)	**Pushbroom Imaging Spectrometer** **Detector:** two HgCdTe arrays **Spectral Range:** 400 to > 5200 nm **Spectral Resolution:** 5 nm from 400 to 2600 nm **Spectral Resolution:** 10 nm from 2600 to 5200 nm **Spatial Resolution:** 25 m from 100 km orbit **FOV:** 9.2 deg cross-track **IFOV:** 0.25 mrad **Articulation:** Along-track scan mirror	MRO CRISM Chandrayaan MMM	
Chemistry Team	UV Spectrograph (UVS)	**Grating Spectrometer + High-Speed Photometer** **Detector:** MCP + position sensitive anode **Format:** 1024 spectral x 64 spatial pixels **Spectral range:** 70 – 200 nm **Spectral Resolution:** 0.5 nm **Spatial Resolution:** 100 m from 100 km orbit **FOV:** 3.7 deg cross-track **IFOV:** 1 mrad **Articulation:** 1-D scan system for stellar occultations	Cassini UVIS New Horizons Alice	
Chemistry Team	Ion Neutral Mass Spectrometer (INMS)	**Reflectron Time-of-Flight Mass Spectrometer** **Mass Range:** 1 to > 300 Daltons **Mass Resolution:** > 500 **Pressure Range:** 10^{-6} to 10^{-7} mbar **Sensitivity:** 10^{-4} A/torr **FOV:** 10 x 40 deg	Rosetta ROSINA RTOF	
Geology Team	Thermal Instrument (TI)	**Temperature Sensing Thermopile Array** **Detector:** Thermopile array with filters **Detector Configuration:** 21 pixels cross-track, 6 bands **Spectral Bands:** 8-20µ, 20-100µ, 21µ, 28µ, 40µ, 17µ **Temperature Range:** >160K to 80K **Spatial Resolution:** 250 m **Resolution:** 2K **IFOV:** 2.5 mrad	MRO MCS LRO Diviner	
Geology Team	Narrow-angle Camera (NAC)	**Pushbroom and Framing Imager** Panchromatic Pushbroom Imager + Color Framing Imager **Detector:** CMOS array or CCD array + line array **Detector Size:** 2048 pixels wide **Color Bands:** 9 plus panchromatic **Spatial Resolution:** 1 m from 100 km orbit FOV: **1.2° IFOV: 0.01 mrad IFOV** **Mechanism:** Filter wheel	New Horizons LORRI	
Geology Team	Camera Package (WAC+MAC)	**WAC - Pushbroom Imager with fixed color filters** **Detector:** CMOS or CCD line arrays (4) **Detector Size:** 1024 pixel line arrays (4) **Color Bands:** <450 nm, 630-670 nm, >930 nm **Spatial Resolution:** 100 m from 100 km orbit **FOV:** 58° line scan, **IFOV:** 1 mrad **MAC - Panchromatic Pushbroom Imager** **Detector:** CMOS or CCD line array **Detector Size:** 2048 pixels **Spatial Resolution:** 10 m from 100 km orbit **FOV:** 11.7 deg line scan **IFOV:** 0.1 mrad	MRO MARCI MESSENGER MDIS New Horizons MVIC	
Fields & Particles Team	Magnetometer (MAG)	**Dual 3-axis Fluxgate Magnetometer** **Boom:** 10 m **Sensor Location:** 5-m and 10-m from s/c **Dynamic Range:** 3000 nT **Sensitivity:** 0.1 nT **Sampling Resolution**: 0.01 nT **Maximum sampling rate:** 32 Hz	MESSENGER MAG Galileo MAG	
Fields & Particles Team	Particle and Plasma Instrument (PPI)	**Plasma: Top Hat Analyzer** **Energy Range:** 10 eV to 30 KeV electrons **Energy Range:** 10 eV to 30 KeV ions with composition **FOV:** 360° x 90° **Particles: Puck Analyzer** **Energy Range:** 30 KeV to 1 MeV electrons **Energy Range:** 30 KeV to 10's of MeV ions **FOV:** 120° x 20° **High Energy Electrons: Omnidirectional SSDs** **Energy Ranges:** >2 MeV, >4 MeV, >8 MeV, >16 MeV	DS1 PEPE MESSENGER FIPS New Horizons PEPSSI JEDI	

Optical Instrument Fields of View



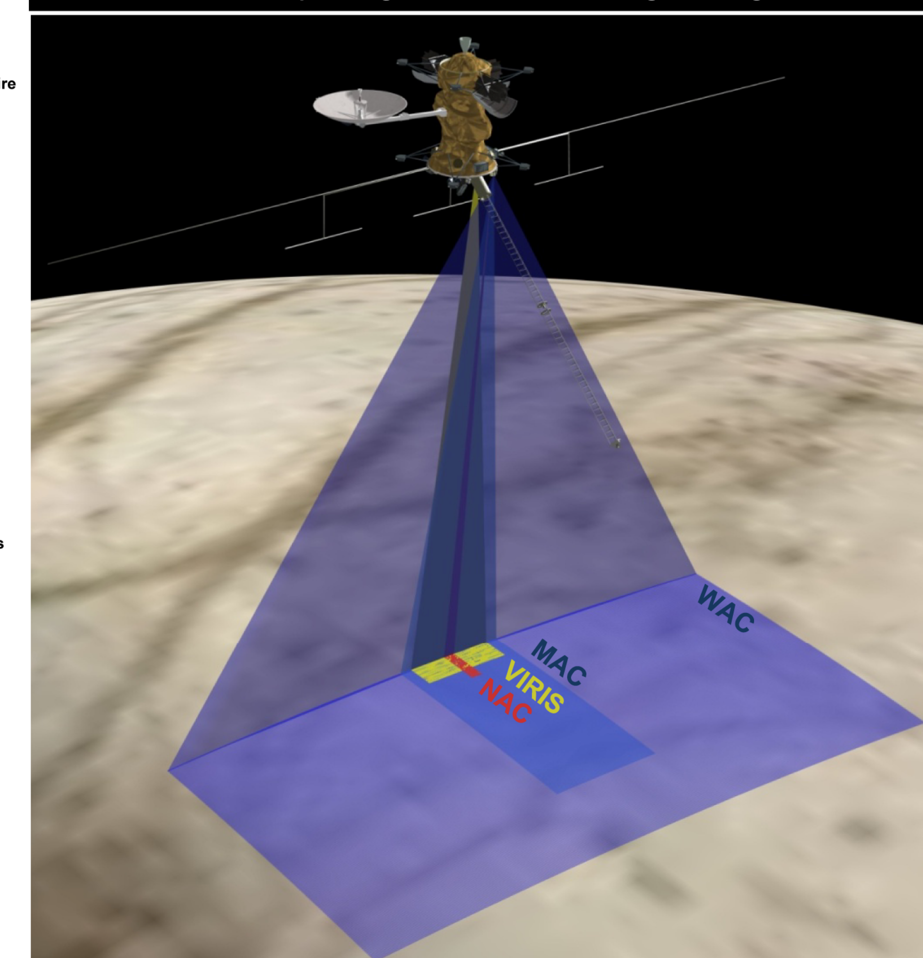
In-Situ Instrument Fields of View





Instrument electronics are co-located for efficient radiation shielding

JEO capturing a coordinated target image



passive radiators, mounted so their view is directed away from the Sun and away from Europa at all times. Jupiter will move across the radiator field of view (FOV) every 3.5 days, subtending a small portion of the radiator FOV and presenting a transient perturbation to instrument thermal system designs. Preliminary analysis indicates that a 0.25 m^2 radiator is sufficient to achieve a detector temperature of 80 K with less than 5 K variation in detector temperature due to the effect of Jupiter. The impact on instrument thermal design and/or operational constraints imposed by this thermal perturbation will be addressed during Phase A.

The remote sensing instruments will require spacecraft pointing control to better than or equal to 1 mrad, stability to 10 μrad/s and reconstruction to 0.1 mrad. Pointing requirements are driven by the Narrow-angle Camera (NAC) which has a 10 μrad pixel field of view and while NAC exposure times in Europa orbit are on order of 1 ms, longer exposure times will be required during the tour phase of the mission. To achieve the Europa geophysical science objectives connected with characterizing the subsurface ocean and the overlying icy shell, the JEO orbit must be reconstructed to an accuracy of 2 m in the radial direction. To achieve this level of accuracy, adequate levels of Doppler tracking are required and with thruster firings restricted to not more than one per 24 hours.

The limited capacity of the spacecraft solid state recorder (SSR) (see §4.4.3.5), coupled with near-continuous collection and downlink of instrument data during Europa orbit, requires that high-data-rate instruments perform data reduction and data compression before sending the data to the SSR. The notional model payload block diagram (**FO-5**) assumes this data system architecture with SpaceWire interfaces baselined for the instruments having high data rates and Mil-Std-1553 interfaces assumed for those having low data rates.

4.2.1.2 Radiation and Planetary Protection

The severe radiation environment at Europa presents significant challenges for the science instruments, as does the need to meet the planetary protection requirements outlined in §4.7. These challenges have been addressed by a notional payload architecture that efficiently implements radiation shielding, the use of radiation hardened application specific integrated circuits (ASICs) throughout the payload, and by a thorough study of both radiation effects and the impact of planetary protection protocols on detectors by a Detector Working Group (DWG). The DWG developed a methodology for determining the required radiation shielding for successful instrument operation in the severe transient radiation environment at Europa, assessed degradation of detectors due to total dose and displacement damage effects, and assessed the compatibility of candidate detectors with the planetary protection protocols.

Payload Architecture

The mission radiation design point (§4.1.4) is 2.9 Mrad behind 100 mils of aluminum shielding without design margin, as described in §4.5.3.2. Therefore, sensors and supporting electronics require significant shielding. The most mass-efficient approach to providing radiation shielding is to centrally locate as much of the instrument electronics as possible, minimizing the electronics that must be co-located with the sensor portion of the instrument. The model payload design presented here assumes instrument partitioning in this manner, as shown in **FO-5**, and includes a science electronics chassis implemented using the industry standard 6U Compact PCI form-factor. Space for 22 electronics boards is baselined, with radiation shielding sufficient to allow use of components hardened to 300 krad without additional spot shielding. The total radiation shielding mass for the science electronics chassis is estimated to be 16.6 kg. Internal partitioning of the science electronics is baselined to provide electrical isolation between instruments and to mitigate electromagnetic interference (EMI). Louvers provide thermal control of the science electronics chassis in the same manner used for the spacecraft avionics systems.

Application Specific Integrated Circuits

At present it is assumed that field programmable gate arrays (FPGAs) will not be used on JEO pending further analysis of radiation effects and long-term reliability of these devices (currently ongoing). Radiation-hardened ASICs have been assumed instead of FPGAs. Both existing, heritage radiation-hardened ASICs and new ASIC developments are shown in the notional instrument designs presented in this report. This is a conservative position that will be reassessed as new information becomes available.

Detector Working Group

The Detector Working Group (DWG), established as part of our study, was charged with assessing the existence of a feasible pathway for photonic detector technologies required by the JEO model payload. The DWG included experienced instrument, detector, and radiation environment experts from APL and JPL. The DWG used an empirical approach to determine worst-case estimates of the effects of electrons and protons incident on detectors. This information was used to assess the performance potential of existing detector technologies subjected to the end-of-mission total dose. Additionally, the impact of radiation-induced transient noise in each detector technology was evaluated for radiation flux levels encountered during Europa orbit as well as at mission peak flux during Io flybys. Finally, the tolerance of each detector technology to dry heat microbial reduction (DHMR) for planetary protection was evaluated.

The DWG concluded that the radiation and planetary protection challenges facing the model payload are well understood. The question of detector survivability and science data quality is not considered to be a significant risk provided appropriate shielding is allocated to reduce cumulative TID, DDD and instantaneous electron and proton flux at the detector, and early mitigation approaches are implemented. Radiation shielding allocations and the impact of radiation-induced transient noise on science data quality are presented for each instrument of the model payload in subsequent sections of this report. The full DWG assessment report may be found under separate cover (*Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study,* JPL D-48256). Specific activities to support early education of potential instrument providers to the complexity of meeting radiation and planetary protection requirements have been identified, and the first of a series of instrument workshops has been completed.

Detector Radiation Noise Methodology

The impact of radiation-induced transient noise on detectors was analyzed by estimating the number of high-energy electrons and protons penetrating the radiation shield and assessing their effect on the detector material. The flux of incident electrons reaching the detector for different radiation shielding thicknesses T can be estimating by applying the cutoff energy E determined from

$$E(\text{MeV}) = [T(\text{gm/cm}^2) + 0.106]/0.53$$

[*Zombeck 1982*] to the external integral electron flux. For 1 cm of Ta shielding, an estimated 4.3×10^5 electrons/cm^2·s would reach the detector while in orbit at Europa. During Io flybys, the flux of incident electrons would increase by approximately a factor of 8 to a rate of 3.5×10^6 electrons/cm^2·s. The flux of incident protons reaching the detector can be estimated by applying a 100-MeV cutoff energy to the external integral proton flux. For 1 cm of Ta shielding, about 50 protons/cm^2·s would reach the detector while in orbit at Europa. During Io flybys, the flux of incident protons would increase by approximately a factor of 18 to a rate of 920 protons/cm^2·s. The predominance of electrons in the Jovian environment is the determining factor for the detector radiation shielding analysis presented in subsequent sections.

Planetary Protection Protocols

The approach to planetary protection compliance for the JEO mission is presented in full in §4.7 and can be summarized as follows:

- Pre-launch sterilization to control the bioburden for areas not sterilized in flight,
- In-flight sterilization via radiation prior to Europa orbit insertion.

The preferred method of sterilization is DHMR. It is assumed that each instrument will be separately sterilized before integration onto the spacecraft. Current planetary protection protocols include a time vs. temperature profile ranging from 125°C for 5 hours to 110°C for 50 hours. It is anticipated that in some cases contamination control bake-out parameters can be modified to allow bioburden reduction credit. During assembly, test and launch operations (ATLO) it is assumed that cleanliness will be maintained (as for the Mars Exploration Rovers and the Mars Science Laboratory) to ensure that surface spore density does not exceed 300 spores/m^2, so that remaining surface spore bioburden will be sterilized via radiation during flight. To prevent recontamination after sterilization and to support cleaning operations during ATLO, high-efficiency particulate air (HEPA) filters and instrument aperture covers with biobarriers are baselined.

The project will generate and disseminate planetary protection guidelines to potential instrument providers early, allowing providers to adequately address planetary protection issues during the instrument selection process. A mid-Phase B Payload Planetary Protection Review is baselined so that issues and mitigation strategies can be identified and addressed. Instrument-specific planetary protection concerns are addressed in subsequent sections.

4.2.2 Instrument Descriptions

4.2.2.1 Laser Altimeter

The notional Laser Altimeter (LA) is a diode-pumped Cr:Nd:YAG Q-switched laser transmitting at 1.064 µm with an optical receiver and time-of-flight (TOF) sensing electronics. The notional design employs elements of the Lunar Orbiter Laser Altimeter (LOLA), the Mercury Laser Altimeter (MLA), and the NEAR Laser Rangefinder (NLR). The LA baselined for JEO is tailored to satisfy the following science requirements, as indentified in §2.5.

- Topographic differences at cross-over points from globally distributed topographic profiles with:
  – Better than or equal to 1 m vertical accuracy (1 m rms in range to the same spot)

Instrument Description

The notional LA includes a 0.5 mrad beam expander to produce a single 50 m laser spot from the 100 km orbit. A pulse rate of 26 Hz provides contiguous spots and 50 m along-track resolution, assuming a 1300 m/s ground track rate from the 100-km orbit. With each orbit crossing every previous orbit twice, in the course of 60 days over 1 million points are available for cross-over analysis.

The notional laser transmitter is based upon the "Heritage Laser" developed by the multi-year NASA Laser Risk Reduction Program (LRRP) [*Seas et al. 2007*] and shown in **Figure 4.2-1**. The Heritage Laser design incorporates elements of the MLA and LOLA instruments and lessons learned from the LRRP effort itself. The baseline characteristics of the passively Q-switched diode pumped Cr:Nd:YAG laser allow up to 30 mJ, 6 ns pulses at rates up to 150 Hz. For JEO, a nominal output of ~3 mJ at 26 Hz is baselined, maintaining similarity to the LOLA laser transmitter. The Cr:Nd:YAG slab is assumed to be side pumped with a gallium arsenide (GaAs) diode array at 809 nm similar to that used by NLR.

The notional optical receiver is based on a scaled version of the lightweight reflective telescope used by NLR and shown in **FO-5**. The output of the telescope is passed through a spectral filter and presented to an avalanche photodiode (APD) operating in linear mode with gain of ~100 (per NLR) to minimize radiation effects.

Telescope sizing is obtained by comparison to the NLR link analysis, which assumes a 15 mJ transmitter, 8.9 cm-diameter receiver telescope with ~50-cm^2 unobscured collecting area, and 15% surface albedo. While initially designed for a 50 km range, NLR achieved a 95% probability of detection for a single shot at 160 km range using 15 mJ of transmit power (vs. the initially specified 5 mJ) [*Cole et*

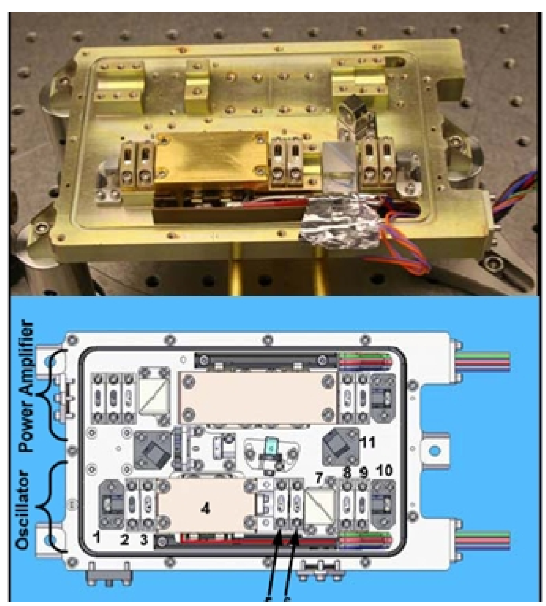


Figure 4.2-1. *Heritage Laser developed by the NASA Laser Risk Reduction Program and baselined for the notional JEO Laser Altimeter.*

al. 1997]. Scaling for lower transmit power, (2.7 mJ is assumed per the LOLA transmitter), a range of 200 km and a surface albedo of 67% at Europa, an unobscured collecting area of ~100 cm^2 is required for the notional LA. Assuming the same obscuration ratio as the NLR telescope, a 12.5-cm-diameter receiver telescope is baselined for JEO. Comparisons to MLA and LOLA link analysis provided similar results.

The notional TOF system is a low-power design based on the range measurement system used by MLA, which employs a coarse counter (5 MHz) and precision timing offset measurements made using multiple radiation hardened TOF ASICs to achieve timing resolution equivalent to a 2 GHz counter [*Cavanaugh et al. 2007*]. A commandable range gate masks system noise during laser firings and masks transient background radiation noise in the APD detector. The MLA range measurement scheme can acquire and downlink multiple returns per shot, and this system can be adapted to directly measure return pulse dilation to correct for topographically induced range-walk. The MLA range error budget [*Cavanaugh et al. 2007*] totals 1 m rms with errors dominated by spacecraft orbit knowledge errors (0.75 m) and spacecraft pointing angle uncertainty (0.13 mrad). The expected performance of the JEO spacecraft, 0.25 m radial orbit knowledge (with Ka-band) and 0.10 mrad pointing uncertainty, allows the notional LA to meet the 1 m rms vertical accuracy requirement.

A physical and functional block diagram of LA is shown in **Figure 4.2-2**. The laser transmitter and optical receiver are located on the nadir-facing deck of the spacecraft while the laser transmitter power supply, TOF system, system controller, and spacecraft interface electronics are packaged as two 6U cPCI boards and located in the science electronics chassis, which provides radiation shielding sufficient for components tolerant of 300 krad.

Radiation Effects and Shielding

The LA laser transmitter contains four main components requiring radiation shielding: GaAs laser diodes, Cr:Nd:YAG laser slab, LiNbO3 Q-switch and the fiber optic pickoff that provides the start pulse to the TOF system. The significant radiation issue for GaAs laser diodes is proton displacement damage. Testing with 5.5-MeV protons to a level of 6×10^9 MeV/g, beyond the expected JEO end-of-mission dose, showed only a minor shift in threshold current and no change in quantum efficiency [*Johnston 2001*]. The significant radiation issue for Cr:Nd:YAG is total dose. Testing to 500 krad showed a negligible change in output power, with the level of Cr_3^+ doping a determining factor [*Rose et al. 1995*]. Significant radiation issues for $LiNbO_3$ are total dose and displacement damage. Gamma irradiation of $LiNbO_3$ to levels far beyond that expected by JEO showed a minimal change of insertion loss [*Tsang and Radeka 1995*]. No corresponding data on displacement damage were reviewed for this study. The significant radiation issue for fiber optics is total dose. Testing observed only a 0.5 dB/m transmission loss in single-mode Ge-doped fiber optics after irradiation with 1×10^6 gray (Gy) [*Henschel et al. 1995*]. While an exhaustive survey of radiation test results for the materials required

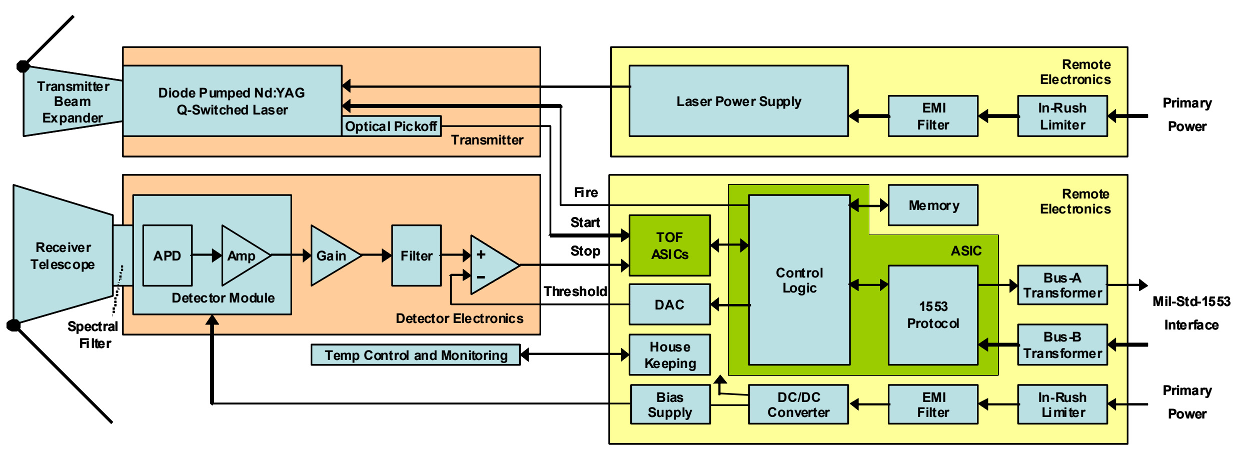


Figure 4.2-2. *Block diagram of the notional Laser Altimeter.*

for the LA laser transmitter is beyond the scope of this study, sufficient information has been reviewed and summarized in *JPL D-48256* to indicate the feasibility of operating a laser transmitter for the duration of the JEO mission. Based on this information, shielding of the LA laser transmitter to a level allowing use of materials tolerant of 400 krad is assumed.

The LA optical receiver uses an APD operating in linear mode to detect the return signal from the laser transmitter. Both silicon and germanium devices experience dark current increases due to total dose and proton damage and are susceptible to transient background radiation, which can create a signal larger than that produced by the optical return. The large detector area, typically 0.5 mm^2, results in a high probability of a transient radiation event during the period of the range gate, assumed to be 67 µs for this analysis, and corresponding to an altitude range of 10 km. With 1 cm of Ta shielding, an estimated 4.3×10^5 electrons/cm^2·s and 50 protons/cm^2·s reach the APD through the shield while in orbit at Europa (see §4.2.1.2). With the notional detector area and range gate, an estimated 14% of laser firings will be corrupted by background radiation. Increasing the shielding to 3 cm of Ta reduces the estimate to ~1.5% of laser firings. During Io flybys, an 8× increase in flux results in an estimate of ~12% of laser firings effected by transient radiation assuming no additional mitigation achieved by threshold discrimination or the use of multiple TOF channels. This level of shielding reduces the total dose seen by the detector to 10 krad and requires a detector tolerant of 20 krad assuming 2× design margin. At this level of dose, dark current increases are modest [*Becker et al. 2003*] and can be accommodated by electronic adjustments and detector cooling.

Resource Estimates

The mass estimate for LA is based on NLR (5 kg), adjusted for receiver telescope size, the mass of LRRP Heritage Laser, and radiation shielding of the laser transmitter, APD detector and detector electronics. The LRRP Heritage Laser, implemented with an aluminum chassis, is ~1.1 kg with ~300-mil chassis walls (equivalent to 0.125 cm Ta) and interior dimensions of ~13 × 9 × 2 cm. To allow components tolerant to 400 krad, 0.3 cm of Ta shielding is required, per the dose-depth curve in §4.5.3.2. The additional 0.175 cm of Ta shielding for the LA laser transmitter is estimated at 0.94 kg. Shielding of the APD (~1 cm in diameter) with 3 cm of Ta is estimated at 3.0 kg. Shielding of the detector electronics (assumed to require an 8 × 8 × 2 cm interior volume) with 0.2 cm Ta (1 Mrad components) is estimated at 0.6 kg. Shielding of the fiber optic is allocated 0.2 kg, resulting in an overall mass estimate for the notional LA of 9.7 kg.

The power estimate for LA is 15 W based on NLR and assumptions for simplification of LOLA from a five-spot, five-receiver system to a single-spot, single-receiver system. The telemetry rate is estimated at 2 kbps, which allows output of ~75 bits per shot. A 100% duty cycle is assumed in Europa orbit.

Planetary Protection

Planetary protection concerns can be met for LA through dry heat microbial reduction. Temperature effects on the non-imaging reflective optics are not considered to be an issue. Temperature effects on the laser transmitter materials themselves are not likely to be problematic, although maintaining alignment of the transmitter components over a wide temperature range will require careful design and a thorough test program. A one-time opening telescope door, as used by NLR, with an added biobarrier seal is baselined to prevent recontamination after sterilization.

4.2.2.2 Radio Science

The JEO spacecraft telecommunications system includes redundant small deep-space transponders (SDSTs) that receive commands from Earth tracking stations at X-band and transmit data to Earth at Ka-band, a configuration used on the Deep Space 1 and Kepler projects. Redundant traveling-wave tube amplifiers (TWTAs) provide amplification for the downlink channel. The SDST also supports X/Ka Doppler range, and delta-differential one-way range (ΔDOR) for orbit determination. The SDST-based Doppler measurement accuracy is better than 0.1 mm/s for 60-s integration time. As discussed in §2.4.2.1, simulations [*Wu et al. 2006*] show that these measurements can determine the radial component of the orbit about Europa to 2-m accuracy as well as making useful accuracies of gravity and tidal parameters. Because the

SDST/TWTA elements used in radio science are parts of an engineering-critical subsystem, the approach to accommodation and radiation protection for these elements addressed in §4.4.

To meet the better than 1-m radial orbit determination accuracy required for the Laser Altimeter instrument, and to provide higher-accuracy estimation of tidal and gravity parameters, the telecommunications subsystem includes a Ka-band Translator (KaT) that can receive a Ka-band signal from Earth and supports a Doppler measurement accuracy of 0.01 mm/s for 60-s integration times. To support radio occultation experiments, the telecommunications subsystem includes an ultrastable oscillator (USO) with stability better than 2×10^{-13} over timescales of 1 to 100 s.

Ka-band Translator

The KaT is based on the Ka/Ka experiment performed with Cassini and planned for Juno with the same Doppler accuracy as specified for JEO. The notional KaT is based on a design under development at JPL that is expected to be at TRL 6 by 2010 (see block diagram, **Figure 4.2-3**). Unlike the KaT to be used for Juno, the new KaT includes no digital circuitry. Most components are radiation hardened to 300 krad and require 0.4 cm of Ta radiation shielding. Some components are radiation hardened to 100 krad and require an additional 0.4 cm of Ta for spot shielding. The mass of the KaT configuration shown in **Figure 4.2-4** is estimated at ~1.5 kg without radiation shielding, and the required enclosure radiation shielding (4.6 kg) and spot shielding (0.4 kg) bring the notional KaT mass estimate to 6.5 kg. Power is estimated at 13 W. The KaT will be connected to the TWTA via a wave-guide combiner as shown in the telecommunications architecture shown in §4.4.3.6.

Ultrastable Oscillator

The notional USO is based on an oven-controlled crystal oscillator like those used on many missions, including the Galileo probe and more recently the GRAIL spacecraft planned for launch in 2011. The performance requirement for the USO is the same as that for the GRACE and GRAIL projects. For the Galileo probe, the USO was pre-conditioned with a 1-Mrad dose from a cobalt-60 source to make frequency stability less susceptible to radiation effects in the Jovian environment. Radiation dose rates of 1 rad/s can cause frequency drift of order 10^{-9} [*Atkinson 1989*]. Most components within the USO are radiation hardened to 300 krad and require 0.4 cm of Ta radiation shielding. Some components are radiation hardened to 100 krad and require an additional 0.4 cm of Ta for spot shielding. The mass estimate for the unshielded USO is ~1.5 kg. The USO is

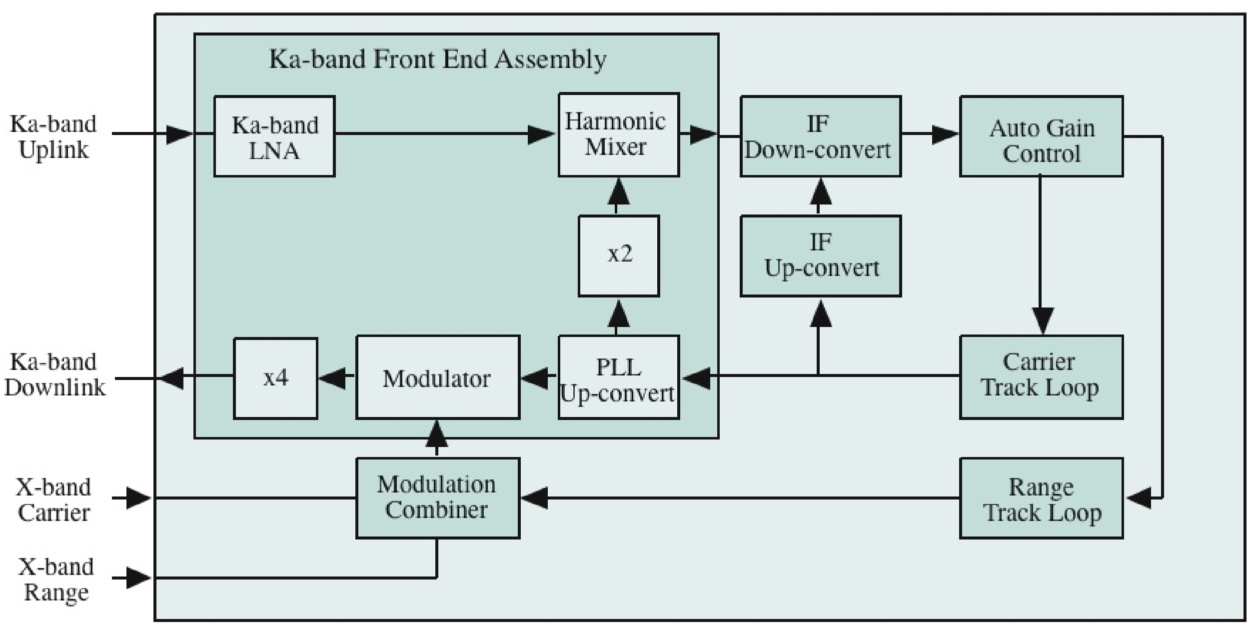


***Figure 4.2-3**. Block diagram of the notional Ka-band Transponder.*

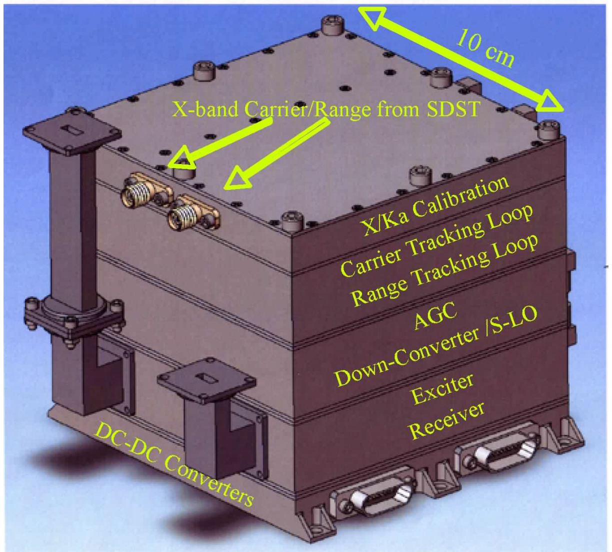


Figure 4.2-4. Notional Ka-band Transponder.

packaged together with the SDST and its portion of the radiation shielded housing mass is ~5 kg. The USO power is estimated at 2.2 W.

4.2.2.3 Ice Penetrating Radar

The notional Ice Penetrating Radar (IPR) is a dual-frequency sounder (nominally 5 MHz with 1 MHz bandwidth and 50 MHz with 10 MHz bandwidth). The IPR is similar to the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on Mars Express and the Shallow Radar (SHARAD) instrument on the Mars Reconnaissance Orbiter (MRO). The higher-frequency band is designed to provide high spatial resolution (footprint and depth) for studying the subsurface above 3 km depth at high (10 m) vertical resolution. The low-frequency band is designed to search for the ice/ocean interface on Europa or the hypothesized transition between brittle and ductile ice in the deep subsurface at a depth of up to 30 km (and a vertical resolution of 100 m). This band mitigates the risks posed by the unknown subsurface structure both in terms of unknown attenuation due to volumetric scattering in the shallow subsurface and thermal/compositional boundaries that may be characterized by brine pockets. Additionally, the low-frequency band is less affected by the surface roughness that can reduce the coherence of the reflected echo and potentially increase the clutter noise. However, because the low-frequency band has to compete with the Jupiter noise within the radar band when operating on the Jovian side of the moon, it is necessary to increase the radiated power compared to MARSIS and SHARAD radar sounders currently deployed for sub-surface studies of Mars. The Jupiter noise should not impact the radar performance on the anti-Jovian side of Europa. It should also be noted that the Jupiter noise is expected to be transient even in the Jovian side. The Ice Penetrating Radar baselined for JEO is tailored to satisfy the science requirements indentified in §2.5.

- Profiling at depths of 100 m to 3 km:
  - 10 m vertical resolution
- Profiling at depths of 1 to 30 km:
  - 100 m vertical resolution

Instrument Description

The notional IPR uses a dual antenna system with a nadir-pointed 50 MHz dipole array with a backing element that also serves as a dipole antenna for the 5 MHz system. Because this instrument is a depth sounder operating at relatively low frequencies and using a dipole antenna, the FOV is very wide and there are no strict pointing requirements. A 30 m dipole similar to those used by MARSIS and SHARAD is baselined (shown folded in **FO-5**). Deployment releases the folded antenna elements in the nadir direction and is baselined for early in the mission before the magnetometer boom is deployed.

A physical and functional block diagram of IPR is shown in **Figure 4.2-5**. The transmitters and matching network are located close to the antenna array. The receivers, digital electronics, and power supply are located remotely, occupying six 6U cPCI boards within the shielded science electronics chassis. The IPR will rely on its own internal processing capability, employing range compression, pre-summing, Doppler filtering, data averaging, and resampling as needed to reduce output data volume.

IPR essentially has three operating modes. The first is the raw data mode, in which a burst of unprocessed data is collected over a short orbit segment. The data from this mode can be used for high-resolution focused processing on the ground. This mode will be capable of capturing short bursts of raw radar data at a number of preselected rates up to a peak of 30 Mbps. Due to the high data rate, this mode

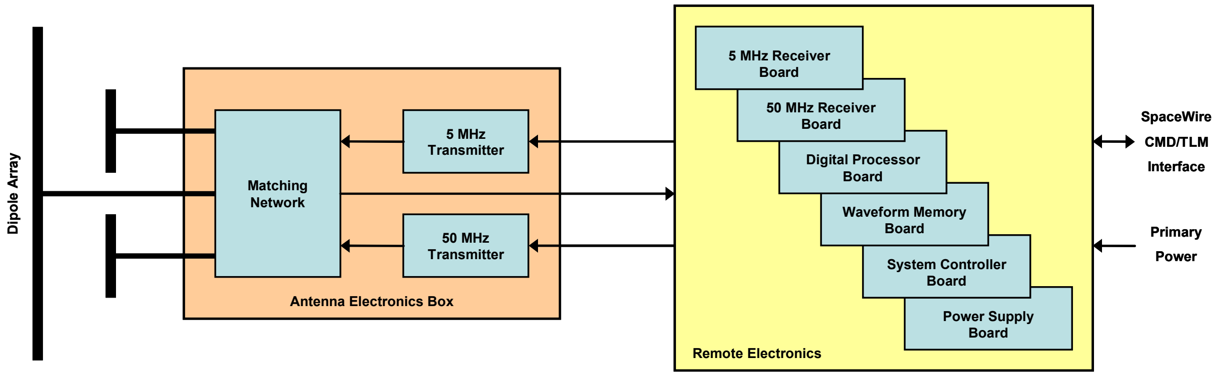


Figure 4.2-5. *Block diagram of the notional Ice Penetrating Radar.*

will be used only over high-value science targets and for instrument check-out and calibration, using full power for several minutes at each target and producing up to 900 Mb of data. The second mode is the shallow investigation mode, in which the radar provides high-resolution (i.e., <3 km depth targets at 10 m range resolution) range data over short receive windows that are suitable for shallow depth investigations. The third mode is the deep investigation mode, which has a relatively lower range resolution (<30 km depth targets at 100 m resolution) but can investigate the subsurface to a depth of 30 km. Both the shallow investigation mode and the deep investigation mode employ onboard processing to produce an output data rate of ~280 kbps and ~140 kbps respectively. All radar modes have similar power consumption of ~45 W. Stand-by power is ~12 W for the non-operating portion of the orbit. For non-IPR orbits, the IPR will be off and will need 2 W for heaters.

Radiation Effects

Space-qualifiable parts that are radiation hardened to 2.2 Mrad are currently available for use in the IPR transmitter and matching network, and 5 kg of radiation shielding mass is allocated to protect this hardware, which is located adjacent to the dipole array. The rest of the IPR electronics are located in the science electronics chassis which provides shielding sufficient for use of parts tolerant of 300 krad.

Planetary Protection

All of the IPR electronics can be sterilized for planetary protection using dry heat microbial reduction. The deployed dipole array will be sterilized via radiation in flight.

Resource Estimates

The mass estimate for the IPR includes 7 kg for a stiffened 30 m dipole and 3 kg for a 5 m dipole array based on scaling from existing MARSIS and SHARAD designs. A mass estimate for the transmitter/matching network of 8 kg is derived from previous work performed under the High Capability Instrument for Planetary Exploration (HCIPE) program with an additional 5 kg allocated for radiation shielding mass. Harness and antenna feeds are estimated at 3 kg, while electronics housed in the science electronics chassis are estimated at 5 kg, resulting in a total mass estimate for the IPR of 31 kg. The power estimate for IPR is 45 W, driven by the full complement of onboard processing functions.

4.2.2.4 Vis-IR Imaging Spectrometer

The notional VIS-IR Spectrometer (VIRIS) is a pushbroom imaging spectrometer with a single-axis along-track scan mirror system. Functionality is similar to that of the MRO Compact Remote Imaging Spectrometer for Mars (CRISM) instrument and the Moon Mineralogy Mapper (MMM) developed for the Chandrayaan-1 mission, both shown in **FO-5**. Two primary modes of operation are defined for VIRIS. The targeted mode uses target motion compensation and the full spectral and spatial resolution of the instrument to generate high-resolution data products over limited, selected areas while in Europa orbit and during flybys. The mapping mode employs data processing and data reduction within the instrument to produce lower-resolution data products matched to the constraints upon JEO downlink telemetry bandwidth. VIRIS is tailored to meet the science requirements identified in §2.5.

- 25 m spatial resolution from 0.4 to 2.5 µm
- 5 nm spectral resolution from 0.4 to 2.5 µm
- Signal to noise ratio (SNR) > 128 from 0.4 to 2.5 µm
- 50 m spatial resolution from 2.5 to 5.2 µm
- 10 nm spectral resolution from 2.5 to 5.2 µm
- SNR > 32 from 2.5 to 5.2 µm

Instrument Description

The notional VIRIS consists of a single reflective telescope with a beam splitter feeding dual grating spectrometers and dual detectors. The short-wavelength (0.4 to 2.6 µm) detector has a 0.25 mrad IFOV to produce a 25 m pixel footprint from the 100-km orbit. To increase signal levels at the long-wavelength (2.6 to 5.2 µm) detector, additional fast relay optics are employed to perform 2:1 focal reduction, resulting in a 0.50 mrad IFOV and 50 m pixel footprint from the 100 km orbit.

The notional detectors are 640 × 480 HgCdTe arrays, as used previously by CRISM and MMM, with wavelength cutoffs adjusted as required for each detector. Extensive radiation shielding will be required to minimize transient radiation noise in the HgCdTe detector elements, which effectively mitigates concerns over total dose effects on these detectors. The use of 640 cross-track pixels on the short-wavelength detector and 320 pixels on the long-wavelength detector results in a 9.2° instrument FOV. Spectral resolution of 5 nm from 0.4 to 2.6 µm requires the use of 440 columns on the short-wavelength detector, while spectral resolution of 10 nm from 2.6 to 5.2 µm requires the use of 260 columns on the long-wavelength detector.

To achieve the required SNR at long wavelengths in the high-resolution targeted mode (25 m and 50 m spatial resolutions), target motion compensation is added via an along-track scan mirror that enables extended exposure times. In mapping mode (200 m spatial resolution is assumed here), SNR is improved by a selectable combination of spatial binning and spectral binning similar to that implemented by CRISM.

Preliminary VIRIS performance analysis has been completed assuming the pixel performance characteristics (quantum efficiency, well depth, 27-µm pixel size) of the Teledyne TMC6604a HgCdTe image sensor. Low surface reflectance at Europa at 5 µm limits system performance and drives the need for target motion compensation in targeted mode. Assuming a 108-mm focal length telescope with 43-mm aperture (*f*/2.5), a 2:1 focal reducer, an optical efficiency of 75%, a grating efficiency of 66% at long wavelengths, 80% detector quantum efficiency, and 2% surface reflectance at long wavelengths, ~1270 signal-electrons per pixel would be collected at 5 µm per 38-ms exposure (1300-m/s ground track at 50 m/pixel, no target motion compensation). Assuming 100 electrons of read noise from the TMC6604a detector produces an SNR of 12. Applying target motion compensation via the scan mirror to allow 154-ms exposures, ~5100 signal-electrons are collected, resulting in an estimated SNR of 42 at 5 µm. Due to increased solar flux, the SNR at 4 µm improves to ~70 and at 2.6 µm reaches ~160.

Many options exist for data reduction in mapping mode to achieve an output telemetry allocation of 100 kbps. One option presented for performance analysis is 8:1 cross-track binning on the short-wavelength channel and 4:1 cross-track binning on the long-wavelength channel coupled with 154-ms exposure times, yielding 200-m spatial resolution. Output of ~40 selected spectral channels is possible at this notional bandwidth allocation. This option results in an estimated SNR of ~80 at 5 µm, again increasing with shorter wavelengths. The SNR values estimated for targeted mode and mapping mode do not include noise due to transient radiation noise in the HgCdTe detectors.

A physical and functional block diagram of the notional VIRIS is given in **Figure 4.2-6**. Consistent with the payload architecture described in §4.2.1, minimal electronics are packaged at the focal plane with the detector, with most of the VIRIS electronics housed in the science electronics chassis which provides an environment shielded sufficiently for use of parts tolerant of a 300 krad total dose. The scan mirror motor, with ~±45° range, is assumed to be a limited angle torque motor (LAT) with no internal electronic components. Scan mirror position sensing is assumed to be via a multi-speed resolver or Inductosyn, also

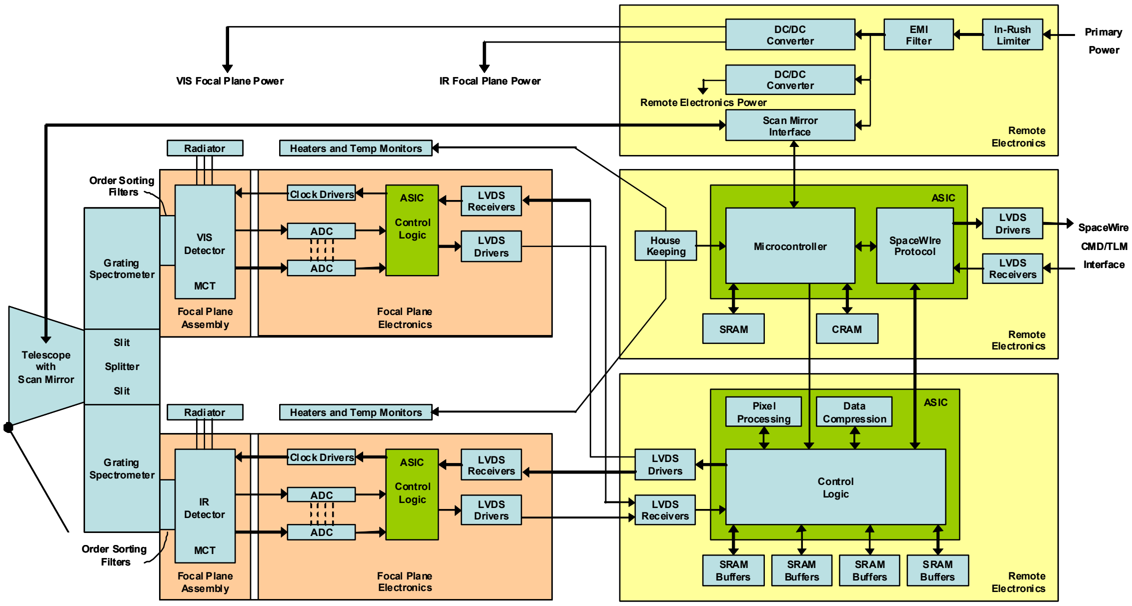


Figure 4.2-6. Block diagram of the notional VIS-IR Spectrometer.

with no internal electronic components. Motor drive and position sensing interface electronics and the VIRIS low-voltage power supply make up one of three 6U cPCI electronics boards in the science electronics chassis. The second board contains detector interface logic, pixel processing, and data compression. The third board contains the system controller and a SpaceWire interface to the spacecraft. These functions are implemented in radiation-hardened ASICs that use external radiation-hardened static RAM (currently available as 16-Mb devices) for temporary buffering of incoming spectrometer data, performing pipe-lined pixel processing, storing data compression intermediate products, and buffering incoming and outgoing SpaceWire command and telemetry data.

Data compression is assumed to be wavelet based with commandable degrees of compression. Wavelet data compression algorithms developed for MESSENGER have been tested using CRISM flight data and assuming onboard subtraction of a dark image (requiring ~8 Mb of SRAM) to remove fixed pattern noise prior to compression. Results of this testing show acceptable noise levels with a 3:1 compression ratio as shown in **Figure 4.2-7** [*Scott Murchie, JHU/APL, private communication*].

A passive thermal design is baselined for VIRIS with desired detector temperatures of ~80 K for the long-wavelength detector and ~160 K for the short-wavelength detector. Accommodation of these radiators is discussed in §4.2.1.1.

Radiation Effects and Shielding

While longer exposure times obtained through the use of target motion compensation can be used to increase the SNR, longer exposure times also increase the vulnerability to noise induced by background radiation. With 1 cm of Ta shielding, an estimated 4.3×10^5 electrons/cm^2·s and 50 protons/cm^2·s would reach the HgCdTe detectors through the shield while in orbit at Europa (see §4.2.1.2). Assuming 27-μm pixels and 154-ms exposure times, an estimated 45% of all pixels would be struck by an incident electron during an integration period. Each incident electron is estimated to deposit an average of 12,000 signal-electrons in the HgCdTe detector (per *JPL D-48256)* while ~5100 signal-electrons due to optical input are estimated at 5 μm for 154-ms exposures. Clearly, the VIRIS detectors will require additional radiation shielding. With 2 cm of Ta shielding, approximately 20% of VIRIS pixels would be struck during a 154-ms exposure. With 3 cm of Ta shielding, that rate is reduced to approximately 5%. During Io flybys, an 8x increase in radiation flux is offset by much higher albedo (~80% vs. ~2%). For the notional VIRIS, a 3-cm Ta shield is assumed,

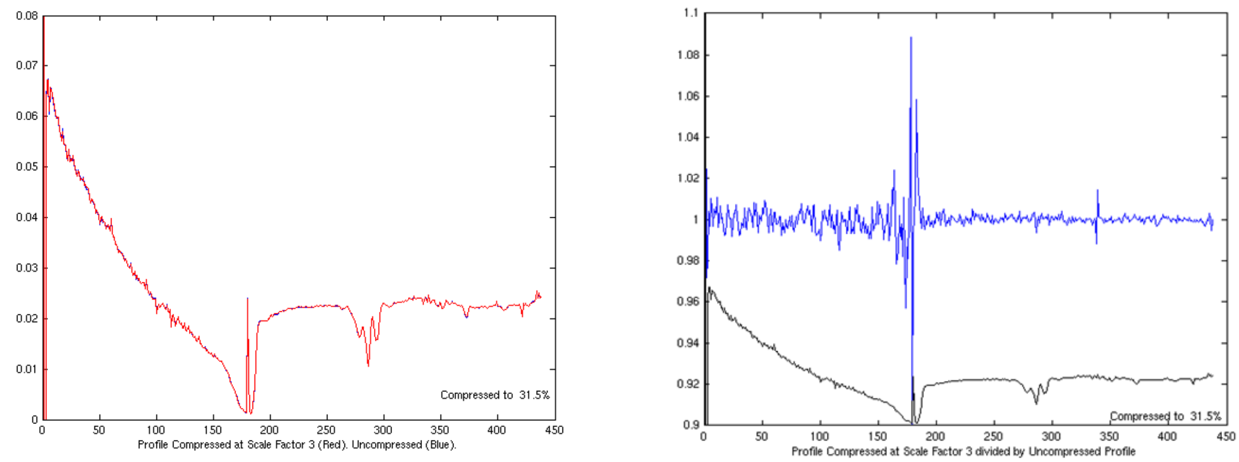


Figure 4.2-7*. Left plot shows CRISM IR spectra (% reflected light vs. detector row number) before and after 3:1 wavelet data compression. Right plot overlays in blue the ratio obtained by dividing compressed data with uncompressed data. Areas exceeding 1% rms error are due to edge effects of order-sorting filters.*

and at this level of shielding, the mission dose-depth curve shown in §4.5.3.2 indicates ~10 krad of total dose received by the VIRIS detectors.

Each detector radiation shield is estimated at 4.6 kg; a notional configuration providing front-side detector shielding is shown in **Figure 4.2-8**. This conceptual drawing also shows a notional implementation of the fast relay optics baselined for the VIRIS long-wavelength channel and the location of the spectrometer order-sorting filters; all located within the shielded detector housing. Shielding of the detector electronics, assumed to require an $8 \times 8 \times 2$ cm interior volume, with 0.4 cm of Ta (300-krad components) is estimated at 1.30 kg each.

Transient radiation noise suppression in near-IR focal planes has seen considerable development effort due to its potential benefit to military systems. Various filtering approaches have been considered [*Parish 1989*] and some have been demonstrated within the ReadOut Integrated Circuits (ROICs) underlying the HgCdTe detector elements. The Sensor Hardening Technology Program successfully implemented gamma noise suppression circuitry, including optical pulse suppression, within a ROIC using the BAE Systems 0.8-µm radiation-hardened CMOS process [*Hairston et al. 2006*]. Transient suppression was achieved by dividing each image integration period into

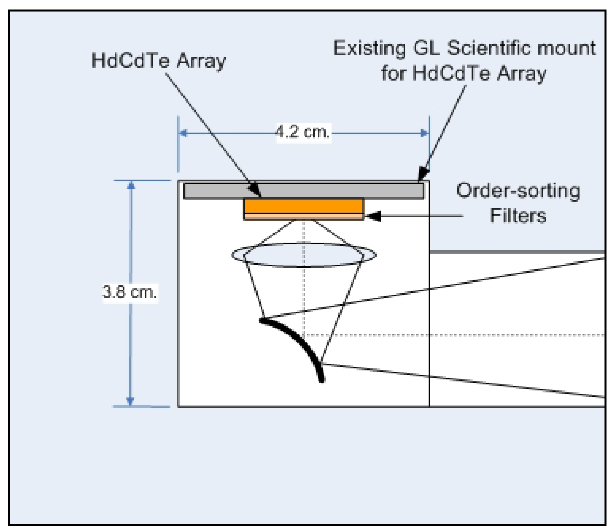


Figure 4.2-8*. Notional shielded VIRIS detector housing with fast realy optics baselined for the long-wavelength channel concept*

subframes using a Compact Signal Averager within each pixel to monitor each subframe and suppress outliers prior to charge integration within the ROIC. This technique is most effective in suppressing large transient events, and its overall effectiveness depends upon the pulse height distribution of the transient noise reaching the detector through the radiation shielding. While a factor of 50 pulse suppression was achieved in the cited reference, the actual performance of such a system in the JEO environment is unknown at this time. This technology suggests a possible radiation noise mitigation approach to be employed by VIRIS, but its implementation is not assumed for this report.

Resource Estimates

The mass estimate for the notional VIRIS is based on two sources; the first based on simplifying CRISM to the configuration of VIRIS and the second on converting MMM to a dual-spectrometer, dual-detector system with scan mirror. The total mass estimate for VIRIS is 27.5 kg, of which 11.8 kg is radiation shielding. Power dissipation for the notional VIRIS is estimated at 25 W based on a bottoms-up estimate using both CRISM and MMM data.

The telemetry bandwidth estimate for the notional VIRIS in targeted mode is based on output of 640 cross-track pixels by 440 spectral pixels on the short-wavelength detector and 320 cross-track pixels by 260 spectral pixels on the long-wavelength detector every 154 ms with 12 bits per pixel and a nominal 2.5:1 data compression ratio producing a telemetry rate of 11.4 Mbps. In mapping mode, various combinations of spectral binning, spectral editing, spatial binning, and spatial editing are used to reduce the compressed output data rate to a 100-kbps allocation used for mission model purposes.

Planetary Protection

Planetary protection concerns would ideally be met for VIRIS through dry heat microbial reduction, but survivability of the HgCdTe detector elements using the currently defined JEO planetary protection protocol is in question. A new “bake-stable” process has recently been developed that produces HgCdTe focal plane arrays which can be baked at 90º to 100ºC for extended periods or 110ºC for 24 hours. While this proprietary process has not yet been applied to the science-grade devices typically used for planetary space missions, it is thought that the “bake-stable” process can be applied to any HgCdTe focal plane array [*James Beletic, Teledyne Imaging Sensors, private communication*]. A risk reduction effort to fully quantify the performance impact of high-temperature bake-out on HgCdTe detector elements at the temperatures called for by the JEO planetary protection protocol is recommended. After dry heat sterilization of VIRIS, a one-time opening telescope door with biobarrier seals is used to prevent recontamination.

4.2.2.5 UV Spectrometer

The notional Ultraviolet Spectrometer (UVS) uses stellar occultations to characterize Europa’s tenuous atmosphere and images targets in the Jovian system including the Io torus. Performing a similar role to the Cassini UVS shown in **FO-5**, the notional UVS is a simplification of that instrument which uses only a single imaging spectrometer channel and the high-speed photometer (HSP) channel of the Cassini UVS. The notional design of the UVS imaging spectrometer is derived from the FUV channel of the Cassini UVS instrument but has much in common with the design of the New Horizons ALICE instrument. The UVS baselined for JEO is tailored to satisfy the science requirements identified as top priority by the JJSDT, and outlined in §2.5.

1) Characterize the structure, composition, variability and dynamics of Europa’s sputter-induced atmosphere using stellar occultations
2) Investigate Ganymede’s aurorae, Io’s torus, and the sources and sinks of Io’s crustal volatiles and atmosphere
   – Wavelength range: 70–190 nm
   – Spectral resolution: better than 0.5 nm
   – Signal to noise ratio: >5

Instrument Description

The notional UVS consists of an imaging spectrometer stacked with a high-speed photometer in manner similar to the Cassini UVS instrument. Boresight of the stacked instruments is offset from nadir by a spacecraft-supplied mounting bracket, and an instrument-controlled single-axis scan mirror that allows both sensors to view a 90° field of regard from nadir to the spacecraft anti-ram axis as shown in **Figure 4.2-9**. Analysis completed for this study indicates that while in Europa orbit, multiple stellar occultations are available per day within a 6-mrad wide FOV. A given star will be available for every orbit for a day or more, allowing longitude sampling at a single latitude for each star. The distribution of star’s declinations will allow latitude sampling.

The imaging spectrometer has a detector format of 1024 spectral by 64 cross-track spatial pixels. A 1-mrad instantaneous field of

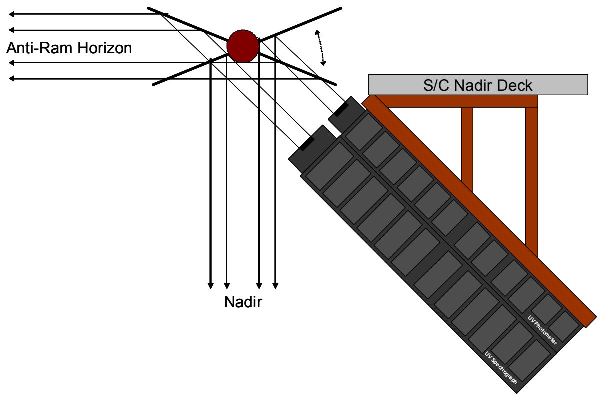


Figure 4.2-9. Notional single-axis UVS scan system used for stellar occultation tracking.

view (IFOV) provides an instrument FOV of 3.7° cross-track. The optical path of the far-ultraviolet (FUV) spectrometer consists of a single-mirror telescope followed by an entrance slit and a concave grating. A slit change mechanism allows a tradeoff between spectral resolution and light collection capability.

The detector choice for the notional imaging spectrometer is a two-dimensional imaging photon-counting detector using a microchannel plate (MCP) with a position-sensitive anode and a solar-blind photocathode coating of CsI. A vacuum door mechanism, similar to that employed by the Alice instrument on New Horizons, protects the CsI photocathode against damage from exposure to moisture and contamination during ground operations, and when opened in flight allows detector response to 70 nm. A MgF_2 window in the vacuum door allows testing of the detector at wavelengths greater than 115 nm with the vacuum door closed and provides partial redundancy during flight should the door mechanism fail to open.

The high-speed photometer, with design similar to that of the Cassini UVS, employs a telescope mirror approximately 10 times larger than that used in the imaging spectrometer, which allows integration times as short as 2 ms. An aperture stop limits the FOV to 6 mrad, minimizing background signal, and a small MgF_2 lens images the telescope mirror onto the detector to minimize movement of the star on the non-uniform detector photocathode due to small changes in pointing. The notional detector for the high-speed photometer is also an MCP with a CsI photocathode. A MgF_2 window protects the detector from contamination and limits response to wavelengths greater than 115 nm.

A physical and functional block diagram of the notional UVS is shown in **Figure 4.2-10**. Detector electronics and high-voltage power supplies are located in the imaging spectrometer and high-speed photometer, while all other electronics are contained on a single 6U cPCI board in the science electronics chassis. This includes drive and interface electronics for the scan mirror and slit change mechanism, detector event processing, system controller, spacecraft interface, and low-voltage power supply. The scan mirror is assumed to be driven by a limited-angle torque

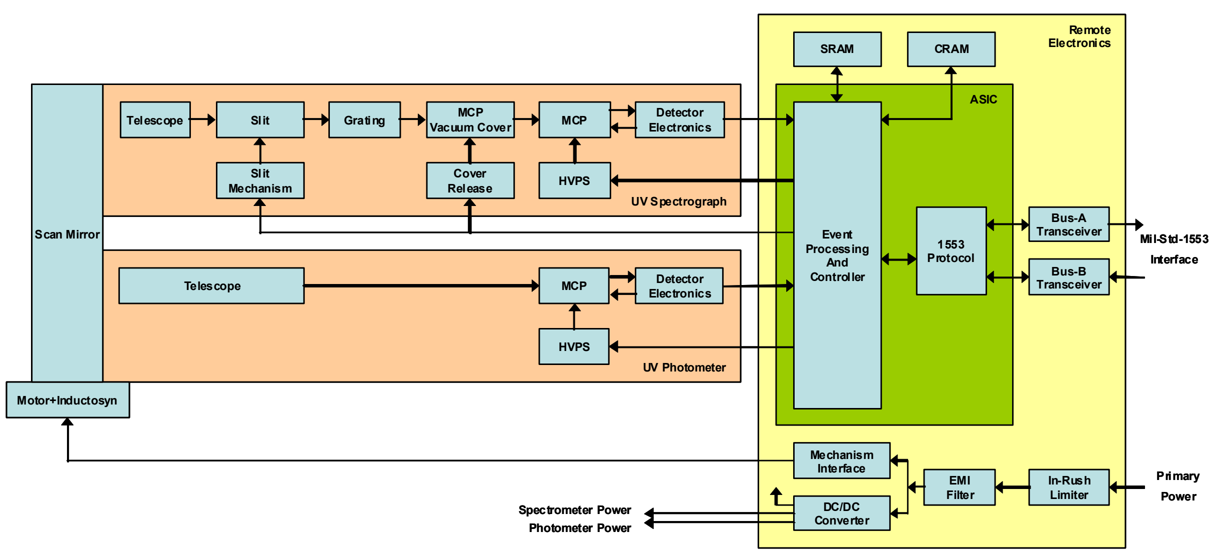


Figure 4.2-10. Block diagram of the notional Ultraviolet Spectrometer.

motor using an Inductosyn for position feedback. Neither component has radiation-sensitive electronic parts. The slit change mechanism is assumed to driven by a small stepper motor.

Radiation Effects and Shielding

An estimate of the count rate due to background radiation for the notional UVS instrument is derived from the performance of the Galileo UVS instrument. Near the magnetic equator at Europa, the MCP detector in the near-ultraviolet (NUV) channel of the Galileo UVS instrument recorded 1800 counts/s due to background radiation with a detector area of 28 mm^2. Scaling that background count rate to the 164 mm^2 detector area of the notional JEO UVS instrument results in an estimated count rate due to background radiation of ~10,500 counts/s for the entire JEO UVS detector. A spectrum of Beta Centauri taken by the Cassini UVIS instrument using a detector equivalent to that of the notional JEO UVS instrument is shown in **Figure 4.2-11** and represents the signal expected during JEO UVS stellar occultation measurements. Each point on the Beta Centauri spectrum is the result of summing four cross-track pixels (4 of 64 available spatial pixels where the stellar input is located) and eight spectral pixels (8 of 1024 available spectral pixels to produce a 128 point spectrum), with each point in the spectrum thus corresponding to the output of ~0.05% of the total UVS detector area. With ~10,500 counts/s due to background radiation

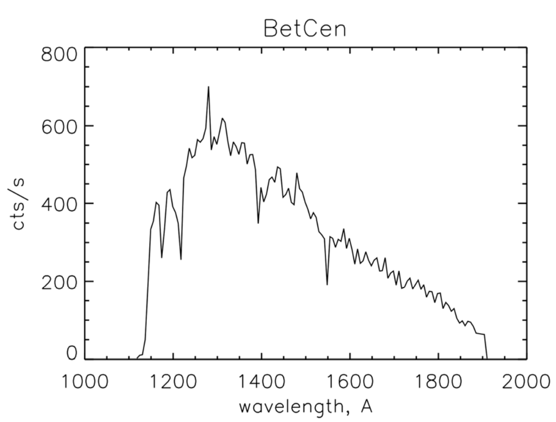


Figure 4.2-11. UV spectrum of Beta Centauri captured by the Cassini UVIS instrument and representative of JEO UVS stellar occultation data.

assumed for the entire detector, the count rate for each point on the Beta Centauri spectrum is ~5 counts/s. Comparing this to a signal level ranging from ~600 to ~75 counts/s per pixel, as shown in the Beta Centauri spectrum, SNR ranging from ~120 to ~15 is estimated. With an average of 300 counts/pixel for the 128 binned pixels in the Beta Centauri spectrum, the total count rate due to optical input is ~38,500, which coupled with ~10,500 counts/s due to background radiation (most of which is rejected as outside the FOV of the star) is ~49,000 counts/s. This count rate is well within the capabilities of existing detector electronics designs.

This estimate of the count rate due to background radiation assumes radiation shielding of the notional JEO UVS detector to a level equivalent to that of Galileo UVS detector. For this study, shielding of the UVS imaging spectrometer detector with 1 cm of Ta is assumed, with the shielding mass estimated at 1.25 kg. Due to the larger optical signal available to the UVS high-speed photometer, its detector is shielded with 0.6 cm of Ta, with the shielding mass estimated at 0.65 kg. Detector electronics and high-voltage power supplies packaged in the imaging spectrometer and the high-speed photometer are assumed to be hardened to 1 Mrad requiring a 0.2 cm of Ta radiation shield and 0.6 kg of shielding mass for two $10 \times 6 \times 4$ enclosures.

While the secondary emission surfaces of MCPs are not susceptible to radiation damage, each radiation hit that initiates a charge multiplication event contributes to the total charge drawn by the MCP during its lifetime. MCPs exhibit a gradual reduction of gain as charge is drawn, with early, more rapid gain changes mitigated by scrubbing. Levels of charge draw of 1 to 10 coulombs/cm^2 are considered usable for MCPs and this corresponds to a fluence on the order of 10^{13} hits/cm^2, producing charge multiplication when operating at 10^6 gain. A combined count rate due to background radiation and optical input on the order of 10^5 counts/cm$^2\cdot$s implies an MCP lifetime of ~3 years of continuous operation, well beyond JEO requirements.

Resource Estimates

The mass estimate for the notional UVS is derived by deconstruction and apportioning of the Cassini UVS instrument with electronics other than detector electronics and high-voltage power supplies assumed to be relocated to the science electronics chassis. This results in an estimate of 2.4 kg for the imaging spectrometer, 1.0 kg for the high-speed photometer, 1.0 kg for harnessing due to instrument partitioning, 3.1 kg for radiation shielding, 1.5 kg for the scan mirror system and 0.7 kg for a 6U cPCI electronics board. The total mass estimate for the notional UVS instrument is 9.5 kg. The UVS telemetry rate is estimated at 10 kbps, and power dissipation is estimated at 5 W based on similarity to the Cassini UVIS instrument.

Planetary Protection

Planetary protection concerns can be met for UVS through dry heat microbial reduction, although temperatures must be limited to 110°C. Two materials used in UVS are of potential concern; the CsI photocathode material and the alloy used to seal the MgF_2 window to the high-speed photometer MCP. Discussions with Photek, a manufacturer of flight detectors, indicate that CsI is evaporated during the manufacturing process, then heated to 135°C for many hours to seal the cathode material to the body of the detector. Subsequent heating of CsI to a lower temperature for instrument sterilization is tolerated by the material. The photometer MCP window can be sealed with an Indium–Tin alloy that has a melting point of 118°C and can tolerate the 110°C planetary protection protocol, although tight control of the process temperature is required.

4.2.2.6 Ion and Neutral Mass Spectrometer

The notional Ion and Neutral Mass Spectrometer (INMS) determines the elemental, isotropic, and molecular composition of Europa's atmosphere and ionosphere from orbit, and those of Io, Callisto, and Ganymede during close flybys. Performing a role similar to that of the Cassini INMS, the notional JEO INMS is adapted from the more recent design of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) Reflectron Time-of-Flight (RTOF) instrument shown in **FO-5**. The INMS baselined for JEO is tailored to satisfy the following science requirements identified in §2.5.

Characterize the composition of sputtered products from energetic particle bombardment of the surface and positive ions and neutral particles:

- Mass range: 300 Da
- Mass resolution: $M/\Delta M \geq 500$
- Pressure range: 10^{-6} to 10^{-17} mbar
- Energy resolution: 10%

An RTOF mass spectrometer was selected as the notional approach because of its ability to achieve the required mass range and mass resolution and because of its flight heritage. The Rosetta ROSINA RTOF INMS has demonstrated a mass range of 500 Da, a mass resolution of $\Delta M/M$ of 1500 to 4500 depending on mode, and detection of species at densities as low as $10^{-2}/cm^3$ [*Balsiger et al. 2007*]. The sensitivity of the notional INMS to various species at Europa is shown in **Figure 2.4-11**.

Instrument Description

The notional RTOF INMS shown in **Figure 4.2-12** collects exospheric ions and gases (which are ionized) and accelerates them to sensors that determine their mass and mass-to-charge ratios. A clear 20º × 40º FOV in the spacecraft ram direction is required for ion and gas collection. A storage ion source stores continuously produced ions prior to their extraction into the TOF section. The RTOF contains two storage ion sources: an electron impact storage ion source for analyzing neutrals, and an orthogonal extraction ion source for analyzing ions. The ions are then simultaneously extracted from storage sources into a drift space, where they are time-focused and temporally compressed from ~800 ns at the exit of the ionization region to ~5 ns at the first time-focus plane. These very short ion bunches are imaged by the drift section onto the detector with arrival time at the detector proportional to their mass. An 18-mm MCP detects the ion bunches, and its output is sampled by one of two data acquisition systems: a high-speed waveform capture system for analysis of neutrals or a TOF system for analysis of ions. High-speed memory captures the output of the data acquisition systems for post-processing.

For the purposes of this study, it is assumed that the INMS data acquisition systems can be relocated from the sensor assembly to the science electronics chassis to make most efficient use of radiation shielding mass. This

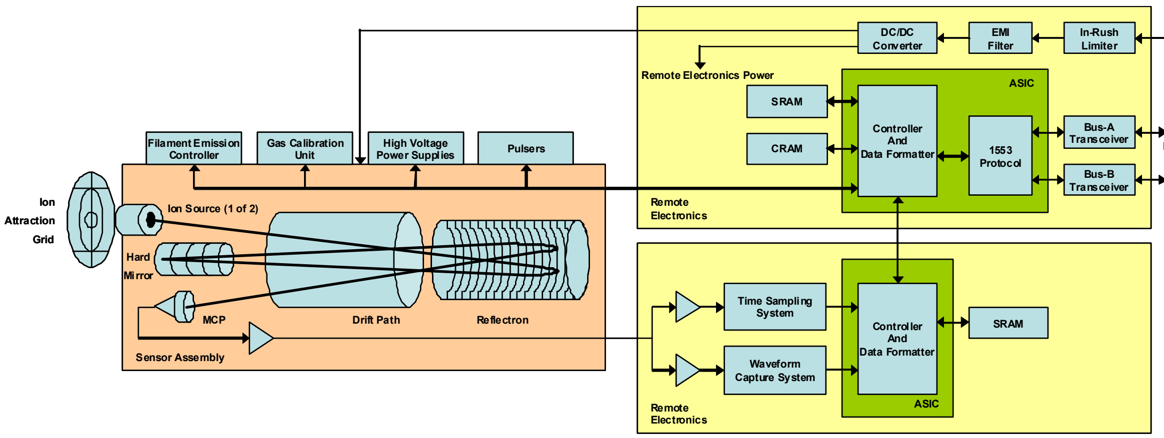


Figure 4.2-12. Block Diagram of the notional Ion and Neutral Mass Spectrometer.

is feasible for cable lengths up to 1 m [*Peter Wurtz, University of Bern, private communication*].

Radiation Effects and Shielding

There are two main areas of concern for radiation effects on the notional INMS: the high-speed data acquisition systems and the MCP detector. The reflectron itself, consisting of mechanical parts at high voltage, is not sensitive to radiation.

The high-speed data acquisition systems on ROSINA employ analog-to-digital converters (ADCs) and high-speed memory. Existing ADCs from Honeywell and ST Microelectronics are hardened to 300 krad and provide 12-bit resolution at speeds of 20 and 50 MHz, respectively. Modern radiation-hardened memory offers access times as low as 20 ns with radiation hardness of up to 1 Mrad.

Transient radiation effects on the INMS MCP detector are mitigated by the extremely short duration of the burst of data acquisition performed when an ion bunch is released towards the detector. A multi-pass delayed sampling technique is employed with sample and hold times on the order of 0.5 ns. With 0.6 cm of Ta shielding, an estimated 8.7×10^5 electrons/cm^2·s and 50 protons/cm^2 s would reach the MCP through the shield while in orbit at Europa (see §4.2.1.2). With a notional 18-mm-diameter detector, (similar to the ROSINA RTOF), a 1-ns digitization window, and a worst-case assumption that each incident electron or proton generates an MCP output, ~0.2% of A/D samples will be corrupted by background radiation. This represents a tolerable noise floor in the multi-sampled mass spectra, even during Io flybys where ~8X radiation flux is expected. Given the small size of the MCP, only ~100 g of radiation shielding is required for the MCP. Total dose effects on MCPs are addressed in §4.2.2.5.

Electronics remaining in the notional INMS sensor unit, including front-end electronics, pulsers, and high-voltage power supplies, are assumed to be hardened to 1 Mrad, requiring a 0.2 cm Ta radiation shield and 2 kg of shielding mass for two $10 \times 10 \times 2$ cm enclosures.

Resource Estimates

The mass estimate for the notional JEO INMS is derived by deconstructing and partitioning of the ROSINA RTOF instrument, with a significant portion of its electronics assumed to be modernized and relocated to the science electronics chassis. The resulting mass estimate for the INMS sensor assembly is 10.5 kg (compared with 15 kg for ROSINA RTOF). Of that mass reduction, 1.5 kg comes from replacing an in-flight re-closable cover with a simple one-time-opening cover. Two 6U cPCI electronics boards in the science electronics chassis (1.5 kg total) are assumed, with 1 kg of harness mass allocated due to instrument partitioning. Total shielding mass is estimated at 2.1 kg, resulting in a total mass estimate for the notional JEO INMS of 15.1 kg. The notional INMS telemetry rate is estimated at 2 kbps, and power dissipation is estimated at 33 W based on ROSINA RTOF.

Planetary Protection

Planetary protection concerns will be met for INMS through dry heat microbial reduction. The bare unpowered MCPs can tolerate high temperature soaks, and the entire reflectron assembly can be baked out at 150°C [*Balsiger et al. 2007*]. After dry heat sterilization of INMS, a one-time-opening door with biobarrier seals is used to prevent recontamination.

4.2.2.7 Thermal Instrument

The notional Thermal Instrument (TI) is a pushbroom imaging thermopile array with two wavelength bands for determining surface temperature over a range of 80 K to 160 K and four wavelength bands dedicated to Jupiter atmospheric measurements. Using uncooled thermopile detectors, the notional TI is adapted from the MRO Mars Climate Sounder (MCS) and Lunar Reconnaissance Orbiter (LRO) Diviner instrument shown in **FO-5**. The TI baselined for JEO is tailored to satisfy the following science measurement requirements identified in §2.5.

Mapping of thermal emissions and measurement of thermal inertia of surface materials:

- Better than or equal to 250-m spatial resolution from a 100-km orbit
- Better than or equal to 10% radiometric accuracy
- Better than 2 K temperature accuracy

Instrument Description

The notional TI has a 2.5-mrad wide IFOV to produce a 250-m pixel footprint from the 100-km orbit. Nine 21-element linear arrays of thermopile detectors are oriented to provide a 3.0° cross-track instrument FOV and a 5.25-km swath width from the 100-km orbit. Two line arrays and filter bands are dedicated to surface temperature measurements, while four line arrays are dedicated to Jupiter atmospheric measurements.

- Filter 1: 8–20 µm
- Filter 2: 20–100 µm
- Filter 3: 21.0 ± 3 µm
- Filter 4: 28.2 ± 5 µm
- Filter 5: 40.0 ± 5 µm
- Filter 6: 17.2 ± 3 µm

Filter 1 provides maximum temperature sensitivity at 160 K. Filter 2 provides maximum sensitivity at 80 K. Filters 3–6 allow retrieval of temperatures between 100 and 500 mbar, retrieval of para-H_2 from the spectral shapes associated with S(0) and S(1) transitions, and cross comparison with the 16.7-µm filter band in the JGO thermal instrument.

To evaluate performance of the notional TI, a D* (Detectivity) value of 10^9 cm × √Hz/W was assumed for the thermopile detectors, per the published performance of the silicon-based thermopile array developed for the MCS instrument [*Foote et al. 2003*] and shown in **Figure 4.2-13**.

The 240 × 480 µm pixels in this array with a 10-Hz readout coupled with a compact reflective telescope with 136-mm focal length and 68-mm aperture (*f*/2) provides a signal of ~21 nW at 80 K using the 20- to 100-µm filter and an assumed optical efficiency of 65%. For Δ2 K at 80 K and assuming the system performance is limited by detector noise, the contrast produced is ~2.6 nW for SNR of ~25. The 8- to 20-µm filter provides a signal of ~125 nW at 160 K and for Δ2 K at 160 K, the contrast produced is ~12 nW for SNR of ~112. Of the four filter bands dedicated to Jupiter atmospheric science, the lowest signal levels are provided by Filter 6, which sees a surface irradiance of ~1.6 W/cm^2. Assuming Jupiter fills the TI FOV, this provides 7.5 nW of detector power and SNR of ~70.

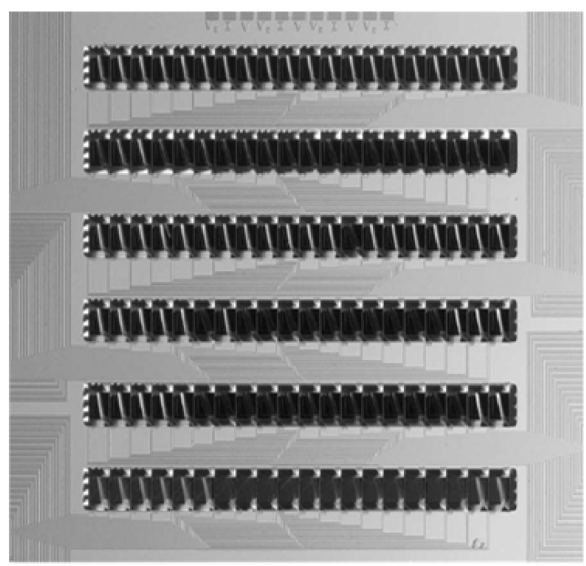


Figure 4.2-13. *Thermopile line arrays developed for the MRO MCS instrument and baselined for the notional JEO Thermal Instrument.*

A physical and functional block diagram of TI is shown in **Figure 4.2-14**. Per MCS and Diviner, ASIC-based readout electronics and an ADC are packaged at the focal plane with the thermopile array. While the existing MCS and Diviner ASICs are not radiation hardened, conversion of the existing design or development of an equivalent radiation hardened device is considered to be low risk. Shielding of the thermopile array and focal plane electronics to 300 krad requires 0.4 cm of Ta, with this shielding estimated at 1.3 kg for an 8 × 8 × 2 cm enclosure. The system controller, low-voltage power supply, and spacecraft interface electronics are packaged on a single 6U cPCI board located in the science electronics chassis.

Two-point calibration is achieved with a motorized flip mirror providing frequent looks at deep space and a warm calibration flag or shutter providing a second reference point. Given the relative insensitivity of thermopile arrays to focal plane temperature, only modest control of focal plane temperature is required.

Radiation Effects and Shielding

Neither thin-film thermopile detectors composed of antimony and bismuth arms nor silicon-based thermopile detectors composed of active polysilicon and aluminum layers separated by dielectric layers are assumed to have significant issues with exposure to ionizing radiation with test results for the latter discussed in JPL D-48256 . Thermopile arrays with integrated CMOS readout circuitry constructed for use in satellite attitude control systems have demonstrated radiation tolerance to several hundred krad [*van Herwaarden 2000*] limited by the CMOS readout circuitry rather than the detector elements. Transient radiation reaching the detector through the 0.4 cm Ta shield has a negligible impact on the thermopile detector elements as the thermal energy imparted by incident protons and electrons is negligible compared with the contrast signal required for a Δ2 K temperature measurement. A detailed analysis to support this is provided in JPL D-48256.

Resource Estimates

For an orbital ground track speed of 1300 m/s in the 100-km orbit, 250-m spatial resolution requires a sampling interval of 192 ms. Assuming sampling at this rate, 12 bits per sample, and 3:1 data compression, the 126 detector elements in the notional TI generate ~3 kbps of telemetry. The mass estimate for TI is based on a simplification of the MCS and Diviner instruments, using a single telescope and focal plane and deleting the azimuth and elevation articulation stages.

Planetary Protection

Planetary protection concerns will be met through dry heat microbial sterilization of TI. Temperature effects on optical filters, optical mounts, and the thermopile array are a key aspect of the component and material selection process. A one-time-opening telescope door with biobarrier seal is baselined to prevent recontamination after sterilization.

4.2.2.8 Narrow-Angle Camera

The Narrow-angle Camera (NAC) is a dual-role instrument providing high-resolution imagery of selected targets in the Jovian system and on the surface of Europa. It also will provide optical navigation (OpNav) images to support spacecraft tracking. Candidate observations using a NAC in the Jovian system include flyby imaging (and mosaic imaging) of satellites during both targeted and "non-targeted" encounters,

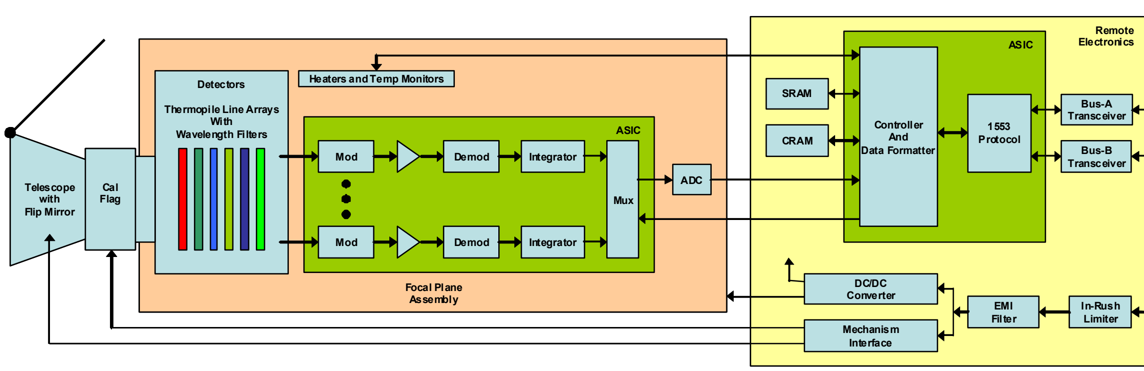


Figure 4.2-14. Block diagram of the notional Thermal Instrument.

monitoring of the Jupiter atmosphere and of Io. The NAC has basic functionality similar to that of the New Horizons Long Range Reconnaissance Imager (LORRI) shown in **FO-5** and is tailored to satisfy the following science measurement requirements in §2.5 and assumed OpNav requirements based on experience from previous missions.

- High-resolution panchromatic imagery of Europa from orbit:
  - 1-m spatial resolution from 100-km orbit
- High-resolution color and panchromatic imagery of the Jovian System:
  - 10-μrad spatial resolution
  - At least 3 color bands plus panchromatic
- Collection of optical navigation images:
  - Better than 25-μrad spatial resolution
  - Framing mode

Instrument Description

The notional NAC has a 0.01-mrad IFOV to produce a 1-m pixel footprint from the 100-km orbit. Use of a 2048-pixel-wide image sensor results in an instrument FOV of ~1.17° full angle. A reflective telescope similar to but smaller than that of the LORRI instrument is baselined. A detector operating in pushbroom mode is required for imaging Europa from orbit, and a framing mode detector is required for collection of accurate OpNav images. Two approaches to meeting these seemingly disparate requirements have been identified. The first approach is development of a detector, either a charge coupled device (CCD) or a CMOS active pixel sensor (APS) with multiple elements on a single substrate similar to that developed by e2v Technologies for the New Horizons Multispectral Visible Imaging Camera (MVIC). In this case one element would be a 2048-pixel-wide line array for pushbroom operation while the other element would be a framing detector for OpNav use. The second approach is development of a CMOS APS that provides a region-of-interest readout zone which can be used to read a line or small number of lines for pushbroom operation or the full array for framing operation. While not meeting the performance requirements for NAC, the radiation hardened Cypress STAR1000 image sensor is an example of a detector designed with this readout capability. While future instrument proposers have a choice of available detectors, the higher radiation tolerance of CMOS APS devices and continued improvements in their performance for scientific applications [*Janesick et al. 2008*] make them the nominal detector choice for the notional JEO NAC.

A motorized filter wheel provides color capability for NAC imaging of distant targets within the Jovian system. A 10-position filter wheel similar to that used by the MESSENGER Mercury Dual Imaging System (MDIS) is baselined. To protect the filters from radiation degradation, 1 kg of radiation shielding is allocated.

Preliminary NAC performance analysis has been completed using the pixel characteristics (quantum efficiency, 13-μm pixel size, 100-K e- well depth) of the e2v CCD47-20BT image sensor used by the New Horizons LORRI instrument as *an example* of the performance expected from the NAC image sensor. Assuming a 1300-mm focal length telescope with 130-mm aperture (*f*/10), an optical efficiency of 85%, an average detector quantum efficiency of 60%, and a low surface reflectance of 20% at Europa, approximately 3650 electrons per pixel are collected during the maximum exposure time of 770 μs (panchromatic). The required NAC pixel readout rate for a 2048-pixel line array is 2.7 MHz, which, in comparison with LORRI's readout rate of 1.2 MHz and its measured 20-electron system read noise, yields an assumed 30-electron read noise for the notional NAC. Coupled with photon noise and barring background radiation noise, the estimated panchromatic SNR is ~55. Application of four lines of on-chip time-delay-and-integrate (TDI) on a CCD (2048 × 4) would result in SNR of >200 while preserving the 2.7-MHz readout rate. Readout of 16 lines from a region-of-interest zone of a CMOS APS and co-adding in the digital domain (pseudo-TDI or digital-TDI) would result in SNR > 100 limited by the added read noise of the required readout rate of 42 MHz.

A physical and functional block diagram for NAC is provided in **Figure 4.2-15**. Consistent with the instrument architecture described in §4.2.1, minimal electronics are packaged at the focal plane with the detector. The signal chain shown in the focal plane electronics contains elements required for a CCD image sensor (clock drivers, correlated double sampler, A/D

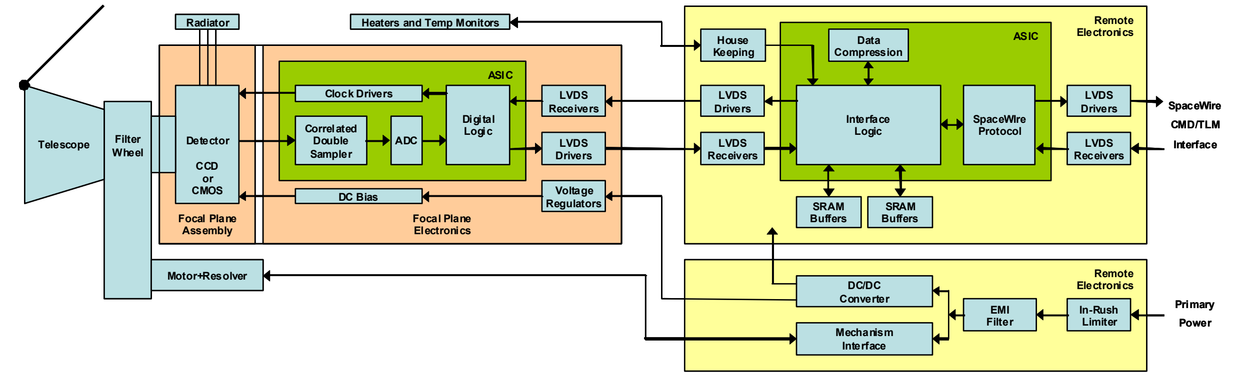


Figure 4.2-15. Block diagram of the notional Narrow-angle Camera.

conversion) which are either not necessary or are typically implemented within a CMOS APS device. A highly integrated CMOS APS device is an ideal solution for the JEO NAC, as it minimizes components at the focal plane that require radiation shielding.

Two 6U cPCI electronics boards are baselined, with one board containing camera interface logic, pixel processing, image data compression and a SpaceWire interface to the spacecraft. A single radiation-hardened ASIC and 3:1 nominal wavelet data compression are assumed. A second 6U cPCI electronics board provides drive and position sensing for the NAC filter wheel and DC/DC power conversion.

The NAC detector is cooled by a passive Sun-protected radiator. A detector anneal heater is baselined as a means to mitigate radiation damage.

Radiation Effects and Shielding

To protect the NAC image sensor from total dose, displacement damage and transient radiation noise, radiation shielding with 1 cm of Ta is baselined, comparable to shielding used by the Galileo Solid State Imager (SSI). The JEO mission radiation dose depth curve indicates a ~35 krad total dose behind 1 cm of Ta shielding, which, with a required design margin of 2, allows use of detectors tolerant of 70 krad. While a CMOS APS device is favored for the notional JEO NAC, this dose level allows a choice of silicon device technologies including CMOS APS, P-channel CCD, and arguably N-channel CCD.

Shielding mass of 2 kg is allocated for a 1 cm Ta, 5 × 5 × 4 cm enclosure slightly larger than that shown in **Figure 4.2-16**, which is designed to house a STAR1000-based CMOS APS and its interface electronics. The slight increase in dimensions allows for additional circuitry required for a CCD-based focal plane or additional electronics required by a multi-output CMOS APS device.

Background radiation noise is mitigated by the very short exposure times employed by NAC. With 1 cm of Ta shielding, an estimated 4.3×10^5 particles/cm^2·s would reach the detector through the shielding (see §4.2.1.2). Assuming 13-µm pixels and 770-µs exposure times, it is estimated that ~0.06% of all pixels would be struck by an incident electron during the integration period. Assuming co-adding of 16 reads for digital-TDI in a CMOS APS device, an estimated 0.1% of all pixels would be affected, which is a tolerable level. During Io flybys, an 8X increase in radiation flux will increase the number of affected pixels, presenting a trade-off between longer exposure times and increased transient radiation noise.

The NAC electronics present no significant radiation concerns beyond those particular to

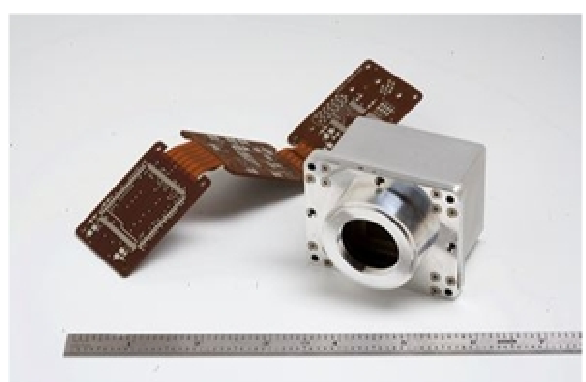


Figure 4.2-16. Miniature focal plane assembly for a STAR1000 CMOS APS indicative of the NAC focal plane electronics.

the detector and use of parts tolerant to 300 krad is assumed. To protect the NAC color filters from radiation degradation, 1 kg of radiation shielding is allocated.

Resource Estimates

The NAC mass estimate of 13.4 kg (including 3 kg of shielding mass) is derived from similarity to the New Horizons LORRI instrument and assumed values for harness mass and the 6U cPCI electronics boards. Power dissipation is estimated at 14 W during image acquisition and is driven by pixel rate, data compression and the high-speed SpaceWire interface.

For pushbroom operation with an orbital ground track speed of 1300 m/s in the 100-km orbit, the NAC line period is 770 µs. Assuming 12 bits/pixel, the NAC uncompressed data rate is 31.9 Mbps, and the compressed data rate (with compression factor of 3 assumed) is 10.6 Mbps.

Planetary Protection

Planetary protection concerns for NAC can be met through dry heat microbial reduction. Discussions with Omega Optical indicate that optical filters constructed by sputtering SiO_2 and Nb_2O_5 layers on a SiO_2 substrate are tolerant of temperatures exceeding JEO planetary protection requirements. Temperature effects on other optical materials, the adhesives used in optical mounts, and the image sensor will require thorough testing early in instrument development. A one-time-opening telescope door with biobarrier seals is baselined to prevent recontamination after sterilization.

4.2.2.9 Camera Package

The Camera Package consists of a Wide-angle Camera (WAC) and a Medium-angle Camera (MAC) with basic functionality similar to that of dual imaging systems on MESSENGER (MDIS) and the camera on LRO (LROC). The notional JEO WAC and MAC are, as separate items, similar to the MRO Mars Color Imager (MARCI) and New Horizons MVIC instruments shown on **FO-5**. The WAC and MAC imagers will be used in Europa orbit at several altitudes, and will generate context imaging near closest approach of targeted flyby satellite encounters. The Camera Package baselined for JEO is tailored to satisfy the following science measurement requirements identified in §2.5.

- WAC—Global color imaging:
  - Better than 100-m spatial resolution from a 100-km orbit
  - Panchromatic plus three color bands
- WAC—Stereo topography:
  - Better than 100-m spatial resolution from a 100-km orbit
  - ~20-m vertical resolution
- MAC—Context imaging:
  - Better than 10-m spatial resolution from a 100-km orbit

Instrument Description: WAC

Collection of a WAC global map with 100-m spatial resolution in 8 Eurosols (~28 Earth days) while using only every other 100-km orbit requires an image swath width >60 km. This results in a requirement for >600 WAC pixels cross-track, and a 1024-pixel-wide image sensor is baselined to allow for ample cross-track swath overlap for stereo imaging. The notional WAC has a 1-mrad IFOV to produce a 100-m pixel footprint from the 100-km orbit. The 1024-pixel-wide image sensor results in an instrument FOV of ~58° full angle. Vertical resolution provided by stereo imaging from the 100-km orbit is shown in **Figure 4.2-17**. A digital elevation model (DEM) vertical resolution of 20-m is achieved at a stereo convergence angle of 60º, approximately the largest convergence angle available with WAC. Multiple passes (N) will improve vertical resolution by SQRT(N), extending the area at which 20-m resolution is achieved.

A compact wide-angle refractive telescope similar to that of the MRO MARCI instrument and a detector configuration similar to that of the New Horizons MVIC are baselined. A detector with four independent line arrays on a single substrate operating in pushbroom mode, similar to that shown in **Figure 4.2-18**, is baselined. Three fixed-color filters superimposed directly on the image sensor satisfy the global color imaging requirement with a minimum of complexity.

Preliminary WAC performance analysis has been completed using the pixel characteristics (quantum efficiency, 13-µm pixel size, 100-K e- well depth) of the e2v CCD47-20BT image sensor used by the New Horizons

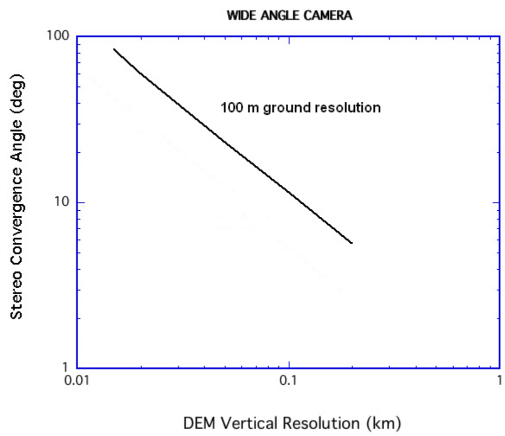


Figure 4.2-17. Predicted Wide-angle Camera vertical resolution obtained by stereo imagery based on parallax computations and use of modern auto-correlators.

LORRI instrument as *an example* of the performance expected from the WAC image sensor. The measured LORRI system readout noise of 20 electrons was assumed, although the LORRI pixel readout rate is considerably higher than that required for WAC (1.2 MHz vs. 13.3 KHz). Nominal selections for the color filters defined by the JEO SDT are:

- Band #1 <450 nm
- Band #2 630–670 nm
- Band #3 >930 nm

The wavelength-dependent quantum efficiency of the CCD47-20BT (*example only*) indicates that the line arrays for Band #1 and Band #2 will receive ~1/10 of the illumination of the panchromatic channel, while the line array for Band #3 will receive ~1/20 of the illumination. To balance the exposure times between the panchromatic and color channels, a neutral density filter, nominally ND-1, can be assumed in lieu of independent exposure control for each line array element.

Assuming a 13-mm focal length telescope with 2.6-mm aperture (*f*/5), an ND-1 filter on the panchromatic channel, an optical efficiency of 75%, and a high surface reflectance of 60%, the 100-K e- full well depth of the CCD47-20BT is reached in ~20 ms, or ~25% of the 77-ms available integration time. Barring radiation-induced transient noise, this results in a very high SNR (~300) driven by photon noise rather than system noise and allows for longer exposure times over low-contrast surfaces. Performance

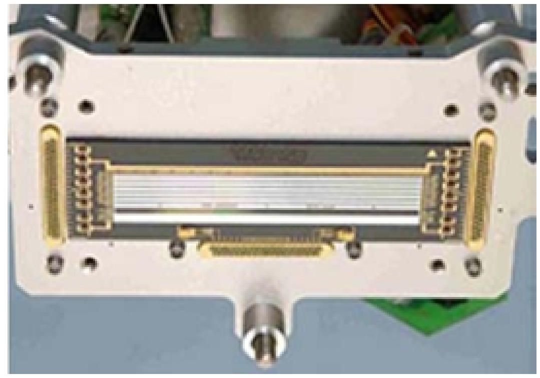


Figure 4.2-18. New Horizons MVIC detector containing multiple line arrays on a single substrate and indicative of the notional WAC detector.

of Band #1 and Band #2 will be similar to that of the panchromatic band with an ND-1 filter applied. The SNR of Band #3, which receives about half the light of the other bands, is ~200.

Instrument Description: MAC

The notional MAC has a 0.1-mrad IFOV to produce a 10-m pixel footprint from the 100-km orbit. Use of a 2048-pixel-wide image sensor results in an instrument FOV of ~11.7° full angle. A compact refractive telescope similar to that of the MDIS-WAC instrument (10.5° FOV) is baselined although off-axis reflective designs are possible. A single line array detector and panchromatic imaging are baselined. Preliminary MAC performance analysis has been completed in the same manner as for WAC using the pixel performance characteristics of the e2v CCD47-20BT image sensor as *an example* of the expected performance of the MAC line array. The measured LORRI system readout noise of 20 electrons was used here as it was for the WAC analysis. Assuming a 130-mm focal length telescope with 23.2-mm aperture (*f*/5.6), an optical efficiency of 75%, an average detector quantum efficiency of 60%, and a low surface reflectance of 20%, the 100-K e- full well depth of the CCD47-20BT is reached in the 7.7-ms available integration time. Barring radiation-induced transient noise, this results in a very high SNR (~300) driven by photon noise rather than system noise and allows for shorter exposure times over brighter surfaces. Use of slower (and cheaper) optics or a detector with lower quantum efficiency would potentially result in a requirement TDI operation to improve the SNR.

Instrument Description: Common Elements

A physical and functional block diagram of the Camera Package is given in **Figure 4.2-19**. Assuming pushbroom operation for both cameras, the functionality of WAC and MAC are identical except for the color filters particular to WAC. To prevent a single-point failure that could cause the loss of both WAC and MAC, two independent but identical sets of electronics are baselined with unique spacecraft interfaces to both WAC and MAC.

Consistent with the instrument architecture described in §4.2.1, minimal electronics are packaged at the focal plane with the detector. The signal chain shown in the focal plane electronics contains elements required for a CCD image sensor (clock drivers, correlated double sampler, A/D conversion) that either are unnecessary or are typically implemented within a CMOS APS device. A highly integrated CMOS APS device is an ideal solution, as it minimizes components at the focal plane that require radiation shielding.

A passive thermal design is baselined for both WAC and MAC with anti-sunward radiators used by both. Detector anneal heaters are baselined to mitigate radiation damage.

Each camera is baselined with one electronics board (6U cPCI format) housed remotely in the science electronics chassis. The board provides DC/DC power conversion for both the camera and the electronics board itself. Camera interface logic, image data compression, and a SpaceWire interface to the spacecraft are contained in a single radiation-hardened ASIC. Data compression is assumed to be wavelet based with commandable degrees of compression. Radiation-hardened static RAM (currently available as 16-Mb devices) is included for buffering incoming imager data, data compression intermediate products, and incoming and outgoing SpaceWire command and telemetry data. Co-development of WAC and MAC lends itself to development of a single ASIC design for use in both the WAC and MAC electronics.

Radiation Effects and Shielding: WAC

To protect the WAC image sensor from total dose, displacement damage and transient radiation noise, radiation shielding with 1 cm of Ta, comparable to that used by the Galileo SSI, is baselined. The JEO mission radiation dose depth curve indicates a ~35 krad total dose behind 1 cm of Ta shielding which, assuming a required design margin of 2, allows use of detectors tolerant of 70 krad. While a CMOS APS device is favored for the notional JEO WAC due to its potential for high radiation tolerance, this dose level allows a choice of silicon device technologies including CMOS APS, P-channel CCD, and (arguably) N-channel CCD. Shielding mass of 1.5 kg is

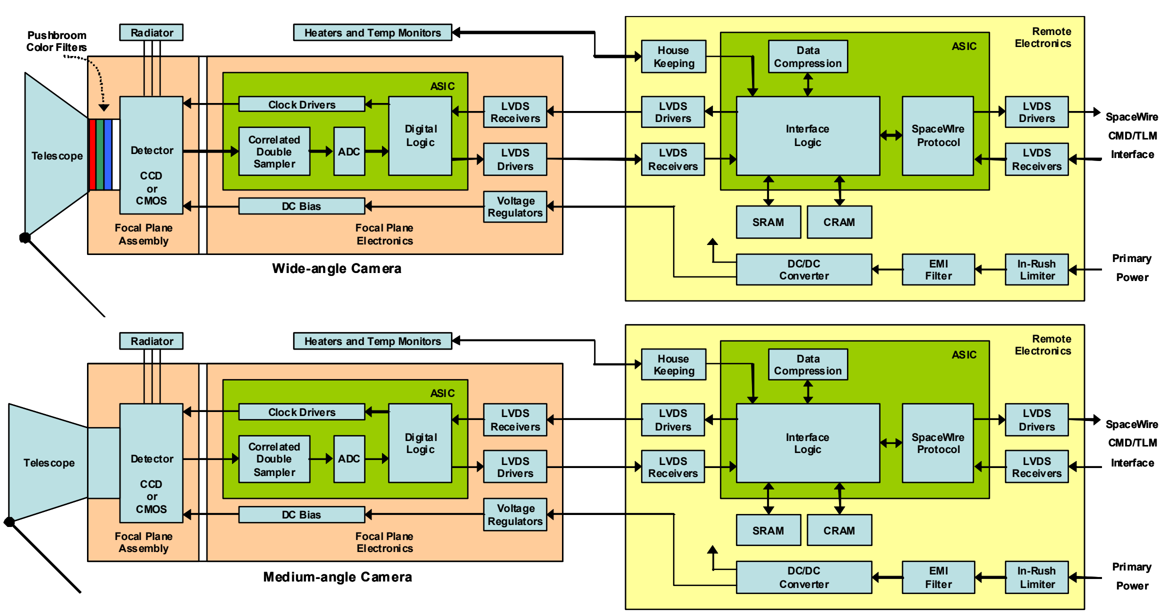


Figure 4.2-19. Block diagram of the notional Camera Package.

allocated for a 1-cm Ta, 5 × 3 × 4 cm enclosure similar to that shown in **Figure 4.2-16**, which is designed to house a STAR1000 based CMOS APS and its interface electronics.

The impact of radiation background noise on WAC has been analyzed by estimating the number of high-energy electrons and protons penetrating the 1-cm Ta shield and assessing their effect on the silicon detector. An estimated 4.3×10^5 electrons/cm^2·s would reach the detector through 1 cm of Ta shielding (see §4.2.1.2). For a typical silicon image sensor, each incident electron can be expected to generate an average of 2000 signal electrons in the detector (per *JPL D-48256)*. Assuming 13-µm pixels and a maximum exposure time of 77 ms for the notional WAC, a "hit rate" of 5.6% of pixels per integration time is expected in orbit at Europa. With the assumption that the signal-electrons generated by the incident particles are concentrated on a single pixel, the method of calculating the SNR adopted for the Galileo SSI camera can be employed [*Klaasen et al. 1984*]. Based on empirical data, the radiation-induced noise was approximated as 35 × SQRT(mean radiation signal per pixel). For a 5.6% hit rate and 2000 electrons per hit, the radiation-induced noise would contribute 370 electrons to the WAC SNR calculation. This reduces the WAC SNR to ~200 for panchromatic and to ~110 for color. The number of incident protons reaching the detector through the 1 cm Ta shield can be estimated using the external integral 100-MeV flux level at Europa. The expected 50 protons/cm^2·s, when combined with 13-µm pixels and a maximum 77-ms exposure time, result in a hit rate of 0.0065% of pixels per integration time in orbit at Europa. While the proton is expected to cause a strong signal (~10,000 signal-electrons) in a pixel or pixel group at the impact site, the low number of occurrences, ~7 per 1-Mpixel image, and the strong signal are expected to have no significant impact on Europa science after ground-based post-processing to remove artifacts. During Io flybys, the 8X increase in radiation flux will require shorter WAC exposure times or increased radiation shielding to limit transient radiation noise.

Radiation Effects and Shielding: MAC

Background radiation noise is mitigated by the relatively short exposure times MAC uses. With a 10-fold reduction in exposure times relative to WAC, an estimated 0.56% of pixels will be hit by incident electrons. Assuming concentration of all 2000 electrons on a single pixel, the method employed for computing the SNR for Galileo SSI approximates the per-pixel contribution due to radiation as 117 electrons, resulting in minimal impact on the WAC SNR. Applying a 10-fold reduction in the proton hit rate relative to WAC results in an estimate of >1 hit within a 1-Mpixel image or ~3 hits within a 2048 × 2048 MAC image. This is expected to have no significant impact on Europa science after ground-based post-processing. Radiation shielding mass of 1.5 kg is allocated for a 1-cm Ta, 5 × 3 × 4 cm enclosure similar to that shown in **Figure 4.2-16**, which is designed to house a STAR1000 based CMOS APS and its interface electronics. As with MAC, operation during Io flybys will result in an 8X increase in transient radiation noise.

Radiation Effects and Shielding: Common Elements

The WAC and MAC electronics present no significant radiation concerns beyond those particular to the detector, and use of parts tolerant to 300 krad is assumed. Total dose and displacement damage effects on optical materials can be mitigated through use of a combination of fused silica and radiation-hardened glasses. In a system with a refractive telescope, the telescope itself acts as a "forward shield" for the image sensor, with the remainder of the image sensor surrounded by radiation shielding material. In a system with a reflective telescope, a folded off-axis design can act as a "baffle" for radiation shielding of the detector, enabling shielding of the image sensor from all radiation input angles.

Resource Estimates

Mass estimates for WAC (3.8 kg including 1.5 kg of radiation shielding) and MAC (4.0 kg including 1.5 kg of radiation shielding) are derived from similarity to the camera subassemblies of MESSENGER MDIS and from assumed values for harness mass and the 6U cPCI electronics boards. Power estimates for WAC (5.9 W) and MAC (7.2 W) are based on measured values of the MESSENGER MDIS camera subassemblies and New Horizons LORRI electronics.

For an orbital ground track speed of 1300 m/s in the 100-km orbit, the WAC line period is 77 ms. Assuming 12 bits/pixel from each of the four line arrays, the WAC uncompressed data rate is 639 kbps and the compressed data rate (with compression factor of 3 assumed) is 213 kbps.

For an orbital ground track speed of 1300 m/s in the 100-km orbit, the MAC line period is 7.7 ms. Assuming 12 bits/ pixel from each of the four line arrays, the MAC uncompressed data rate is 3.19 Mbps and the compressed data rate (with compression factor of 3 assumed) is 1.06 Mbps.

Planetary Protection

Planetary protection concerns for the Camera Package will be met through dry heat microbial reduction. Temperature effects on optical materials, optical mounts, and the image sensor are similar to those of NAC. One-time-opening telescope doors with biobarrier seals are baselined to prevent recontamination after sterilization.

4.2.2.10 Magnetometer

The notional Magnetometer (MAG) measures the magnetic field at Europa with sufficient sensitivity to resolve the induction signal generated in Europa's ocean as a response to Jupiter's magnetic field. Operation in Europa orbit for an extended period allows sounding at multiple frequencies to determine ocean thickness and conductivity. Performing a role similar to that of the Galileo magnetometer, the notional MAG is adapted from more recent designs, such as the MESSENGER MAG, and from ongoing developments in ASIC design for highly integrated magnetometer electronics. The MAG baselined for JEO is tailored to satisfy the following science requirements identified in §2.4.

- Characterize the magnetic environment at Europa to determine the induction response from the ocean:
  - Measurement rate: 8 vectors/s
  - Measurement sensitivity: better than 0.1 nT
- Measure ion-cyclotron waves and relate to plasma-pickup and erosion:
  - Measurement rate: 32 vectors/s
  - Measurement sensitivity: better than 0.1 nT

Instrument Description

The notional MAG contains two sensors located on a 10-m boom: one at the tip and the other at the halfway point. The dual magnetometer configuration can quantify and separate the spacecraft field from the background field, thereby improving the overall sensitivity of the system. Its also provides a level of redundancy if in-flight calibrations are performed to assess the spacecraft-generated magnetic field. The expected magnetic field range over the full JEO mission is 0–3000 nT, with the upper range set by the Io torus. To achieve the required sensitivity, a magnetic cleanliness program is required to limit the magnetic field of the spacecraft at the 10-m point of the boom to <0.1 nT, with variation of <0.03 nT. During this study, an analysis of the impact of using ASRGs as the spacecraft power source confirmed that with a 10-m boom this level of cleanliness could be achieved.

The notional MAG sensors use three orthogonally mounted ring-core fluxgate sensors and are based on the MESSENGER MAG sensor assembly shown in **FO-5**. The sensors are excited by an AC signal that is also used to synchronously detect the signals from the fluxgate sensors. In an analog fluxgate magnetometer, the output from each synchronous detector is applied to an integrator, which supplies the feedback current used to null the field seen by the sensor. The output of the integrator is directly proportional to the component of the magnetic field along each orthogonal axis and is sampled by a high-bit-count A/D converter. In a digital fluxgate magnetometer, the output from each synchronous detector is applied to an integrator whose output is digitized by an A/D converter. All subsequent filtering is done in the digital domain, and feedback to null the field seen by the sensor is generated by a D/A converter.

Digital fluxgate magnetometers capable of meeting the JEO science requirements have been demonstrated [*O'Brien et al. 2007*], and substantial progress has been made in development a Magnetometer Front-end ASIC (MFA) that incorporates a complete magnetometer signal chain including synchronous detection, high-bit-count ΣΔ A/D converters, digital filtering, ΣΔ D/A converters for sensor feedback and basic output data formatting into a single device [*Valavanoglou et al. 2007*]. Although current versions of MFA do not meet all of the JEO radiation requirements, with further development this technology is likely to be available for JEO and this approach is baselined for the notional MAG instrument.

A physical and functional block diagram of the notional MAG is shown in **Figure 4.2-20**. A single 6U cPCI electronics board located in the science electronics chassis contains ASICs for magnetometer signal processing, spacecraft interface electronics and a low voltage power supply.

Fluxgate sensors suffer from small drifts in their zero levels that require periodic calibration. During the cruise phase, calibrations can be achieved using the rotational nature of the interplanetary magnetic field. Once inside Jupiter's magnetosphere, slow spacecraft spins around two orthogonal axes will be required every 2 to 4 weeks.

Radiation Effects and Shielding

Fluxgate magnetometer sensors contain no active electrical parts, and with proper selection of materials present no issues in meeting the JEO radiation requirements. The notional MAG electronics are located in the science electronics chassis, which provides radiation shielding sufficient for components hardened to 300 krad. A fully radiation-hardened magnetometer signal-chain ASIC similar to the current MFA is assumed for the notional JEO MAG.

Resource Estimates

The mass estimate for the notional MAG is based on the as-built mass of the MESSENGER MAG sensor (250 g), the as-built mass per unit length of the MESSENGER MAG harness (113 g/m), and the estimated mass of a 6U cPCI board. The total mass estimate for MAG is 3.2 kg, slightly more than half of which is required by harnessing. MAG power dissipation is estimated at 4 W based on scaling measured performance of the MESSENGER MAG for two probes. The MAG telemetry rate is estimated at 4 kbps based scaling of the MESSENGER MAG telemetry rate for a higher sampling rate (32 Hz max) and two sensors.

Planetary Protection

Planetary protection concerns for MAG will be met through dry heat microbial reduction. With proper selection of materials for the MAG sensor, no issues are expected.

4.2.2.11 Particle and Plasma Instrument

The notional Particle and Plasma Instrument (PPI) consists of two main measurement capabilities: plasma and energetic particles. The first detection system is a low-energy top-hat plasma sensor with a wide FOV measuring the spectra and angular distribution of low-energy electrons and mass-resolved

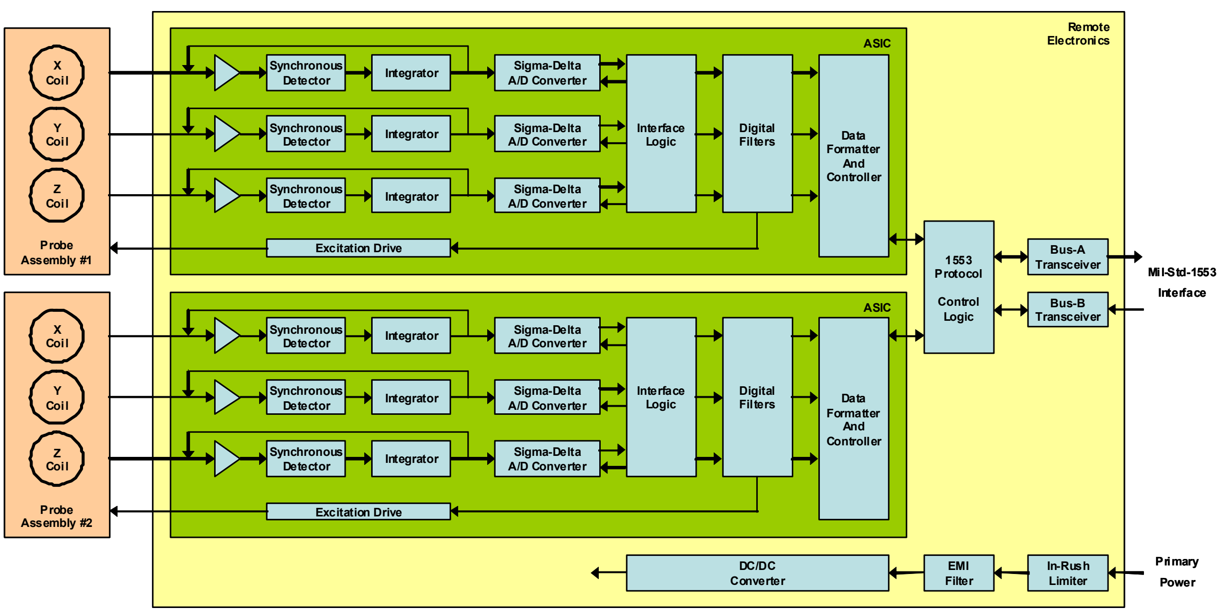


Figure 4.2-20. Block diagram of the notional Magnetometer.

ions in an energy range of ~10 eV up to ~30 keV. As currently envisioned, the plasma detection FOV is 90º × 360º. The second detection system is for energetic charged particles. Here a puck-like sensor head with a 160º × 12º fanbeam FOV measures the spectra and angular distribution of electrons between tens of keV and 1.5 MeV and ions between tens of keV and about 10 MeV. This sensor is complemented with a set of omni-directional integral electron detectors that measure the population of very energetic electrons >2 MeV.

The JEO PPI instrument detects plasma for several reasons. In the Jovian system, plasma moments such as flow direction and electron temperature tell us about the ability of the magnetospheric system to maintain co-rotation and about the rate of impact ionization of the iogenic and other neutrals, respectively. Close to Europa, in addition to determining the plasma moments, we will attempt to determine the contribution of the plasma to the magnetic signal. This will help isolate that part of the magnetic field measurement due to inductive response.

Energetic particles are measured in the Jovian system for a number of reasons, including the study of the radiation environment of all of the satellites. Precipitating charged particle fluxes are used to connect optical detections of the surface with radiolytic weathering. Electrons and their secondaries deposit energy into the surface, catalyze reactions, and create molecules such as peroxide. Energetic heavy ions sputter the surface, re-depositing volatiles from the high precipitation regions. In the magnetosphere itself, the presence of electron beams and their connection to auroral emissions, the rate and distribution of ion and electron injections, and other dynamic processes will be investigated. The PPI baselined for JEO is tailored to satisfy the following science requirements identified in §2.5.

Measurement of the flux of trapped and participating ions (with composition) and electrons:

- Energy range: 10 eV to 10 MeV
- Energy resolution: ΔE/E = 0.1
- Angular resolution: 15º
- 4π coverage desirable

The notional PPI is based on the performance capabilities and resource utilization of the Deep Space 1 Plasma Experiment for Planetary Exploration (PEPE) shown in **FO-5** and the Juno Energetic-particle Detector Instrument (JEDI). While still in development, JEDI is based closely on the New Horizons Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI), shown in **FO-5**, which has similar performance characteristics and resource utilization except that radiation shielding has been added for the Juno mission. The omni-directional electron detectors are assumed to interface to existing electronic channels in the energetic particle instrument. Together this group of heritage sensors meets the science requirements, other than obtaining the desired 4π coverage. A physical and functional block diagram of PPI is shown in **Figure 4.2-21**.

Instrument Description

The notional PPI particle detector head contains a collimator, an energy system for measurement of total particle energy, and a TOF system for measurement of particle velocity. The energy system uses an array of solid-state detectors (SSDs) and existing radiation-hardened energy measurement ASICs. The TOF system consists of start and stop foils, an MCP with position-sensitive start and stop anodes, and existing radiation-hardened time-to-digital converter (TDC) ASICs. Its is assumed for JEO that TDCs, data acquisition and event processing circuitry, spacecraft interface electronics, and low-voltage power supplies are relocated from the sensor head to the science electronics chassis for effective use of radiation shielding mass.

The notional plasma sensor head contains integrated ion and electron optics with MCP detectors, high-voltage and bias-voltage power supplies, and front-end amplifiers. As with the particle detector head, it is assumed that TDCs, coincidence logic, data acquisition and processing electronics, and spacecraft interface electronics are relocated from the sensor head to the shared instrument electronics chassis. To increase the radiation tolerance of the original PEPE design, the same radiation-hardened ASICs used by the notional energetic particle detector are assumed for the notional plasma detector.

The omni-directional integral electron detectors consist of two sets of four silicon SSDs housed under nearly hemispherical metal

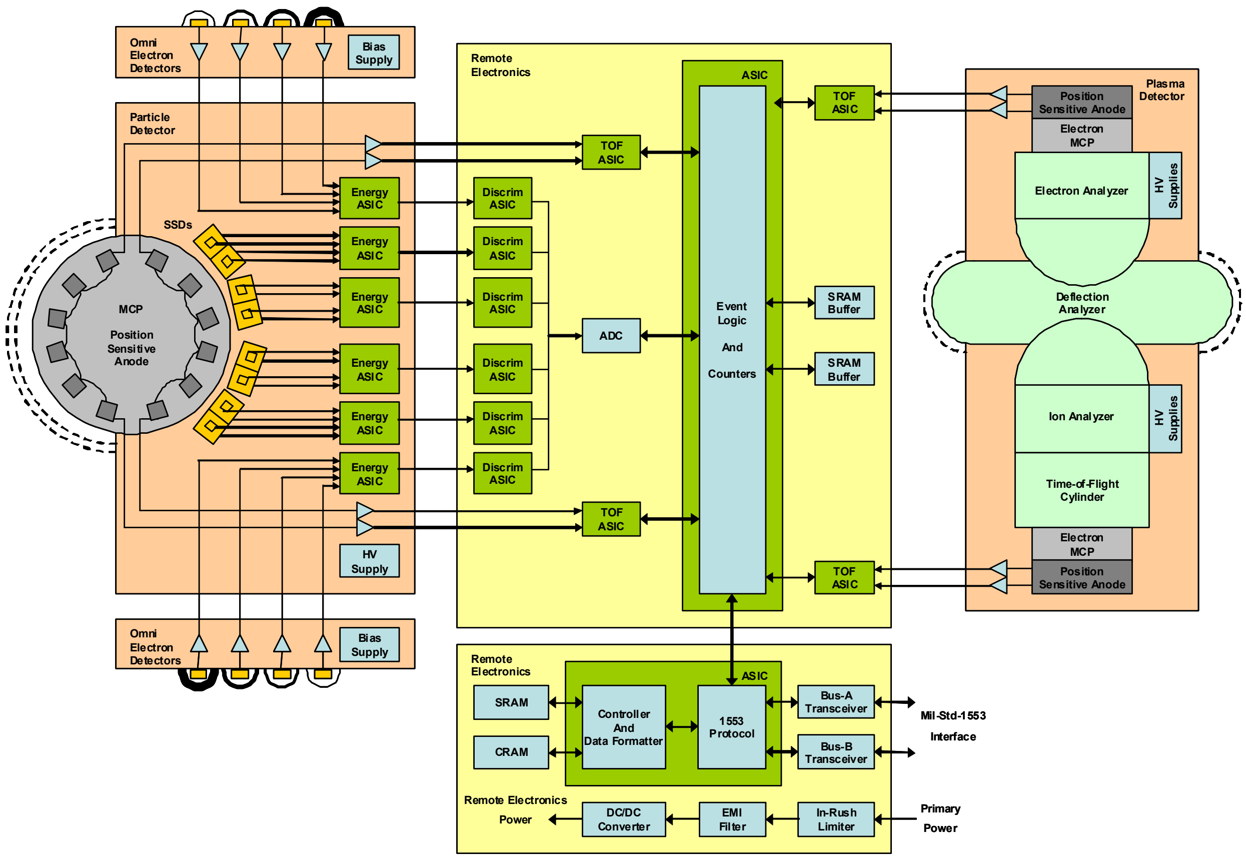


Figure 4.2-21. *Block diagram of the notional Particle and Plasma Instrument.*

domes at different locations on the spacecraft. The thickness and material of the dome determine the energy required to penetrate the dome and generate a detectable signal. The notional energy bands for the integral electron detectors are >2 MeV, >4 MeV, >8 MeV, and >16 MeV.

Radiation Effects and Shielding

Mass estimates for radiation shielding to reduce background radiation noise in the PPI MCPs are derived from analysis of raw singles rates of the Galileo Energetic Particle Detector (EPD) start-MCP that were recorded during eight encounters at Europa. The expected flux of particles reaching the EPD start-MCP during these encounters through an estimated thickness (T) of 5 g/cm^2 of radiation shielding can be estimating by applying a 10-MeV cutoff energy (E) derived from

$$E(\mathrm{MeV}) = [T(\mathrm{g/cm^2}) + 0.106]/0.53$$

[*Zombeck 1982*] to the external integral flux at Europa. Although EPD data indicate that an estimated 2.7×10^6 particles/cm^2·s reached the EPD start-MCP through its radiation shielding, the instrument registered only an average of 21.5×10^3 counts/cm^2·s. This methodology, which inherently includes all secondary radiation products such as X-rays generated by Bremsstrahlung, indicates that the effective yield for incident background radiation on an MCP is ~1%. Given uncertainties in this "recipe" for determining MCP yield, a 2% yield rate is assumed for this report.

For the notional particle sensor, 0.6 cm of effective Ta MCP radiation shielding is baselined. This level of shielding is estimated to reduce the incident flux at the MCP to 8.7×10^5 particles/cm^2·s.The anode design for the 50-mm JEDI MCP reduces the active area of the MCP to ~5 cm^2. Assuming this active area and a 2% MCP yield rate, a background rate due to radiation of 8.7×10^4 counts/s is predicted. This rate, with typical coincidence logic applied, is low enough to allow proper instrument operation. Degraded instrument operation at Io with this level of radiation shielding is assumed.

Increasing the thickness of the JEDI radiation shielding by 50% gives a front cover thickness of 0.8 cm Ta, a back cover thickness of 0.4 cm Ta, a cylinder thickness of 0.4 cm Ta, and an expected overall effective shielding thickness of 0.6 cm Ta when factoring in the shielding of the adjacent front-end electronics. The front-end electronics are assumed to be hard to 1 Mrad and require shielding with 0.2 cm Ta with a 10 × 10 × 2 cm enclosure. Modeling of these components and the tungsten-copper radiation shields used by JEDI to protect its SSDs results in an estimate of 2.8 kg for radiation shielding of the notional JEO particle sensor head.

For the notional plasma sensor, 0.6 cm effective Ta MCP radiation shielding is also baselined to reduce the background radiation count rate to an acceptable level. One 25-mm MCP and one 50-mm MCP are assumed, with nominal shielding masses of 0.3 and 1.3 kg, respectively. The exposed nature of the MCPs within the electron and ion analyzers makes shielding the input side of the MCP difficult; therefore 3.0 kg of radiation shielding is allocated for the plasma sensor MCPs. Electronics adjacent to the plasma sensor head, including front-end electronics, bias supplies, and high voltage power supplies, are assumed to be hardened to 1 Mrad, requiring a 0.2 cm Ta radiation shielding and 1.0 kg of shielding mass for four 8 × 6 × 2 cm enclosures.

Total dose effects on MCPs are addressed in §4.2.2.5.

Resource Estimates

The mass estimate for the notional plasma sensor is derived by deconstruction and partitioning of the PEPE instrument, with a portion of its electronics assumed to be modernized and relocated to the science electronics chassis. This repartitioning is assumed to be slightly above mass-neutral after factoring in the intra-instrument harnessing required by the partitioning. Shielding mass for the MCPs and front-end electronics totals 5.0 kg, and one 6U cPCI electronics board is assumed, which results in a mass estimate of 9.6 kg for the notional JEO plasma sensor.

The mass estimate for the notional energetic particle detector assumes the mass of the JEDI "puck" sensor head, one 10 × 10 cm electronics board (PEPSSI form-factor) adjacent to the sensor head, and intra-instrument harness mass required by the partitioning. Shielding mass for the MCPs and front-end electronics totals 2.8 kg, and one 6U cPCI electronics board is assumed, which results in a mass estimate of 4.8 kg for the notional JEO energetic particle detector.

The mass estimate for the notional omni-directional electron sensors assumes dome thicknesses equivalent to 0.06, 0.12, 0.25, and 0.50 cm of Ta for the four desired energy ranges and a 2.5-cm inside diameter for housing the SSD. Each group of four domes is assumed to be mounted on top of a 13 × 4 × 1.5 cm enclosure housing preamps and a bias supply. Shielding with 0.2 cm of Ta (1 Mrad parts) is assumed for these two enclosures, which results in a mass estimate of 2.1 kg for the notional JEO omni-directional electron sensors.

The total mass estimate for PPI is thus 16.4 kg, including 8.8 kg of radiation shielding. The PPI telemetry rate is estimated at 2 kbps based on the combination of PEPE and JEDI telemetry rates. The PPI power estimate is 13 W, also based on a combination of PEPE and JEDI.

Planetary Protection

Planetary protection concerns for PPI will be met through dry heat microbial reduction. The bare unpowered MCPs and SSDs can tolerate high temperature soaks, but selection of epoxies and other materials used to mount detectors and high-voltages foils will require careful selection and testing. The PEPSSI and JEDI instruments have two-piece clamshell aperture covers that can be upgraded to include biobarrier seals to prevent recontamination after sterilization. The existing PEPE design does not include a flight cover, instead using a red-tag remove-before-flight cover. Incorporation of a flight cover on a top-hat analyzer with 360 FOV will present a design challenge to the PPI design team.

4.3 Mission Design Overview

The JEO flight system will be launched on an Atlas V 551 from Cape Canaveral Air Force Station on a Venus-Earth-Earth Gravity Assist (VEEGA) interplanetary trajectory. After a cruise of just under six years, JEO will flyby Io just prior to performing the Jupiter orbit insertion (JOI) with a large main engine burn. JEO will then perform a 30-month gravity-assist tour to lower its orbital energy with respect to Europa. Such a tour provides the further benefit of extensive opportunities for Jovian system science. In particular, the tour begins with an Io Campaign involving three Io flybys after JOI, and continues with a System Campaign which involves flybys of each of the other Galilean satellites.

The tour ends with another large main engine burn that results in capture into low circular orbit at Europa. A roughly five day engineering assessment and orbit adjustment period ensues. The next 8 eurosols (~28 days) of the Europa orbital mission are known as the Global Framework Campaign, which is performed at an altitude of approximately 200 km. After concluding the first Europa Science campaign, the flight system will maneuver to a circular orbit of approximately 100 km to begin the Regional Processes Campaign, which lasts 12 eurosols (~43 days). The third campaign, the Targeted Processes Campaign, takes 8 eurosols (~28 days) and ends about 105 days after Europa Orbit Insertion (EOI). The Focused Science Campaign comprises the rest of the prime mission and ends at EOI + 9 months. **Foldout 6** (**FO-6**) depicts a summary of the mission design.

For discussion of data acquisition scenarios, data return strategies, and communication strategies, see §4.6 and Appendices G and H.

4.3.1 Mission Overview and Phase Definitions

General descriptions of each phase and the related activities are provided in **Table 4.3-1**.

4.3.2 Launch

An Atlas V 551 will launch JEO with a maximum C_3 of 12.8 km^2/s^2 during a 21-day launch period opening on 29 February 2020. The launch vehicle and launch period parameters are shown on **FO-6E**. The flight system is designed to launch on any given day in the launch period without re-configuration or modification.

4.3.3 Interplanetary Trajectory

The baseline trajectory used for the JEO mission is a VEEGA (**FO-6A**). Cruise navigation will use Doppler, range, and ΔDOR observations from the Deep Space Network

Table 4.3-1. *Mission Phase Definition and Description*

Phase	Activity	Start/End
Interplanetary	Launch and Early Operations: Begins with the launch countdown. Activities include launch, initial acquisition by the DSN, checkout and deployment of all major flight-system subsystems and a moderate maneuver to clean-up trajectory errors from launch vehicle injection	Feb/Mar/Apr 2020 30 day duration
	Cruise: Activities include science instrument calibrations, Venus and Earth gravity-assist flyby operations, potential asteroid flyby target of opportunities (currently out of scope), annual spacecraft health checks, trajectory correction maneuvers, and operations readiness tests (ORTs)	Mar/Apr 2020 to Jun 2025
	Jupiter Approach: Activities include final preparations, training, and ORTs for all mission elements in preparation for JOI and Jovian Tour, and an optical navigation campaign to improve satellite ephemerides prior to the pre-JOI Io flyby. The phase includes the Io flyby just a couple of hours before JOI and ends with completion of JOI.	Jun 2025 to JOI (Dec 2025)
Jovian Tour (Required to be <33 months)	Io Campaign: The first ~year of the mission , including three Io and one Callisto encounters, ending at the last close Io encounter	JOI to I4 (Dec 2025 – Dec 2026)
	System Campaign: The remainder of the tour, characterized by multiple (20+) flybys of Europa, Ganymede, and Callisto to shape the trajectory for the purpose of getting into orbit around Europa with as little positive ΔV as possible while accomplishing important Jupiter system science along the way. The final month of the phase includes large deterministic maneuvers aimed at setting the final approach to Europa and EOI itself	I4 to EOI Dec 2026-Jul 2028
Europa Science	Begins after achieving the orbit around Europa and continues for 9 months. Consists of four science campaigns, preceded by a short checkout period: Europa Campaign 1: Global Framework Europa Campaign 2: Regional Processes Europa Campaign 3: Targeted Processes Europa Campaign 4: Focused Science	Jul 2028 – Mar 2029

(DSN). The deep-space ΔV required on the opening day of the launch period is zero, but it grows steadily until reaching about 93 m/s on the last day of the launch period. That ΔV occurs near aphelion on the Earth-Earth leg of the trajectory. The interplanetary trajectory design will comply with all required NEPA assessment and safety analysis (see §4.11.9).

During the final couple of months before JOI, optical navigation, using the NAC science instrument, will provide significant improvement of the ephemerides of the members of the Jupiter system.

4.3.4 Trajectory at Jupiter

On the initial approach to Jupiter, JEO will flyby Io for a gravity assist prior to JOI. The current design conservatively plans for an Io flyby altitude of 1000 km, although the planned optical navigation will allow future consideration of much lower altitudes, thereby allowing a further reduction in JOI magnitude (~50 m/s if the flyby altitude is dropped to 500 km). JOI straddles the 5.2 Jovian radii (R_j) perijove and puts JEO into an orbit with a period of about 200 days. This Io strategy is a change over last year's strategy [*Clark et al. 2007*], which used a Ganymede gravity assist prior to JOI. The current strategy takes advantage of the benefit of performing JOI deep within Jupiter's gravity well, resulting in a ΔV savings of 200 m/s (flight system dry mass increase of roughly 160 kg) over a Ganymede-first strategy (employing perijove as low as $9R_j$). The higher radiation dose experienced by the flight system using the Io strategy (about 0.4 Mrad higher than for the Ganymede strategy due to the many additional perijove passages near Io) will cost an additional 40 to 60 kg of shielding, yielding over 100 kg of additional mass margin. The current estimated total mission radiation dose, to the end of Europa Campaign 3, is 2.8 Mrad behind 100 mils of Al, with an RDF (Radiation Design Factor) of 1.

Near apojove of the first orbit, a maneuver targets JEO to the second Io encounter of the mission, which will be the first Io encounter of the tour. In the process, it will correct for the solar perturbations induced as a result of the rather large initial orbit and remove any remaining errors from the initial Io flyby and JOI.

Many possible tour designs exist. A tour ending at Europa typically lasts 1.5–3 years and requires flyby-cleanup ΔV of an average of about 8 m/s per satellite flyby based on the Galileo experience. A study derived requirement is to limit the tour to no more than 33 months and have a radiation dose of less than 1.65 Mrad behind 100 mils Al. The baseline tour chosen for this report (known as 08-008, the eighth tour designed in 2008) is only one possible design, to illustrate feasibility. The 30-month baseline tour takes advantage of the gravity assists from Jupiter's moons to decrease the ΔV (and associated propellant), required to get into Europa orbit by at least 3 km/s. The baseline tour follows guidelines for tour development originally generated for Europa Orbiter and augmented in this study based on the scientific desires identified in **FO-3**. It includes three close Io encounters (after JOI), six with Europa, six with Ganymede, nine with Callisto prior to EOI as shown in **Table 4.3-2**. Tour 08-008 achieves several of the science desires given in **FO-3**, including a low-altitude flyby (300 km) over the active volcanic region of Io called Amirani, and early Europa flyby at V_∞ <7 km/s, and one high-latitude flyby of Callisto. Designing a tour which achieves all of the science desires was beyond the scope of this study, but experience on Europa Orbiter from 1999 to date indicates that further refinement is very likely, given more detailed analysis. Future analyses will also take planetary protection into consideration, following the reliability-based probability of impact approach used for Juno.

In addition to the observations acquired during satellite flybys, science observations of the Jovian magnetosphere and atmosphere, and monitoring of Io, will be possible between encounters during the Jovian Tour phase.

The three most closely spaced consecutive flybys are on orbits C22 and G23, with separations of 4.9 and 7.2 days. These turnaround times are within JPL's experience envelope, especially given the high altitudes involved and the fact that it is late in the tour when ephemerides and the spacecraft system will be better known and calibrated. A more detailed analysis of this issue will be conducted in Phase A, and the tour requirements adjusted if needed.

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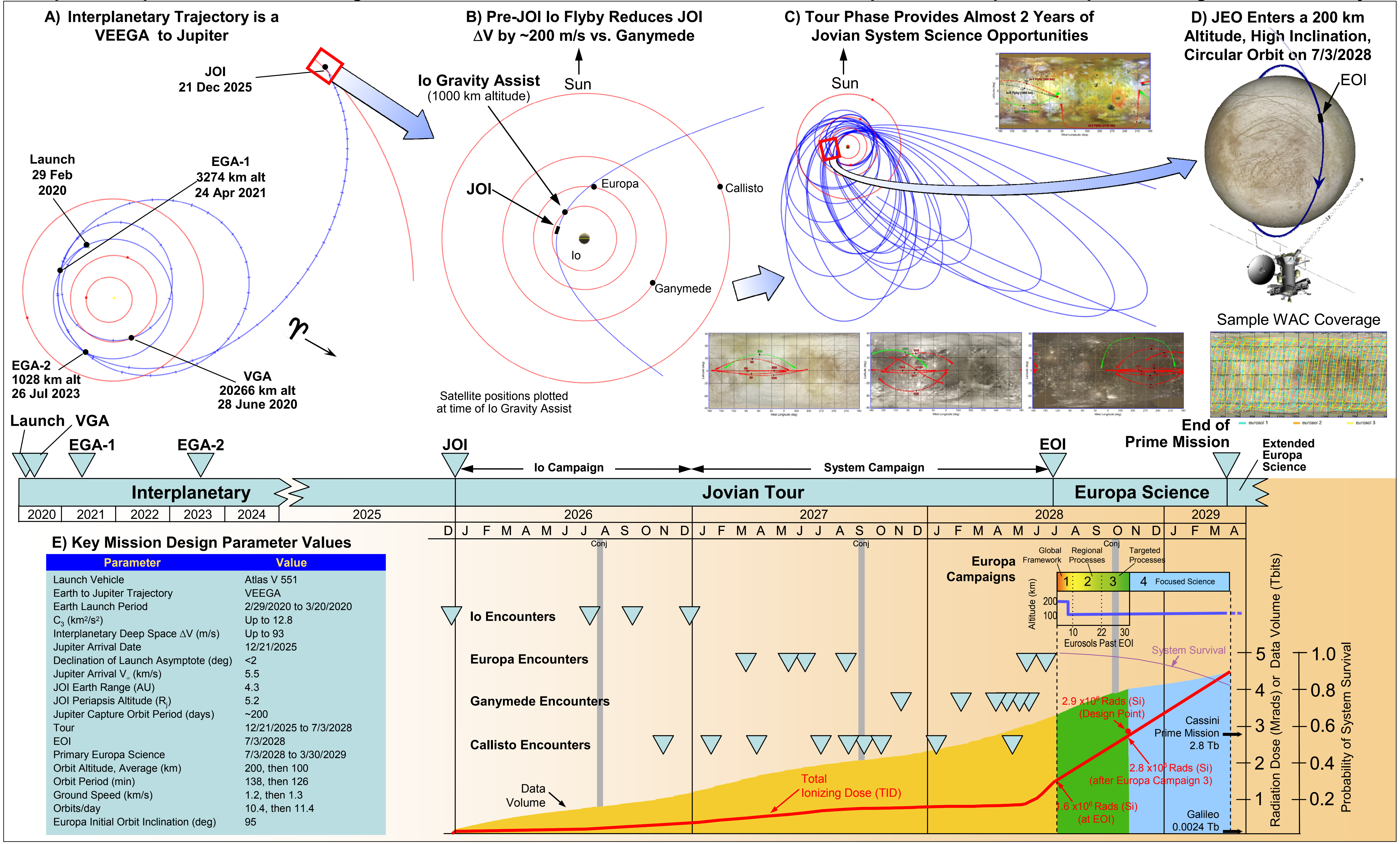
Jupiter Europa Orbiter Mission Design Delivers 11 Rad-Hard Instruments to Low-Altitude Europa Orbit to Explore Europa to Investigate Its Habitability



E) Key Mission Design Parameter Values

Parameter	Value
Launch Vehicle	Atlas V 551
Earth to Jupiter Trajectory	VEEGA
Earth Launch Period	2/29/2020 to 3/20/2020
C_3 (km²/s²)	Up to 12.8
Interplanetary Deep Space ΔV (m/s)	Up to 93
Jupiter Arrival Date	12/21/2025
Declination of Launch Asymptote (deg)	<2
Jupiter Arrival V_∞ (km/s)	5.5
JOI Earth Range (AU)	4.3
JOI Periapsis Altitude (R_J)	5.2
Jupiter Capture Orbit Period (days)	~200
Tour	12/21/2025 to 7/3/2028
EOI	7/3/2028
Primary Europa Science	7/3/2028 to 3/30/2029
Orbit Altitude, Average (km)	200, then 100
Orbit Period (min)	138, then 126
Ground Speed (km/s)	1.2, then 1.3
Orbits/day	10.4, then 11.4
Europa Initial Orbit Inclination (deg)	95

Table 4.3-2. *Dates of close, targeted encounters of Galilean satellites during the representative Jovian Tour phase known as 08-008. Orbits starting with a J are orbits on which there are no targeted encounters.*

Tour 08-008														
Encounter Characteristics												Jovicentric Post-Encounter Orbit		
Orbit Identifier	Event	Date	Time Since Last Event	Altitude	V-infinity	Latitude @ C/A	West Longitude @ C/A	Phase @ -1 hr	Phase @ C/A	Phase @ +1 hr	Satellite-Centered Inclination	Period	Perijove Radius	Inclination
		(yy/mm/dd)	(days)	(km)	(km/s)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(days)	(Rj)	(deg)
I0	Io	25/12/21	0	1000	11.15	6.5	120.48	14.73	94.79	167.53	15.93	-	-	-
I0	JOI	25/12/21	0.1	-	-	-	-	-	-	-	-	210.1	5.2	7
I1	Io	26/07/09	199.8	300	10.28	18.2	115.41	18.7	84.75	160.26	24.99	56.6	5.1	7.8
I2	Io	26/09/03	56.6	3125	10.25	-73.52	212.54	16.43	74.72	153.44	90.86	55.1	5.1**	7.2
C3	Callisto*	26/10/30	57	362	9.44	77.6	297.86	10	85.72	167.58	77.82	59.9	5.2***	1.2
I4	Io	26/12/27	58	75	9.55	-34.5	122.84	19.41	72.28	158.26	34.59	31.5	5.1	0.3
C5	Callisto	27/01/26	29.8	2101	8.69	-3.5	248.98	70.92	153.54	123.31	176.47	38.4	5.8**	0.3
E6	Europa*	27/03/08	40.7	215	10.96	-1.0	86.61	53.62	141.83	129.89	178.92	28.1	5.6***	0.3
C7	Callisto	27/04/03	25.8	315	8.27	5.53	250.38	80.02	165.92	106.44	174.47	39.1	7**	0.4
E8	Europa*	27/05/14	41.4	231	9.12	27.9	76.38	76.82	149.34	106.69	152.04	28.4	6.8	0.3
E9	Europa*	27/06/11	28.4	1197	9.09	-7.2	78.24	82.94	166.16	105.11	172.75	23.7	6.7	0.2
C10	Callisto*	27/07/07	25.4	289	7.52	0.8	286.4	43.63	43.11	129.75	0.81	33	8.4	0.2
E11	Europa*	27/08/07	31.3	866	6.61	39.0	58.48	84.59	141.57	102.17	141	26.3	8.3***	1
C12	Callisto	27/08/31	23.9	175	7.15	51.6	256.59	91.16	129.49	92.65	128.34	33.4	9.5	4.2
C13	Callisto	27/10/03	33.4	78	7.15	-33.2	257.53	98.46	145.32	85.96	146.74	50.5	11.3	0.5
G14	Ganymede	27/11/24	51.8	315	6.90	-0.4	103.65	75.1	11.65	98.26	1.02	24.9	10.3	0.5
J15	Perijove	27/12/20	-	-	-	-	-	-	-	-	-		10.3	-
C16	Callisto	28/01/12	48.3	407	6.32	-12.1	259.2	107.2	160.89	80.4	167.89	36.9	12.5**	0.9
G17	Ganymede*	28/02/20	39.8	143	5.60	-5.7	75.14	124.93	146.99	60.13	174.06	18.3	11.3	0.4
C18	Callisto*	28/03/11	19.9	1283	5.16	-1.2	280.32	92.61	10.44	71.76	1.26	24.6	13.7	0.3
G19	Ganymede*	28/04/03	22.7	135	4.05	40.8	72.84	132.09	121.63	50.24	138.03	14.3	12.8	4.8
G20	Ganymede*	28/04/17	14.3	454	4.05	-48.64	70.86	148.88	114.93	36.78	130.26	10.4	11.6***	0.2
J21	Perijove	28/04/27	-	-	-	-	-	-	-	-	-		11.6	-
C22	Callisto	28/05/03	15.3	3219	1.99	42.6	225.98	149.5	89	28.61	135.54	12	14.6	5.4
C22	Ganymede*	28/05/07	4.9	600	2.17	1.4	71.17	133.19	62.77	42.62	146.05	7.2	12.4	5.9
G23	Ganymede*	28/05/15	7.2	1566	2.16	43.55	98.03	99.3	55.42	65.83	131.61	5.5	9.3***	0.7
J24	Perijove	28/05/18	-	-	-	-	-	-	-	-	-	-	9.3	-
J25	Perijove	28/05/24	-	-	-	-	-	-	-	-	-	-	9.3	-
E26	Europa*	28/05/29	14.5	100	1.63	-10.3	25.32	55.31	40.31	135.69	168.63	4.7	9.1***	0.5
J27	Perijove	28/06/02	-	-	-	-	-	-	-	-	-	-	9.2	-
J28	Perijove	28/06/07	-	-	-	-	-	-	-	-	-	-	9.2	-
E29	Europa*	28/06/12	13.9	633	1.17	-0.11	24.17	13.62	74.79	162.84	179.89	4.2	9.1***	0.5
J30	Perijove	28/06/16	-	-	-	-	-	-	-	-	-	-	9.2	-
J31	Perijove	28/06/20	-	-	-	-	-	-	-	-	-	-	9.2	-
J32	Perijove	28/06/24	-	-	-	-	-	-	-	-	-	-	9.3	-
J33	Perijove	28/06/29	-	-	-	-	-	-	-	-	-	-	9.3	-
E34	Europa-EOI*	28/07/03	21	200	0.77	-	-	-	-	-	-	-	-	-

Notes: * Outbound encounter
** S/C passes twice thru listed perijove: Once just after current inbound encounter, and once just before the *next orbit's* outbound encounter
*** S/C doesn't pass thru listed perijove on this orbit: When an outbound encounter is followed *on the next orbit* by an inbound encounter, the perijove passage is preempted

While the early tour strategy uses Io rather than Ganymede**,** the end of the tour resembles the low-radiation tour developed by Europa Orbiter, called 99-35. The early tour flybys are designed to quickly reduce orbit period so as to reduce the overall duration of the tour. Such flybys will normally also depress perijove, exacerbating the radiation dose. Because the initial perijove is not far inside of Io's orbit, the Io flybys don't depress perijove much, as can be seen in **Table 4.3-2**. Said in a different way, the V_∞ contours on the period vs. perijove plot are nearly vertical for the Io campaign.

The final Ganymede gravity assist sets up a near-Hohmann (minimum energy) transfer to Europa. This transfer is followed by two Europa flybys that reduce the orbital period to a 3:4 resonance (meaning that JEO goes around Jupiter three times in the time it takes Europa to go around four times) and then to a 5:6 resonance prior to EOI. Propulsive maneuvers are performed near one or more of the apojoves following those flybys to efficiently reduce arrival speeds at Europa. This final approach phase requires about 49 days following the last Ganymede flyby.

This final approach takes place within a high radiation environment, so flight time for this phase is a key characteristic that can be traded with ΔV (propellant mass) to result in an optimal combination for the mission. Several innovative techniques for designing captures at Europa were developed as part of the Jupiter Icy Moons Orbiter (JIMO) work and will be analyzed for applicability to a high-thrust mission as conceived for the current study.

Based on Galileo's experience, at least two flybys of each satellite (at different Jupiter centered, inertial longitudes) are necessary for radio-metric data to tie down the ephermeris, otherwise, eccentricity errors remain. Optical navigation would therefore be planned through the G17 encounter, after which, radiometric data would have tied down the satellite ephemerides sufficiently well as to preclude any further benefit of optical navigation. Without optical navigation, the amount of statistical ΔV would have to be increased by 100–200 m/s for the tour as a whole, and/or the flyby altitudes would have to be increased for the first half of the tour. These changes would also lengthen the tour duration and increase the radiation exposure. The use of optical navigation will be the subject of more detailed trade studies in Phase A, indeed its use may result in a reduction of the current statistical ΔV budget.

4.3.5 Orbits at Europa

As described in **FO-3**, the science orbit at Europa needs to be low altitude (100–200 km), near circular, high inclination, with solar incidence angle near 45° (specifically, a 2:30 p.m. orbit). An example is shown in **FO-6D**. To meet the lighting requirements over the duration of the first three Europa Campaigns, a retrograde orbit must be chosen, and the intersection of all the other science constraints puts the required inclination between 95° and 100°. If left uncontrolled, arbitrary orbits with these characteristics become more eccentric, due to Jupiter's gravitational perturbations, and generally impact Europa within about a month. These orbits need to be maintained on a regular basis.

Special cases of "frozen orbits" have been demonstrated to increase orbital lifetimes several fold. These near-circular, long-lifetime orbits provide an efficient mechanism for minimizing orbit maintenance ΔV and maxi-mizing time between required maneuvers. The exact "frozen" orbital conditions depend on the details of the gravity field (especially J_3) which cannot be known *a priori*. The gravity field will be determined from two-way Doppler measurements from a near-circular orbit at an altitude of 200 km during the post EOI engineering assessment and the Global Framework Campaign, the first ~33 days of the Europa Science phase. Based on estimates of the dominant gravity field terms from Galileo measurements, the expected average eccentricities of the frozen orbits are < 0.01. Due to the third-body perturbation, the semi-major axis and inclination will have periodic variations of a few km and a couple degrees, respectively.

During Europa Campaign 1, the parameters for the second orbit will be chosen after determining the lower-order gravity field terms. Then the flight system will transfer from the initial 200 km orbit to a 100 km orbit from where the Regional Processes, Targeted Processes, and Focused Science Campaigns will occur.

At 200 km altitude, the orbit period is 2.3 hr and the maximum occultation durations by Europa are 33% of the orbit period. For a 100-km altitude orbit, the orbit period is 2.1 hr, and occultations by Europa can last up to 37% of the orbit period depending on the orientation of the orbit. The primary constraints on the orbit orientation are the required inclination and nodal phase angle. The chosen orbital parameters are shown in **FO-6E**. With every Europa orbit around Jupiter (3.551 days), there is also an occultation by Jupiter that lasts 2.5 hr.

The frequency of thruster activity, whether for momentum wheel desaturation or for science orbit maintenance, directly impacts the orbit determination and associated gravity science. A trade exists between the frequency and total ΔV required for the maintenance maneuvers, with smaller, more frequent maneuvers potentially resulting in less ΔV overall. However the more frequent maneuvers may significantly degrade the ability to accurately reconstruct the orbit and gravity-field signatures. Preliminary analysis shows that orbit maintenance maneuvers would not be required any more often than once every week and momentum wheel desaturations no more than once per day, meeting the requirement as stated in **FO-3**. The precise elements for the science orbits and their associated orbit maintenance strategies will be studied further during development and ultimately refined during the first weeks in orbit around Europa.

The mission ends with the flight system in the science orbit at Europa. Due to third body effects on JEO's orbit, the ultimate disposition of the flight system will be eventual impact on the surface of Europa. It is this ultimate fate which drives the derived planetary protection requirement for sterilization.

4.3.6 Mission ΔV

A summary of the ΔV for the mission is provided in **Table 4.3-3**. **Figure 4.3-3** shows roughly how the ΔV is spread throughout the mission. See Appendix E.1.3 for calculations of propellant loading based on ΔV and thruster usage.

The interplanetary trajectory (**FO-6A**) has a low ΔV cost over the 21-day launch period, including a small allocation for Earth target trajectory biasing. Coupling the low interplanetary cost with the low V-infinity at Jupiter arrival makes the 2020 VEEGA very low in ΔV cost. For Tour 08-008, the sum of the Europa Approach and the EOI ΔV is more than 140 m/s higher than has been demonstrated in previous Europa Orbiter tours,

***Table 4.3-3.** ΔV Summary for the End-to-End Trajectory*

Activity	ΔV [m/s]	Description
Launch Injection Clean-up	20	Estimate to correct S/C injection errors from launch vehicle
Earth Targeting Bias Allocation	50	Bias aim-point of Earth flyby away from planet. May be integrated with other TCMs or performed separately
Deep Space Maneuver + Clean-up	96	Maneuver on Earth-Earth leg (near aphelion) — maximum required over the 21-day launch period, occurs on last day; opening day requires no deep-space maneuver
Remaining Interplanetary Statistical TCMs	50	Estimate for navigating the interplanetary phase; comprised of many small maneuvers
JOI + Clean-up	618	Jupiter orbit insertion (including minimal gravity losses) + 3% to correct errors
I1 Targeting Maneuver	80	Counteracts solar perturbations on the large initial orbit and targets the first Io encounter of the Jovian Tour.
Tour Deterministic Allocation	100	Deterministic maneuvers needed during tour with Io, Europa, Ganymede, and Callisto gravity-assists, designed to reduce energy at Europa
Tour Statistical Allocation	200	Many small statistical maneuvers during the tour, average of 8 m/s per encounter
Europa Approach	165	Large ΔV-leveraging maneuver(s) performed at apojove designed to further reduce Europa-relative energy beyond what is possible from the tour alone
Europa Approach Statistical	10	Estimate for navigating the Europa Approach phase; many small maneuvers
EOI Impulsive + Gravity Losses	792	Europa orbit insertion (including gravity losses) + 3% to correct errors
Europa Altitude Change	40	Hohmann transfer from 200 km circular to 100 km circular orbit
Orbit Maintenance Allocation	39	ΔV to maintain desired circular orbit for 9 months at average of 1 m/s per week. This value is a conservative estimate based on work performed for JIMO in 2005
TOTAL	2260	

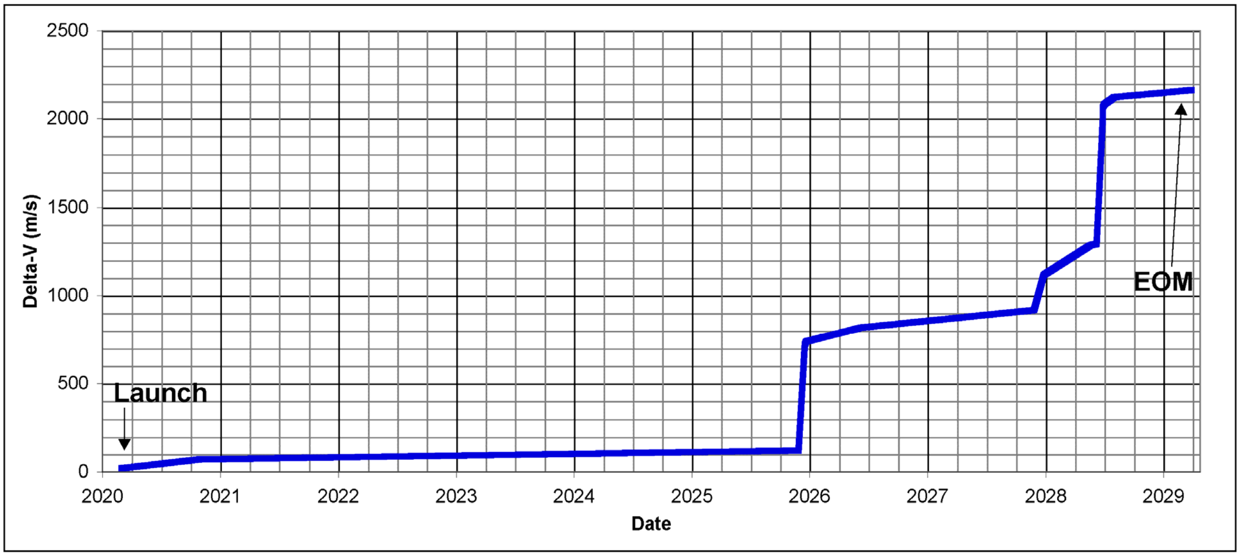


Figure 4.3-3. *Rough distribution of ΔV as a function of mission timeline.*

Table 4.3-4. *Planned DSN coverage as a function of Mission Phase*

Description	Subnet	Year	Hours/ track	Tracks/ week	Duration (weeks)
Interplanetary Phase **Feb 2020 to Dec 2025**					
Launch to L+30	34BWG	2020	8	21	4
Maneuvers & Interplanetary Housekeeping	34BWG	2020–2025	8	10	11
Annual health checks	34BWG	2020–2025	8	7	4
Eng telemetry + Nav (till JOI – 12m)	34BWG	2020–2025	8	1	276
Eng telemetry + Nav (till JOI – 2m)	34BWG	2020–2025	8	3	71
JOI Approach Light Tracking**	34BWG	2025	8	14	6
JOI	34BWG	2025	8	20	2
Jovian System Tour **Jan 2026 to Jul 2028**					
Jupiter System Science	34BWG	2025–2028	8	7	99
Fly-by Prep & Science (22 fly-bys)	34BWG	2025–2028	8	14	40
Europa Science **Aug 2028 to May 2029**					
EOI	34BWG	2028	8	21	2
Europa Campaigns 1,2,3 & Ka-Band RS	34BWG	2028	8	21	13
Europa Campaign 4 & RS	34BWG	2028–2029	8	7	26

**ΔDOR tracking would be used during approach and as needed during cruise, not called out separately.

e.g., 99-35 and 00-22, suggesting that future 08-008 tour design work can improve on ΔV.

The ΔV allocations in the table were based on a preliminary design for the orbit insertion and orbit maintenance and were selected to conservatively encompass the possible strategies.

4.3.7 Mission DSN Coverage

The planned usage of the DSN is shown in **Table 4.3-4**.

4.3.8 Spacecraft Disposal

As noted above, the ultimate disposition of the flight system will be eventual impact on the surface of Europa within weeks to a few months, depending on the orbit at EOM.

4.4 Flight System Design and Development

The JEO flight system concept is based on the wealth of work performed in the past, most notably in last several years: the *Europa Explorer FY07 Final Report,* which in turn was based on the *Europa Explorer Design Team Report 2006* as well as from previous Europa Orbiter (2001), Europa Geophysical Explorer (2005) and numerous trade studies conducted over the past decade. Over the last decade, the technology to fly such a mission has advanced, especially in areas of avionics, radioisotope power sources, and detectors. **Figure 4.4-1** illustrates the flight system's resultant evolution over the last 3 designs. While showing incremental improvements, the overall configuration has become remarkably stable, indicating that the requirements are well-understood.

4.4.1 Flight System Overview

Key design drivers on the spacecraft are Jupiter's radiation environment, planetary protection, high propulsive needs to get into Europa orbit, the large distance from the sun and Earth and the accommodation of the instrument payload.

The high-level constraints and assumptions on the JEO flight system design are:

- The flight system design shall employ technology that either exists already or is under development and is planned for qualification early in the JEO project lifecycle.
- The mission reference radiation design dose (referenced to 100 mil aluminum shell) is 2.9 Mrad.
- The required total ΔV is 2260 m/s.
- Approximately 7.3 Gbits of science data is returned per Earth-day during the Europa orbit phase and ~3.6 Gbits per Earth-day during the Jupiter tour phase.
- Retransmission of downlinked data is not required while in Europa orbit.
- 34 m DSN antenna used during normal operations, with limited 70 m antenna use (or equivalent) for critical or emergency events.
- Heliocentric operating range of 0.7 AU to 5.5 AU, with a maximum Earth range of 6.5 AU.

Radiation is the key defining challenge and life limiting parameter for the flight system. As will be described in greater detail in §4.5, the JEO radiation design approach is multi-pronged and incorporated at the system design level: screening parts for rad-hardness and then communally shielding electronics of similar rad-hardness. Grouping similarly-rad-hard parts together in separate boxes (as opposed to using a single vault for all parts, regardless of their need) optimizes shield mass and allows for flexibility in box location. The analysis and modeling of the design and environment will be developed with significantly higher fidelity by means of dedicated radiation systems engineering and experts in the field. The mission and spacecraft concept are driven by the radiation design needs. An advisory group, made up of key experts from NASA, academia, DoD, DoE, and industry will be engaged throughout the design and implementation process.

The JEO spacecraft is designed to meet the planetary protection requirements from the onset. The mission would be classified as Category IV under COSPAR and NASA policy, which specifies that JEO show that the

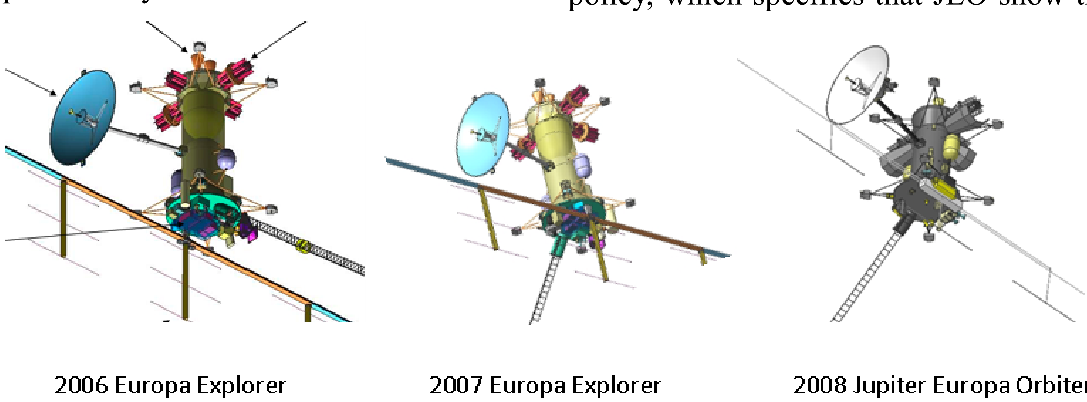


Figure 4.4-1. The design of the Europa Orbiter spacecraft is stable

probability of inadvertent contamination of an Europan ocean be less than 1×10^{-4}. JEO would meet this requirement with cleanliness strategies embedded into the design, build and integration process, as discussed in §4.7.4.

The flight system is a mostly redundant, 3-axis stabilized flight system powered by Radioisotope Power Systems (RPSs). The baseline flight system has 11 instruments including the radio system for gravity science investigations. The flight system launch mass is 4745 kg, including the required 33% margin, with respect to the currently quoted Atlas V 551 capability of 5040 kg. The conceptual flight system functional block diagram is shown in Foldout 7 (**FO-7**).

The high propulsive requirements to get into Jupiter orbit and subsequently into Europan orbit drives the large propellant load required and the dry mass of the propulsion subsystem to hold the propellant. The dual-mode propulsion system includes a gimbaled 890 N (200 lbf) bipropellant main engine plus smaller monopropellant thrusters. Orbit maintenance ΔV maneuvers are performed using 4.5 N monopropellant thrusters, which are also used for attitude control.

Given the tight pointing requirements for this mission, the instrument and telecommunications subsystem power requirements, and the harsh radiation environment (>5× the dose of the Juno mission), the power system trade strongly favors the use of radioisotope power sources over solar array power systems at these distances. Five Multi-Mission RTGs (MMRTGs) would power the flight system, providing about 540 W of electrical power at End of Mission (EOM). Lithium-ion (Li-ion) batteries provide for power demands that exceed the MMRTG capability during Europa Science orbit and other times during the mission. Waste heat from the MMRTGs is used for thermal control to the maximum extent practical, in order to reduce electrical power that would otherwise be allocated for heaters. Radioisotope Heater Units (RHUs) and Variable RHUs are also used for the same reason.

The distance from Earth varies from 4 to 6.5 AU during the course of the orbital mission at Jupiter. This large distance requires a very capable telecommunications system to return the significant data required to meet the science objectives. The flight system includes a 2-axis articulated 3 m high-gain antenna (HGA), using Ka-band, for high rate science downlink, as well as X-band for uplink and downlink.

The data processing and handling architecture includes a dual-string RAD750 computer that is capable of performing all science and engineering functions including identified science data compression. Data storage is implemented using a hybrid Solid State Recorder (SSR) that contains 1) 3.1 Gb of non-volatile chalcogenide random access memory (CRAM) with 1 Gb currently allocated for science use, and the remaining 2.1 Gb allocated for engineering and science flight software (FSW), engineering telemetry, processing space, and margin, and 2) 16 Gb of volatile synchronous dynamic RAM (SDRAM) dedicated to science use, particularly around the Galilean satellite flybys. The SDRAM is not required to survive the radiation environment through the Europa orbital phase. FSW is a key component of the system architecture with features that allow for ease of operations during flight and for a fault response approach that balances continued degraded mission progress with transient fault recovery. Section 4.4.2.4 provides more details on the fault protection approach.

The flight system attitude is controlled primarily with reaction wheels during science operations. Small thrusters, 4.5 N (1 lbf) each, are used to reduce post-launch separation rates, to provide attitude control during cruise, small ΔV maneuvers, and to desaturate the reaction wheels during the Jupiter tour and Europa orbit phases. Because the detection of the tidal signature requires an orbit reconstruction with a radial error of about 1 m, residual ΔV must be minimized during the Europa Science phase so the 4.5 N thrusters are coupled and redundant.

Key changes on the spacecraft from the FY07 design [*Clark et al. 2007*] are listed in **Table 4.4-1**

4.4.1.1 Configuration

The conceptual configuration of the baseline flight system is shown in **Figures 4.4-2 (Stowed in LV)**, **4.4-3 (Deployed S/C)**, and **4.4-4 (Operational Configuration)**. The configuration accommodation of the payload is

***Table 4.4-1.** Spacecraft changes from EE2007 design*

Spacecraft	Changes
Power (w/o RPSs)	Similar architecture to last year, no major changes. 2 smaller redundant batteries vs 1 internally redundant battery.
C&DH	Baselined a hybrid SSR with added 16 Gb SDRAM for science
Telecom	Refined HGA mass, replaced Ka 3.5W SSPA for 25W TWTA for downlink during science phase
Structures & Mechanisms	Performed grassroots estimate of structure, added main engine 2-axis gimbals
Thermal	No major changes
Propulsion	Switched to one main engine. Reduced number of thrusters to 16 from 24 and removed TVC thrusters. Changed valve isolation design, tanks are sized for less propellant.
ACS	Removed fine sun sensors. Star tracker mass increased for detector radiation shielding.
Cabling	No major changes
Radiation Monitoring System	Unchanged
RPS System	Removed one MMRTG
Spacecraft Radiation Shielding	See changes described in §4.5
Propellant	Sized for full capability of Atlas V 551 on 2020 trajectory. Last year was 2015 launch on Delta IV H
System Margin	**30% required in 2007, 33% required in 2008**

shown in §4.2, **FO-4**. Major configuration drivers were as follows:

- Nadir pointing fields-of-view for the remote sensing instruments,
- Simultaneous pointing of instruments and pointing of HGA at Earth,
- Large boom and radar antenna accommodation,
- Usage of propellant tanks with existing diameter sizes,
- Atlas V fairing envelope and access door size and number (3 doors, each at 1.22 m × 1.83 m or 4 feet by 6 feet each), accommodating 5 MMRTGs and the HGA,
- MMRTGs view of each other and to space with maximum distance to instruments,
- Eight thruster clusters with placement driven by the coupling requirement and plume impingement considerations on instruments, HGA, and MMRTGs.

To improve operability, a 2-axis articulated HGA is incorporated into the design. In earlier studies this design was traded with adding a scan platform to meet mission requirements and was found to be the optimal design, primarily for mass reasons.

The configuration is developed with general modularization in mind. The lower equipment module houses the MMRTG's, the core structure primarily houses the propulsion system, the electronics bus houses all electronics (except for the telecom electronics which are located behind the HGA), and the instrument deck houses all the instruments. This approach provides for ease of integration and the potential benefit to partition development.

4.4.2 Systems Engineering

Four specific, cross-cutting areas are key focus disciplines for this mission's success: radiation, planetary protection, long-life, and operability including fault protection. As the JEO design evolves, system engineering trades across these areas will produce an efficient, robust design.

JEO has captured limited use of current hardware and software designs from JPL's institutional avionics product line (Multi-mission System Architectural Platform, MSAP), the Cassini Propulsion System, Europa Orbiter and JIMO developments, and the MMRTG. Due to the long life, planetary protection requirements and harsh radiation environment, it is envisioned that all electrical circuits will be new (with new parts and analyses) but the basic approaches and functions can be inherited.

In addition to the radiation environment, the spacecraft design will also address magnetics, surface charging, and electro-magnetic compatibility (EMC). These issues will not be different from previous missions to Jupiter so standard design practices and mitigation schemes can be used for flight system design. The magnetic cleanliness requirements specified in **Table 2.5-1** will be met.

4.4.2.1 Radiation

Due to the high radiation environment at Jupiter, the flight system must be designed from the onset to address its radiation tolerance. The JEO radiation approach goes well-beyond conventional approaches to address a mission in such a harsh environment. The radiation protection for the JEO flight system will involve an approach that starts with a conscientious mission design to limit radiation dose while meeting JEO science objectives, a significant program to judiciously select radiation hardened parts and material capability, detailed shield mass composition

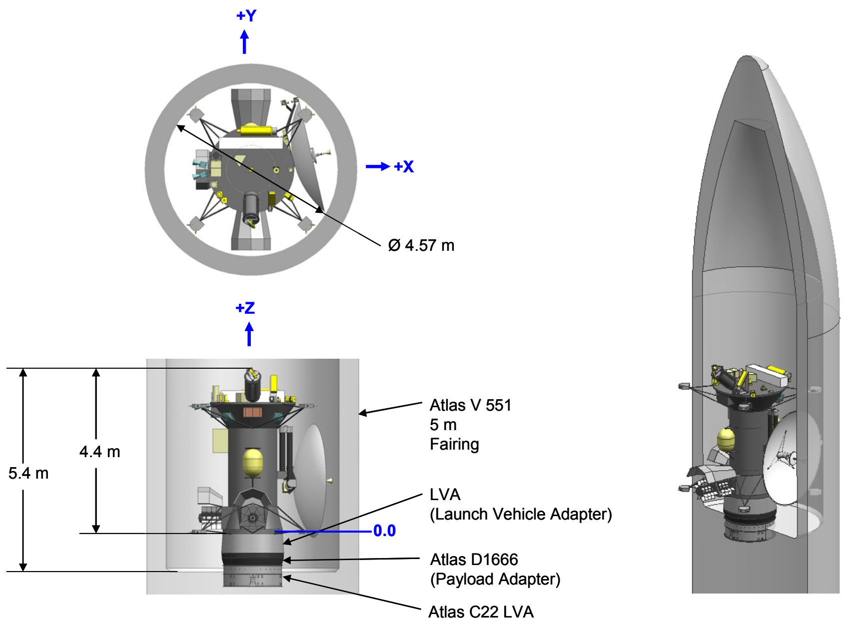
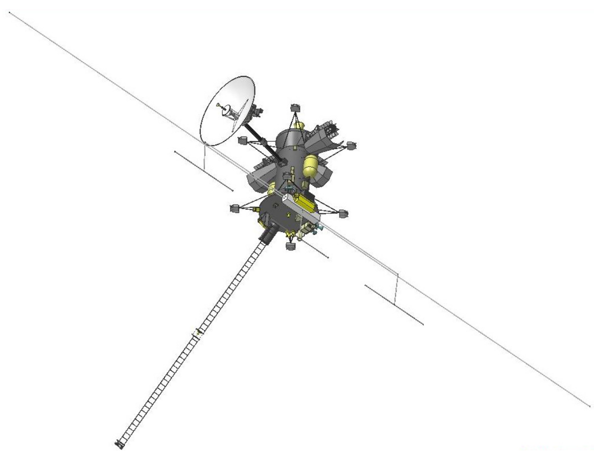


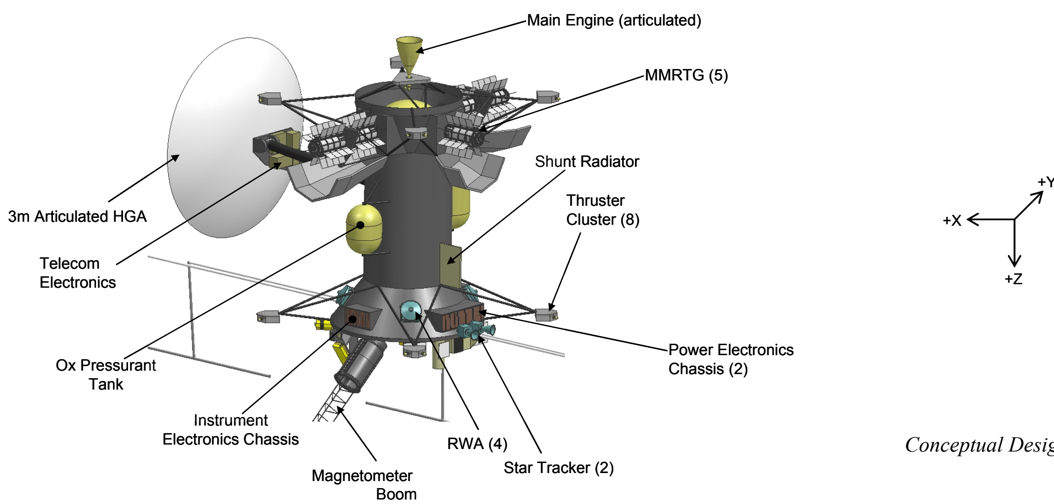
Figure 4.4-2. Stowed Configuration of JEO Flight System in Atlas V LV Fairing

Conceptual Design



Conceptual Design

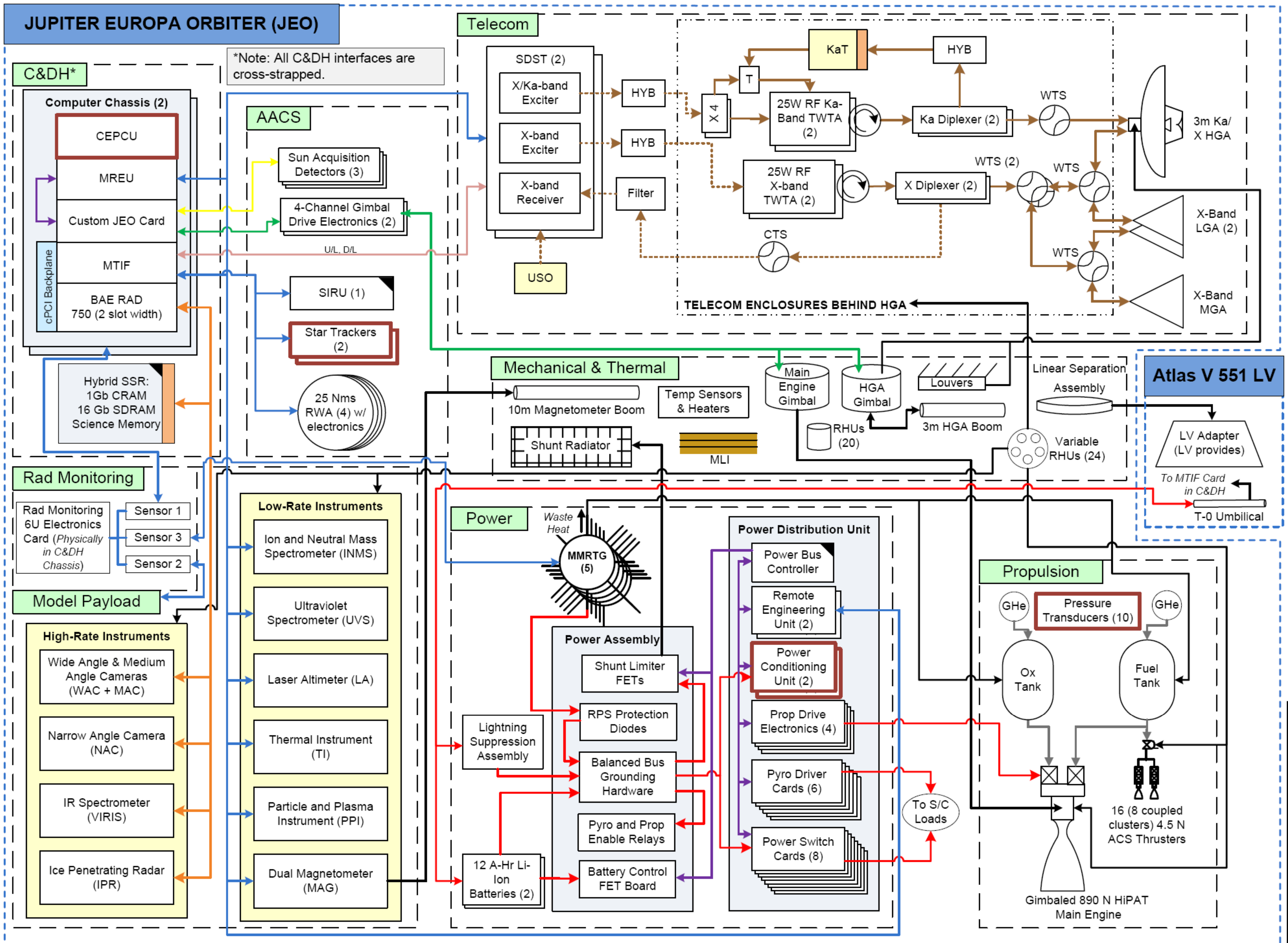
Figure 4.4-3. JEO Deployed Flight System

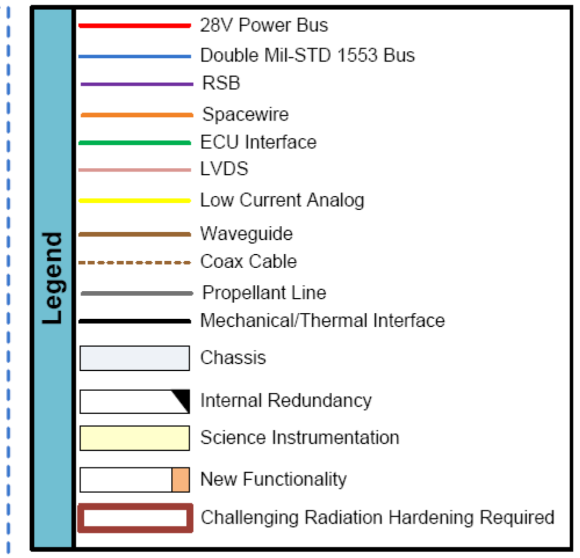


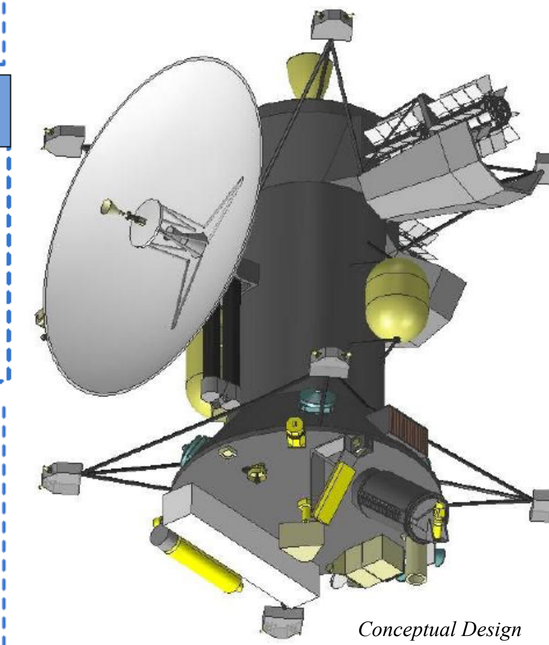
Conceptual Design

Figure 4.4-4. Operational Configuration of the JEO Flight System

FOLDOUT 7
FLIGHT SYSTEM BLOCK DIAGRAM







Conceptual Design

JEO Baseline Mass Summary (kg)	
Payload (CBE)	**165**
Model Payload	106
Payload Radiation Shielding	59
Spacecraft (CBE)	**1210**
Subsystems	1078
Spacecraft Radiation Shielding	132
Flight System Total Dry (CBE)	**1375**
33% System Margin	**566**
Flight System Total Dry with Required Margin	**1941**
Propellant	**2681**
Flight System Total Wet	**4622**
LV Adapter with required margin	**123**
Flight System Launch Mass Wet	**4745**
Atlas V 551 Capability for 2020 VEEGA	**5040**
Additional (Unallocated) Margin	**295**
System Margin (33% required per study guidelines)	**43%**

design, deliberate component placement within assemblies, and systematic refinement of reliability assessment modeling of the electronics and subassemblies from the ground up. System lifetime analyses have been performed and provide the basis for projected mission duration of JEO.

The baseline (and costed) approach for all electronics on the flight system is that all electronics will need to be redesigned to incorporate rad-hard parts. Analyses and packaging will need to be re-done. Thus, no off-the-shelf electronics are assumed. Also, all electronics are assumed to use ASICs instead of FPGAs. This is the more conservative approach until FPGAs can be adequately evaluated and their design requirements understood. If, and when, certain FPGAs are considered available for this mission, then the cost and schedule associated with ASICs would be returned to project reserve. These issues and design guidelines are addressed in the "Risk Mitigation Plan: Radiation and Planetary Protection."

The radiation design approach and analysis is captured in §4.5. The flight system described herein has taken into account the methodologies and analysis described in §4.5. For example, given the parts and shielding approach in §4.5, the electronics are packaged and shielded in multiple boxes rather than a single vault as other missions have designed. The JEO approach allows flexibility for different part tolerance levels (100 krad to 1 Mrad) to avoid having to shield everything down to the "lowest common denominator" part tolerance level at a heavier shield mass penalty and allows for placement of electronics in strategic locations, such as the TWTAs on the back of the HGA.

4.4.2.2 Planetary Protection

As described in more detail in §4.7, the approach to planetary protection compliance for the JEO flight system will involve a combination of both the control of bioburden material during development, and sterilization of the flight system by the radiation doses in the Jovian environment. Trade studies will need to be performed that compare dry heat sterilization approaches to the radiation resistance of various components of the flight system.

Two significant assessments have also been performed by senior JPL engineering teams in the last 18 months for the Mars Program related to sterilization capability for parts and materials for a potential Mars astrobiological Lander [*Mars System Sterilization Study 2006*], based on MER and MSL equipment. Neither study identified any commonly used parts and materials that could not be qualified for JEO use based on the proposed planetary protection approach.

4.4.2.3 Long Life—High Reliability

Long life, highly reliable, deep space missions are founded in NASA's institutional design practices and processes. These systems are required to operate over long periods of time and over great distances with limited human interaction. Lessons learned from Voyager, Galileo, Cassini, and others, are incorporated into practices and designs including Extreme Value Worst Case Analysis, Parts Stress Analysis, block redundancy, autonomous fault recovery, cross-strapping, internal redundancy and functional redundancy in appropriate combinations to eliminate all non-exempt single point failures (SPFs).

The redundancy in JEO's spacecraft study concept design reflect the best practices and experience as mentioned. Given the 9+ year mission, the high radiation environment estimated for this mission, and the operational objectives of this mission, the flight system is almost fully redundant except for standard single point failure exemptions (such as structure, tanks, HGA, etc) and a few exceptions: 1) a single main engine, 2) HGA boom deployment, 3) MMRTGs. In each of these cases, robust margins, graceful degradation, and/or a robust testing program will be needed with future analysis to lower the residual risk. The decision to baseline a single main engine was made in consultation with experienced propulsion engineers at a Propulsion Tabletop Review this year (see §4.4.3.2). The HGA deployment devices and MMRTGs are passive elements which degrade gracefully and have historically been single string with high reliability. The notional payload is currently all single string; after an AO-selection is complete and more detailed analysis is complete, any recommendations for selected redundancy can be made.

All redundancy, fault-protection logic, and cross-strapping circuitry are validated in the system testbeds or in integration and tested prior to launch. For remaining SPFs, a risk evaluation will be performed early in the design process. As a result, the SPF will be eliminated or a waiver to the Single Point Failure policy will be generated (requiring institutional approval).

In parts selection and qualification, the Project is governed by the JPL Institutional Part Program as tailored in the Project Requirements document (D-47664). In compliance with these requirements, all critical electronics are subjected to destructive physical analysis (DPA), residual gas analysis (RGA) and particle impact noise detection (PIND), as appropriate. All parts will require certification for radiation either by radiation hardness established by the manufacturer and agreed to by the project or additional Radiation Lot Acceptance testing (RLAT) [*JPL D-47664*].

4.4.2.4 Operability and Fault Protection

Maximizing the return of mission science will rely largely on the operability of the spacecraft, including its ability to continue safely in a degraded mode. A Europa mission necessarily compresses a series of essential activities into the confined space of months. This aggressive timeline is driven by high radiation levels in the vicinity of Europa. Fortunately, addressing the needs for JEO is within capabilities that have been demonstrated in past missions but now applied to JEO's requirements.

Three scenarios, in particular, pose a notable challenge to fault protection and mission operations. First are several targeted satellite encounters, spaced closely in the final weeks leading to Europa orbit insertion (EOI). Next is the interval around EOI needed to set up, enter, and establish the desired orbit for Europa science. After prime mission, observations from Europa orbit begin to compete with the management of system deterioration, as cumulative effects surpass radiation expected capability levels.

Historically on similar missions, suspensions of days to weeks have accompanied the unplanned interruption of normal operations. Except for critical events, this has generally been tolerable, because long term consequences to the vehicle from such disruptions tend to be minor. For JEO though, each disruption extends intense radiation exposure at the expense of limited productive time in Europa orbit, a one-for-one loss, where a week's suspension removes a week of productive effort in the limited mission life. During the multiple satellite encounters, even a brief suspension at the wrong time could lead to weeks (or even months) of added exposure. Such outages are problematic for JEO because a substantially elevated rate of disruptive transient events must be anticipated throughout the sensitive phases. In addition, the likelihood of changes needed to keep up with accumulating radiation effects will accelerate over time.

As with Jupiter orbit insertion, EOI is a single, brief opportunity and therefore requires the usual elevated attention given to critical events through specialized command sequences and fault protection. However, treating the other phases as critical would be both expensive and impractical, due to their extended and varied nature.

This can be addressed with substantially reduced exposure to non-productive time by reducing the frequency of large disruptions, making recovery from necessary disruptions more rapid, and facilitating the accommodation of operational changes. These desirable features have been bundled under the heading of "fail-operational" design. The "fail operational" design approach builds on current practices.

Outside of critical events, systems can rely on safing when normal activities are disrupted by fault responses. This approach is more disruptive to nominal operations, but provides a simplified on-board response. However, another common response is to forego safing when responses can be shown to present no significant risk to the system. Cassini, MER, and many other systems operate this way, where local fault responses are often used to mask transient effects. This is accomplished through retries, resets, or related means, which can clear the symptoms of a transient and resume normal function. In other cases, it may be appropriate to exploit a redundant unit, if ground intervention is needed to restore operation of the affected unit. Such brief outages are frequently tolerable with little perturbation to overall activities, especially when the architecture follows basic principles of robust behavior, as JEO intends. If so, then safing is not necessary.

Even when activities must be halted, rapid resumption at a future point can sometimes be facilitated through segmentation, where boundary conditions have been engineered properly. The lost segment is merely sacrificed. This is especially appropriate for mapping phases, such as during early Europa orbits, where the loss of an orbit or two is acceptable. It is a small step to go from ground-mediated resumption to automated resumption, if the criteria for safe restarts can be confidently prescribed—the configuration of which would remain in operators' hands.

Somewhat more disruptive are cases where only a partial suspension is plausible. For example, MRO will switch off a problematic instrument and discontinue commands to it, without stopping other science or engineering sequencing. Similarly, systems such as MER, which allocate time for catch up, are capable of postponing sequenced activities to accommodate minor interruptions. Graceful degradation is a related approach, where reverting to lower performance capability can sometimes be preferable to safing. Cassini will switch to thruster control, for example, when fault protection suspends reaction wheel control. Depending on circumstances, safing is avoided. Such features would be used for JEO, as well, where partial disruption can leave most activities going, or perhaps only suspended for a short time.

The familiar approaches outlined so far reduce exposure to disruption by reducing the frequency of large non-productive time. JEO provides such capabilities without substantial deviation from established capabilities. When a large disruption does occur, however, (or when the consequences of a small disruption ripples significantly into downstream plans) recovery can be ponderous without the right assets. This is where additional needs arise to hasten recovery and ease operational changes.

In assessing the suitability of an architecture, much has to do with the quality of insight and the flexibility of control that a system affords. These are closely related in that both can be confounded by a wide conceptual gap between system concerns and required actions in both flight software and mission operations. For example, many systems require extensive parametric tuning, but provide no explicit mechanisms to ensure coherent change across the system; many systems forego overt coordination mechanisms and safety checks on commands, which could avoid conflicts or violations of resource usage; many systems derive behavior indirectly from commanded modes and settings, while reporting behavior in disparate and equally indirect terms; and so on. Features such as these introduce incidental complexities that obscure what is happening and make systems brittle. This in turn slows analysis and planning in order to avoid risk, and it also makes operational changes very difficult.

JEO avoids such pitfalls through architectural features that deal directly with the coordination of system activities and resource usage, and which relate operational objectives directly to the prescribed and reported behavior of the system. Considering the sweeping range of fielded capabilities among flight systems, from fairly poor to very good, achieving the required quality of insight and the flexibility of control on JEO merely means careful adherence to best practices.

Recovery from necessary disruptions can be improved further by extending such features into fault protection, which invariably demands far more coordination and flexibility than routine engineering operations. Even outside critical events, fault protection for planetary missions has typically involved comparatively elaborate behaviors, because telecommunication, thermal safety, and so on need to muster a broad range of system resources before ground intervention is even possible. Moreover, fault protection must do so from nearly arbitrary starting conditions and under the handicap of faulty performance. Many of the issues attributed to difficult fault protection (confused perceptions, convoluted relationships, unintended side effects, etc.) arise from the same shortfalls in coordination and flexibility that stymie rapid recovery from sequencing disruptions. So anything that addresses both fault protection and ground mediated recovery will be an important asset.

The staple of fault protection, of course, is safing. Safing reduces to a well-validated core the number of operating modes needed and the level of performance required. Nonetheless, safing for a planetary mission already requires most engineering functions to preserve some operational configuration. Very little of the system's engineering hardware is sidelined, and fault protection remains in full force during safing. The main objective of safing is therefore not so much to drop functions, but rather to improve their operating margins against risk.

In this light, it is clear that there is little operational difference between a spacecraft in safing and one ready to resume certain planned activities. For instance, if the system were in a stable, nadir-pointed attitude in Europa orbit, activating lower power or lower data rate instruments would have little effect on operating margins. Similarly, certain engineered activities such as reaction wheel momentum management, could be continued according to plan just as well as an autonomous counterpart. In fact, reasserting the planned version is probably less disruptive overall to the recovery process. As part of a fail-operational approach, such measures are therefore viewed as viable options for further study. They are in the realm of past experience gathered from a variety of flying systems.

The approach envisioned would be to make such resumptions initially conditional on ground authorization. With permission though, the flight system could then return to selected operations without the need to uplink new or revised plans. This could be sufficient in most situations to address large disruptions without undue risk, and even in the worst case, the system would preserve the ability to fall back to safing, as always. Whether such capability would ever be exercised autonomously would probably be decided only after recovery from a particular recurring anomaly had become routine.

In total though, a fail-operational approach to JEO operations requires only the disciplined application of current best practice in operations and software design. Within the experience base from past missions, this approach can substantially reduce the susceptibility of JEO to transient events and degradation within the harsh radiation around Europa, with concurrent benefits to operability and reliability.

4.4.2.5 Payload Interfaces

The spacecraft will accommodate the payload described in §4.2 by providing for a view in the nadir direction for the remote sensing instruments and in the ram direction for the INMS when in orbit around Europa. The UVS is provided access to both nadir and ani-ram directions.

The instruments are all located on an instrument deck as distant as possible from the MMRTGs. The spacecraft will maintain base body pointing control to 1 mrad and stability to 10 µrad over 1 s under most science observation modes. Section 4.4.3.3 describes the pointing capabilities in further detail.

The accommodation for the future AO-selected payload on electrical, thermal, and mechanical interfaces will be developed between the spacecraft development team and the payload teams. With currently identified thermal needs, the WAC, MAC, NAC and VIRIS are positioned on the same side with FOVs for radiators. The spacecraft will provide for a specified thermal interface using MLI, thermal interfaces, thermal conduction control and variable RHU's. Instrument electronics that are separable from the detectors are co-located in the instrument chassis and protected by a common shield which enables lower overall shielding mass. The system functional block diagram in **FO-7** shows the data interfaces for the instruments, which is described in §4.4.3.5. For particular sensitivities of an instrument, such as magnetic cleanliness or vibrations, the spacecraft meets the current requirements.

The notional payload resource requirements and accommodations are listed in **Table 4.2-1**. Instrument fields of view and volumes were estimated based on currently flying missions and are accommodated as shown in **FO-3**. Instrument data rates and compression factors are noted in **Table 4.6-2**.

4.4.2.6 Launch Vehicle Interface

In the launch configuration, the JEO flight system is mounted to the Atlas V launch vehicle (LV) as shown in the **Figure 4.4-2**. The flight system's LV adapter is mounted to the LV via a permanently bolted field joint. The separation of the flight system from its LV adapter and the launch vehicle is assumed to be via a linear separation device (Superzip).

To fit within the Atlas fairing envelope, there are three assemblies that are in a folded/stowed configuration. The HGA, Ice Penetrating Radar (IPR) antennas, and Magnetometer boom are stowed and deployed soon after launch.

4.4.2.7 Resource Margin Summary

4.4.2.7.1 Managing Payload Resources

JEO will employ a market-based system approach for allocating resources (e.g., mass, power, data rate, budget, etc.) for instrument development. The benefits of market-based systems are that they move the control of resources back to the individuals that have the information (i.e., the users themselves); are web-based and thus allow for distributed operations; and remove the need for time-consuming appeals and multiple integration meetings [*Wessen and Porter 2000*].

Market-based systems were used successfully for the instrument development on both the Cassini Mission and the Terra (EOS AM-1) Platform. In the Cassini case, their market-based system known as the Cassini Resource Exchange, was able to limit instrument development cost growth to less than 1% of the initial estimate and mass growth actually decreased by 7% [*Wessen and Porter 1998*].

4.4.2.7.2 Calculating Margins

A conservative margin approach has been taken on JEO which provides significant room for mission concept modifications without large impacts on the primary resource constraints (number of RPS units and launch vehicle injected mass capability).

Study guidelines dictate a 33% margin should be held in all areas, calculated per the method described in the JPL Design Principles and Practices (DPP), where the margin is calculated as the Maximum Possible Resource Value (MPRV) minus the Proposed Resource Value (a.k.a. Current Best Estimate, CBE). For JEO, the MPRV correlates to the Atlas V 551 launch vehicle capability for calculating mass margin and to the EOM power output of five MMRTGs for the power margin calculation. The margin percentage is then calculated as

$$Mrgn\ (\%) = \frac{MPRV - CBE}{MPRV} \times 100$$

Table 4.4-2. Example of Calculating Required Margin and Corresponding Contingency

	Value	
Max Possible Resource Value (MPRV)	100 kg	Example Value
Required Margin per Study Guidelines	33 kg	= 33% * MPRV
Maximum Allowable	67 kg	= MPRV – Req'd Mrgn
Contingency Percentage to apply to CBE to achieve MPRV	49.3%	$= \frac{(MPRV)}{(Max\ Allowable)} - 1$
Check Calculation	100 kg	= Max CBE * (100% + 49.3%)

Table 4.4-3. Example of Calculating Additional and System Margins

	Value	
Current Best Estimate (CBE)	200 kg	Example value
CBE + Contingency to achieve required margin	299 kg	= CBE * 1.493
Max Possible Resource Value (MPRV)	325 kg	Example Value (e.g. Launch Vehicle Capability)
Additional Margin (above required 33%)	26 kg	= MPRV – (CBE*1.493)
System Margin	38%	$= \frac{(MPRV - CBE)}{MPRV} \times 100$

Holding 33% margin against the MPRV, per this method, translates into adding 49% contingency onto the Current Best Estimate (CBE) values, as shown in the calculated example (**Table 4.4-2**).

Table 4.4-3 shows an example of calculating additional margin and system margin. Additional margin is defined as any margin beyond the required 33% defined in the study guidelines. System margin is then the total margin measured against the Maximum Possible Resource Value (MPRV) and can be thought of as the required margin plus the additional margin. To be compliant with the study guidelines, the system margin has to be greater than or equal to 33%.

4.4.2.7.3 System-Level Mass Summary

The JEO mass summary is shown in **Table 4.4-4**. The full mass equipment list can be found in Appendix E.1.1.

The flight system has a total launched wet mass of 4745 kg which includes a 1941 kg dry flight system and 2681 kg of propellant. The propellant mass is sized for the entire injected mass capability of the Atlas V 551 launch vehicle (5040 kg), per DPP, therefore ensuring

Table 4.4-4. Mass Estimates for JEO Flight System

JEO Baseline Mass Equipment List	Flight System Mass, kg			Comments
	CBE	Cont.	CBE+Cont.	
Payload	165	30%	215	
Model Payload	106	30%	137	CAM, NAC, VIRIS, UVS, LA, IPR, TI, MAG, PPI, INMS
Payload Radiation Shielding	59	30%	77	Shielding for instrument detectors and electronics chassis
Spacecraft	1210	29%	1500	
Power (w/o RPSs)	55	30%	72	Power distribution, converters, switches, & 12 Ahr batteries
C&DH	34	17%	40	Redundant Rad750 SFC and 3GB CRAM SSR
Telecom	56	27%	70	X/Ka 3 m HGA, X MGA & LGAs, 25 W Ka and 25 W X TWTAs
Structures & Mechanisms	320	31%	420	S/C structure, HGA gimbal, mag boom, and S/C side LVA
Thermal	68	30%	88	MLI, Venus/perihelion protection, heaters, (V)RHUs, etc.
Propulsion	159	28%	203	890N main engine, RCS thrusters, and COPV tanks
AACS	69	33%	91	Reaction wheels, SIRU, star trackers, and sun sensors
Cabling	83	30%	108	7% of CBE S/C bus dry mass excluding shielding
Radiation Monitoring System	8	30%	10	8kg allocation from Europa Explorer has not been refined.
RPS System	226	0%	226	5 MMRTGs
Spacecraft Radiation Shielding	132	30%	172	Shielding accounts for 2.9 Mrad reference mission
Flight System Total Dry	1375	25%	1714	Includes P/L, S/C, shielding, and subsystem contingency
Additional System Margin to achieve study req.			227	Additional cont. on S/C and P/L to obtain 33% margin
Flight System Total Dry with Required Margin			1941	Includes P/L, S/C, shielding, and system contingency
Propellant			2681	Fuel, oxidizer, pressurant, residuals/holdup, and RCS prop
Flight System Total Wet			4622	Includes P/L, bus, shielding, system contingency, and prop
LV Adapter with required margin			123	LV-side adapter, LSA, cabling, blankets, and margin
Flight System Launch Mass Wet			4745	**Entire wet s/c with LV adapter and required margin**
Atlas V 551 Capability for 2020 VEEGA			5040	
Additional Margin			295	**Mass margin beyond the required 33% margin**
System Margin (33% required per study guidelines)			43%	**JEO easily fits on the Atlas V 551***

*Note: Mass margin excludes MMRTGs from calculation because the MMRTG mass is considered a Not-To-Exceed value, and is therefore fully margined.

a propulsion system capable of delivering the fully margined JEO flight system plus accounting for any additional future growth up to the launch vehicle capability. The complete delta V table and corresponding propellant budget is in Appendix E.1.3.

With the exception of cabling, all mass estimates were provided by the engineers of their respective subsystem. The cabling mass estimate was computed as a percentage (7%) of the CBE flight system dry mass minus the radiation shielding mass. This approach is based on the cabling mass of several historical space missions and provides a reasonable estimate for designs at this phase.

Each subsystem evaluated the maturity of their design and applied appropriate contingency at the component level. Then, system level mass (227 kg) was added in order to achieve the 33% margin required by the study guidelines on both the payload and the spacecraft mass.

There are 295 kg of additional dry mass margin beyond the required 33% margin. This corresponds to a total system dry mass margin of 43%, which means JEO is very robust to mass changes in the future.

The RPS masses were provided in RPS_Spec_Sheets_Rev09-Final.doc and adjusted for the JEO mission conditions. The mass of 45.2 kg per MMRTG was considered a Not-To-Exceed value, as was agreed to in communications with NASA HQ, so no additional margin was carried.

The total radiation shielding carried for JEO is 192 kg. This includes 132 kg for spacecraft subsystem shielding, 43 kg for instrument detector shielding, and 17 kg for the instrument electronics chassis shielding. See §4.5 for shielding methodology. The shielding mass does not include shielding for the star tracker optical head which is carried with the star trackers since they are assumed to be procured components.

4.4.2.7.4 System-Level Power Summary

The power estimates for each subsystem are identified in Table 4.4-5. The detailed power equipment list is in Appendix E.1.2.

All power levels were provided by the subsystem engineers as current best estimate (CBE) values. A system-level contingency of

49% was applied to the CBE (including losses) power to achieve the required 33% margin.

***Table 4.4-5.** Power Estimates for JEO Flight System*

JEO Power Profile (W)				Europa Orbit	
*Please Note: Orbital payload power shown is the average over the two-orbit science scenario and reflects a duty cycle on each of the instruments. Flyby payload power shown represents the average payload power during the 2 hours surrounding closest approach.	Launch	Tour Fly-By	Safe	On-Orbit Science with Telecom	On-Orbit Science no Telecom
	3 hr	2 hr	24 hr	83 min	55 min
Payload	0	42	0	71	71
Model Payload	0	42*	0	71*	71*
Spacecraft	162	263	217	277	207
Power Electronics Standby Power (ASIC-based)	10	10	10	10	10
C&DH	52	52	52	52	52
Telecom	0	82	58	82	30
Structures & Mechanisms	13	0	0	15	0
Thermal	12	23	23	23	23
Propulsion	27	1	25	1	1
AACS	44	90	44	90	86
Cabling - Losses Tracked Below	0	0	0	0	0
Radiation Monitoring System	4	4	4	4	4
Flight System Total Without Losses (CBE)	162	305	217	348	278
Power Losses (7% for wire, switching, & conversion losses. Does not include battery recharge losses tracked in scenario tool)	11	21	15	24	19
Flight System Total With Losses (CBE)	172	325	232	372	296
System-Level Radiation Load (5% on CBE + Losses)	9	16	12	19	15
Additional System Margin to achieve study req.	89	168	120	192	153
Flight System Total Power Demand with Required Margin	270	510	363	583	464
5 MMRTG Capability	625	545	540	540	540
Additional Power Available	355	35	177	-43	76

Negative value indicates battery usage required in this mode. Battery usage also possible during launch mode.

Power losses were calculated as 7% for wire, power switching, and power conversion losses, plus 10 W for power electronics assembly standby power, per the power subsystem engineer. Power losses from battery discharging and charging are taken into account by a scenario modeling tool used for scenario analysis.

In addition to standard power losses, a power load was added to accommodate flight system performance changes due to radiation. This system level radiation load was calculated as 5% of the CBE (including losses), and was derived from Galileo experience.

The most stressing power mode is the Europa mapping orbit phase. The power required for the JEO flight system is 532 W averaged over two successive Europa science orbits during Campaign 1 (one IPR orbit and one imaging orbit, see §4.6). This average power includes 49% contingency on the CBE power (including losses) plus the system-level radiation load. The two-orbit average power load represents the RPS sizing case for the JEO mission and results in the need for five MMRTGs and a modest battery to cover the nominal periods each orbit when instantaneous power demands may temporarily exceed the available RPS power. The power demands in the other modes such as launch and safe mode are then easily met, as shown in **Table 4.4-5**. The five MMRTGs produce 540 W total power at the end of 9.1 years. All orbit mode calculations were done using this worse-case degradation scenario.

Figure 4.4-5 shows the power profile over the course of two orbits. The profile assumes the science two-orbit observing scenario with one target set per orbit (small power spikes occur when targeting instruments are powered on). The power profile assumes an 8% recharge loss due to internal resistance and an 80% charge efficiency, typical of Li-ion batteries. As this is a battery dominated, direct energy transfer power system, the MMRTGs will operate at off-peak power voltages during battery charge and discharge.

The battery depth of discharge (DOD) is limited to no more than 40%. In the two-orbit science case, the maximum battery DOD is approximately 6%, which does not include transient instrument start-up currents not modeled in this early phase of the design. Assuming a 28 V bus, the energy demands are met with readily available 12 A-hr Li-ion batteries. The batteries are charged when excess RPS power is available.

Figure 4.4-6 shows the power scenario during an Io flyby. The flyby scenario represents the two hours surrounding closest approach where the instrument operations are modeled so as to fill the science portion of the SSR. The battery depth of discharge in this example only reaches a 2% depth of discharge.

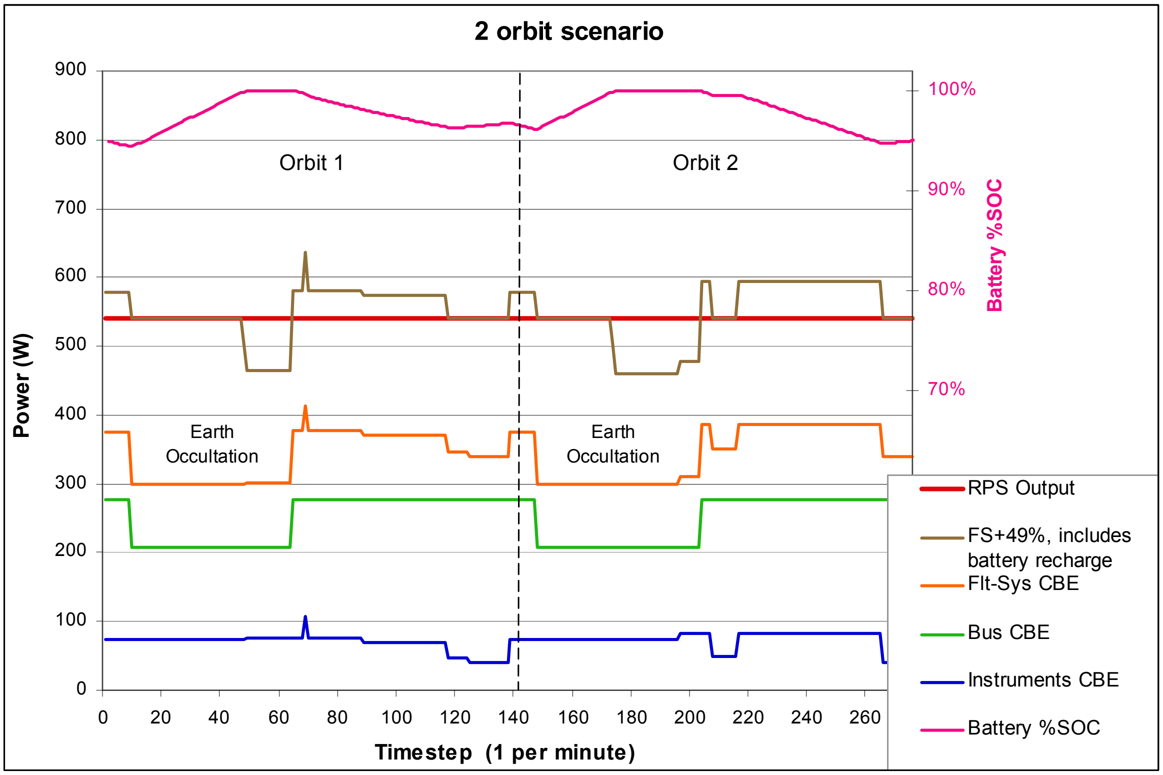


Figure 4.4-5. Power profile for JEO two orbit observing scenario during Campaign 1

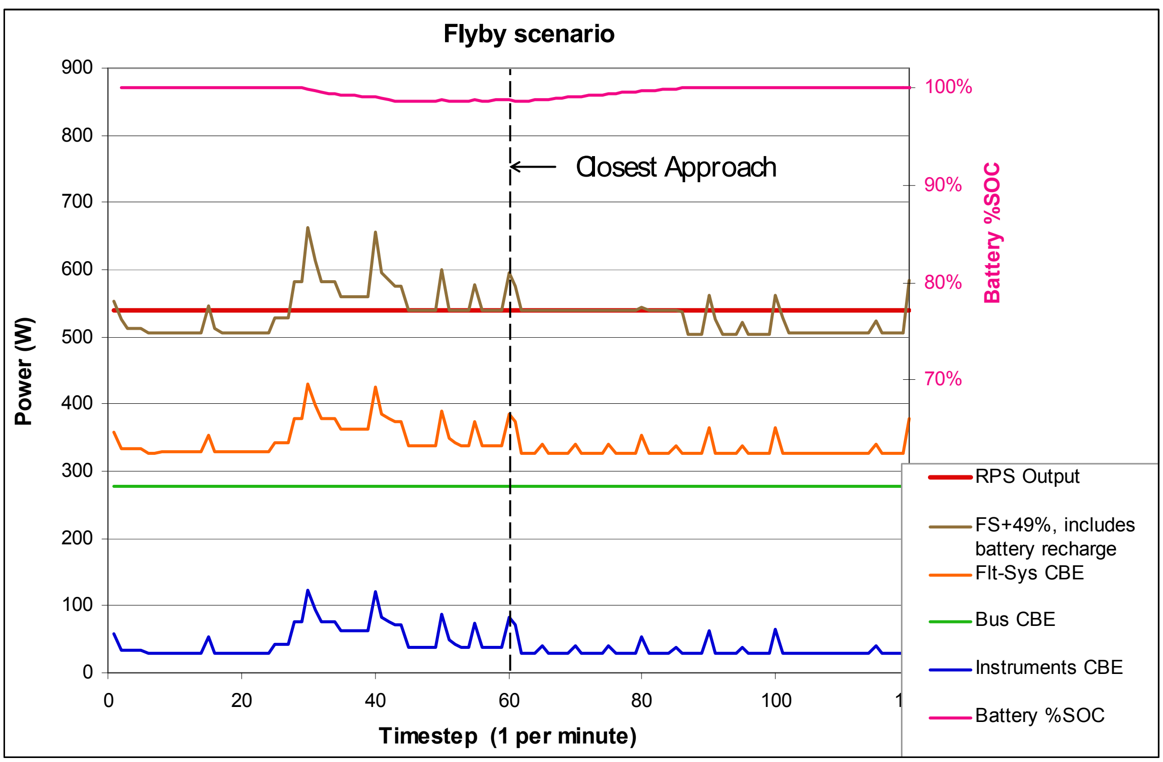


Figure 4.4-6. Power profile during an Io flyby.

4.4.3 Subsystem Descriptions

4.4.3.1 Structures and Mechanisms

The JEO structures and mechanisms approach was based on analogy to prior concepts and missions, specifically Europa Orbiter and Cassini. The major driver on the structures design is the propulsion tanks sizes The JEO Structures Subsystem consists of the Launch Vehicle Adapter (LVA), the Propulsion Module Structure, the Electronics Bus, the Lower Equipment Module and Secondary Support Structure. The JEO Mechanisms Subsystem consists of the Main Engine Gimbal, the HGA Boom and Gimbal and the Magnetometer Boom.

The LVA structure is a machined aluminum structure that interfaces with the ATLAS V Launch Vehicle C-22 Adapter. Above the LVA is the Lower Equipment Module which supports the MMRTG's similar to Cassini's design, the lower thruster assemblies and the main engine. The MMRTGs (5 total) are mounted in 3 locations spaced 90 degrees apart. This configuration was chosen to limit the number of doors required in the launch vehicle fairing to 3, which eases integration issues and has been vetted by the Launch Planning Office at KSC. Each outer MMRTG mounts directly to the Lower Equipment Module via a milk-stool truss structure. The four lower thruster assemblies are spaced 90 degrees apart and are supported onto the Lower Equipment Module by a tri-pod support structure. The main engine is articulated using a 2-axis gimbal based upon the Cassini's main engine gimbal design and is mounted to the Lower Equipment Module with three bi-pods. The Lower Equipment Module is a machined Al structure.

The Propulsion Module structure is located above the Lower Equipment Module. It is a large cylindrical structure made up of graphite composite face sheets and aluminum honeycomb core construction, based on Cassini's design, selected for mass efficiency and stiffness properties. The Propulsion Module Structure supports the fuel, oxidizer and pressurant tanks. It also supports the 3-meter Diameter HGA and deployable boom. The HGA is restrained during launch then boom-deployed and articulated using a 2-axis gimbal. The HGA Deployment/Latch Mechanism will utilize two passive spring dampers for deployment, one at each hinge axis. The boom material is composite. Heritage for viscous spring dampers are Voyager, Galileo, NSCAT and Aquarius. The HGA gimbal will be similar to the MRO HGA gimbal.

Above the Propulsion Module structure is the Electronics Bus Structure which is machined Al and houses the JEO electronics, the ACS Reaction Wheels, the upper thruster assemblies, and the science instruments. The magnetometer boom is deployable 10 m boom based on Cassini and Galileo mag boom and deployment mechanism designs. The upper thruster assemblies are spaced 90 degrees apart and are supported onto the Electronics Bus Structure by a tri-pod support structure.

The structures mass estimate was based upon analogy to other missions. Mass estimates for the Launch Vehicle Adapter, the Propulsion Module Structure, Electronics Bus Structure and secondary support structure were based upon the previous EO study. The MMRTG support structure mass estimate was based on the Cassini and Mars Science Laboratory data. The main engine gimbal was based upon the Cassini engine gimbal mass. The Magnetometer Boom mass was scaled from the Galileo Magnetometer Boom mass. Lastly, the linear separation device (Superzip) was estimated using the Cassini data scaled to the current JEO LV interface diameter.

Note that all structure and mechanism CBE design mass estimates assume growth of other subsystems to their maximum allocations.

4.4.3.2 Propulsion Subsystem

The leading design drivers for the propulsion system are the mission duration and the required ΔV to get to Jupiter and into orbit around Europa. The high ΔV requirement results in high engine throughput, many engine start-ups, and associated valve cycle usage. This, in turn leads to the selection of a robust, 890 N main engine and thrusters with good qualification margins and an extensive test history. The mission life expectation of 9.1 years is within the proven propulsion designs of the Cassini and other long life outer planets missions.

Radiation primarily affects two propulsion components; pressure transducer electronics and soft goods within electrical valves. Current state-of-the-art flight pressure transducers are not designed to be rad-hard. Upgrading of op amps will be needed. Further research into pressure transducers used in the nuclear power industry is still required. The primary soft goods in valves are the sealing materials, such as Teflon, AF-E-411 (rubber), Vespel, etc. Better characterization of the properties and performance of these materials in high radiation environments is required Further discussion on radiation susceptibility of materials is found in §4.5.4.3

In a Propulsion Tabletop Review this year, technical experts recommended a future trade study between a bang-bang and a mechanical pressure regulation system. Transducers of the bang-bang approach may be too sensitive for use in the high radiation environment that JEO will experience. This trade study will be performed in Phase A.

The propulsion system design shown in **Figure 4.4-7** is based on the Europa Explorer study, with modifications to accommodate JEO specific requirements. An illustration of the physical configuration on the flight system is shown in **Figure 4.4-8**. It is a dual mode, bipropellant system using hydrazine (N_2H_4) fuel and nitrogen tetroxide (N_2O_4 or NTO) oxidizer. Approximately 2681 kg of propellant is carried in a hydrazine (fuel) tank and a oxidizer tank. The propellant load has been calculated to assume the full launch vehicle capability is used at the time of launch.

The propellant tanks are COPVs making use of CP (commercially pure) titanium liners, conventional graphite / epoxy overwrap, and titanium surface tension type PMDs. Radiation susceptibility of materials are discussed in §4.5.4.3. The inner diameter of the tanks is 1.242 m making use of the existing ETS-8 tank tooling and heritage.

Large COPV bipropellant tanks have flown on the Chandra mission decades ago. The tanks are not off the shelf but make use of existing tooling and design practices. The PMDs are of conventional design but will be custom designed for the mission. Tank mounting will make use of a composite skirt attached to each tank's cylindrical section. All these elements have proven flight heritage and will be incorporated into JEO's specific tank design. The N_2H_4 and N_2O_4 are used by the 890 N (200 lbf) bipropellant main engine. The hydrazine is also used by the monopropellant RCS thrusters.

The pressurant tanks are COPVs (graphite/epoxy with aluminum liners). The tanks have an inner diameter of 0.508 m and make use of seamless aluminum alloy liners (0.762 mm thick). Tank design and fabrication is conventional making use of technology flown on dozens of spacecraft and boosters.

The baseline for the main engine is an 890 N (200-lbf) thrust NTO/N_2H_4 bipropellant engine currently being developed by Aerojet,

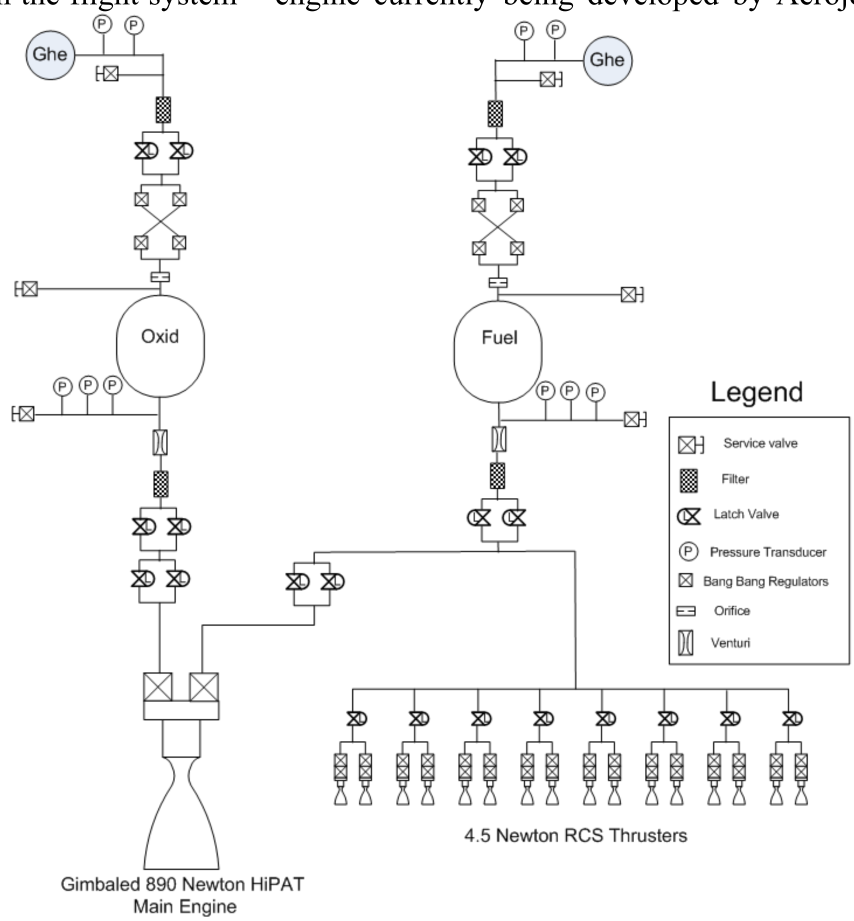


Figure 4.4-7. Propulsion system block diagram

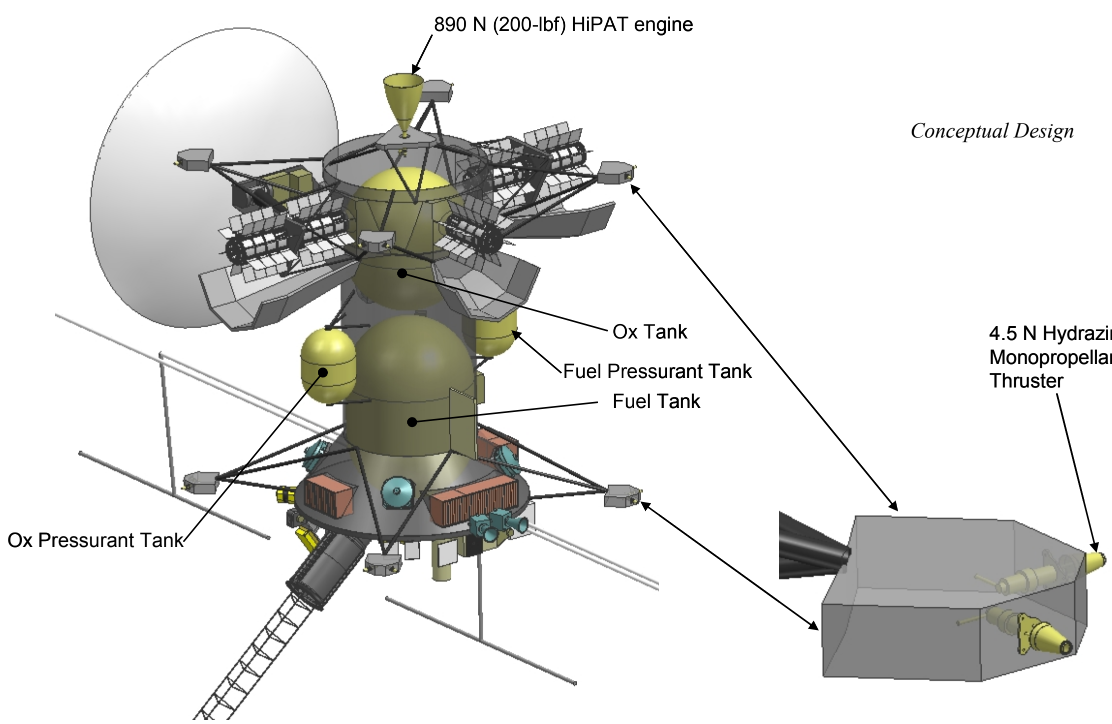


Figure 4.4-8. *Physical configuration of propulsion on the flight system*

Redmond. This engine has a 200:1 expansion ration nozzle and a minimum ISP value of 323 lbf-sec/lbm. The engine is a scaled up version of their 450 N (100-lbf) class HiPAT engine, with a delta qualification program baselined and costed by JEO. The decision to baseline a single main engine was made with consultation with senior propulsion engineers. The rationale is that the 890 N, in family with the 450 N engine, had the reliability to be single string and was acceptable especially when compared with the complexities that come with operating redundant engines. A future trade for the main engine is to reconsider the need for a cover. At the time of this concept development, based on the understanding of this engine vs. the Cassini main engine, it was decided not to include a cover given that the 890 N engines do not have the coating sensitivity issues nor the ring crossing issues that Cassini had. However, since that design decision, Juno analyses has determined a need for an engine cover. Their rationale for adding a cover will be reviewed to see if one is needed for JEO.

A driving thruster configuration requirement is the need to minimize residual ΔV during momentum wheel desaturations. When combined with a redundancy requirement, this led to a configuration of 16 thrusters located on the eight "corners" of the flight system (**Figure 4.4-4**). Sixteen Aerojet 4.5 N (1-lbf) MR-111 thrusters (8 primary and 8 redundant) are baselined to provide attitude control (e.g., 3-axis limit cycle control, reaction wheel desaturations, flight system turns, etc.) for the flight system. In addition, the thrusters may be used for very small ΔV maneuvers. A future study can be to consider further reducing the number of branches and clusters. By allowing the spacecraft to turn to unload RWA's on a selected pair of coupled thrusters could eliminate half the clusters and resolve potential plume impingement issues.

Dry heat sterilization during tank cure will be used to minimize planetary protection concerns. Levels similar to MSL's can be used for the pressurant tanks.

4.4.3.3 Attitude and Articulation Control Subsystem

The JEO Attitude and Articulation Control Subsystem (AACS) points the spacecraft body to meet science instrument and engineering pointing needs. The JEO spacecraft is three-axis controlled with a two-axis articulated HGA and main engine.

***Table 4.4-6.** JEO Pointing Requirements*

Basebody Pointing	
Control	± 1 mrad (3σ, per-axis)
Knowledge	± 50 µrad (3σ, per-axis)
Stability	± 10 µrad/sec (3σ, per-axis)
HGA Pointing	
Control (Ka-band)	± 1 mrad (3σ,radial)
Control (X-band)	± 3 mrad (3σ,radial)
Knowledge	± 0.5 mrad (3σ, radial)
MGA Pointing	
Control	± 160 mrad, or 9º (3σ, radial)
Main Engine Pointing	
Control	± 30 mrad (3σ, per-axis)
Knowledge	± 4 mrad (3σ, per-axis)

Pointing requirements on the spacecraft are listed in Table 4.4-6

The pointing knowledge requirement is driven by HGA pointing. The pointing control requirement assumes reasonably tight control of the spacecraft body attitude in order to reduce undesirable interactions between the HGA and basebody controllers. Reaction wheel assemblies (RWA) will control spacecraft attitude during all fine pointing scenarios. During peak radiation environments, such as near Io, the pointing knowledge performance will be degraded as the stellar reference unit (SRU) may experience false star identification. The degraded performance expected is discussed in §4.4.3.3.1 and is acceptable at this time. Future work in Phase A will better detail additional pointing requirements at specific modes.

Figure 4.4-9 shows the AACS functional block diagram. An illustration of the physical configuration on the flight system is shown in Figure 4.4-10.

The RWAs are configured in 3 orthogonal directions with a fourth skewed backup RWA. The dominant external torque acting on the JEO spacecraft is the gravity gradient torque experienced in Europa orbit which acts along the spacecraft Y-axis. The RWAs are oriented to allow for symmetric gravity gradient momentum build-up on each of the three prime RWAs increasing the storage capability of the RWAs, reducing total revolutions and increasing robustness to a failed RWA.

RWAs are sized with 25 Nms angular momentum storage capacity which can support at least 24 hours of continual operation during Europa orbit phase without requiring a momentum unload or exceeding 50% of the storage capacity on any single wheel. AACS baseline design includes four Teldix RSI 45, 25 Nms RWAs. A larger flywheel can be used if more angular momentum storage capacity is needed in the future.

The reaction control system (RCS) is comprised of 16 4.5 N hydrazine blow-down thrusters capable of providing 3-axis control with redundant couples and vectored translation in the spacecraft X-Y plane. The RCS is used to unload excess RWA momentum, provide three-axis control during coarse pointing scenarios and perform small ΔV maneuvers below the capability of the 890 N main engine. The JEO thruster configuration (Figure 4.4-11) provides high control authority with five degree-of-freedom control. The sixteen thrusters are arranged in 8 clusters of 2 thrusters each, with latch valve isolation for each cluster. The isolation strategy guarantees that the loss of a single

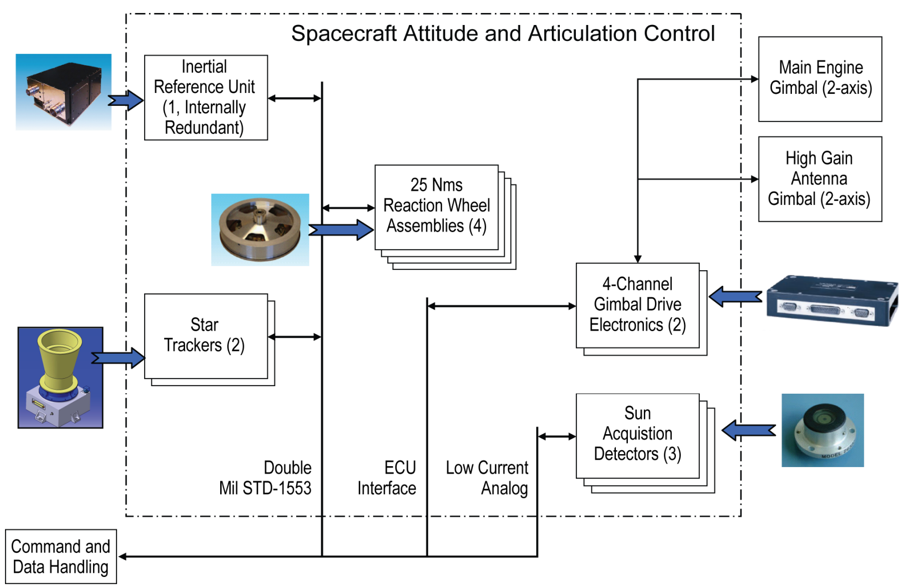


***Figure 4.4-9.** AACS Functional Block Diagram*

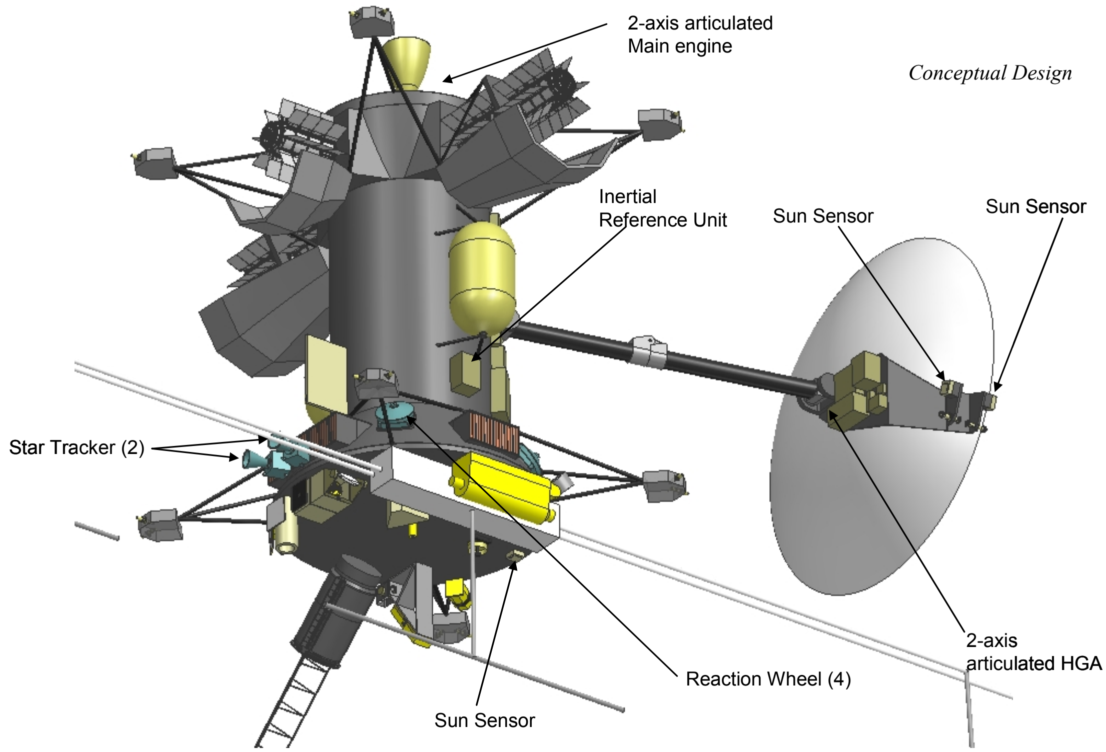


Figure 4.4-10. AACS physical configuration on the flight system

thruster or thruster cluster does not preclude AACS from providing 3-axis control with couples. The JEO AACS will leverage from Cassini algorithms which has comparable AACS hardware performance.

AACS sensors include a single internally redundant inertial measurement units (IMUs), rad-hard stellar reference units (SRUs), and coarse sun sensors. To provide redundancy and improve measurement accuracy the star trackers are not co-aligned. AACS flight hardware redundancy is provided by block redundancy and cross-strapping.

The Litton scalable SIRU is an internally redundant rad hard IMU. The SIRU contains redundant electronics and 4 gyros, 3 orthogonal sense axis and a fourth skew axis used as a parity checker. Loss of any single gyro or other single internal failure does not result in the loss of 3-axis rate information, although it may result in the loss of parity checking which will impact FP algorithms. The SIRU utilizes hemispherical resonating gyros (HRGs) which contain no moving parts allowing for longer life.

AACS functions begin by employing the IMU and RCS to null the residual spacecraft rate imparted by the upper stage tip-off following launch. Once accomplished the sun sensors are used to acquire the sun-line and the spacecraft is oriented to a thermally Safe sun-pointed attitude from which it takes stellar attitude updates. This process is also employed following any subsequent attitude reinitialization.

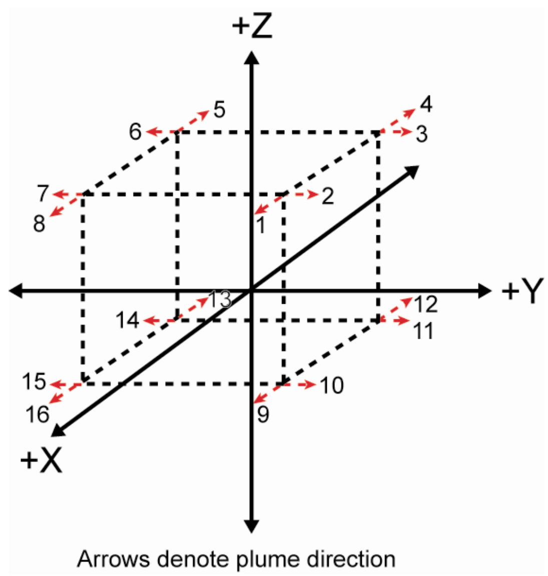


Figure 4.4-11. JEO thruster configuration

Cruise operations uses RCS, IMUs, SRUs, and SSAs. The RWAs are not powered until Jupiter tour operations except for checkout activities and a few periods of fine pointing during cruise. Attitude control will be provided by the RCS during the cruise phase of the mission. Loose deadbands will be maintained during cruise except for a few short periods of tight pointing at which times RWAs will be utilized for increased pointing stability and for hydrazine consumption.

Large maneuvers such as JOI and EOI are performed using the 890 N main engine gimbaled in 2 axis. Thrust vector control is provided via the 2-axis main engine gimbal, roll control is provided by RCS 4.5 N thrusters. Small maneuvers are performed by RCS thrusters using 4 X- or Y-facing thrusters. The thrusters are off-pulsed to ensure zero net torque imparted over the maneuver due to the center-of-mass (CoM) not aligning with the thruster mechanical frame.

After the EOI maneuver the spacecraft maintains a gravity gradient stabilized science attitude for the remainder of the mission except during orbital maintenance maneuvers. During this time the spacecraft flies with +Y-axis to ram and –Z-axis to nadir.

Hydrazine usage can be broken into two categories: one-sided limit cycling during cruise and trajectory correction maneuvers (TCMs).

One-sided limit cycling requires approximately 1.8 kg of hydrazine per year during cruise. Propellant carried for cruise attitude control: 18.7 kg which includes conservative margins.

For TCMs, 1 TCM per year during cruise is assumed, 3 orbit trim maneuvers OTMs per orbit at Jupiter and 2 OTMs per month at Europa orbit. Using four 90 deg slews per maneuver (2 turn strategy employed to slew to the burn attitude and return to waypoint) the estimated hydrazine usage is roughly 0.05 kg/TCM. Given the large number of maneuvers, about 6 kg is assumed for the TCM/OTM slews or 8 kg with 30% margin.

In rounder estimates, 20 kg of propellant is allocated for cruise phase deadbanding, 10 kg of propellant for all of the maneuvers, 10 kg for the momentum management of the RWAs and another 10 kg for unexpected thrusting such as Safing recovery.

AACS provides gimbal and actuator driver electronics for the HGA 2-axs gimbal and the 2-axis main engine gimbal with 2 cross-strapped MOOG 4-channel electronic control units (ECUs).

AACS hardware electronics are screened for radhard parts and further protected by radiation shielding. Only the star tracker head and sun sensors are exposed to the harsh radiation environment.

SRU Detector Technologies and Associated Radiation Effects

JPL has extensive prior experience with radiation mitigation strategies for SRUs in the Jovian environment as a result of work performed with SRU vendors for NASA's Juno New Frontiers Mission and the Europa Orbiter SRU Concept Design Study of 1999–2000. In both cases, shielding was key for detector total-dose survival as well as reduction of the transient noise and false stars, due to external electron and proton flux. SRU survival is discussed in this section; transient noise and false stars are discussed in a following section on star identification. Additional details may be found in the JEO Detector Working Group report (*Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study, JPL D-48256*).

Most existing SRU products are based on n-channel CCD or CMOS active pixel sensor (APS) sensor technologies. The current base line utilizes 1 cm-thick Ta to shield the SRU detector. Including a RDF of 2, the TID and DDD requirements for the SRU focal plane array are 70 krad(Si) and 1.3E8 MeV/g(Si), respectively. This dose level requirement allows for a choice of Si imagers including CMOS APS, n-channel CCD, and arguably p-channel CCD. The HAS (High Accuracy Sensor) is the latest generation radiation hardened CMOS APS star tracker sensor product from Cypress/FillFactory, Belgium. ESA has sponsored an extensive space qualification process for the HAS, including radiation testing to TID levels that are very close to, and DDD levels that are well in excess of, JEO's requirements (the formal release of ESA's HAS qualification report is expected in 2008). Radiation testing of the HAS was also performed by EADS SODERN for the Juno SRU study phase in 2007. With the exception of offset shifts and increases in dark current, no significant parametric shifts were observed at any tested radiation level. In addition, the observed changes in offset and dark signal were small enough to have no significant impact on SRU performance for the Juno application.

Several SRU vendors have developed CMOS APS-based SRUs, targeting the lower mass, power, and cost of this architecture compared to CCD-based SRUs. For example, the HAS is the APS used in SODERN's "HYDRA," an SRU with a separate optical head and electronics unit, radiation hardened lens elements, and configuration options that use from 1 to 5 optical heads per SRU. Hydra's space qualification will be complete in 2008, with the first flight models delivered in 2009. The HAS is also the focal plane array in Selex-Galileo's APS-based Autonomous Star Tracker (AA-STR). The AA-STR was developed for ESA's Bepi Colombo mission, and designed to tolerate the extreme solar flare proton flux environment of Mercury. The AA-STR is currently completing its ground qualification for the AlphaBus GEO Telecommunications platform. A "Flight Demonstration Model" of the AA-STR was integrated in the Proba 2 spacecraft in 2007 and is scheduled to fly during 2009. There are clear options for survivable SRU detector technologies for JEO. The extent to which a given cumulative DDD or TID will affect star signal degradation and SRU performance will be driven by a combination of SRU system features: optical design (i.e., star signal size for a given integration time), the observable sensor parameter degradation under the SRU's specific JEO operational conditions (e.g., FPA temperature), image collection strategies (e.g., readout timing and integration time), operational modes, and image processing techniques.

4.4.3.3.1 AACS Algorithms

Star Identification

Transient effects on star measurements are determined by analyzing the probabilities that transient hits will significantly corrupt measurements for stars of various magnitudes, and the associated accuracy reductions. While a proton hit near a star could make the measurement useless, a proton hit can be discriminated based on the size of the generated signal. For tracking, the number of measurements eliminated by protons is expected to be small given good a priori knowledge from gyro-based attitude propagation (about 1/10 during JOI, and <1/100 at Europa). For attitude initialization, additional proton filtering is expected to be required. Electrons contribute smaller false signal (perhaps 1000 to 2000 electrons per affected pixel per hit), but are much more numerous than protons. The relatively smaller generated signal from electrons can make filtering over many measurements a possible approach. Because of the spatial randomness of the electron strikes, electrons will theoretically produce a flat "white out" effect over many measurements, producing a relatively uniform background. The dimmest star that can be tracked will depend on the number of hits per second that will hit the "track window."

At 5 Rj (JOI and Io flyby environments), approximately 600 electrons will hit the track window per second. A magnitude 5 star signal will be effectively invisible under this condition, but a magnitude 2.5 star could provide valid, but noisy measurements, if multiple samples are averaged, and very good a priori knowledge is available for track window "placement". A magnitude 1 star (only 16 are available in the sky) produces more than 1.2 million signal electrons per second, and should be detectable given 0.5 degree knowledge. The mitigation would be that the entire JOI sequence may need to be performed on gyros, or on sun-line hold, or with the star tracker pointing at bright stars. Analysis of star detection and identification probability is a later activity, which will follow related trades at the system level that identify the overall pointing strategy. During the 1.5 hours preceding JOI, the spacecraft will be between 5.5 and 5 Rj. Availability of magnitude 3 stars will be needed to maintain SRU tracking. Gyro error over 1.5 hours is estimated at 5.8 mrad (3 sigma/per axis).

Although during JOI the radiation environment may prevent accurate SID measurements, there are no restrictions on the roll axis direction during JOI, and a burn attitude can be selected with a favorable SRU orientation so that magnitude 3 or brighter stars are available within the SRU FOV, and tracking can likely be maintained. Even with a favorable burn attitude, SID outages an hour prior to JOI are reasonable to expect, requiring gyro propagation during that time. In this case the angle rate noise (which is the dominating gyro error source) will provide approximately 3 mrad of error (3 sigma/per axis) at the beginning of JOI due to 1 hour of gyro propagation, and approximately 7.33 mrad (3 sigma/per axis) by the end of the maneuver, 45 minutes later. Although the SID outages may persist for several hours following JOI, until after 8 Rj, there are no tight attitude knowledge requirements immediately following JOI.

During Io flybys SID will be impacted by the high radiation environment. The primary science objectives during Io closest approach (ICA) will feature INMS measurements which do not have tight pointing requirements. Inboard approach science objectives include high res mosaicing with the NAC at about one hour prior to ICA. While propagation errors may account for an initial error in the first footprint, the subsequent footprints will have a small relative error.

At 9 Rj (Europa orbit science environment), the electron transient hit rate drops to roughly 71 impinging electrons per second per track window (a factor of 7 reduction from JOI). It should be possible to track a magnitude 4 to 4.5 star under these conditions.

Due to the number of large bright bodies in the Jovian system, and the motion of the node during Europa orbit, star tracker placement that precludes bright bodies entering the FOV is not possible. The star trackers are body mounted and the spacecraft body attitude is constrained by the science pointing objectives, precluding star tracker friendly attitudes in Europan orbit. During Europa orbit operations, Jupiter will have an angular diameter of approximately 12 deg, while the rings will not be likely to cause total outages because of their relative dimness. A large bright body passing through the optical FOV of the star tracker during periods of the orbit can potentially cause detector interference or saturation difficulties for the star tracker.

To mitigate the star identification concerns regarding the bright bodies at Europa JEO will implement flight software logic to suspend star identification, the same function as is performed on Cassini. Stellar attitude updates are suspended during a period of time and attitude is propagated on gyros alone.

These algorithms are well understood and will be leveraged for JEO.

Thrust Vector Control via Main Engine Gimbal

Thrust vector control (TVC) during main engine maneuvers will accommodate the large shifts in CoM for the JEO flight system, due to bi-prop consumption, via a 2-axis gimbaled main engine. TVC is performed about the spacecraft X and Y-axis similar to the Cassini 2-axis gimbal and about the spacecraft Z-axis is performed via 4.5 N thrusters.

HGA Boresight Open Loop Pointing

The most stringent of the AACS pointing requirements for the JEO mission is pointing the HGA boresight to within ±1.0 mrad (3σ, radial). An error budget assessment was performed to demonstrate the feasibility for this pointing.

An un-calibrated and calibrated HGA pointing error budget was developed based on flight performance from the Cassini and MRO spacecraft. The details are provided in Appendix E.5. The HGA is mounted on an MRO-like 2-axis gimbal. In general, terms referring to spacecraft body pointing capabilities use Cassini-like flight performance values, while terms referring to the gimbaled HGA pointing capabilities use MRO-like flight performance values.

In order to meet the finer pointing requirements, in-flight calibrations will need to occur during cruise and Jupiter orbit, reducing the HGA knowledge errors. The following in-flight calibrations will need to be performed: SRU to Attitude determination (AD) reference, and AD reference to HGA base misalignment. Thermal deformation during eclipse periods will also be characterized.

While the JEO HGA pointing requirements are tighter than either those for Cassini or MRO, the error budget is reasonable as the requirements are in family with actual performance seen on Cassini and MRO. Post-calibration HGA pointing performance can meet ±1.0 mrad (3σ, radial) pointing control, which corresponds to ~0.5 dB loss.

4.4.3.4 Flight Software

Highly reliable software for mission-critical applications is essential for this long-life mission. The flight software baseline uses a flight proven architecture implemented in accordance with JPL requirements for NASA Class B (non-human space rated) software development. JPL has established a set of institutional software development and acquisition policies and practices as well as design principles that apply to mission-critical and mission-support software. These practices conform to the NASA Procedural Requirements for Software (NPR 7150.2) and are an integral part of the JPL Flight Project Practices (FPP) and DPP. All flight software will be developed in accordance with JPL institutional policies and practices for deep space missions, which include JPL's Software Development Requirements (D-23713) that address all CMMI process areas up to maturity level 3. Software identified as safety critical shall comply with safety critical requirements, regardless of software classification. Software safety criticality assessment, planning and management will be performed for all software including new, acquired, inherited, and legacy software and for supporting software tools. Software will be identified and documented as safety critical or not safety critical based upon a hazard analysis conducted prior to start of development activities.

The flight software will be written in "C" using the VxWorks operating system, and will be organized in a layered architecture as shown in **Figure 4.4-12**.

The operating system abstraction layer will fully encapsulate the VxWorks operating system and provide the following functions to the applications, services, device manager, and device diver layers:

- Inter-task messaging,
- Task synchronization,
- Task management.

The device driver layer will interface

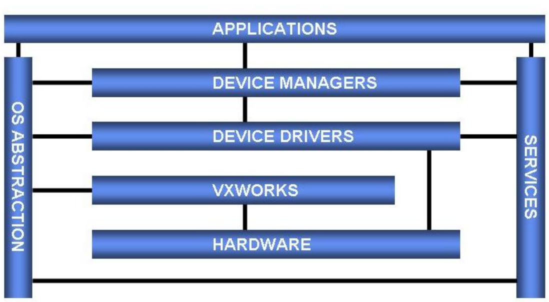


Figure 4.4-12. *Flight Software Architecture*

directly with the hardware. The layer will contain drivers that provide control and data abstractions to the device manager and services layers. The drivers will communicate with the hardware using the device specific syntax. This layer will provide the following functions for each device:

- Convert control requests into lower level activities,
- Manage data transfer between device managers and hardware,
- Provide hardware device protocols that: maintain the correct sequencing of requests, reject bad requests, prioritize valid requests, and inform device managers when requests are satisfied,
- Monitor and maintain hardware states,
- Monitor for events and faults,
- Respond to interrupts,
- Enable and disable correct interrupts at initialization,
- Connect correct handlers to interrupts.

The device manager layer will interface with the device drivers and will not be concerned with the hardware interface syntax. Instead, the layer will provide device operating semantics to the applications and services layers, allowing device managers to be reused independent of hardware interface syntax. This layer will provide the following functions for each device:

- Device management functions through interfaces to the device driver, including functions to configure, enable, disable, and reset hardware and instruments,
- Software service and applications interfaces to process device and instrument control requests and wait for data from device drivers.

The services layer will interface with the device managers, drivers, and OS abstraction layer, and provide common system services and system resource housekeeping functions throughout. This layer will include the following service functions:

- File system data storage and retrieval,
- Science and engineering data management and compression,
- Telemetry data collection, processing, packetization, and framing,
- Event reporting,

- Time services, including alarms and clock references,
- Memory management, including scrubbing and defragmentation,
- Event and time-based command sequencing engines,
- Command dispatch,
- Non-volatile parameter management.

The application layer will interface with the services, device manager, and OS abstraction layers and provide high level behaviors for implementing mission functions. This layer will include the following application functions:

- Uplink and downlink interfaces to the ground system including command receipt verification and validation,
- High level fault protection monitor and response behaviors that detect and recover from anomalies encountered during all phases of the mission, including launch, *and Jupiter and Europa* orbit insertions,
- Fault protection manager,
- Flight software health monitor and self-tests,
- Spacecraft mode and configuration managers,
- Redundancy manager,
- Flight software state manager,
- Activity constraint manager,
- Resource and activity arbiter,
- Communication behavior manager,
- Science behavior manager,
- Instrument behaviors,
- Guidance and control behaviors, including attitude estimation and control, suspend false star identification algorithm, trajectory correction maneuver control, momentum management, and high gain antenna pointing (see §4.4.3.3).

The flight software will incorporate the following functionality to reduce operations cost as recommended by the Mission Operations Lessons Learned Study for The Next Outer Planets Flagship (OPF) Mission (see Appendix K).

- Onboard ephemeris based pointing,
- Onboard file system, and pre-allocation of SSR memory resources by ground rules,
- Automated file playback for downlink,
- CFDP for telemetry, and automated retransmissions for data dropouts,
- CFDP for command uplink.

Several of the above functions have been implemented by previous JPL missions (namely Cassini and MSL), and their design, and in some cases implementation, can be heavily leveraged for JEO. The operating system will be the same as that for Multi-Mission System Architectural Platform (MSAP) and MSL.

A significant portion of the JEO software design will be based on the MSAP development activity and leveraging some of the specific flight applications from missions such as MSL. The software will provide high test and operational flexibility to accommodate science and engineering needs, autonomous fault recovery, and in-flight software updates for the resolution of unforeseen situations. Products such as documentation and the development environment (configuration management, test harnesses, and scripts) for the flight software functionality taken from previous developments would reduce development cost and risk. Further, the MSAP simulation test environment includes simulation for the MSAP supported hardware. Reviews will be performed prior to Phase B to confirm the degree of leveraging that can be assumed for the components.

Table 4.4-7 details the planned functionality for each flight software release and the targeted testing venue. The project schedule shown in **FO-13** depicts the test-bed utilization with major flight software release

Table 4.4-7. *Flight Software Releases are scheduled for an effective testing plan*

Release	Functionality	Test Venue
R1	MSAP developed, basic C&DH	Testbed - GSE, BB integrated, initial checkout
R2	Mission specific C&DH	Testbed - all, single and dual string
R3	AACS and device controls	Testbeds - EM integrated
R4	Engineering interfaces	Testbeds
R5, R5.1	AACS Cruise, Instrument Control	ATLO - supports initial integration of eng'g s/s
R6, R6.1	Instrument FSW, AACS Science phase	ATLO - supports payload integration and functional test
R7, R 7.1	Full functionality, Fault Protection	ATLO - supports FP and Env Test

and ATLO schedule. With mature MSAP software for an early operating system, the phasing of the releases allow for well developed software at each delivery. Full functionality FSW is planned to be developed prior to launch.

4.4.3.5 Command and Data Handling Subsystem

The Command and Data Handling (C&DH) Subsystem is based on the MSAP architecture and uses a block-redundant flight computer to perform flight system processing and control tasks (**Figure 4.4-13**). An illustration of the physical configuration on the flight system is shown in **Figure 4.4-14**.

At this time, the baseline design assumes none of the instruments require data compression services from the C&DH sub-system and that all data compression is performed by the instrument's own electronics. A future trade study in Phase A, after instrument selections have been made, will assess the impacts and benefits of having the C&DH perform instrument data compression. The estimated aggregate payload data collection rates are <25 Mbps during typical operation and <55 Mbps during peak IPR raw data collection modes which is well within the C&DH architecture design capability.

The dual-string C&DH subsystem includes:

- RAD750 Processor with 16 MB of non-volatile SRAM, with options to 128 MB,
- MSAP Telecom Interface (MTIF) with 4 radio interfaces and dual string arbitration capability referred to as a Fault Detection Unit (FDU),
- Power Converter Unit (PCU) provides the secondary voltages required by the other cards in the C&DH Chassis,
- MSAP Remote Engineering Unit (MREU) utilizing the Remote Serial Bus to interface with the Custom JEO Card and gathers both the analog and digital engineering telemetry for the C&DH subsystem,
- Custom JEO Card (CJC) with digital and analog interfaces needed to support the motor drive electronics as well as the Analog Sun Sensors.

The C&DH uses four primary paths to

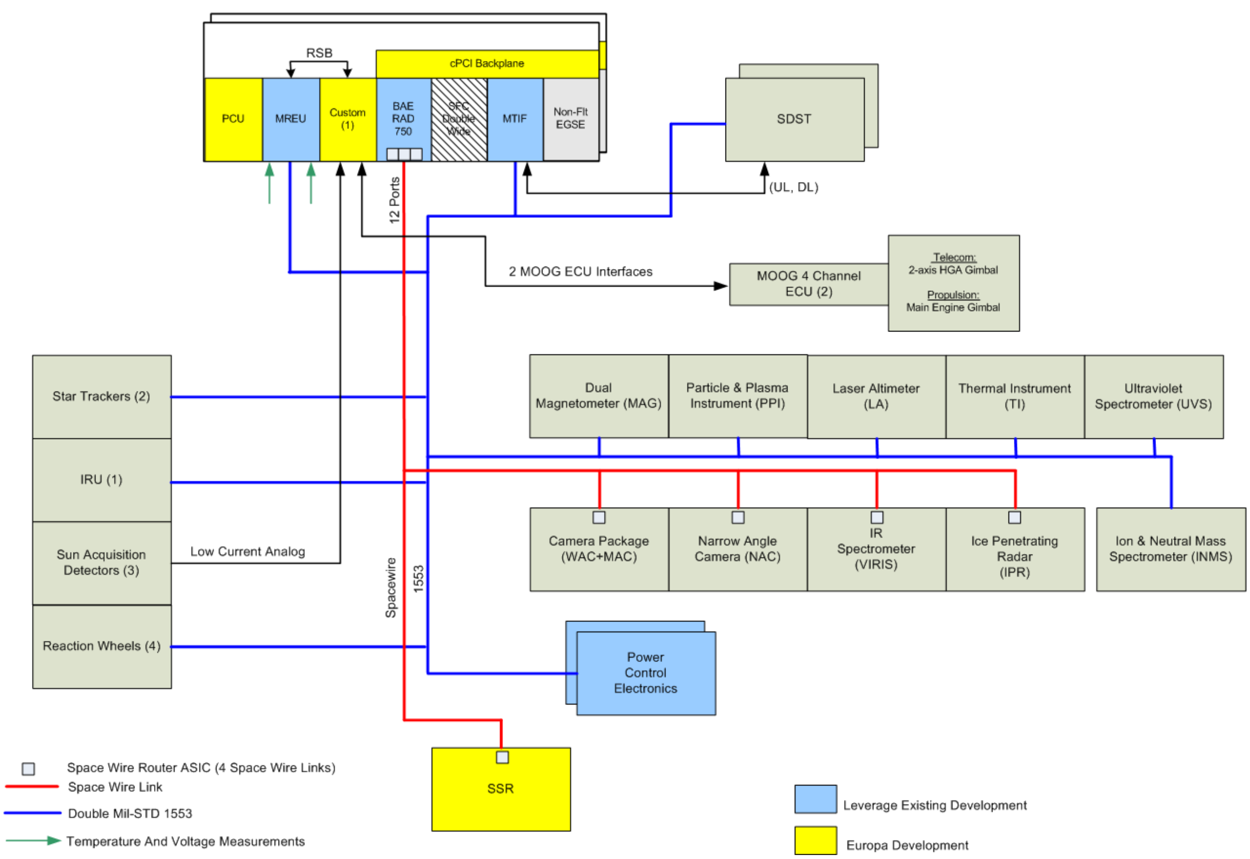


Figure 4.4-13. C&DH Block Diagram

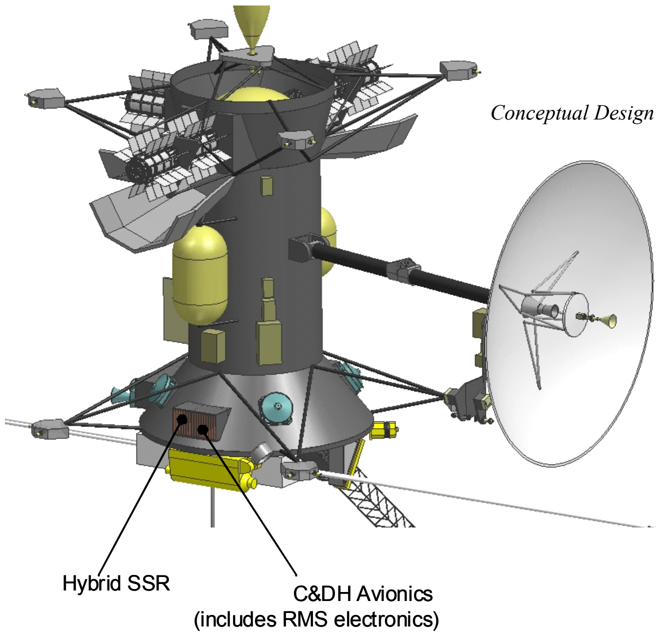


***Figure 4.4-14**. C&DH physical configuration on the flight system*

interface with the subsystems and components that it supports. The first of these is the arbitration interface found in the MTIF and the CJC. These states will be defined in more detail in the Fault Tolerance section. The second of the primary paths is the 1553 bus which is used for communication between the two C&DH strings and for communication with spacecraft peripherals that have such an interface. The third path is the Remote Serial Bus (RSB), which is a 1 Mbps multi-drop serial bus used within the C&DH subsystem to interface to low data rate devices connected through the custom card. The fourth primary path is SpaceWire, which is a high speed point to point link configured in a star topology with the RAD750 as the hub.

C&DH Card Descriptions:

The Spacecraft Flight Computer is a Rad750 processor running at 200 MHz with 16 MB of SRAM and 12 SpaceWire ports capable of supporting up to 200 Mbps each. The SRAM parts are 1 Mrad hard components. Note, the 12 SpaceWire ports are a result of three SpaceWire router ASICs being present on the JEO tailored flight computer.

The MTIF houses the 1553 bus controller which is used in conjunction with FSW to manage the 1553 devices found throughout the spacecraft. The MTIF contains the FDU which is used for dual string arbitration as well as telecommunication interface ports. Lastly, the MTIF also houses the Ground Support Equipment (GSE) interface, which includes T-Zero functionality and the Launch Vehicle (LV) interface, used to receive downlink from the spacecraft before launch vehicle separation.

The MREU is the C&DH subsystem's source for engineering telemetry and as such has 118 analog sensors which include 52 Platinum Resistor Thermometers (PRT), 16 temperature sensors and 48 differential analog voltage measurement circuits. In addition, the components needed to support wakeup and shutdown functionality (used when the backup string configuration is off), are also located here.

The CJC provides the C&DH subsystem with an interface to the motor electronics used to drive the gimbals located throughout the system as well as the required signal conditioning and analog to digital conversion of the sun sensor outputs. Digital telemetry from the CJC will be passed over the MREU's RSB to the MREU and then to the flight computer via the 1553 connection between the MREU and the MTIF.

The PCU reduces the spacecraft power bus to the set of secondary voltages required by the aforementioned cards.

A board-by-board evaluation of MSAP's C&DH designs was performed to assess their ability to be adapted to JEO's radiation environment. Cassini's as-built parts list was used in conjunction with MSAP's lists to identify the magnitude of change required and availability of equivalent parts. JEO's radiation investigation is still ongoing, but it was determined that the necessary modifications to these designs were understood, within the experience base of JPL, and sufficiently limited thereby not necessitating a system level re-design. Details of the evaluations are reflected in the radiation discussion in §4.5.

Solid State Recorder (SSR)

JEO's C&DH architecture is reliant upon a Solid State Recorder (SSR) for all of its memory needs (with the exception of the SFC on-board memory which is only used for FSW execution and interface buffering). JEO's SSR is located in its own enclosure and connected to both C&DH strings via redundant SpaceWire links. This allows the mass memory data to be shared between the primary and backup computers. The detailed description of the SSR is located in Appendix E but the C&DH levied requirements are as follows:

- 1 Gbit: Science data storage during Europa orbit phase which will experience the total mission radiation,
- 16 Gbits: Additional science data storage to be used during the Jupiter tour phase which is roughly the first half of the accumulated radiation dose,
- 2 Gbits of non-volatile memory for spacecraft engineering use: boot code for the RAD750, flight software (2 copies) including any instrument FSW, engineering parameters and telemetry. Total volume estimated at 0.5 Gb with 75% design margin per design principles (**Figure 4.4-15**).

Given the radiation effects on memory devices, a hybrid SSR is conceptualized to meet JEO's needs (see Appendix E.4 for details).

In summary, the conceptual design of the hybrid SSR is based on:

Device Selection:

- Chalcogenide RAM (CRAM), Phase Change for NVM and science data storage needs at Europa orbit (3.1 Gb, includes 300 kb unallocated margin in this concept),
- Synchronous dynamic RAM (SDRAM) for additional science data storage needs at Jupiter tour (16 Mb).

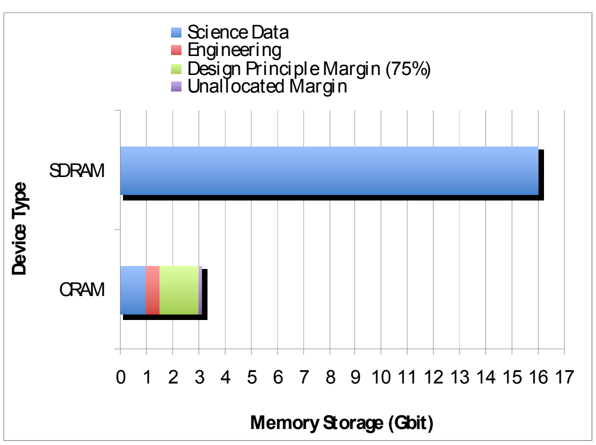


Figure 4.4-15. Solid State Recorder (SSR) Allocation to Science and Engineering Data

Radiation Tolerance:

- CRAM: >1 Mrad; << 1E 11 upsets/bit-day,
- SDRAM: >150 krad, spot shielding if necessary,
- Redundant spacesire interfaces, power converters, controllers/supervisors,
- CFDP compatible.

Thus, since the larger science data storage needs are during the Jupiter tour only, softer components will be used for cost and resource efficiency. Larger memory capacity in orbital phase is limited in usefulness because this phase is downlink bandwidth limited and retransmission of downlinked data is not required during the Europa orbit phase.

Interfaces to Science Payload

Table 4.6-2 shows the list of model payload instruments along with their associated data rates to the C&DH subsystem. Four of the ten science instruments require the use of a high speed interface such as SpaceWire. The aggregate data rate of the remaining instruments totals significantly less than 1 Mbps, and can therefore be accommodated by the 1553 system bus.

Interfaces to Telecom

The C&DH subsystem interfaces with redundant transponders via 1553 for command and control functions. Science and engineering data is handled via unidirectional and dedicated high-speed uplink and downlink channels.

Interfaces to Power

The C&DH subsystem's primary interface with the power subsystem is through an isolated 1553 interface. This architecture was selected in order to simplify the system level design given that the two subsystems will be operating off of different ground systems.

Fault Tolerance

The C&DH primary and backup strings can be used in three different modes: cold, warm or hot backup. Cold backup signifies that the redundant C&DH string is powered off. Warm backup signifies that the redundant string is on, able to respond to commands, send telemetry and ready to be-come the prime string if the fault detection unit (FDU) indicates that the prime string is not healthy.

The hot backup state signifies that the redundant string is running in conjunction with the backup string and can take over spacecraft activities immediately if necessary. The current baseline is to use a cold backup redundant string; however, the C&DH architecture is capable of supporting a warm or hot backup if it is deemed necessary by further design developments.

All components on the 1553 and SpaceWire buses are fully cross-trapped; failure of one interface does not require a string swap, the device can simply talk on the other bus. Fault tolerance is handled in two ways for point to point interfaces. The first is to allocate two point to point interfaces per string, instead of one, to a particular device in order to provide full cross-strapping capabilities. The second is to require that the point to point interfaces that don't have a second interface on the same string to have a redundant unit, but a string swap will be required if one side fails and that component is needed.

4.4.3.6 Telecom Subsystem

Based on science and mission requirements and constraints, the JEO telecom subsystem must provide: 1) reliable and robust low rate engineering command and telemetry links for critical events (launch, JOI, EOI) and safemode; 2) Dual frequency coherent Doppler measurements (X/X, X/Ka, and Ka/Ka uplink/downlink); and 3) High downlink rates for science data in the Europa science phase, during Cruise calibrations, and during Earth and Galilean satellite encounters. The 34 m DSN antenna will be used during normal operations. Limited 70 m antenna use (or equivalent) for critical or emergency events will be required.

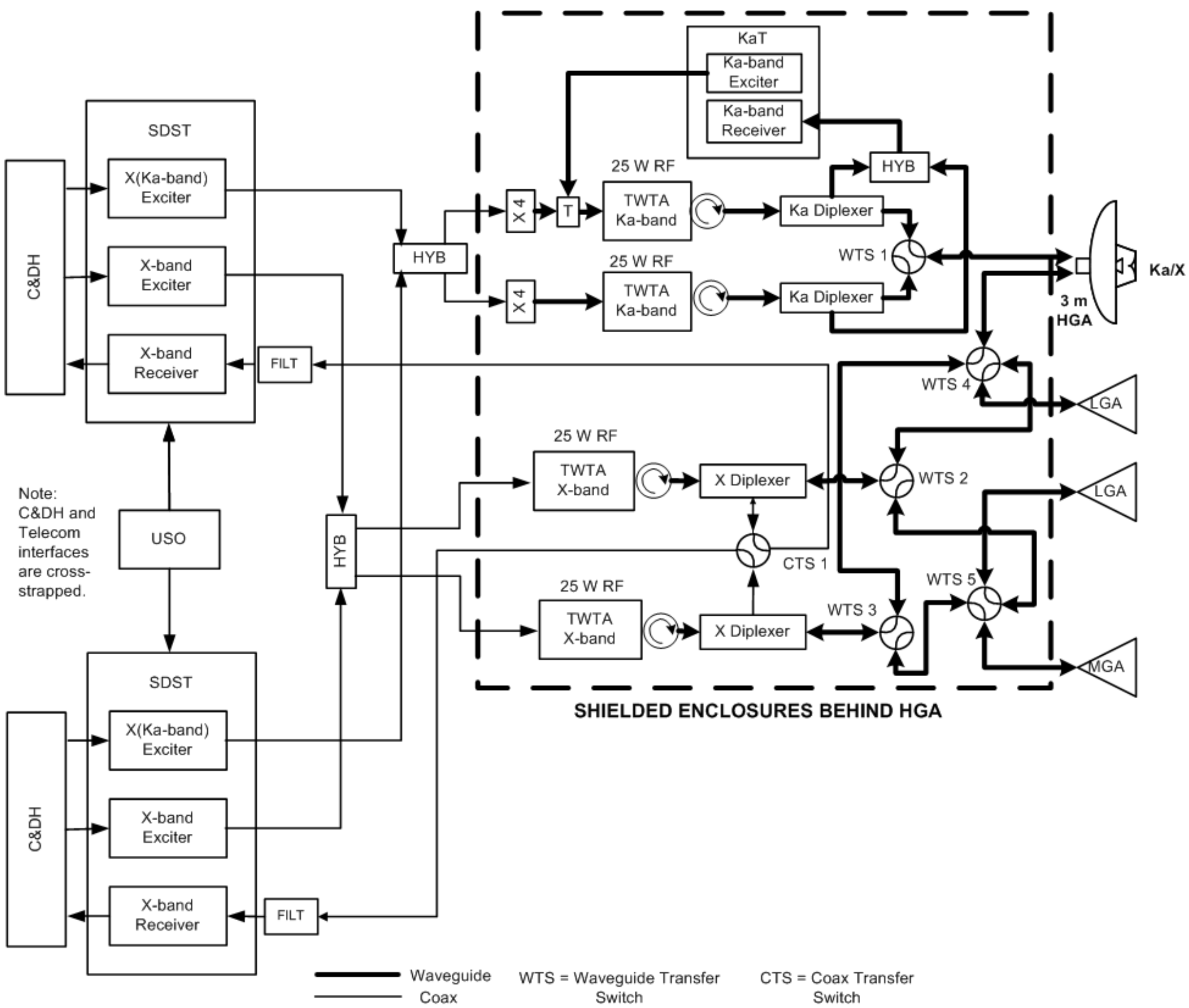


Figure 4.4-16. Telecom Subsystem Block Diagram

A block diagram of the telecom subsystem is shown in **Figure 4.4-16**, and the physical configuration on the flight system is shown in **Figure 4.4-17**.

Significant features of the telecom design include the following:

- Redundant cross-strapped X/Ka-band Small Deep Space Transponders (SDSTs),
- Redundant cross-strapped 25 W Ka-band traveling wave-tube amplifiers (TWTAs),
- Redundant cross-strapped 25 W X-band TWTAs,
- One 3-m X/Ka high gain antenna (HGA),
- One X-band medium gain antenna (MGA),
- Two X-band low-gain antennas (LGAs),
- One Ultra Stable Oscillator (USO) for radio science,
- One Ka-band Transponder (KaT) for radio science.

The number and configuration of the RF switches was carefully considered to make the design single-fault tolerant and to minimize the number of required switch actuations. During operations, occasionally one of the four switches in the X-band transmit path (WTS 2, 3, 4, or 5) will be actuated, and the design is robust to a failure of any single switch in that path.

Driving geometry parameters include range to Earth, Sun-Earth-Spacecraft angle, Sun-Probe-Spacecraft, orbit period, and occultation durations (for Europa and Jupiter). For a detailed discussion of mission geometry, see §4.3 and **FO-6**. The range to Earth varies from 4.4–6.5 AU at Jupiter, and strongly affects the supportable data rate. SPE angle varies from 0–12.3 degrees during the Jupiter operations portion of the mission, and affects the safemode communications strategy, which involves either sun pointing or earth pointing the MGA. The safemode communications strategy is discussed further in Appendix H. Orbit period and occultation duration determine the available downlink time. This is 55% to 60% depending on orbit altitude and includes losses for DSN lockup time.

The selected design for this study is a Ka-band high rate system for science data return. There is also an X-band high and low rate communications system during cruise, safing, critical events, and for all uplink commanding, as well as a Ka-up/Ka-down carrier-only system for science. Ka-band was

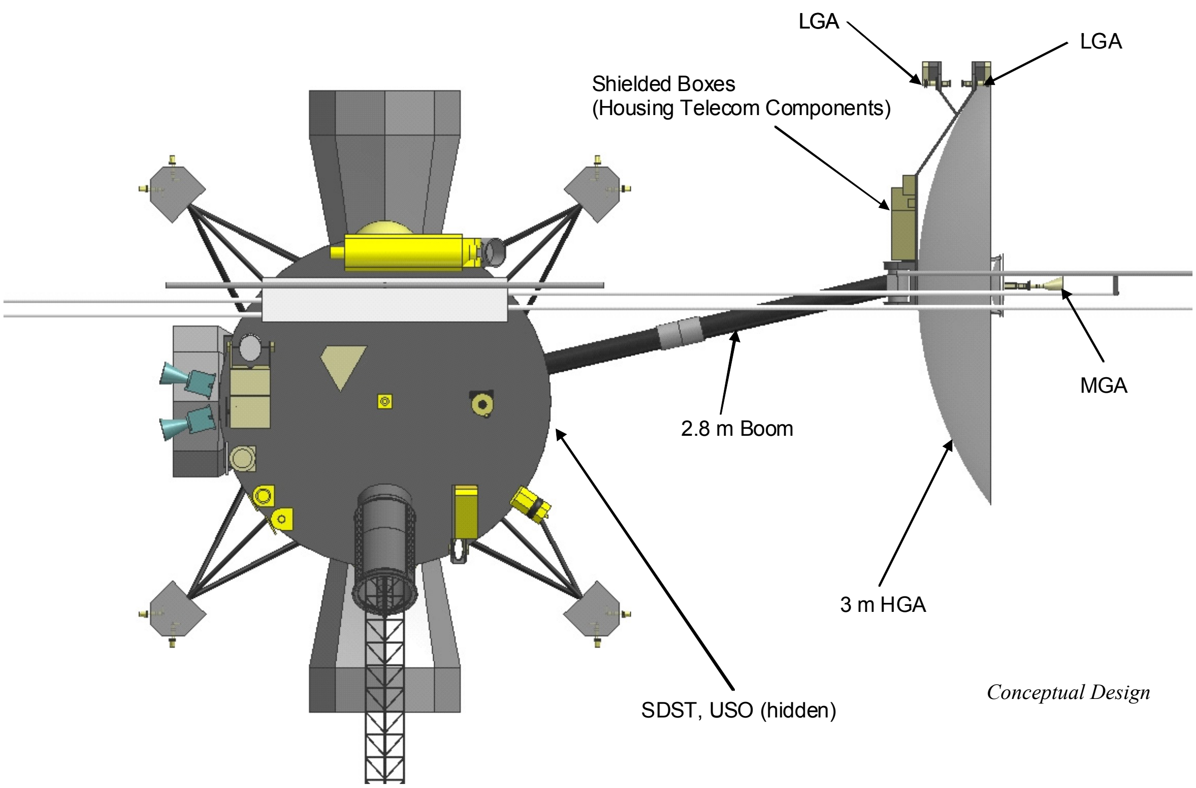


Figure 4.4-17. Telecom subsystem physical configuration on the flight system

selected because X-band cannot meet the desired science rates without 70 m antennas (or equivalent), or higher on-board power. The 70 m antennas or equivalent are assumed available only for critical events such as JOI or emergency safing. The current 3 m HGA mounted on the +X side of the spacecraft meets the downlink needs within the current design. If a larger antenna is desire later in the design phase to alleviate other resources, a different mounting scheme would likely be required to fit within the LV fairing.

Most of the telecom hardware is mounted on the back of the HGA thereby reducing the circuit loss between the output of the high-power amplifiers and the antennas. The MGA is co-boresighted with the HGA, and is mounted on the HGA structure. The two LGAs, also mounted on the HGA, point in opposite directions with the co-boresighted LGA being the primary safe mode antenna.

Cruise communications are primarily X-band via the HGA (or MGA), with the LGAs used for ranges less than 1 AU from the Sun and for safing out to 1.5 AU to Earth. The MGA is then used for safing to obtain minimum data rates above 40 bps and, if geometry allows, for orbit insertions. Two sun sensors are mounted on the HGA for safemode attitude on the MGA. Appendix H provides the link analysis, including safe mode performances.

The SDSTs, which are mounted on the spacecraft bus instead of the HGA, receive X-band uplinks, and provide X-band and/or Ka-band Doppler, ranging, and telemetry downlinks. A dual feed HGA allows X- and Ka-band to be used simultaneously, if desired.

For science enhancement, the telecom subsystem includes a Ka-band Translator (KaT) and a USO to complement the primary communications system. The KaT provides a 2-way coherent, Ka-band carrier for radio science by turning around a Ka-band uplink received from the ground. The Ka-band outputs originating from the SDST and the KaT are combined using a magic tee, which allows them to share one of the two 25-W Ka-band TWTAs, with 90% of the TWTA output allocated to the SDST and 10% allocated to the KaT. The USO, with an Allan Deviation of ~1E (–13) at integration times of 10–100 seconds, provides a stable frequency reference for the SDST (for one-way mode science measurements such as radio occultations).

Evaluation of the telecom electronics for the expected radiation environment has been performed and is discussed in §4.5. All hardware with few exceptions is expected to meet a 300 krad part capability per the parts upgrade plan.

During the Jupiter tour phase, the telecom subsystem provides Ka-band link performance of 64–144 kb/s over the 4.2 to 6.5 AU range to a DSN 34 m antenna. The link carries 3 dB of margin, and assumes 90% weather, 20 deg station elevation, Turbo coding (8920, 1/6) with frame error rates (FER) of 10^{-4}, and residual carrier BPSK modulation. Detailed supporting analysis and selected link design control tables can be found in Appendix H.

Traditional link designs typically assume worst case station elevation angles and other system noise sources (yearly weather effects, Jupiter hot body noise, etc.) when determining supportable data rate. By taking advantage of actual elevation angles and Jupiter noise conditions for each orbit lockup at occultation exit, planned data rates can be increased by roughly a factor of 2. For the Europa orbit phase, this strategy is assumed and the Ka-band link performance increases to 134–280 kbps over the 4.2–6.5 AU range to a 34 m DSN antenna. Section 4.6.4 and Appendix H contain detailed analysis and discussion of this technique and other data return strategies.

4.4.3.7 Radiation Monitoring Subsystem

The block diagram shown in **Figure 4.4-18** is the Radiation Monitoring Subsystem (RMS) that provides continuous monitoring of real-time radiation environments at multiple key locations and has three driving requirements: measure the radiation and surface charging environment, collect data to determine the effectiveness of the shielding design, and collect data to understand anomalies in the computer system due to Internal Electrostatic Discharge (IESD) and Single Event Upsets (SEUs). There is a main interface electronics box and three sensor boxes will be placed at key locations around the spacecraft (on instrument deck, in the C&DH electronics chassis, and near the MMRTG). The instrument deck and MMRTG units will contain surface charging sensors, IESD

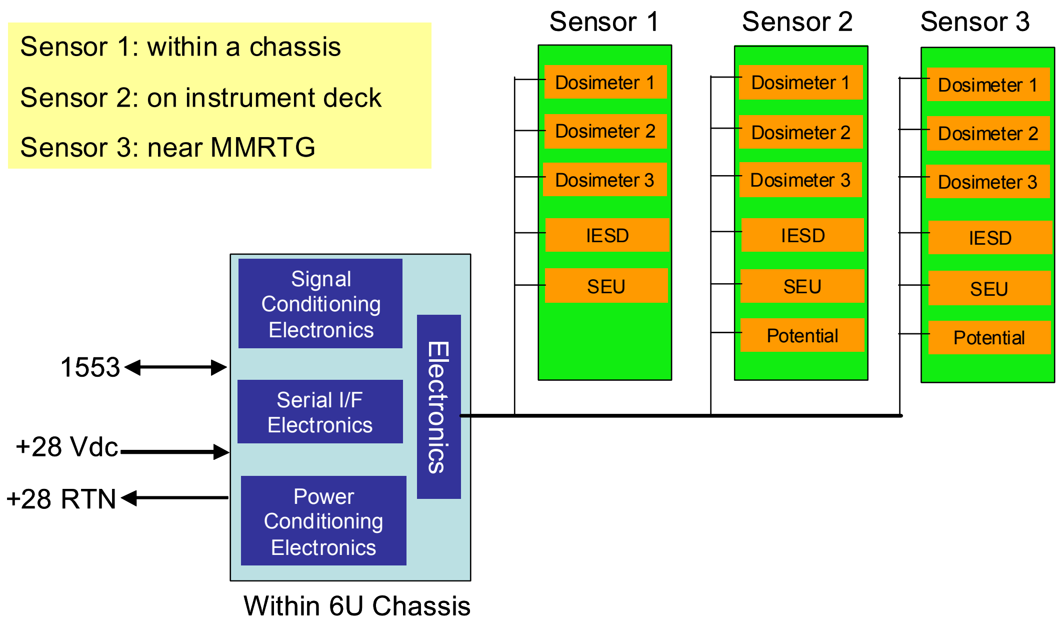


Figure 4.4-18. *Radiation Monitoring Subsystem measures actual radiation dose throughout the Flight System*

sensors, SEU detectors, and Total Ionizing Dose (TID) dosimeters. The chassis unit will be similar except it will not require a surface potential monitor. These boxes are similar in concept to the previously flown Compact Environmental Anomaly SEnsor (CEASE) or the MERLIN Space Weather Hazard Monitor designs. The small individual "RADFET" dosimeters associated with each box are distributed so as to measure the TID behind and within various shielded locations. Signals from the distributed dosimeters, IESD, and SEU sensors are collected via the main electronics box and sent to the C&DH at very low rates (~10 kb/day) via the 1553 data bus.

4.4.3.8 Power Subsystem

The JEO spacecraft is RPS-powered by 5 multi-mission radioisotope thermo-electric generators (MMRTGs) with an unregulated, nominal 28 Vdc main power bus (22–36 VDC). Redundant 12-Ah lithium-ion batteries provide for energy storage to handle transient demands for power throughout the mission. The power subsystem block diagram is illustrated in **Figure 4.4-19**. An illustration

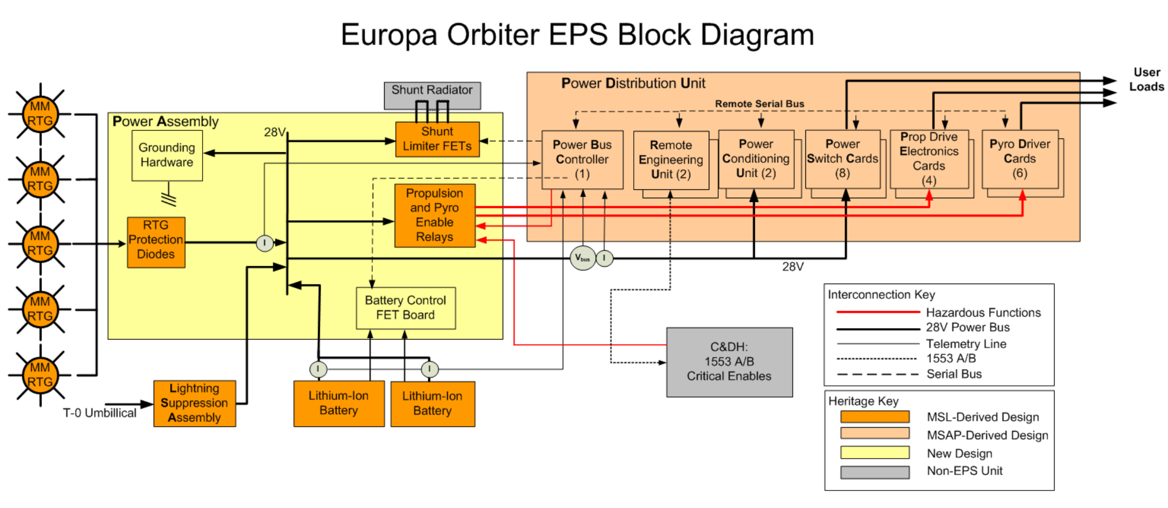


Figure 4.4-19. *JEO Power System Block Diagram*

of the physical configuration on the Flight System is shown in **Figure 4.4-20**.

The 5 MMRTGs produce a minimum of 625 watts at beginning of life, and with a 1.6% loss per year across the mission, produce 540 watts at 9.1 years. MMRTGs do not require venting so that no power output degradation is expected during launch.

Energy storage is provided by dual, eight-cell lithium-ion batteries. Bus control is accomplished via shunt regulation using a 2-out-of-3 majority voted, digital control scheme. The batteries are operated directly off the main power bus, with the range safety required battery control and monitoring circuits.

This is a battery dominated, direct energy transfer power system. The MMRTGs will operate at off-peak power voltages during battery charge and discharge.

Grounding is established for a balanced bus, with both high side and return floating from spacecraft chassis for additional fault tolerance. Pyros are fired directly off the main bus power through the Arm and Enable switches. All power electronics are designed to be radiation hard to 1.0 megarad.

The power electronics suite is composed of two assemblies, the power distribution unit (PDU) and the power assembly (PA). The PDU provides load switching for general purposes, propulsion, and pyro activation, and produces control signals. All load switching is on both high and return side rad-hard MOSFETs. The fault-containment region size for this architecture is at the 6U board level. Separate digital command ASICs activate for high side and return side MOSFETs on each board. These boards are cross-strapped to redundant remote serial buses for commanding, and housekeeping power. Main power bus sense and control and battery control signal generation are also accomplished in the PDU. Communication from the C&DH to the power subsystem is via redundant 1553 buses, and within the PDU through a remote serial bus. All of these functions are planned for on the MSAP development, providing leverage to the PDU development.

The JEO PA uses custom packaging for the more challenging items such as: the main power bus junction, relays—mounted in shock isolation trays, power FETS—mounted on heat sinks, current sensing hardware, etc. The

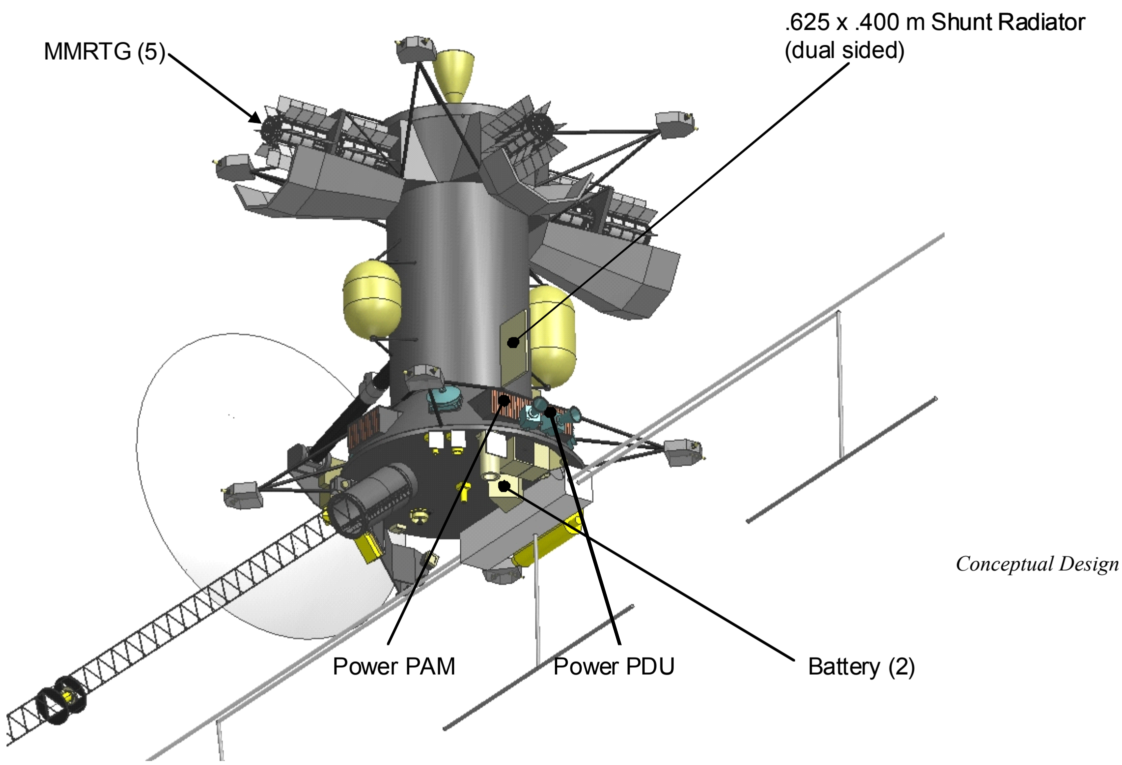


Figure 4.4-20. JEO Power System physical configuration on the flight system

battery cell bypass FET functions are also found in the PA, with sense and control coming from the PDU as described above. A lightening suppression assembly is required for the launch configuration, and is included in the design.

The power electronics approach is to leverage all developments from the MSAP effort for the PDU boards while evaluating radiation tolerance at the part level. Starting with the EM level unit designs, rad-hard, silicon-on-oxide ASIC chips will be used. The mission specific functions contained in the PDU will be new slice designs, but with circuits adapted from MSL's PA slice designs.

For energy storage, two eight-cell, 12 Ah prismatic, lithium-ion battery's are assumed, with a complete mission possible with a one-battery-failed state, and JPL design rules in effect for DOD (40% maximum). Sizing of the batteries is linked to science and telecom sequencing in the satellite flyby phases as the batteries primary function is power load leveling. They have additional roles of providing a low impedance source on the main power bus to stabilize voltage during load transients, such as blowing pyros.

4.4.3.9 Thermal Control Subsystem

The thermal control subsystem provides temperature control for the flight system including the spacecraft bus, a steerable high gain antenna mounted with telecom electronics, a propulsion module, 5 MMRTGs, and the science payload interfaces. The thermal control subsystem must handle several environmental and spacecraft related challenges:

- Large range of solar distances ranging from 0.7 AU for the Venus range to Europa orbital flights with a maximum solar distance of 5.5 AU,
- Venus environment inputs due to the close approach during the Venus gravity assist
- Requirement to minimize spacecraft electric power consumption,
- Support instrument thermal interface requirements.

While the thermal design for this mission is unique due to the environmental and spacecraft challenges, the thermal control subsystem utilizes flight proven thermal control elements, thus minimizing the subsystem development risk. There are several engineering development requirements, but no new technology development is required for this mission. The thermal control elements used in the thermal design for this mission are multilayer insulation (MLI), thermal surfaces, thermal conduction control, thermal louvers (both external and internal), electric heaters and thermostats, engineering sensors, Radioisotope Heater units (RHUs) both fixed and variable, MMRTG shades, and utilization of MMRTG waste heat. An illustration of the physical configuration on the flight system is shown in **Figure 4.4-21**.

The Venus gravity assist flyby will impose the Venus IR thermal load as well as the direct solar incident energy on the flight system. The conceptual design will protect the flight system from both the Venus IR thermal load as well as the direct solar incident thermal energy using additional MLI layers with appropriate stand-off distances.

The use of RHUs and MMRTG waste heat minimizes the electrical power requirement for the thermal control subsystem with a constant heat source.

The thermal louvers (both internal for the MMRTG waste heat system and external), variable RHUs, and thermostatically controlled electric heaters provide the means of varying the thermal energy to various flight elements as needed for different operational modes and solar distances.

The spacecraft bus uses MLI, thermal surfaces, thermal conduction control, electrical heaters, and RHUs both fixed and variable to keep the elements within specified temperature limits. For power modes that have significant on/off power differences, such as a communications downlink mode or propulsive maneuver, louvers and variable RHUs enable a minimal electrical heater load variance. The thermal control for the shunt radiator uses RHUs to keep radiator elements above its minimum electric element temperature requirement. The shunt radiator will be thermally isolated from the spacecraft with a clear view to space away from low temperature hardware and instruments so that when in operation, it can operate at a relatively high temperature (100 C is a safe upper operational temperature for the resistors).

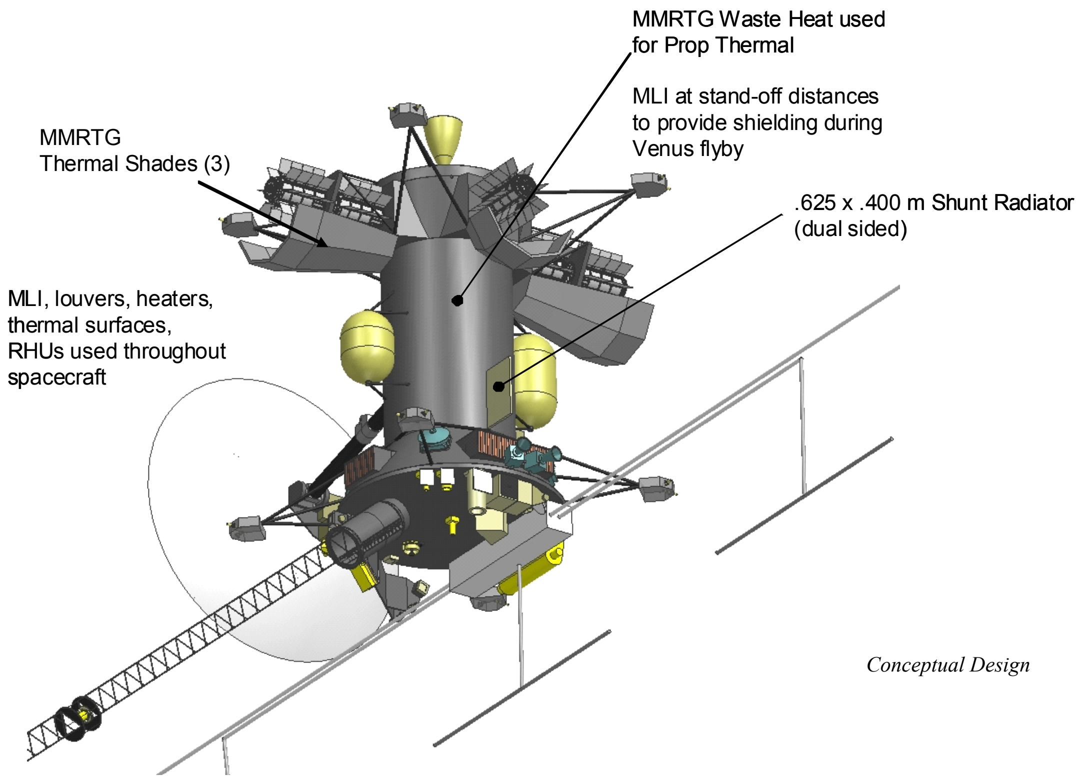


Figure 4.4-21. *JEO Thermal System physical configuration on the Flight System*

The thermal control subsystem also supports the instrument interfaces, and will maintain the mechanical interface temperatures using MLI, thermal surfaces, thermal conduction control, and variable RHUs. Several instruments for this mission operate at relatively cold temperatures. The instrument will provide the cooling technology required by the individual instrument, such as radiators, but the spacecraft thermal control will provide any shielding required to block thermal energy sources that are a part of the spacecraft.

The thermal control for the Telecom subsystem uses the above elements including variable RHUs, as well as a thermal louver/radiator to account for the large variation in thermal dissipation because of its duty cycle to minimize electrical heat needs.

The main propulsion module uses the waste heat from the MMRTGs to keep the propellant, tanks, lines, and valves above the freezing point. Assuming a thermal radiated loss of 2/3 by the MLI, the propulsion system will need between 170–350 W of thermal energy. The MMRTG end plates at 170 deg C will provide 380 W from 3 MMRTGs, which are radiated into the propulsion system area. The MMRTG waste heat utilization system consists of an IR transfer element, distribution element, and internal louvers to control the amount of thermal energy entering the propulsion module. There are several areas where the RHUs and MMRTG waste heat system cannot be used, such as the propellant lines to the thruster clusters and the main engine valve module where electric heaters are used instead. This design is similar to the one currently used on the Cassini spacecraft.

The MMRTGs are thermally isolated from the propellant module structure. Thermal shielding will be developed as necessary to protect the flight system elements from the thermal energy from the MMRTGs.

4.4.4 Verification and Validation

JEO will verify and validate the mission system to ensure it meets specifications and is capable of accomplishing the science objectives. A combination of system analysis, modeling and simulation tools, engineering development unit hardware and testbeds, flight software testbeds utilizing simulations and engineering model (EM) hardware, flight system functional/environmental testing

(Assembly, Test and Launch Operations, ATLO) and readiness tests will be used.

4.4.4.1 Simulation Capability

A high fidelity model-based simulation capability (S-Sim) is baselined for flight software test and verification, fault protection development and test, AACS system level verification and validation as well as mission activity development and test. The first S-Sim version will be available to support the first flight software release and continue on with expanded capability in support of testing of subsequent flight software builds. The simulation environment will be available on all software developers' and testers' workstations including full software simulators in a closed loop environment operating in nominal and off-nominal modes. These simulators will be built to allow for interchangeability between software models and hardware EMs later in the "hardware-in-the-loop" testbeds in such a way that is transparent to the flight software. This will enable the ability to use the same test scripts whenever the testbed models are interchanged with EMs.

In addition to the simulation capability described above, JEO will have three primary system testbeds: two single-string and one dual-string. First on line will be the single string Real-time Development Environment (RDE) testbed that is, among other things, integrate to Ground Support Equipment (GSE) hardware and software development and test, test scripts development and validation and database maturation. The Flight Software Testbed (FSTB) will be a single string "hardware in the the loop" testbed dedicated to flight software development and integration. The Mission System Testbed (MSTB) will be a dual-string high-fidelity testbed dedicated to system Verification and Validation (V&V), flight software fault tests, mission system tests, and ATLO support.

Supporting the FSTB will be one GSE development station called the RDE dedicated to GSE hardware and software development and test. Multiple workstation testbeds will also be available to all software developers and testers during development.

These testbeds will include the C&DH, ACS, power, telecom, and harness subsystems. Only the MSTB will have hardware versions of the engineering subsystems; they will be simulated on the other testbeds.

The testbeds will include the Ground Data System (GDS) hardware and software as well. The EM versions of all flight system engineering subsystems and instruments pass through the testbeds for integration and interface verification. No flight units are required to flow through the testbeds unless there are major modifications from the EM, however, the testbeds can support flight hardware integrations if needed. There will be a simulation environment for V&V that can off-load the hardware-in-the-loop testbeds as well as using the EM integration effort to help enhance evaluation of model fidelity. The simulation environment interfaces and procedures will be compatible with those of the hardware testbeds. The testbeds will also be used to train test analysts to support ATLO testing as well as to support ATLO procedure development and anomaly investigation. All flight software versions will be verified on the testbeds prior to being loaded onto the Flight System in ATLO or in operations.

4.4.4.2 ATLO and I&T Approach

The JEO system integration and test (I&T) approach is modeled after the Cassini ATLO effort as these two missions share a great deal of similarity in complexity and design. The JPL 25-foot thermal vacuum chamber will be utilized for system thermal vacuum testing with two planned tests, one using the solar simulator for testing near Venus environments and one without the solar simulator for testing stowed at launch and deployed at Jupiter environments. All testing will be performed by ATLO system engineers, with extensive support from subsystem and instrument engineers and the actual operations team. The JEO GDS will be used in all the functional and performance tests to allow for end-to-end data flow testing and tools suites validation. Operational Readiness Tests (ORTs) will be performed to assess the infrastructure and team's ability to execute the operational phases of the mission.

A Developmental Test Model (DTM) will be built that will effectively be the EM for the spacecraft structure. The DTM is used to alleviate the schedule impact of the flight unit. The DTM will be used to do static and modal testing which allows the flight unit to be integrated in parallel. In addition, the DTM is used to do fit checks and cable or mass mock ups. The DTM will also be used to validate the sterilization philosophy for planetary protection. Once this model has fulfilled its DTM functions, it will also be used to support the "trailblazer" at the launch site.

A trailblazer activity, using the DTM model, is planned to ensure that the procedures and processes for integration of the MMRTGs to the flight system are compatible and streamlined during the launch preparations. Recent experience in RPS integration include New Horizons and MSL and will provide guidance in JEO's integration. Planning begins in early Phase C where requirements and storyboards are put together to understand the constraints imposed at the launch site. In Phase C mock ups of the hardware and facilities are created to physically simulate the integration. Ultimately, in Phase D the ground support equipment, MMRTG simulators and DTM meet at the cape to walk thru the simulated installation process to ensure adequate clearances, procedures and safeguards. This will be conducted in time for any KSC facility mods to accommodate the MMRTG integration that might be needed. MSL has gone through this activity and no changes were needed at KSC; and JEO's RPS integration will be less complex than MSL's.

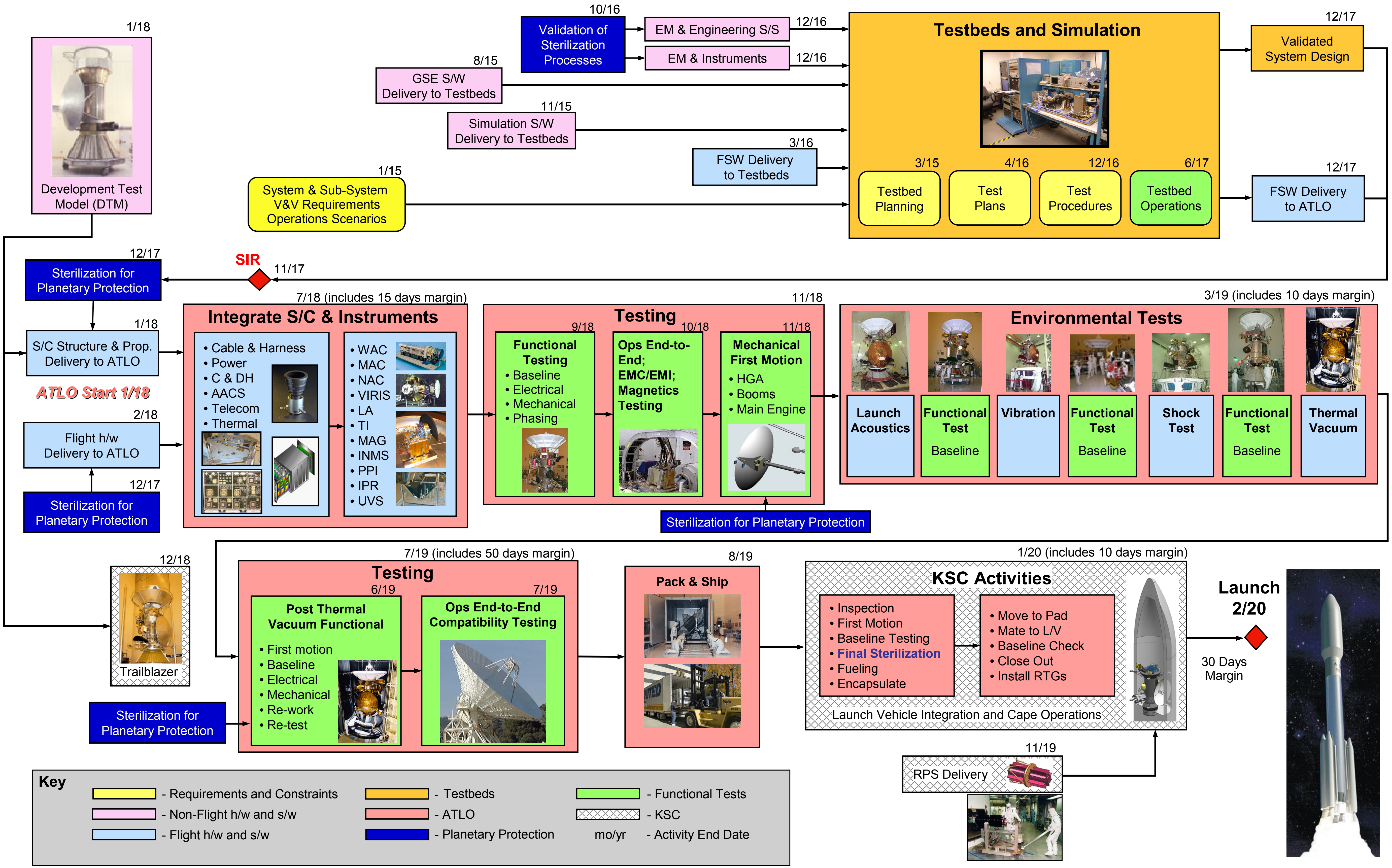
The ATLO schedule and I&T plan are summarized in **Foldout 8** (**FO-8**) and shown in context of the project schedule in **FO-13**.

This process is designed to provide verification of the flight system design and workmanship by subjecting the flight system to a demanding series of functional, operational, and environmental tests, while also maintaining the integrity of the planetary protection approach. Initial assembly begins with delivery of the flight system primary structure, the propulsion subsystem and the electrical cable harness. Each electrical subsystem undergoes vibration, thermal, pyro-shock, Electromagnetic Compatibility/Interference (EMC/EMI) and magnetics testing/characterization, and potentially, sterilization processing prior to delivery to ATLO. Each subsystem with electrical functionality is integrated using assembly plans and test procedures that ensure mechanical and electrical safety and which have been verified in the testbed. Once all of the engineering subsystems are safely integrated and fully functional at the system level, the instrument payloads are integrated with the spacecraft to complete the flight system. A preliminary Incompressible Test List is generated by Project Critical Design Review (CDR) and approved by ATLO Readiness Review (ARR) to identify and assure that all critical testing is performed on the flight system prior to launch. System level functional testing will be performed throughout the ATLO process after key milestones. Mission critical events testing such as Launch and JOI/EOI will be performed at the system level. To ensure that a complete and comprehensive system-level test program is provided, ATLO V&V is augmented with payload simulators, engineering models and the DTM.

The JEO team will maintain a rigorous formal program for testing flight hardware at all levels of assembly ("Test as you fly and Fly as you test"). Electrical testing includes component interface tests, flight system functional tests, DSN compatibility tests, instrument interface verifications, performance tests and environmental tests. HGA boom deployment testing will need to be off-loaded since it is not designed for 1 G testing. Similarly to the policy that all flight software versions are run through the testbeds before being uploaded onto the flight system in ATLO, all electrical test procedures are verified on the testbed prior to being run on the flight system.

The JEO environmental test program is a comprehensive system level test program that ensures that the flight system has been verified to operate in the expected environments of the mission. At the subsystem or assembly level, all flight hardware will be tested to acceptance levels and durations if there has been a preceding qualification test or to protoflight levels and durations if no qualification unit was available. System level environmental tests include system level acoustics, vibration and shock, thermal balance, and thermal vacuum. The system level EMC/EMI, and magnetic cleanliness verification is performed via modeling of the assembly and subsystem level testing performed prior to ATLO. Modal surveys are also done to validate the flight system structural model. Functional tests are

FOLDOUT 8
JUPITER EUROPA ORBITER VERIFICATION & VALIDATION OVERVIEW



repeated after each environmental test to ensure that the test effects have not degraded system performance. Post-environmental tests also facilitate verification of any modification to flight software or flight sequences (see **FO-8**).

Mating surfaces will be re-sterilized at major demating and remating points during the ATLO environmental and launch campaign activities. Early in the preliminary design phase a full storyboard of the ATLO flow will be performed to identify these activities and the associated planetary protection implementation approach. Localized sterilization techniques will be developed and qualified during Phase A/B to ensure that planetary protection requirements can be met within the constructs of the ATLO flow, schedule and facility capabilities.

All flight engineering subsystems are required to track powered-on time. Flight engineering subsystems other than instruments are required to accumulate 200 hours prior to integration and 500 hours (with a goal of 1000 hours) at the system level prior to launch. Instrument electronics are required to accumulate 300 hours prior to integration and 500 hours prior to launch.

The flight system is enclosed in a non-flight biobarrier and trucked intact to the launch site. Functional testing is performed prior to and immediately after shipment to verify that the shipment did not adversely effect its performance. The RPSs will be delivered separately to the launch site by the DoE. The RPSs will be test fitted to the flight system to ensure adequate mechanical and electrical functionality. They will then be removed and stored until final integration on the launch pad.

Final testing, propellant loading, and launch vehicle, RHU and RPS integration is completed and the flight system is ready for launch.

4.4.5 Completed Trade Studies

The JEO team conducted several technical design trades, which were documented separately. **Table 4.4-8** shows a summary of these completed trades. The most significant trade resulted in the use of MMRTGs in the JEO design. Details on the MMRTG versus ASRG trade can be found in §4.4.5.1.

4.4.5.1 Radioisotope Power Source Trade Study

An assessment on the accommodation of the two types of radioisotope power sources (RPSs), the Advanced Stirling Radioisotope Generator (ASRG) and the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), was done to determine the baseline concept for this study. A comparison of their major characteristics is summarized in **Table 4.4-9**. Quantative information on the assessment is provided in Appendix E.3.

Both of these systems are currently in development by NASA and DOE, and are viable options for the concept design. The advantages of an ASRG-based system is that it has a dramatically higher conversion efficiency, giving it an apparent mass/power benefit, as well as using less plutonium for a similar power output, as noted in **Table 4.4-9.** The MMRTG design is technically mature as it is baselined for the Mars Science Laboratory (MSL) mission scheduled to launch in 2009. The ASRG is well behind in maturity and will be undergoing additional design changes during its development over the next few years. The MMRTG-based spacecraft design is baselined for this study primarily due to the maturity and understanding of accommodating it.

The MMRTG accommodation is well-understood since RTG systems have been used in several past missions (Voyager, Galileo, Cassini) and the MMRTG will be flown on MSL. MMRTGs are passive power generation systems and their interactions with spacecraft components are well characterized. Performance, failure modes and operating parameters over long periods of time are well characterized and predictable. The incorporation of the MMRTG into the JEO spacecraft concept thus is very mature taking into account previous accommodation design work.

The ASRG, which uses a dynamic stirling cycle engine, requires different and additional accommodation considerations based on the ASRG spec provided by NASA for the study, the ASRG ICD [*Tantino 2008*] and conversations with cognizant engineers. Per guidelines from NASA, the assessment assumed performance and characteristics of the 850 deg ASRG vs the 650 deg ASRG in the ICD. No concerns have been identified which would preclude incorporating ASRGs into the design. The issues identified below are

***Table 4.4-8.** JEO Completed Trade Studies*

Trade Name	Trade Options	Discussion
RPS System	**MMRTG** vs. ASRG	ASRGs provide a mass, cost, and plutonium savings, as well as an increase in available power, but ASRGs are still early in their development and are not yet flight proven, so MMRTGs were selected as the more conservative choice. There are vibration, thermal accommodation, and EMI concerns that were not able to be sufficiently worked during the time constraints of this year's study. See §4.4.5.1
Power Requirements	4 vs. **5** MMRTGs	5 MMRTGs provide the flexibility required for ops given the telecom and instrument needs. With 4 MMRTGs, there was little power for instruments and downlink periods, science return would be reduced, and operations would be very costly. See §4.4.5.2
Hybrid SSR	CRAM only memory vs. **Add SDRAM**	SDRAM provides high density memory during the tour phase for high data periods at satellite flybys. Since SDRAM is not as rad hard, it is not expected to last the entire mission, when Europa orbit phase data storage requirements are lower(Appendix E.4)
JOI Location	**Io** vs. Ganymede	Although the radiation dose experienced with JOI at Io is about 0.4 Mrad higher than that of a Ganymede-first strategy, the Io strategy ΔV savings of 200m/s equates to a 160kg mass savings. The increased radiation dose costs 40-60 kg in shielding mass, but still yields an overall mass savings of over 100kg. Additionally, the Io strategy provides several science-rich opportunities to fly by Io and Europa early on in the tour.
OpNav Camera	**Include OpNav Capability** vs. No OpNav	Optical navigation is required to improve the delivery accuracy to the satellite aimpoints. Accurate delivery to the desired aimpoint is required to maintain the planned path to Europa. Without OpNav, the cost to correct flyby dispersions would require the expenditure of several times the currently allocated statistical tour ΔV, and a minimum flyby altitude of 500 km would have to be imposed for safety. See §4.3.4
DSN and Telecom Architecture During Orbital Ops	X-band vs. **X-band + Ka-band** vs. Ka-band only to 70m or equivalent vs. **34m** DSN antennas.	2008 study guidelines dictated the use of 34m DSN antennas. This trade was done prior to the guidelines being written, in order to understand the impacts to the baseline Europa Explorer study (2007 concept), which used 70m or equivalent antennas. X-band and X-band plus Ka-band options were considered. The resulting recommendation to use moderate power on both X-band and Ka-band transmitters reflected the science requirement for dual frequency downlink. The 2008 study SDT reduced the Doppler requirement from dual frequency X and Ka-band to Ka-band only. See Appendix G
Fine Attitude Control	**RWAs** vs. MIT Thrusters	RWAs were chosen to perform 3-axis control because while the MITs require less power (by ~35W) and cost less, they are not flight proven and therefore have uncertain development and qualification costs. Additionally, the MITs would require a potentially large mass hit in hydrazine propellant. The RWAs will provide slightly better pointing control, especially with respect to pointing stability.
IMU	MIMU vs. **SIRU**	Although MIMU is less massive and costly (even though 2 are required for redundancy), they have lifetime and rad hardness issues. The internally-redundant SIRU was selected for its rad hardness and longer life capability. Trade will be revisited in Phase A.
Thruster Layout	**Coupled** vs. Uncoupled Thrusters	Coupled thrusters were used in the JEO design to control perturbations in orbit. Coupled thrusters provide double the control authority, and therefore higher reliability.
Main Engine	**Single** vs. Dual	Outcome of a propulsion system table top review. Two engines for redundancy introduces complexities that have not yet been worked. The expenditure of resources (cost, mass) to implement this redundancy was not deemed the best use of these resources to justify a two main engine implementation.
Thrust Control	**Gimbaled engine** vs. TVC thrusters	Outcome of a propulsion system table top review. Even though a gimbaled main engine is more costly, it is a more robust design. Gimbaling provides a wider range for the CG.
Engine Cover	Include Engine Cover vs. **No Cover**	No engine cover is needed at this time for JEO, as there is low concern of particulates or long life issues affecting the main engine. This trade will be revisited in Phase A.
Propellant Tank Material	Titanium vs. **COPV**	COPV tanks are industry standard and are significantly less massive and less expensive than traditional Titanium tanks.
Instrument Interface Type	**SpaceWire** vs. RSB vs. LVDS vs. Diversified Interfaces	SpaceWire is an industry standardized interface and accommodated by MSAP. JEO also uses 1553 for instruments that don't need SpaceWire's high data rate capabilities, but can take advantage of a distributed bus. This architecture best meets the instruments' needs and is consistent with MSAP implementation.

deemed to be solvable, though the mass, power, and cost impacts of the accommodations cannot be adequately assessed at this time given the level of maturity of the

Table 4.4-9. *Key Parameters Comparison for ASRG and MMRTG*

Parameter	ASRG (5)*	MMRTG (5)
Power Output (@ 9 yrs, W)	550 (688 for 5)	540
# of GPHS Modules/Unit	2	8
RPS Mass (incl contingency, kg)	160	226
RPS Accommodation Mass (incl contingency, kg)**	54	23
Total mass (kg)	214	249

** Includes a redundant unit*

*** Does not include outstanding liens (Appendix E.3)*

ASRG. It is believed that an ASRG implementation would fall within the current mass and power resources allocated for the MMRTG implementation but the quantitative data is not available to support this. Thus, the lower risk implementation is the MMRTG option at this point in time.

The assessment identified key areas to study: 1) instrument sensitivities to the ASRG-induced vibration and magnetic environments, 2) induced loads on spacecraft, 3) performance characteristics based on external environment (electrical, thermal, structural), 4) re-design of the propulsion thermal design, 5) nominal and failure modes and their impacts on spacecraft design, 6) lifetime, 7) rad-hardening of components, and 8) planetary protection issues.

1) Instrument sensitivities to the ASRG-induced magnetic and EMI/EMC environments:

   The magnetic field emissions have been measured on a Technical Development Controller unit and documented in the ASRG specification. Based on the specification requirements, initial analysis on the total of 5 ASRG impact to the magnetometer showed acceptable levels. Recent testing on the engineering unit shows that the units may not be meeting all requirements at this time. Design changes to the ASRG, spacecraft, or instruments may be required if ASRG does not meet the current requirements.

   Mitigation Strategy: Add shielding or distance between affected components

   Major Impact: Mass

2) Induced loads on spacecraft:

   The specification for induced loads on a 1000 kg (dry spacecraft) 2 meter diameter by 2 meter high cylinder is 32 N at 102 Hz under nominal conditions. Under a single failed unit, assuming no balancer, the requirement rises to 294 N at 102 Hz. Recent testing at Glenn Research Center indicates that the actual induced vibration levels may be significantly lower than specification by an order of magnitude and thus, this requirement may change in the future. Though these numbers could present an issue to the spacecraft main body, balancers, vibration isolators and increased main body stiffness could be incorporated to mitigate this issue primarily at the expense of mass. Analysis is needed to understand effect on a flexible body, such as the IPR antenna, magnetometer boom and fuel slosh interactions.

   Mitigation Strategy: Decouple systems with isolation and minimize impact with dampening system

   Major Impact: Mass

3) Performance characteristics based on external environment (electrical, thermal, structural):

   The operational characteristics of the ASRGs are impacted by three major external influences; electrical, thermal and structural. The function of the ASRGs depends heavily on the electrical characteristics of the spacecraft power bus. A control loop exists between the power subsystem and the ASRG controller. The ability of that control loop to operate impacts the ability of the spacecraft to deliver power as advertised to the loads. Changes to either the spacecraft power system electronics or the ASRG controller electronics may be required as the designs mature and the control loop is adequately analyzed.

   Mitigation Strategy: High fidelity modeling and early analysis

   Major Impact: Cost

   For Europa, the Controller is most likely going to be mounted separately from the Generator to facilitate shielding the electronics. A loss of dc power delivered to the power system will result as of the length of the AC power cable 0.50 W/ft (two-way). Since, only a cursory cable layout is possible, an estimate of this loss is approximately 2–3 W/ASRG (10–15 W total).

Mitigation Strategy: minimize distance between controller and generator (may negatively impact ability to share shield mass)

Major Impact: Power

The power output of ASRG is a function of its heat rejection or housing surface temperature, which is relatively low. As a result, the performance of ASRG will be sensitive to its thermal interaction with the spacecraft and therefore must be included as part of the integrated thermal analysis and design of the spacecraft. According to the ICD, the highest temperature profile that the ASRG is required to perform at is near-Earth and the lowest temperature profile is at the end of mission. The thermal conditions expected during the inner-solar system portion of the trajectory, including the Venus flybys, need to be evaluated for potential impacts. These impacts could include thermal shades or configuration or operation constraints to keep the ASRGs from direct solar illumination.

Mitigation Strategy: Use operational constraints to minimize exposure to sun, put on shades, or test to show acceptable performance under extended conditions

Major Impact: Mass

4) Re-design of the propulsion system thermal design:

To minimize electrical heater power required to keep the propulsion tanks within acceptable temperature range, the waste heat generated by the radioisotope power sources (RPS) has been used in previous missions as "free" heat. Radiative systems were used on Galileo, Cassini and New Horizons transport the predictable heat load from the RPS end domes to the propulsion system. The more thermally efficient ASRGs do not produce enough heat to radiatively couple the ASRGs to the propulsion systems. Conductive systems such as capillary heat pipes can be designed to fulfill the transportation purpose. A conceptual design was developed during the study which uses a heatpipe and capillary pumped loop system to transport heat from 3 out of the 5 ASRG's. This system could transfer up to 1 kW of heat to within 5 deg C controlled by electronics. This new system adds new interfaces (both on the spacecraft and on the ASRG itself), complexity, and cost, in addition to the mass and power impacts. Additionally, micrometeroid protection may be required for the heatpipes exposed to the external environment.

Mitigation Strategy: Use heat pipe system to transport heat from ASRG fins to propulsion system

Major Impact: Mass and Cost

5) Nominal and failure modes and their impacts on spacecraft design and operation:

The nominal and failure modes of the ASRG are defined in the ICD. These modes need to be assessed by the System Engineering Team for completeness and potential impact to fault protection software, fault containment regions or operational modes (potential sun keep-out regions).

Mitigation Strategy: Account for all operating modes in operational scenarios

Major Impact: Complexity

6) Lifetime:

Life testing is addressing the lifetime of Stirling engines. The electronics can be designed to work for 10–14 years assuming similar design techniques are used as for many other electronics on long-life missions. The most unknown issue related to lifetime is how stable the control loop is over time with the degradation of operating characteristics over time. Because this type of testing is extremely difficult, comprehensive simulation/analysis is required with well characterized components. These components do not currently exist and thus their operating characteristics over time cannot be accurately modeled. Once understood, modifications to the power system interface may be required to accommodate aging characteristics of the ASRG.

Mitigation Strategy: High fidelity modeling and early analysis

Major Impact: Cost

7) Rad-hardening of components:

The ASRG consists of 2 major units, the Generator and the Controller. The Generator includes the Stirling Engines, the General Purpose Heater Units (Pu heat source), thermal insulation and miscellaneous other components. A very preliminary assessment was performed in 2007 by the ASRG program to look at the radiation hardening of both these units for a Europa-type environment. No show-stoppers were found at the time. Between the inherent radiation-tolerance and shielding, a solution is extremely likely with some mass impact. An estimate of shield mass based on very preliminary assessment was calculated to be 17 kg explicitly for shielding the 5 controllers. No shield mass was identified for the generators themselves.

Mitigation Strategy: Early assessment, component (part or material) replacement and shielding

Major Impact: Mass and Cost

8) Planetary protection issues:

A preliminary assessment was done in 2007 to determine if there was an issue with heat sterilization of the ASRG. One potential component was identified that may cause a problem. An extensive analysis was not performed, nor was an evaluation of alternative sterilization methods performed. It is anticipated that radiation sterilization or some combination of approaches will be found to be acceptable.

Mitigation Strategy: Early assessment, component (part or material) replacement approach development

Major Impact: Cost

In addition, several still-to-be-studied questions remain, see **Table 4.4-10.**

These open issues do not represent show-stoppers, but reflect the level of immaturity of accommodation at this time. An estimate of the mass and power impacts of changing from the well-defined MMRTG implementation to the ASRG implementation is summarized in **Table 4.4-9**. It appears as though the resources required to implement either RPS solution are comparable when uncertainties are taken into account. Thus, during Pre-Phase A, as the design of the spacecraft and ASRG continue to devolve, this incorporation of ASRGs could be absorbed without major mass or power impact.

In summary, the assessment concluded that there appear to be no technical reasons why either RPS could not be used for this mission. Accommodation of the ASRG appears achievable within the mass and power resources currently allocated for the MMRTG. However, given the significant outstanding issues related to the ASRG-based design vs. MMRTG-based design, the accommodation of the MMRTG is better understood at this time, as well as providing a more resource conservative approach. Since the ASRG is still in the prototyping phase, there are still ongoing changes in its characteristics and accommodation needs so providing a more thorough ASRG-based design is more difficult. The MMRTG-based spacecraft provides the study concept with healthy mass and power margins (see §4.4.2.7). So the baseline spacecraft for this year's study is MMRTG-based, with a viable option to switch to ASRG during Pre-Phase A when more time, information and staffing resources are available.

4.4.5.2 Four vs. Five MMRTGs Trade Study

Reducing the number of MMRTGs in the design would be a significant benefit in reducing the amount of plutonium needed, a limited national resource, as well as a cost - saving benefit of procuring the 5th MMRTG. A study was made on what mission could be accomplished on 4 MMRTGs.

The finding was that a reduction of one MMRTG from 5 to 4 would significantly reduce the science return and severely reduce the trade space flexibility in design and operational capabilities. **Figure 4.4-22** illustrates an example power profile for a driving power use scenario, (Europa orbit) comparing the baseline

Table 4.4-10. *Some Questions for Future Work on ASRG Accommodation*

Electrical Interface to Spacecraft	
ASRG	What new functions needed on Power Controller board for cmd/tlm interface of ASRG?
	Are diodes used to isolate ASRG's (as in MMRTG's)?
Thermal Design	What new electrical interfaces needed in C&DH to cmd/control/tlm heat pipe/capillary pump system?
Mechanical Interface to Spacecraft	
ASRG	What ACS isolation filter system may be needed to reduce vibration effects?
	What new electrical interfaces needed in C&DH to cmd/control/tlm heat pipe/capillary pump system?
	What are the microphonics effects on instruments?
	What additional shielding mass needed for electronics?
Thermal Design	What micrometeoroid protection needed?
	What leakage conditions are there for a long life mission?
	What the vibration effects on the thermal system
Controller development	
	What additional controller development needed to be flight ready?
	What is the effort needed to upgrade parts to be rad hard for a still developing design?
	What are the effects of single event gate rupture on drive FETs In controller?
Others	
	What is the recovery mode with an engine fails?
	What additional considerations for configuration accommodation?
	What new procedures needed for ATLO installation?
	What considerations needed to be compatible with planetary protection processes?
	What are the impacts after more detailed analysis of magnetic and electric emissions on instruments and other sensors
	What radiation effects are there on the heat pipe/capillary pump loop system?

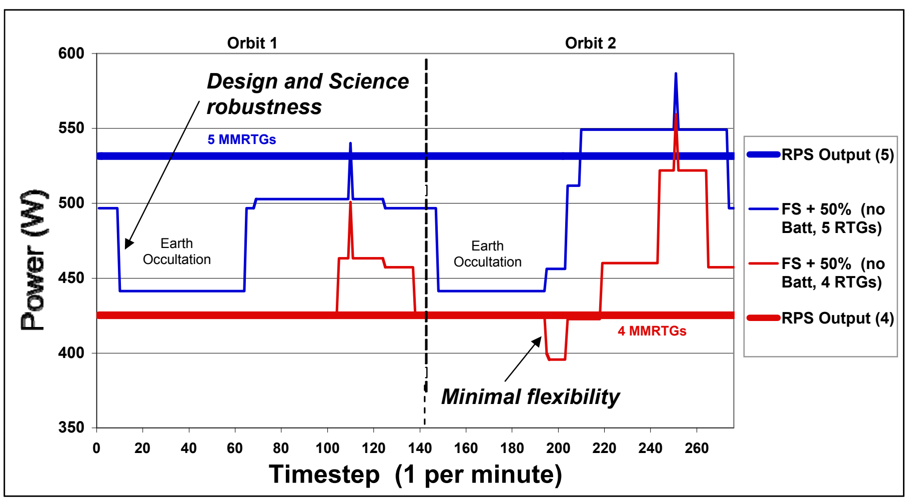


Figure 4.4-22. *Power profile in Europa orbit for number of MMRTGs Trade Study*

5 MMRTG design to a 4 MMRTG one. To fit in the 4 MMRTG design, power reductions were taken in the time to downlink (only downlinking 1/3 time of baseline) and in the operational time of the instruments (on 2/3 of the baseline time). The analysis included power contingency for loads uncertainty. Even so, more reductions will likely be needed, as this case has no unallocated margin for flexibility on future system trades, for the actual AO-selected instruments, or any additional instruments that might be contributed. Some of the power reductions assumed in engineering loads for the 4 MMRTGs profile will need further study for feasibility. In addition, the Jupiter system science will see a similar reduction in science return with fewer MMRTGs.

The current baseline (5 MMRTGs) maximizes the science return to the spacecraft capability by downlinking whenever Earth is in view, and completes instrument operations that meet the current science objectives.

The recommendation was not to proceed with the 4 MMRTG option.

4.5 Radiation

Radiation poses a unique technical challenge for the JEO mission due to the flight system spending a significant time in the harsh Jovian radiation belts. The radiation dose level, transient noise and dose rate effects experienced by JEO will be unprecedented for long duration NASA missions. JPL has years of experience in designing spacecraft with instruments that will operate in the Jupiter environment. To date there have been seven flybys of Jupiter by spacecraft (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini, and New Horizons) as well as the Galileo orbiter. Vital lessons learned from Galileo's radiation-related anomalies have been summarized in the Europa Explorer Radiation Issue Report [*JPL D-34103 April 2006*]. Mission designers will be able to assimilate these lessons learnt as part of the risk mitigation strategies for the JEO mission.

Presently JPL, in concerting efforts with Lockheed Martin, is developing internal charging guidelines and radiation mitigation strategies for the New Frontiers Juno Jupiter mission. The spacecraft is expected to arrive at Jupiter almost twenty years after Galileo's first Jupiter encounter. The Applied Physics Laboratory (APL), co-lead of the 2008 JEO Mission Study, has begun detailed design of the Radiation Belt Storm Probes (RBSP), scheduled for a 2011 launch. The twin spacecraft will orbit the Earth, following the same path and sampling the harsh radiation belt environment where major space weather activity occurs. The data collected will permit scientists to understand how the belts change in both space and time by taking identical measurements of the particles, magnetic and electric fields, and waves that fill geospace.

The design of the 2008 JEO mission draws upon these experiences and prior 2006 and 2007 Europa Explorer (EE) Mission Studies. Both the 2007 EE and 2008 JEO mission designs have implemented all major recommendations listed in the Europa Explorer Radiation Issue Report mentioned earlier. These are:

- Incorporating a new radiation dosimeter subsystem as discussed in § 4.4.3.7;
- Expanding parts testing program during Pre-Phase A activities to take into consideration radiation effects on circuits and systems;
- Developing a refined radiation model to include statistical distributions;
- Formulating an Approved Parts and Materials List to incorporate parts with a Total Ionizing Dose (TID) capability beyond 300 krad and up to 1,000 krad (Si);
- Considering active annealing where parts may be heated to accelerate recovery;
- Refining a system lifetime model that reflects realistic mission conditions to avoid an excessively conservative system design;
- Assessing performance of notional instruments, such as imaging and UV, to understand transient effects prior to AO.

In FY08, JPL began execution of a four-year plan as described in the "Risk Mitigation Plan: Radiation and Planetary Protection" [*JPL Publication D-47928*] to address the findings from the 2007 EE Mission Study. Significant progress has been made this year in developing design guidelines, characterizing radiation-induced effects on sensors and detectors, and testing radiation susceptibility of critical components such as FPGAs, non-volatile memories, microprocessors and power converters under various dose rate conditions. The following sections describe the Galileo experience, the systems engineering approach, the Jovian environment, and radiation tolerant design for the JEO. These efforts will retire a majority of radiation risks as shown in **Figure 4.10-1**. Details of the plan, progress, and deliverables are described in §4.5.5.

4.5.1 Galileo Experience and Conventional Design for High Radiation Environment

Galileo provided JPL with the unique competency and accomplishment of operating a scientific spacecraft in the most intense regions of the radiations belts. The JEO mission design capitalizes on Galileo's remarkable discoveries and leverages significantly on its technical know-how. Concomitantly, invaluable experience gained from Juno and RBSP will benefit the formulation of the JEO mission during Phase A and Phase B.

The Galileo mission design followed the conventional JPL engineering practice in which mission designers multiplied the estimated TID level by a radiation design factor (RDF) of 2. The resultant 2X environment was used for the selection of parts, materials, detectors and sensors for radiation susceptibility, and shielding designs. This conventional approach (as illustrated in **Figure 4.5-1**) has resulted in mission designs that function well beyond its intended design environment. For example, Galileo's mission was extended three times with the spacecraft accumulating an estimated radiation dose of at least 8 times its design level. This estimate is derived from science data collected during the Galileo mission [*Jun et al. 2002, 2005*] although there was no dosimeter on board to measure the actual environment. At the end of its mission, after almost 8 years at Jupiter, the spacecraft was still functioning.

4.5.2 Systems Engineering Approach for Radiation Environment

The 2007 EE Mission Study [*Clark et al. 2007*] recognized the advantages of identifying and utilizing excessive margins in the development chain from parts selection, design of electronic subsystems and final system integration. This approach improves the traditional process and simultaneously provides a more accurate method of estimating mission lifetime. Application of this system approach for radiation mitigation offers a new paradigm in the underlying process for designing long duration missions. Specifically, Appendix C of the 2007 EE study report includes synopses from five (5) external, independent peer review reports commissioned between April 17 and May 21, 2008. The Peer Reviews covered five technical areas and involved domain experts on each radiation engineering discipline. The four discipline reviews covered the radiation environment and modeling, transport analysis and shielding design, parts and materials, and systems engineering and operations. The results of these reviews were reported in the 5th peer review to a larger panel of systems experts, including chief engineers and managers with radiation design and mission experience. The following excerpts from the final Integrated Systems Peer review summarize the 2007 EE Mission Study radiation effort:

> *"The JPL team is performing high-quality work in preparing for the Europa Explorer mission. ... The visibility of radiation issues and the integration of radiation expertise on the Europa programare commendable and essential for success. ... The inclusion of an excellent peer review process on the program is notable."*

Understanding the hidden margins embedded in the conventional radiation design

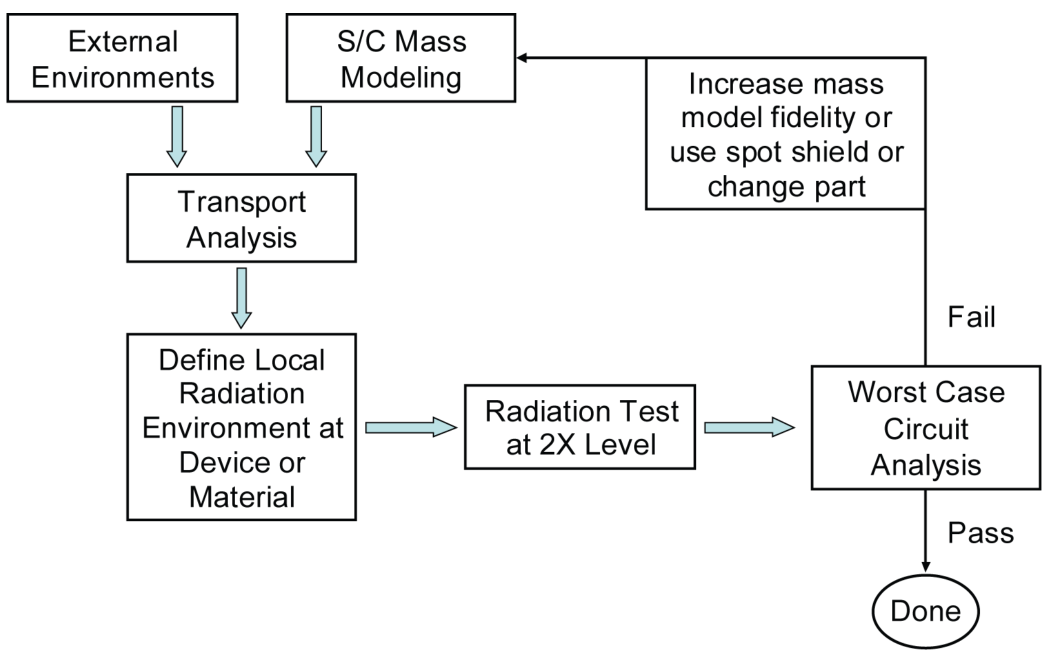


***Figure 4.5-1**. Conventional radiation shielding design approach focuses on tradeoffs between shield mass and lifetime based on selection of parts and materials. It is generally a deterministic decision making process at the parts and circuit design level.*

approach and using those hidden margins to design a robust spacecraft with a better grasp of mission lifetime requires attention at the system level.

4.5.2.1 Improvements over Conventional Approach

In the conventional approach a basic trade in the design for radiation environment is one of shield mass versus lifetime. Many elements influence the trade space including: parts and material capability, shield mass composition, natural shielding by moons or other spacecraft elements (e.g., propulsion tanks), and even component placement within assemblies.

Even taking advantage of the best options among these previous elements, if the mission designer applies the conventional approach to the JEO mission, the resulting shield masses required would be large for long missions in the Jovian radiation belts. On the other hand, reducing this added "dead mass" to a more acceptable level would significantly reduce the mission lifetime and increase the risk of premature mission failure. A more systems oriented approach can go further to identify and utilize hidden margins to allow a larger trade space to be evaluated and resources to be better allocated.

Comparing the design process shown in **Figure 4.5-1** to the systems-engineering approach shown in **FO-9** demonstrates a cross-discipline design. As in the conventional approach, the mission design starts with quantifying the radiation environment for the mission given the initial trajectory. However, in the systems engineering approach, the spacecraft trajectory is adjusted to lessen the radiation impact without sacrificing the science objectives, or permit acceptable increases in TID in order to maximize the likelihood of achieving specific science objectives. These are some of the trades the systems engineering approach considers.

Another example of the systems engineering approach is the shielding design process. Working as a team, shielding designers and spacecraft configuration engineers, can achieve the optimum shield effect at the spacecraft system level by strategic placements of these shielding boxes.

Recent advances in electronics for military and nuclear applications have made many parts available up to several hundred krad (Si). Taking advantage of these newly available components and fabrication processes, coupled with more thorough testing and characterization as well as careful circuit configuration and layout, will significantly enhance the robustness of the electronic subsystems and thus extend the lifetime of the JEO mission.

Furthermore, refined methodologies developed for incorporating reliability results from lower levels into systems engineering analysis to quantify the overall design lifetime and manage margins provide tremendous insight into prioritizing science collection, designing fault protection and developing contingency plans to ensure graceful system degradation. These system-level implications can then be optimized in trade studies and risk analysis.

The blue boxes in **FO-9** emphasize activities characterized by the conventional design approach. The maroon boxes highlight activities that will be included as part of the new systems approach to radiation mitigation. **Table 4.5-1** compares and contrasts features between the conventional approach and the systems engineering approach.

4.5.2.2 Approach for Mission Success

Recognizing that early risk assessment and mitigation activities can severely impact development and operational costs, JPL and APL began drafting a "Risk Mitigation Plan" in February 2008 to specifically address issues related to mitigating those radiation risks. The resulting four-year plan incorporates recommendations of the 2007 NASA Science, Technical, Management and Cost (TMC) Review panel. Successful execution of this four-year plan will retire a majority of the radiation risks by approximately the beginning of Phase A, assuming a launch year of 2020.

Based upon the conventional design approach, the JEO would have a mission lifetime of the end of Europa Campaign 3 (105-day in Europa orbits). However, the mission designer would not be able to provide any information about the likelihood of surviving beyond the 105 days. On the other hand, the systems engineering approach captures the state of the JEO design in a system lifetime model that shows that the system will function well beyond Europa Campaign 3. The initial model was developed for and described in the 2007 EE Mission

Table 4.5-1. *Conventional versus systems engineering approach for harsh radiation environment*

Attribute	Conventional Approach	Systems-Engineering Approach	Discussed in
1. Application	1. Applied to Galileo mission and New Frontier Juno Jupiter mission	1. Will be applied to Jupiter Europa Orbitor (JEO)	1. Section 4.5.1
2. Mission Design	2. Based on limited prior knowledge of radiation environment from Pioneers and Voyagers	2. Optimized trajectory to takes advantage of better radiation knowledge including Europa self shielding effects	2. Section 4.5.3
3. Shielding Approach	3. Centralized vault (e.g., Juno approach) protects the electronic assemblies.	3. Distributed/Strategic approach to avoid shielding the "lowest common denominator" part tolerance level	3. Section 4.5.4.2
4. Annealing of Radiation Damage	4. Passive only in Galileo	4. Passive and active – where parts may be heated to accelerate recovery	4. Section 4.5.4.3
5. Radiation Tolerance Test Data	5. Limited to low radiation requirements (<50 krad) and short life times (<5 years) with little if any characterization of tolerance above these levels.	5. Needed to extend to 1 Mrad and address low dose rate effects	5. Section 4.5.4.3
6. Worst Case Analysis (WCA)	6. Conducted with Extreme Value Analysis even where it is virtually impossible condition could occur.	6. Relaxed to reflect realistic mission conditions.	6. Section 4.5.4.5
7. Electronic Components	7. Restricted to fabrication processes and parts level radiation tolerance capabilities	7. Many components (e.g., ASIC) now available are radiation hardened by design up to 1 Mrad	7. Section 4.5.4.4
8. Reliability Systems Engineering	8. Generally ignores science objectives and potential graceful degradation.	8. Explicitly includes science value, fault protection and contingency plans to facilitate graceful degradation.	8. Section 4.5.2.1
9. Reliability Assessment	9. Limited to parts and circuit level.	9. Extended to system-level enabling trade studies,risk analysis and management of margins.	9. Section 4.5.2.2

Study. Recent refinements based on the JEO Master Equipment List (MEL) further improve the survivability estimate. There are ample design margins that the JEO mission would likely be operational up to one-year in the Europa orbit. Section 4.5.5.3 describes the first year's progress of the "Risk Mitigation Plan: Radiation and Planetary Protection" and §4.8.5 describes the future year activities of the plan.

4.5.3 Jovian Radiation Model and Environment

The JEO mission is subjected to four major radiation sources : (1) solar energetic particles (protons, electrons, and heavy ions) during the interplanetary cruise, (2) galactic cosmic rays (protons and heavy ions) during the interplanetary cruise, (3) trapped particles (electrons, protons, and heavy ions) in the Jovian magnetosphere during the Jupiter tour and the orbits at Europa, and (4) particles (neutrons and gammas) from the onboard nuclear power source, MMRTG.

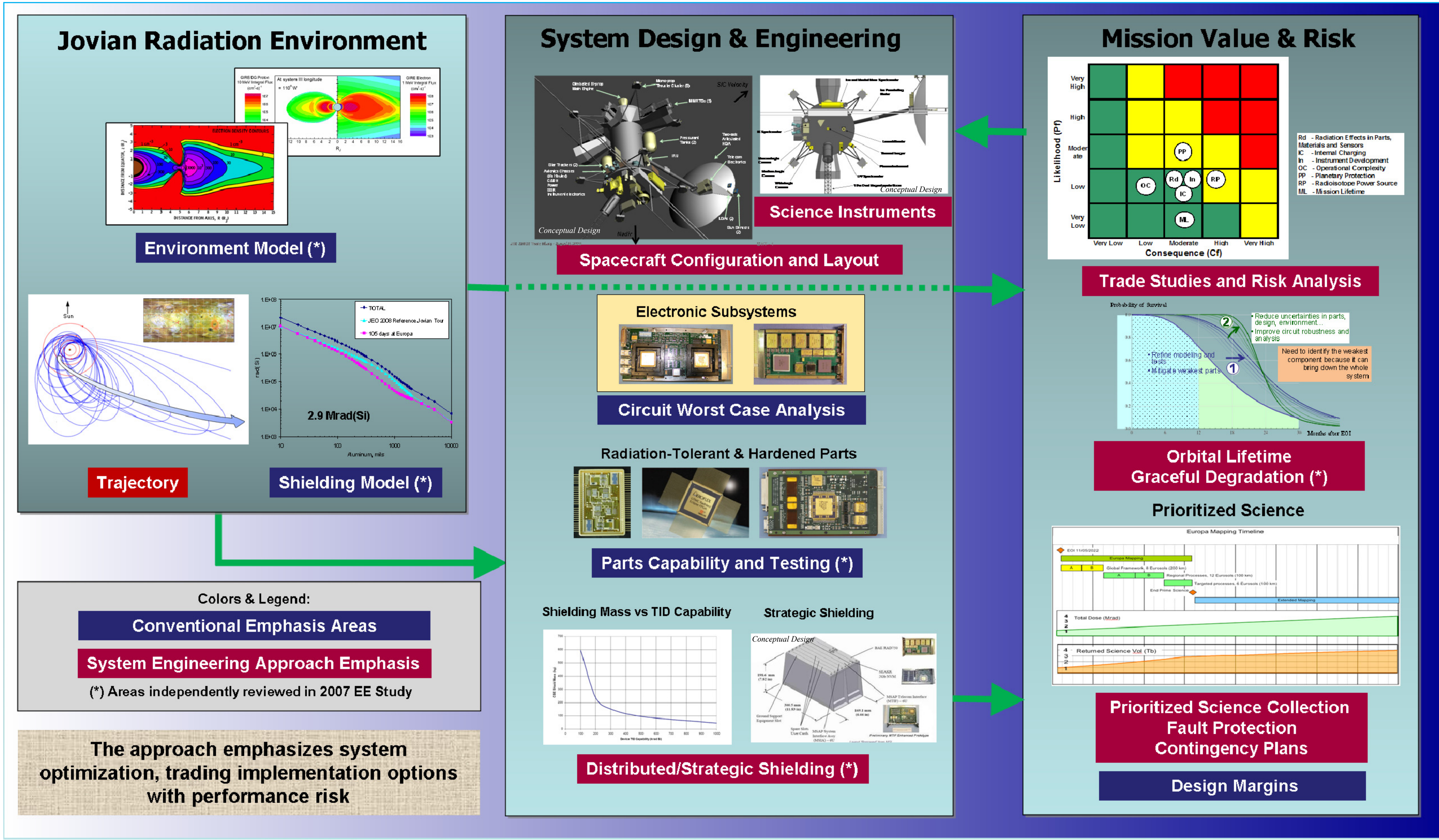
Among the four radiation sources, the high-energy trapped electrons and protons at Jupiter are the dominating contributors to the "life-limiting" total ionizing dose (TID) and displacement damage dose (DDD) effects. The Jovian trapped particles are not static, but vary in intensity and population spatially and temporally. Correctly defining and characterizing the radiation environments allow the mission designer to optimize JEO tour and orbital trajectories; thus constraining the radiation exposure to an affordable design level. The 2008 JEO design includes a radiation dosimeter to monitor the field radiation exposure in real-time. Data accumulated will allow validation of the environment and shielding modeling effort.

The remaining discussion in this section will be focused on the Jovian radiation environments for TID and DDD of the JEO mission. Discussions on single event effects due to solar particles and cosmic rays will be addressed in details in Phase-A and Phase-B. These effects have been investigated in the literature and are not unique to the JEO mission.

4.5.3.1 Environment Model

The Jovian radiation environment model used for JEO is a semi-empirical model based on data collected from Pioneers 10 and 11, Voyagers 1 and 2, and Galileo. Specifically, it is the Divine model augmented by the Galileo high energy electron data [*JPL 03-006*].

FOLDOUT 9
SYSTEMS ENGINEERING APPROACH FOR HARSH RADIATION ENVIRONMENT



The Galileo data are also used to predict a statistical radiation environment [*Jun et al. 2005*]. More recently, Galileo data analysis, together with a theoretical calculation, was carried out specifically to characterize the environment in the near vicinity of Europa [*Paranicas et al. 2007*]. Further development effort will focus on refinement of the model to include temporal variation of the environment and directionality around Europa. These activities are part of the risk reduction effort addressed in the "Risk Mitigation Plan: Radiation and Planetary Protection."

4.5.3.2 Reference Radiation Design Point for JEO

A reference mission scenario has been selected for the 2008 JEO mission. The mission adopts the Io fly-bys for additional science investigation and added dry mass. **Figure 4.5-2** shows the reference TID depth curve. The reference radiation design point is 2.9 Mrad(Si) behind a 100-mil (2.5 mm) aluminum shield with RDF = 1. This is an increase of 0.3 Mrad from the Europa Explorer 2007 mission TID estimate due to differences in the trajectory for optional Io flybys. This mission TID level includes 1.25 Mrad expected for the Europa orbital portion (corresponding to 105 days at Europa).

4.5.4 Radiation Tolerant Design Approach

Due to the harsh JEO radiation environment, early risk identification, assessment and mitigation activities are eminently crucial for the mission. It is paramount to assimilate design methodologies and considerations for long duration missions in the Pre-Phase A to avoid cost increases in later phases.

4.5.4.1 General Considerations

Electronic assemblies are vulnerable to failure when exposed to a high radiation environment for long durations. Though many parts are functional after exposure, the parameter degradation may be different from typical parameters shown on specification sheets from vendors. The availability of radiation tolerant parts from 100 krad to 1 Mrad tolerance and electronic design architectures make a Europa mission much more viable than even 10 years ago. Early identification, documentation and dissemination of available parts, materials and design techniques will enable engineering and payload providers to adequately design for the harsh radiation environment. Furthermore, non-electronic components are generally preferable than electronic counterparts for radiation tolerant considerations. For example, mechanical thermostats may be preferred over electronic controllers.

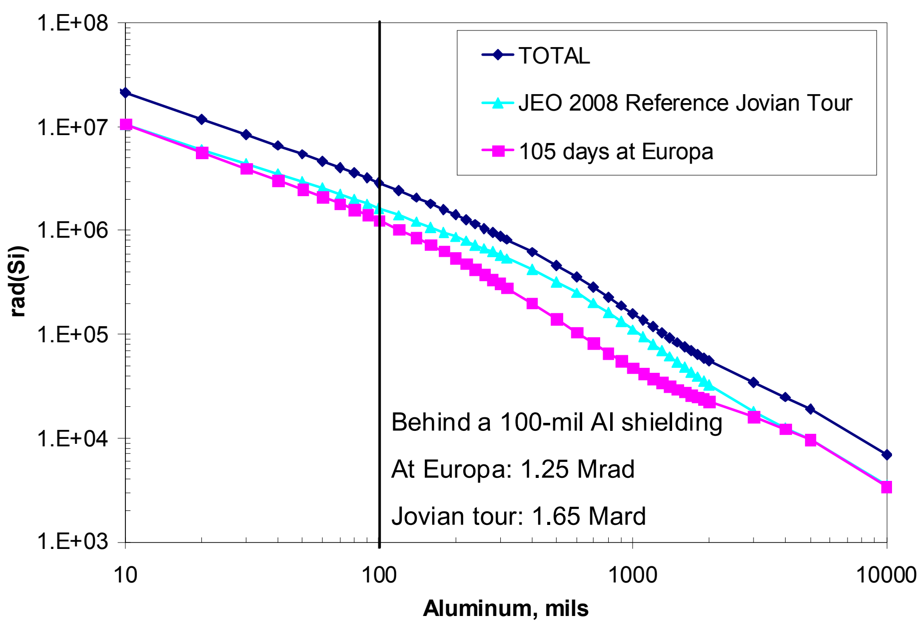


Figure 4.5-2. *JEO Reference Total Ionizing Dose (TID) Depth Curve shows the reference radiation design point for the JEO Mission. There is no radiation design factor (RDF) included in the reference plot (i.e., RDF = 1)*

4.5.4.2 Shielding

The JEO electronic subsystem designs incorporate a combination of shielded 6U chassis and enclosures to protect the electronics and detectors. Spot shielding is used when necessary.

This distributed/strategic approach significantly reduces shielding mass when compared to a centralized design where a single vault (e.g., Juno approach) is used to shield all electronics. The advantage of this approach has been demonstrated and presented for a simple spacecraft geometry at the first OPFM Instrument Workshop held in Monrovia, CA, June, 2008. A more detailed trade study will be performed in Phase A to determine the optimum shielding design and placement. Section 4.8.5 discusses some of these shielding strategies.

Figure 4.5-3 shows the estimated shielding mass, given device TID capability, based on the 2006 EE study. This figure clearly demonstrates that the shielding mass is non-linear versus part tolerance level. Their relationship is not expected to change substantially for the 2008 JEO design. There will be a severe mass penalty if everything is shielded for the lowest radiation tolerant part. In addition, **Figure 4.5-3** shows that there will be a "diminished return" if the mission designer over-specifies the parts requirements.

The selected JEO approach allows flexibility for different part tolerance levels (100 krad to 1 Mrad) to avoid having to shield everything down to the "lowest common denominator" part tolerance level. It also allows for placement of electronics in strategic locations, such as the TWTAs on the back of the HGA. As the design matures and the part radiation tolerance becomes better known, this trade will be periodically re-evaluated to take advantage of the most mass efficient approach.

For the current JEO design, all electronics packaged on standard 6U cards are assumed to use a shielded chassis to reduce the radiation dose to one half the part-level tolerance value; thus satisfying the conventional radiation design point of RDF = 2. For pre-packaged electronics or sensors/detectors, shielded enclosures are used instead. **Figure 4.5-4** illustrates the concept of shielding for enclosures, chassis and spot shielding. As shown in **Table 4.5-2**, the minimum part tolerance level of subsystem components is

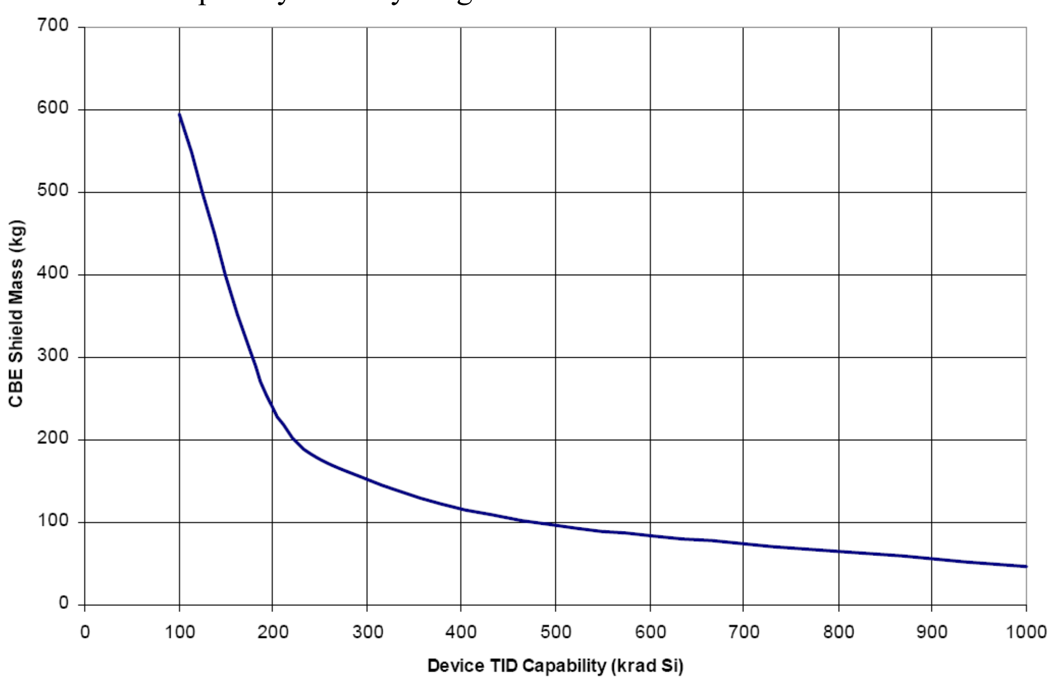


Figure 4.5-3. *Total shielding mass as a function of parts capability. There will be a severe mass penalty if everything is shielded for the lowest radiation tolerant part. This figure also demonstrates the "diminished return" if the mission designer over-specifies the parts requirements. For the JEO mission, device TID capability of 300 krad is a good compromise between the shielding mass and parts capability.*

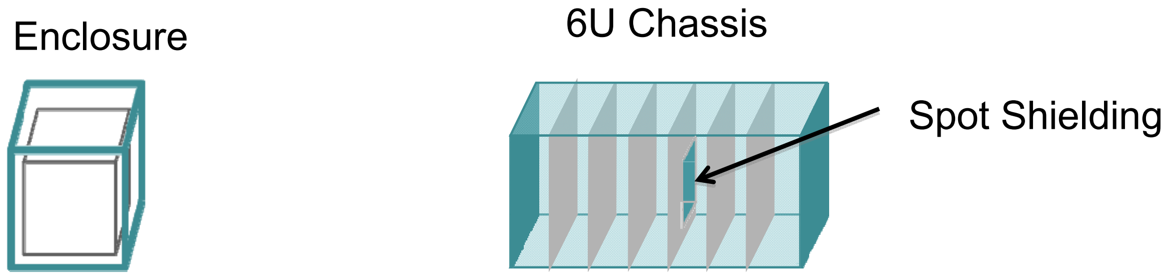


Figure 4.5-4. Shielding Concept: Blue sides illustrate the radiation shielding for pre-packaged electronics (enclosure shielding), for standard 6U format cards (chassis shielding), and spot shielding as needed.

typically 300 krads, with the exception of the propulsion system pressure transducers, which are rated for 75 krads, and the SIRU, which is rated for 200 krads.

For some subsystems (e.g., Telecom-SDST), some individual assemblies may require additional localized shielding to reach the tolerance listed in the tables. The power electronics and mass memory are both rated for a 1 Mrad dose, and the MMRTGs are capable of withstanding multi-Mrads of dose.

The total estimated spacecraft shield mass using Tungsten-Copper is 192 kg (CBE), comprised of 59 kg for payload instrument detector and electronics shielding, and 132 kg for engineering electronics shielding. With the current

Table 4.5-2. Radiation Tolerance of JEO Units Suggests a Distributed Shielding Approach

Subsystem / Description	TID Design Capability (krad)	Shield type	Shielding Mass per Assembly (CBE, kg)	Comments
Payload			**59.4**	
Payload Electronics Boards	300	6U Chassis	16.6	22 6U cards
Detectors	300	Enc	42.8	Calculated and bookkept separately by payload
Power			**8.7**	
Power Distribution Unit (PDU)	1000	6U Chassis	5.8	23 6U cards
Power Assembly (PAM)	1000	6U Chassis	2.8	4 slices (6U double-wide equivalents)
C&DH			**13.7**	
Avionics	300	6U Chassis	10.1	Includes one board for Radiation Monitoring subsystem
Hybrid SSR	1000	6U Chassis	3.6	Includes additional spot shielding for 100 krad SDRAM
Telecom			**53.8**	
Enclosure 1 (SDST, USO)	300	Enc	18.8	SDSTs and USO. On main spacecraft body.
Enclosure 2 (X TWTAs)	300	Enc	8.1	X TWTAs. On back of HGA.
Enclosure 3 (Ka TWTAs, WTS)	300	Enc	10.3	Ka TWTAs and WTS. On back of HGA.
Enclosure 4 (WTS)	300	Enc	9.6	4 WTS. On back of HGA.
Enclosure 5 (CTS)	300	Enc	0.9	CTS. On back of HGA
Enclosure 6 (x4 Multiplier)	300	Enc	1.5	x4 Multipliers (2). On back of HGA.
Enclosure 7 (KaT)	300	Enc	4.7	Includes KaT spot shielding to get from 100 to 300krad. On back of HGA.
Propulsion			**26.1**	
Transducers	75	Enc	2.6	10 pressure transducers
ACS			**30.2**	
SIRU	200	Enc	12.9	
Star Tracker Electronics	300	Enc	7.1	Assumes both ST electronics are co-located. Optical head rad shielding kept with star tracker
Sun Acq. Detectors	300	Enc	0.2	3 sun acquisition detectors
4 RWA Electronics	300	Enc	5.8	Assumes all 4 RWA electronics are co-located.
Gimbal ECU Electronics	300	Enc	4.1	Assumes HGA and Main Engine gimbal drive electronics are packaged together.
Total JEO Shielding Mass (CBE)				**192 kg**

design, the Tungsten-Copper provides over 20% mass saving over aluminum and over 5 times saving in terms of shield volume. Spot shielding estimates for sensitive components such as the star tracker detector are included. The thermal, structural and mechanical subsystems include no radiation sensitive components, and thus do not require any additional shielding. For reference, the shielding mass for the 2007 EE study was 122 kg (compared to 150 kg for JEO), which includes shielding only for the instrument chassis not the remote portion of the instrument (43 kg for JEO).

The shield modeling used in the estimates is based on the radiation shielding analysis performed in the 2006 Europa Explorer Mission Study [*JPL D-34104*] and scaled to the JEO configuration design and environments in this year's mission concept. The 2006 EE study estimated the shielding mass by performing a series of Monte Carlo radiation transport analyses for realistic (but conservative) spacecraft and electronics geometry. The 2007 study retained the 2006 shielding model. However, the high energy electron environment that JEO will experience during the Io flybys is responsible for the increase of the 2008 dose-depth curve around the 1000-mil aluminum shielding thickness. This is the main reason for the increase of this year's shielding mass. **Figure 4.5-5** shows the dose-depth curves from the 2006, 2007, and 2008 studies. As an example, consider a 300 krad assembly, for which the shielding should be designed to meet 150 krad (RDF = 2). From **Figure 4.5-5**, it's seen that the required shielding thickness between 2008 and 2006 are almost identical, while the required shielding thickness for 2007 is much smaller. Therefore, the 2008 shielding mass is larger than the 2007 shielding mass, but similar to the 2006 equivalent.

4.5.4.3 Parts and Materials

The selection of electronic parts for radiation susceptibility and reliability presents the first hurdle to be overcome for the JEO mission. **Figure 4.5-3** indicates how the shielding mass is reduced by higher device TID capability, which translates into lower dry

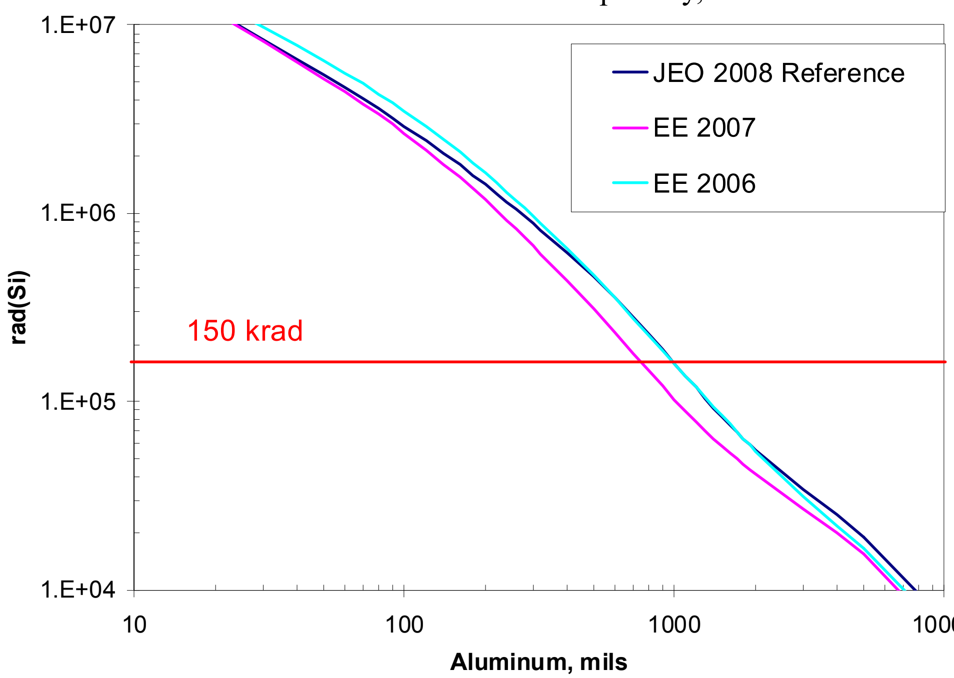


Figure 4.5-5. *Mission total dose-depth curve comparison from the 2006, 2007, and 2008 studies. The curves above illustrates the thickness requirement when the radiation design factor is not included (i.e., RDF=1). To meet the RDF=2 requirement for the 2008 JEO mission design, a horizon line of half of its value is required. For example, a 150 krad line as drawn corresponds to the shielding thickness for a 300 krad assembly. The assembly must be shielded by about 1,000 mil aluminum to protect against the anticipated radiation environment. The shielding thickness required is similar in both the 2008 and 2006 studies.*

mass for the JEO mission. The majority of NASA's radiation test and life test data on electronic parts has been taken in support of missions with low radiation requirements (<50 krad) and short lifetimes (<5 years). Commercially available parts advertized to be compatible with 100 krad up to 1 Mrad environment are not generally used or tested for long duration missions. Therefore, parameter degradations due to high radiation exposure levels have not been fully characterized and documented. Consequently, there is limited data to support parts selection, Worst Case Analysis (WCA), and determination of risk areas for aggressive radiation environments such as those experienced by the JEO mission.

In particular, the following device technologies have been identified as critical areas where early evaluation, testing, and characterization will be pivotal for prudent radiation tolerant designs. The identified device technologies with needed assessments are:

- Non-Volatile Memory—radiation susceptibility and reliability,
- FPGA—availability and reliability,
- Power converter—radiation susceptibility and reliability,
- MicroProcessor/Microcontroller—radiation susceptibility and reliability,
- Data Bus Device—availability,
- Linear Device—radiation susceptibility.

Another issue requiring attention is overly conservative radiation test and analysis methods, which can quickly exhaust the resources available for missions with very high radiation environments. Typical missions employ worst case conditions for testing to ensure that mission conditions are bounded and these conditions do not impose stressful design constraints. For the JEO mission, however, these existing test and evaluation methods can result in excessive conservatism in the development of worst case design parameters and significant unnecessary costs for radiation testing. The JEO mission mandates a low dose rate testing intended to address Enhanced Low Dose Rate Sensitivity (ELDRS) for susceptible parts (bi-polar devices). However, a typical ELDRS test is carried out at dose rates between 5 and 10 mrad/s. At these dose rates, tests for missions with dose levels in the hundreds of krads would take longer than one year. These tests must be started in Pre-Phase A to accommodate their long-lead times so that their results can be included in the flight system design.

Similarly, typical test methods and analyses for total dose in CMOS devices do not allow for annealing or other life extending effects (e.g., dormancy). On long duration missions, some parts could survive higher TID if annealing is considered. This has been an accepted rationale for some of the extra functionality of the Galileo spacecraft during the Jupiter encounter. Presently no guideline or method exists to address the benefit of annealing to extending device performance. JEO will address such clear sources of over-conservatism in tests and analysis methods. All these issues are addressed in the "Risk Mitigation Plan: Radiation and Planetary Protection."

The selection guidelines of materials for radiation susceptibility and reliability has been documented in a report entitled, "Materials Survivability and Selection for Nuclear Powered Missions" by Willis [*JPL D-34098*]. The composite material used on COPV tanks can stand radiation to take surface doses in the anticipated radiation environment without loss of strength for the JEO environment. Dose-depth curves of aluminum, silicone rubber, Teflon FEP, Kynar (polyvinylidene fluoride), polyimide (e.g., Kapton and Vespel), PEEK (polyether-ether ketone), silica, sapphire, and tantalum, parametrized by different energy ranges, are provided in the aforementioned report. This includes many soft goods used within electric valves in the propulsion subsystem. Detailed characterization of the properties and performance of these materials in high radiation environment will be executed as part of the "Risk Mitigation Plan: Radiation and Planetary Protection" in Pre-Phase A.

4.5.4.4 APML and Worst Case Datasheet

JEO is in the process of developing an Approved Parts and Materials List (APML) for the purpose of identifying standard parts approved for flight equipment developed under the project's cognizance. The APML will be populated with a wide assortment of EEE parts and materials, as well as many critical parts such as sensors, detectors, power converters, FPGAs, and non-volatile memories. Each entry will be accompanied with a Worst Case Datasheet (WCD) and application notes describing proper use of the part at selected radiation levels. Dissemination of this information early in the design process is critical to enable engineering and payload providers to adequately design for the harsh radiation environment.

Every approved part listed on the APML will meet the applicable reliability, quality, and radiation requirements specified in the "Parts Program Requirements (PPR)" [*JPL D-47664*]. The APML will accept parts at four (4) radiation levels: 50, 100, 300, and 1000 krad. The APML will be updated quarterly as new radiation data become available. Parts not listed as approved on the APML are defined as non-standard parts and will require a Non-standard Part Approval Request (NSPAR) for use in JEO. All non-standard parts will be reviewed, screened, and qualified to the requirements of PPR.

Every part on the APML will be approved by the Parts Control Board (PCB), co-chaired by both JPL and APL parts program managers. The PCB recommends and approves parts for inclusion in the APML. Criteria will be based on absolute need, the number of subsystems requiring the part, qualification status, TID, Single Event Effects (SEE), and procurement specification review. Mission designers should use standard parts to the maximum extent possible so that they can reduce the radiation testing and qualification expenditure to the minimum.

In FY08, the APML has included over 148 EEE parts, 70 WCDs, and 130 materials for spacecraft components. The list will be updated as new parts and materials become available. Appendix F.5 shows a sample page of the APML and associated WCD.

4.5.4.5 Electronic Subsystem Design and Methodology

In customary JPL practice, a parts data base is constructed to include degradation due to radiation, power supply variation, end-of-life, and part-to-part variation for each component parameter. Often an additional safety margin is levied on the part parameters. The traditional approach of conducting a Worst Case Analysis (WCA), using extreme value analysis (EVA) based on these part parameters, exaggerates the difficulties of the circuit design by requiring that it still functions when subjected to the worst possible combination of part parameters, each at its extreme value. Typically, parts on the same board are assumed to be at different temperature extremes if it drives the worst-case scenario, even if it is virtually impossible that this could occur.

In the event that the initial circuit fails to meet the WCA, for example, due to radiation effects, one approach is to provide spot shielding for the component. However, in designing the spot shield, the packaging engineer is often required to shield to an RDF of 3 instead if 2 in order to allow for higher uncertainties in the shielding analysis. Consequently, due to a compounding effect of conservatism at several levels, a traditional flight system and electronics subsystem design will contain excessive margins that limit resources available for mission science.

To counter these effects and allow a better use of resources across the system, WCA methods will be refined in otherwise marginal cases to eliminate unrealistic cases and to consider, where appropriate the true statistical nature of parametric variations. Furthermore, these analyses will be conducted concurrently with design and selective radiation tests to assure that circuits are making the best accommodation for device characteristics over their lifetime.

As discussed in §4.4.2.1, the baseline approach for all electronics on the flight system is to use ASICs instead of FPGAs. This is a more conservative approach until FPGAs can be adequately evaluated for both TID tolerance and SEE mitigation. The advantages in using FPGAs as intermediate products in developing complex ASICs for flight has prompted the development of guidelines for selection, design, and validation of appropriate FPGAs to support this process. The JEO mission will require improved design methodologies and guidelines to demonstrate the ability of flight engineering subsystems to operate in the Europa radiation environment. These issues and design guidelines are addressed in the "Risk Mitigation Plan: Radiation and Planetary Protection."

4.5.4.6 Effects on Sensors and Detectors

Radiation-induced effects on instrument detectors and other key instrument components ultimately impact the quality and quantity of the mission science return and the reliability of engineering sensor data critical to flight operations. High-energy particles found within the harsh Europa environment will produce increased transient detector noise as well as long-term degradation of detector performance and even potential failure of the device. Transient radiation effects are produced when an ionizing particle traverses the active detector volume and creates charges that are clocked out during readout. Radiation-induced noise can potentially swamp the science signal, especially in the infrared wavebands where low solar flux and low surface reflectivity result in a relative low signal. Both TID and DDD effects produce long-term permanent degradation in detector performance characteristics. This includes a decrease in the ability of the detector to generate signal charge or to transfer that charge from the photo active region to the readout circuitry; shifts in gate threshold voltages; increases in dark current and dark current non-uniformities, and the production of high-dark-current pixels (hot pixels or spikes). It is important to identify and understand both the transient and permanent performance degradation effects in order to plan early for appropriate hardware and operations risk mitigation to insure mission success and high-quality science returns.

A Detector Working Group (DWG) was formed in FY08 to evaluate the detector and laser components required by the planning payload and stellar reference unit. The DWG participants included experienced instrument, detector, and radiation environment experts from APL and JPL. For each technology required for the payload, the DWG (i) reviewed the available radiation literature and test results, (ii) estimated the radiation environment incident on the component behind its shield, and (iii) assessed the total dose survivability (both TID and DDD) and radiation-induced transient noise effects during peak flux periods. The assessment included the following technologies: visible detectors, mid-infrared and thermal detectors, micro-channel plates and photomultipliers, avalanche photodiodes, and laser-related components (pump diode laser, solid-state laser, fiber optics).

The DWG concluded that the radiation challenges facing the JEO notional payload and SRU detectors and laser components are well understood. With the recommended shielding allocations, the total dose survivability of these components is not considered to be a significant risk. In many cases, the shielding allocation was driven by the need to reduce radiation-induced transient noise effects in order to meet science and engineering performance requirements. For these technologies—notably mid-infrared detectors, avalanche photodiode detectors, and visible detectors for star tracking—the extensive shielding (up to 3-cm-thick Ta) for transient noise reduction effectively mitigates all concern over total dose degradation. For the remaining technologies, more modest shielding thicknesses (0.3–1.0 cm Ta, depending upon the specific technology) were judged to be sufficient to reduce the total dose exposure and transient noise impact to levels that could be further reduced with known mitigation techniques (detector design, detector operational parameters, algorithmic approaches and system-level mitigations).

The DWG recommends caution in inferring detector performance in the Jovian environment based on existing radiation test results where the irradiation species is typically not representative of JEO's expected flight spectra. A rigorous "test-as-you-fly" policy with respect to detector radiation testing, including irradiation with flight-representative species and energies for TID, DDD, and transient testing, will be adopted for JEO. The full report *"Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study"* is included as part of the FY08 deliverables of the "Risk Mitigation Plan: Radiation and Planetary Protection." It is available under separate cover [*JPL D-48256*].

4.5.5 Radiation Risk Mitigation Plan

Radiation risk is the single largest technical challenge for the Europa mission. In 2007, the Planetary Science Division had planned to make a substantial investment in radiation effects if a down-select to Europa Explorer had occurred. NASA allocated approximately $650K of the mission study budget, starting February 2008, to specifically address issues related to mitigating radiation risks encountered by a Europa mission. In addition, JPL committed $1M of internal funds in FY08 to facilitate early understanding the implication of the risks encountered by such missions with harsh radiation environments. A detailed three-year radiation risk mitigation plan was developed in early FY08 based on the approach and strategy outlined in the 2007 EE Mission Study Report. The plan also factored in the recommendations of the 2007 NASA Science, Technical, Management and Cost (TMC) Review panel, which would support a FY09 Phase A start with a 2016 launch opportunity.

Midway through the FY08 study, the bilateral NASA-ESA management meeting recommended launch date of EJSM moved from 2016 to between 2018 and 2022 (nominally 2020). As such, the three-year plan was re-evaluated to encompass a four-year plan that is compatible with a launch in 2018. In the four-year plan, the tentative milestones that are based on a September 2018 launch opportunity drive the phasing of tasks and the performance metrics. If a 2018 launch year (about 17 months earlier than the 2020 opportunity) is ultimately selected, this plan would complete closer to the end of Phase A, In either case, an immediate project milestone is to support the 2nd Instrument Workshop planned for November 2009.

The objective of this plan is to mitigate the development and operational risk posed to the spacecraft and instruments of the JEO. The plan addresses issues endorsed by the TMC panel of their radiation findings on Forms B and C of the 2007 EE Mission Study Report. The findings cover radiation-induced effects and susceptibility of sensors to radiation; availability of radiation-hardened parts including FPGAs, non-volatile memories, power converters; and dose rate effects. In addition, the plan will facilitate trades among mission lifetime, mass and power requirements while meeting science objectives and reducing lifecycle cost.

4.5.5.1 Scope of Plan

The extreme conservatism in designing and verifying spacecraft electronics subsystems often leads to excessive design margins and severely underestimates the mission lifetime. This commonly results from a compounding effect of applying worst-case assumptions at every level: from parts selection to system design and engineering. This work plan addresses this deficiency by developing a system-level approach of quantifying the uncertainties through rigorous analysis and validation through laboratory testing. The resulting system lifetime model, Jovian radiation model, radiation design methodology and guidelines, parts selection and testing strategy for various dose rate conditions and annealing effects, and assessment of radiation effects on sensors and detectors of science instruments, will establish a defined pathway to quantitatively perform trades in the mission and science value space. Application of this system approach for radiation mitigation offers a new paradigm in the underlying process for long duration mission designs.

In this work plan, realistic mission conditions and design guidelines will be developed to improve the traditional process and simultaneously provide an accurate picture of estimated mission lifetime. The plan includes the development of design tutorials, the APML, and radiation design guidelines for potential instrument providers; assessment of radiation effects on sensors and detectors of science instruments; evaluation of the availability of radiation-hardened parts such as FPGA, memory, and power converters; identification and more thorough testing of electronic parts; measurements of these parts under various dose rate effects; and establishment of a mission lifetime estimation methodology when subjected to different radiation effects based on the electronic parts database. There are six major elements in the Work Breakdown Structure (WBS) of this work plan. Each element is devoted to specific issues identified in previous sections. The six WBS elements are:

1.0 System Reliability Model;
2.0 Environment and Shielding Models;
3.0 Radiation Design Methods;
4.0 Sensors and Detectors;
5.0 Parts Evaluation & Testing; and
6.0 Approved Parts and Materials List.

The scope of this work plan also includes compliance with the NASA planetary protection (PP) requirements that were established based on recommendations set by the Committee on Space Research (COSPAR), a part of the International Council for Science. In this plan, PP compliance is achieved through close coordination and planning between the PP requirements and two WBS elements: WBS 4.0 – Sensors & Detectors and WBS 6.0 – APML. In the APML, a column designates the PP compliance. Appendix F.5 shows the sample APML format with the "Planetary Protection" column. This list will be provided to instrument and spacecraft providers to understand the impact of PP requirements on payload science and engineering sensors.

4.5.5.2 Implementation Approach

The implementation approach is to extend work started under Europa Explorer in 2006 and 2007 by developing a system-level reliability model for radiation risk reduction. This effort, corresponding to each WBS element, includes:

- Developing a new integrated tool set to allow system engineering to effectively manage risk, resources and science value,
- Developing higher fidelity environment and shielding models,
- Developing and documenting design and analysis guidelines for parts de-rating, worse case analysis, and circuit performance,
- Developing and documenting parts testing requirements for parts degradation and actual failure characteristics,
- Testing and characterizing electronic parts, materials, sensors and detectors to support design trades and solutions,
- Developing a list of approved parts and materials to enforce design discipline and reduce risk.

The PP compliance approach is a combination of controlled bioburden (by sterilization processing before launch) and exposure to radiation from the Jovian environment prior to Europa orbit insertion. Prior to launch, the preferred method of microbial reduction is dry heat microbial reduction (DHMR). In order to achieve compatibility for the mission hardware, it is necessary to consider DHMR (elevated temperature) compatibility in the trade studies alongside the radiation resistance.

A summary of the investment needed is listed in **Table D.5-6** in Appendix D. The table captures all radiation investments directly relevant to the JEO mission. The total four-year investment is $10.5 million in FY08 dollars. The funding for PP efforts are included as part of the Outer Planet Flagship Mission activities and therefore not shown as part of this work plan. This risk mitigation budget supports the following milestones:

- FY08: Identify and obtain highest impact design information for dissemination to the Instrument community for the instrument workshop in June 2008 and November 2009,
- FY09/10: Complete design data gathering and dissemination to the design community, evaluate and structure proof-of-concept system model including identifying required input information to support the release of instrument Announcement of Opportunity (AO) and preparation of System Safety Review (SSR) / Mission Definition Review (MDR),
- FY11: Complete system model and input parameter definitions to support subsystem and instrument designs.

4.5.5.3 Progress To-Date

FO-10 summarizes the FY08 significant accomplishments, major deliverables and representative products by WBS elements. **Table 4.5-3** lists all FY08 deliverables including the tutorials that were presented in the 1st OPFM Instrument Workshop. Detailed description of individual reports are provided in Appendix F.2. Appendix F also includes a guideline to reports, sample page of the APML and the associated Worst Case Datasheet.

In **FO-10**, WBS 0.0 is responsible for managing and coordinating technical developments, and overseeing day-to-day activities. The 3rd column of the table from left shows the overall objectives of individual elements. As an example, the four-year objective of WBS 0.0 is to develop the system model and engineering approach to combat the harsh Jovian radiation environment. The development of this "Risk Mitigation Plan" thus falls in the purview of WBS 0.0. Successful execution of this plan will retire a majority of risks as described in the "2007 EE Mission Study: Final Report" [*Clark et al. 2007*] and endorsed by the TMC panel by the beginning of Phase A of the 2020 launch.

4.5.5.4 Summary

In response to the unique technical challenges posed by the harsh Jovian radiation environment, the JEO mission designers have sought to capitalize on prior deep space flight experience while exercising a systems engineering approach to uncover hidden design margins throughout the development chain. The JEO design leverages on the experiences gained from Galileo, as well as the on-going New Frontier Juno Jupiter and Radiation Belt Storm Probes (RBSP) missions. The systems engineering approach captures the graceful degradation behavior of mission lifetime beyond the Europa Campaign 3 (after 105 days). Efforts are already underway to retire the majority of risks related to the parts and materials, electronic designs and radiation-induced effects on sensors and detectors.

The "Risk Mitigation Plan: Radiation and Planetary Protection" described in §4.5.5 was developed to address issues endorsed by the TMC panel of their radiation findings of the 2007 EE Mission Study Report. The radiation tolerance design approach discussed in §4.5.4 would provide sufficient protection of electronic assemblies to the end of the JEO prime mission. There are no major obstacles perceived ahead with respect to mitigating radiation risks. The joint effort of JPL and APL in the mission design and Pre-Phase A activities gathers the necessary national talent to make the JEO mission successful.

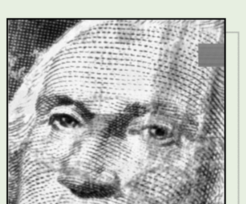
Table 4.5-3. *Complete list of FY08 deliverables in the Risk Mitigation Plan: Radiation and Planetary Protection*

Deliverables	Release	Title	Reference Number	WBS
Report	Final – Public	EJSM Risk Mitigation Plan: Radiation and Planetary Protection	JPL D-47928	0.0
	Final – NASA	JEO Circuit Lifetime Model - Final Report for FY08	IOM# 5133-08-013	1.0
	Final – NASA	Final Report for 2008 JEO System Radiation Lifetime Report	IOM# 313-08-055	
	Final – NASA	Jupiter Europa Orbiter Radiation Environment for the T08-008 Trajectory	IOM# 5132-08-041	2.0
	Final – Public	JEO Designing Circuits and Systems for Single Event Effects	JPL D-33338	3.0
	Initial – NASA	OPFM ASIC via FPGA Guideline with Addendum on Europa ASIC Process Flow	JPL D-48347	
	Final – NASA	JEO FY08 WCA Task Final Report	IOM# 5133-08-012	
	Initial – Public	OPFM Long Life Design Guidelines	JPL D-48271	
	Initial – NASA	JEO Radiation Design Guidelines	JPL D-48258	
	Final – NASA	Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study	JPL D-48256	4.0
	Final – Public	OPFM Test Method for Enhanced Low Dose Rate Damage (ELDRS) Effects in Integrated Circuits	JPL D-33339	5.0
	Initial – NASA	Memory Investigation for JEO Mission	JPL D-48262	
	Initial – NASA	Juno/Europa Extended Radiation Testing - FY08 Task Report	IOM# 5144□08□33	
	Initial – NASA	FPGA Use for Europa Mission – FY08 Task Report	IOM# 5141-08-99	
	Initial – NASA	Power Conversion Approach for JEO Mission	IOM# 5144-08-32	
	Final – NASA	Outer Planet Flagship Missions (Europa and Titan Orbiters): Parts Program Requirements (PPR)	JPL D-47664	6.0
	Final – Public	JEO Total Dose and Displacement Damage Design Guideline	JPL D-33337	
	Initial – NASA	Approved Parts and Material List for OPFM	IOM# 5143-08-079	
Tutorial	Final – Public	Overview of Jovian Environment	Presented at 1st OPFM Instrument Workshop	2.0
	Final – Public	Characteristics of Radiation Environments: Europa Orbiter		
	Final – Public	Planetary Protection for OPFM		0.0
	Final – Public	Space Radiation Effects on Microelectronics		3.0
	Final – Public	Radiation Effects on Materials: Europa Environment		6.0
	Final – Public	Shielding Design Considerations: Europa Orbiter		2.0
	Final – Public	Spacecraft Charging Effects		
	Final – Public	Mission Lifetime Model		1.0
	Final – Public	Introduction to Space Radiation Effects on Materials	JPL D-48274	6.0

Risk Mitigation Plan — Progress To Date

WBS #	Title	Objectives	FY08 Significant Accomplishment	Major FY08 deliverables
0.0	Management and System Engineering	Develop system model and engineering approach for harsh radiation environment	Completed a four-year $10.5 million management and radiation risk mitigation plan that includes PP compliance	Risk Mitigation Plan: Radiation and Planetary Protection (PP)—D-47928
1.0	System Reliability Model	Improve and develop the design capability to predict lifetime for long duration missions	Developed a Circuit Lifetime Reliability Assessment (CLRA) model and system model using Master Equipment List	Final Report on models with Master Equipment List (MEL) and Circuit Lifetime Reliability Analysis
2.0	Environment and Shielding Models	Develop consistent radiation environment estimate for NASA and ESA and model updates	Optimized mission trajectory to reduce total ionization dose (TID); Developed radiation shielding methodology, and charging tutorials and guidelines	Shielding Design Methodology and Preliminary Charging Mitigation Guideline; Design Tutorials for Shielding and Charging
3.0	Radiation Design Methods	Develop methodologies and guidelines that will result in designs with more predictable failure characteristics	Identified four representative radiation-hardened designs to validate the refined WCA process—Secure Communications Channel, Universal Space Transponder, Signal Chain Design, and DC-DC converter; Developed methodology to evaluate current radiation-hardened FPGA and ASIC fabrication process	Radiation Design Guideline; Long-life Design Guideline; FPGA/ASIC Conversion Methodology and Guideline; Design Tutorials for parts selection and circuits
4.0	Sensors and Detectors	Assess radiation susceptibility of the potential detector and component technologies that are unique to the payload and identify mitigation approaches	Developed model for radiation-induced transient noise effects on photonic detectors under peak flux conditions; Conducted proof-of-concept demonstration of CMOS imagers hardened by design and by fabrication (shown below); Completed assessment of photonic detectors and key optical components in notional payload	Report on assessment of radiation risk for detectors and key optical components of science instruments recommended by the Joint Jupiter Science Definition Team (JJSDT)
5.0	Parts Evaluation and Testing	Improve and extend existing radiation and life test database to support device selection and approval	Extended Juno TID test to provide verification of the ELDRS test method; Completed preliminary key device technology evaluation and tests of non-volatile memory CRAM / PRAM / SDRAM, power converters, FPGAs, and micro-processors	Test Strategies and Guidelines for ELDRS and displacement damage; Assessment of COTS, prior designs and recommendation for Power Converters; Assessment report of FPGAs; Extended Juno TID test results
6.0	Approved Parts and Materials List (APML)	Develop a web-based APML of pre-selected parts and materials for radiation environment.	Completed and Released OPFM Parts Program Requirements Document and APML format (shown below); APML includes 148 EEE parts, 70 WCDs, and 130 materials	OPFM Parts Program Requirements Document; APML FY08 release

WBS 4.0



• *Image from hardened CMOS test array after 1 Mrad TID provides proof of concept for JEO science imagers*

WBS 5.0

Europa TID Test Status - 9/24/08

Generic P/N	Part Log #	Description	MFR	Test	Tester	TP	HW	HDR	LDR	Data	REP	Status
LM113	2164 2175	Voltage Ref	NSC	HDR LDR	ETS-300	X	X	100k	133k			Restart HDR @ end of September.
OP484	2178	Op-Amp	ADI	LDR	LTS-2020	X	X	N/A	55k			Restart LDR @ end of September.
AD537	2234 2235	VFC	ADI	HDR LDR	ETS-300	X	X	100k	250k			LDR @ 300k on 10/6/08. Opamp Input bias current, Kelvin temp., VREF,upper range of VREF al, Full scale error, and Linearity error, PSRR, out of spec.(not all devices) Unbiased is
AD574	2204	ADC	ADI	HDR LDR	ETS-300	X	X	100k	700k			LDR @ 1000k on 11/26/08. Biased showing mild degradation, no annealing, 2/3 failing Bipolar Zero Error, Unbiased failed all linearity and were stopped. Will restart HDR aprox. 11/29/08
AD606	2209	Log Amp	ADI	HDR LDR	ETS-300	X	X	1M	300k	HDR		LDR @ 500k on 9/27/08. HDR data complete.
AD652	2224	VFC	ADI	HDR LDR	ETS-300	X	X	1M	250k	HDR		LDR @ 300k on 9/30/08. Ref. Volt, Input Bias current, and Clock iil, V to F al, input offset voltage/current, (out of spec. some fails)-PSRR, VOS RTI (almost out of spec. not all devices).
AD667	2219	8-12-Bit ADC	ADI	HDR LDR	ETS-300	X	X	1M	250k	HDR		LDR @ 300k on 10/6/08. HDR data complete.

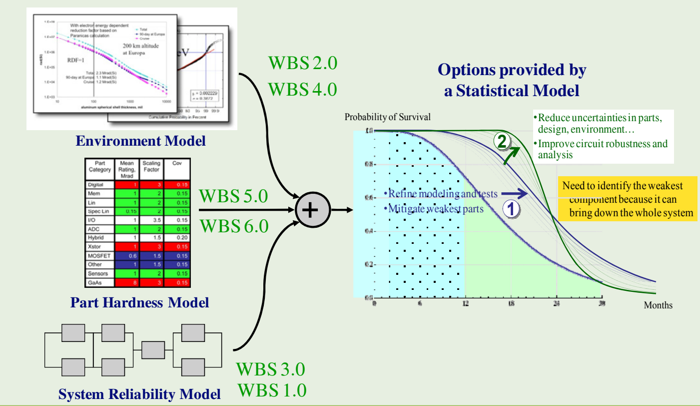
ELDRS Test in Progress

WBS 6.0

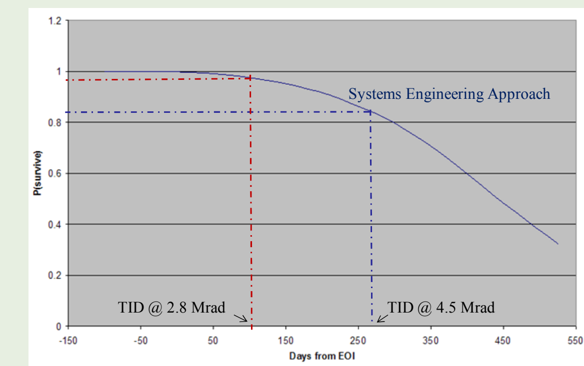
Flight Part #	Parts Status	SEL/ SEGR/ SEB	SEU	SET	SEFI	DD	50K	100K	300K	1000K	NSPAR Number	Planetary Protection	Comments/Recommendations
5962F9568901VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5962F9666302VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5962F9568902VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5962F9563201VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5962F9563101VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5962H0151704VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	A/WCD			
5692R9663601VXC	A	A	A	S	A	A	A/WCD	A/WCD	T	N			
5962R9664101VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N			
5962R9661401VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N			

Representative FY08 Products

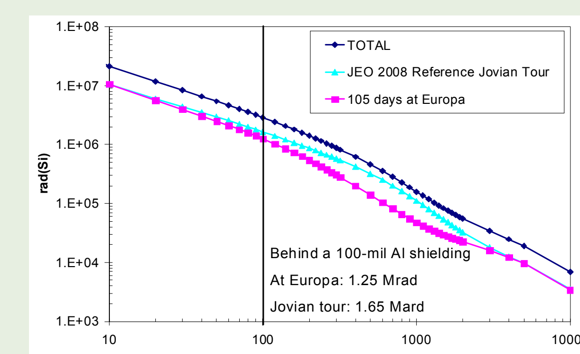
WBS 0.0



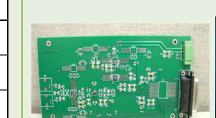
WBS 1.0



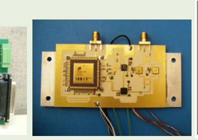
WBS 2.0



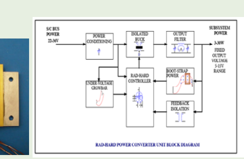
WBS 3.0



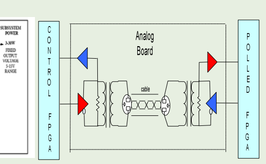
Signal Chain Breadboard



UST – X-band VCO-PLL Synthesizer Test Board



DC-DC Converter Block Diagram



Secure Communication Channel Block Diagram

4.6 Operational Scenarios

Science objectives, investigations, and priorities for JEO are provided by the NASA/ESA Joint Jupiter Science Definition Team (JJSDT). Operations scenarios for JEO are driven by prioritized science objectives and in turn drive the design of model payload, and the flight and ground systems.

The EE 2007 study did not include Jupiter System Science. Only minor modifications to the mission design is needed to capture this broader science.

The model payload configured for Europa orbital science was slightly enhanced to capture highest priority Jupiter system science goals. Flight and ground systems need minimal augmentations to incorporate a 30 month Jupiter system science based tour. These augmentations were primarily a larger on-board mass memory for Jovian Tour operations and slightly increased GDS infrastructure and MOS team size for the modified payload.

Current operations scenarios are based on incorporating key operations items from the 2006 and 2007 concept studies. Some of these items include:

- Make the flight and ground systems operable and maintainable for a high intensity, rapid turn around operations environment in Europa orbit in the possible presence of radiation based anomalies;
- Use modern system engineering methods to model the system behavior as early as possible to balance mission scope with system capability, complexity, risk, and cost;
- Incorporate lessons learned from previous similar missions to guide design philosophy and trade studies.

No new technology will be needed to operate the JEO mission. All needed components for the design of flight and ground operating system components exist for current and near term missions. The long development and operations schedule, however, offers periodic opportunities to incorporate future capabilities when they are shown to improve efficiency, flexibility or increased science return. The JEO operations architecture will be designed to accommodate future improvements as much as practical.

The JEO mission is similar to orbiting science missions (like MRO, Magellan, and MESSENGER) and to previous outer planets flagship missions (Cassini and Galileo). The operations scenarios and the flight and ground systems design likewise incorporate the best features from both mission sets. A comparison of the mission characteristics of previous comparable mission is shown in **Table 4.6-1.** In the Jovian Tour phase JEO will have similar needs to those of Cassini and Galileo. For the Europa Science phase, JEO will need to perform similarly to MRO but with memory constraints more like Magellan. MESSENGER yields a special comparison in that it has similar tour and orbiter phases but at a somewhat smaller mission scale.

The most stringent and driving operational requirements and constraints for JEO are derived from Europa Science needs. This study has focused on ensuring the system functionality and performance needed for operating

Table 4.6-1. *Comparison of Operational Mission Characteristics*

Mission Comparison	JEO	Cassini	MRO	MGN	MER	MSGR
Mission Phase Durations Interplanetary Cruise Primary Science	62 months 30 mo tour/9 mo orbit	84 months 48 months	7 months 26 months	14 months 9 months	7 months 3 months	79 months 12 months
Number of Instruments	11	12	8	4	6	7
On-board Science Data Storage	1 Gb (17 Gb Tour)	3.5 Gb	160 Gb	2 Gb	2 Gb	1 Gb
Data Rate	50–500 kb/s	14–165 kb/s	550–6000 kb/s	270 kb/s	128 kb/s	40-104 kb/s
Daily Data Volume	7 Gb	2 Gb	70 Gb (avg)	13 Gb	0.04 Gb	2 Gb (avg)
Primary Mission Data Volume	4.6 Tb	2.5 Tb	50 Tb	3.5 Tb	0.04 Tb	0.73 Tb
DSN Tracking	21 tracks/wk (105 d) 7 tracks/wk (165 d)	8 tracks/week	19 tracks/week	21 tracks/week	2 ODY relays/day	7 tracks/week
Science Planning:Execution Cycle	1 wk: 1wk	26 wk: 4 wks	2 wk: 2 wks	2 wk: 1 wk	1 day: 1 day	6 wk: 1 wk

in Europa orbit. Analysis and design was undertaken to determine additional requirements and constraints for operating in the Jovian Tour phase of the mission.

This section will provide a high level summary of the operations scenarios for each mission phase, a contextual description of the operations aspects of the major mission systems, detailed data acquisition and return scenarios for the Jovian Tour and Europa Science mission phases, and a summary of the outcomes of major mission trade studies. The MOS is very similar to designs for current missions and is not described in detail in this section. A detailed description of the MOS, as well as details of the analyses performed in this study phase are provided in Appendix G.

4.6.1 Overcoming the Challenges of Operating in Europa Orbit

Europa and its vicinity is a challenging and hazardous environment for operating any science mission. Mapping Europa requires a large and complex payload that collects large volumes of science data. The unknown Europa gravity field represents both a high priority science goal to help characterize its ice shell, oceans and rocky core, but also a challenge to finding and maintaining good quality mapping orbits. These challenges have been considered in depth and have been answered by spacecraft and payload hardware and software concepts and operational strategies. The operational scenarios resulting from these design concepts and strategies provide a means to collect and return the science data needed to meet all of the JEO science objectives.

The ability of memory parts to operate in the radiation environment limits the amount of on-board data storage available for mapping Europa. Fully radiation hardened mass memories of 1–2 Gb can be reasonably accommodated in the JEO flight system design. For earlier phases of the mission, larger capacities of greater than 10 Gb of less radiation tolerant memory can be used.

While in Europa orbit with a few operational constraints commonly encountered in past missions, smaller radiation hardened SSRs can support daily data volumes of an order of magnitude greater than their capacity. These constraints include: near real time data compression and downlink encoding, downlinking all data on the orbit collected, collecting data during downlink sessions, assuming no data retransmission, and scheduling continuous DSN tracking. Analysis of the science scenarios shows that some of these constraints can be relaxed in limited situations.

Short term radiation effects such as SEUs and gradual degradation due to displacement damage can cause frequent fault protection intervention. In most missions the system's reaction to faults, whether major or minor, prevent normal flight system operations while ground operations personnel resolve causes and ensure safe return to operations. JEO will allow on-board fault protection to manage minor faults for instruments and selected subsystems, while permitting the flight system to proceed with normal data acquisition in parallel with ground based troubleshooting and resolution.

Due to limited knowledge of the Europa gravity field and Jupiter's gravitational perturbations, initial orbits will likely need maintenance every week to few weeks. In the first weeks in Europa's orbit, Doppler data will allow rapid increase in the knowledge of the Europa gravity field. Initial orbit parameters will be adjusted for additional stability. A more stable lower orbit will be designed for later mapping activities. Because of increasing knowledge of the Europa gravity field and the change in orbit from 200 km to 100 km, it is expected that orbit maintenance interruptions to science operations should decrease in frequency over the course of the Europa Science phase.

4.6.2 Summary of Operations Scenarios

4.6.2.1 Launch and Cruise

After launching in February of 2020, the mission focus will be on the checkout and deployment of all flight systems. For the first month of operations, the mission will rely on continuous tracking with 34 m DSN stations. Using sequences validated prior to launch, the operations team will characterize the flight system. Real-time commanding predominates during this early period to provide flexibility to respond to unknowns. Sequence-initiated commanding will become the normal command mode as the transition to cruise completes.

The interplanetary cruise phase encompasses the gravity assist flybys of Venus and

Earth, which are needed to add the necessary energy to the trajectory to reach Jupiter. Each flyby will be used to check-out and characterize all instruments and flyby operating processes and tools. During quiet periods of cruise the operations and supporting teams will be testing and training on the tools and processes to be used for the Jupiter system science and Europa science operations. Cruise sequences will last one to two months during quieter periods, and will last one to two weeks near the Venus and Earth flybys. DSN tracking (see §4.3) will be normally once per week with 8-hour 34 m passes. Tracking will increase to nearly continuous levels in the weeks surrounding major maneuvers and gravity assist flybys.

Starting in early 2025, the mission operations and science teams and operations centers will begin staffing up in preparation for JOI and science in the Jupiter system and will deploy and test final flight and ground software. While all critical activities for JOI and science operations at Jupiter will have been tested pre-launch, final updates based on post-launch experience and new capabilities will be deployed. Testing and training will be performed to assure mission readiness after the long cruise phase. DSN Tracking will increase to nearly continuous levels in the two months prior to JOI to support final navigation targeting and to prepare for Jupiter observations and the first Io encounter.

4.6.2.2 Jovian Tour

In the Jovian Tour phase, the flight system will make routine and frequent observations of Jupiter, its satellites, and its environment. The Tour phase is divided into two science campaigns: Io Campaign and System Campaign.

The Jupiter system presents a rich and varied set of observing opportunities. The JEO 30 month baseline tour trajectory enables substantial Jupiter system science in five major themes: satellite surfaces and interiors, satellite atmospheres, plasma and magnetospheres, Jupiter atmosphere, and rings, dust and small moons.

Measurements supporting satellite specific objectives will be accomplished during the satellite flyby encounters. Flyby geometries are highly varied for latitude and lighting but are opportunistic as the trajectory is optimized for meeting the science requirements along with duration, delta-V and radiation dose. The orbiter will be able to collect and return about 14 Gigabits of science data during the closest approach 1–2 hours for each encounter. This will enable NAC, MAC, and VIRIS observations, UVS observations, TI profiles, and altitude permitting, laser altimeter profiles and IPR full and low rate profiles.

Monitoring and measurement of the system plasma environment and magnetosphere will be accomplished through constant data collection from the magnetometer and PPI instruments. Jupiter atmospheric and Io monitoring will make use of the 9-color NAC with detailed observations and dynamic studies every week or two.

Early Jovian Tour sequences will last one to two months with special short term sequences developed for flybys. DSN tracking will be normally one 8-hour 34 m pass per day. Near flybys, additional 34 m passes will be scheduled for increased data return and 70 m passes, or equivalent, for key engineering telemetry and for contingency operations. Tracking will increase to nearly continuous levels in the month prior to EOI to support final navigation targeting and prepare for Europa science operations. The final month prior to EOI will have several closely timed flybys of Europa, setting up the geometry for EOI. Science operations may be reduced in complexity in favor of navigation and maneuver activities.

4.6.2.3 Europa Science

The JEO Europa Science scenarios are designed to obtain Europa Science objectives in priority order. Data collection spans 4 major campaigns:

- Europa Campaign 1, Global Framework at 200 km orbit for 8 eurosols (~28 days),
- Europa Campaign 2, Regional Processes at 100 km orbit for 12 eurosols (~43 days),
- Europa Campaign 3, Targeted Processes at 100 km for 8 eurosols (~28 days), and
- Europa Campaign 4 Focused Science at 100 km for 46 eurosols (~165 days).

Europa Campaigns 1–3

The earliest and highest priority goals will be accomplished during Europa Campaign 1, including 2 global maps, 1–2 degree global grids from the 4 profiling instruments, and several hundred coordinated targets, with multiple instrument in highest resolution modes, of high interest sites.

After the initial campaign, the orbit altitude will be lowered and higher resolution global maps, additional profile grids and hundreds more coordinated target observations will be collected to answer regional process questions. Europa Science Campaign 3 will be devoted almost entirely to acquiring coordinated targets to answer local-scale science questions. The fourth and final campaign will focus on addressing new questions arising from data collected in the first three campaigns.

To meet these science objectives, the flight system will acquire and return an average 7.3 Gbits per day. To balance power, mass, and data volume, continuous tracking by DSN 34 m stations (or equivalent) will return these data volumes.

For Europa Campaign 1 and 2, science data collection is continuous and repetitive with continuous fields and particles, altimetry, and TI and VIRIS profile data collection, along with alternating orbit radar sounding and global imaging. This repetitive data collection represents about 2/3 of the daily average downlink data volume. On orbits when additional data volume is available, targeted data acquisitions comprising either coordinated targets (IPR profiles, NAC, MAC and VIRIS images) or full resolution IPR observations will be collected. Except for the low rate instruments, all observations will be taken when Earth is in view, enabling rapid downlink of high volume science data. Sequences for repetitive mapping activities will be uplinked once per week. Lists of targets to be acquired via on-board targeting software, will be developed and uplinked to the flight system every few days. Quick look data processing, mapping assessment, and target selection processes will all be rapid, needing about one day each. Data return will be via continuous 34 m tracking through the end of Europa Campaign 3. Data rates will be determined every orbit based on the DSN elevation angle and Jupiter radio (hot body) noise for that orbit. These variable data rates increase the average data volume returned by nearly 100% over traditional methods.

Europa Campaign 3 will have similar observing activities as the previous campaigns but the emphasis will shift from global mapping with limited targeted observations to primarily targeted observations with limited profiling and gap fill observations from the WAC.

Europa Campaign 4

Europa Campaign 4 will continue targeted observations but will include new observation activities not permitted in the first 3 campaigns. These might include off nadir imaging, Io and Jupiter monitoring, low altitude observing with imagers and INMS, and other observations designed in response to new questions arising from early observations.

Science data collection during Europa Campaign 4 will be planned for daily 8-hour passes to DSN 34 m stations. Sequence durations will be increased to 2–4 weeks. Target updates will be uplinked once per week.

4.6.2.4 Trajectory Characteristics

The cruise, Jovian Tour trajectories and Europa science orbits are described in §4.3 and shown **FO-6**).

The Tour trajectory is designed to reduce orbit energy for EOI delta-V savings, avoid excessive radiation dose prior to Europa arrival and to achieve science goals as described in §2.5. Optimization of the tour trajectory to achieve all of the science goals is beyond the scope of this study but experience shows that options will be developed in future phases that will achieve most of the objectives. The baseline trajectory achieves multiple flybys for all of the Galilean satellites, including high and low altitude and latitude flybys and varied lighting conditions. Figure A on **Foldout 11** (**FO-11**) shows the JEO range and Jupiter phase during the Tour phase. Opportunities to meet the key objectives for occultation experiments and high and low phase angles for dust and ring observations can be inferred from the phase and range plot. The range and phase space offers frequent opportunities for sunlit viewing of Jupiter's atmosphere. The foldout also shows maps of each Galilean satellite and the groundtracks of each flyby during the Tour phase. The groundtracks shown in green represent example encounters for which observing scenarios with data collection and key geometric parameters have been developed.

The 33 orbits between JOI and EOI offer 3 Io flybys (after the first at JOI), 6 Europa, 6 Ganymede, and 9 Callisto flybys. Flybys are 1 to 2 months apart early in the phase, becoming a week or less apart as the tour ends. Ten Jovian orbits have no targeted flybys allowing comprehensive investigations of Jupiter's atmosphere, rings, dust and small bodies. The trajectory also allows for a large variation of range and sun angles for observing the magnetic and particle environment of the system. Distant viewing opportunities exist to observe Jupiter from less than 1 million kilometers, and Io, Europa, Ganymede, and Callisto from less than 500,000 km

To satisfy the science objectives, the science orbit at Europa will be low altitude (~100–200 km), near circular, high inclination, and have consistent day-to-day lighting. Depending on altitude, there will be 10–11 orbits per day and ground-track speeds will be between 1.2 and 1.3 km per second. Because of the 2–4 P.M. local solar time orientation of the orbit, each orbit will be occulted from the Earth for 30–40% of the time. Twice each week Europa will be occulted and eclipsed from the Earth and Sun respectively for about 2 hours.

4.6.3 Flight System Operability

The JEO flight system is comprised of an orbiter and a planning payload of 11 science instruments. The payload list, operational needs, and data rates are shown in **Table 4.6-2**.

The details of the flight system design are in §4.4. The operations scenario trade studies and analysis leading to the current design are noted in Appendix G. A study of operations lessons learned for four currently flying missions was performed and the results are included in Appendix K. Additionally, a study was performed to provide recommendations for science operations concepts [*Paczkowski et al. 2008*]. JEO makes use of these recommendations to the flight system and mission operations system where appropriate.

Key operability features of the flight system include:

- Reaction wheels and coupled thrusters for greatly reduced trajectory perturbations (resulting in reduced coupling of observation pointing design and attitude control activities),
- Co-aligned remote sensing instruments and independent pointing of the communications system,
- On-board ephemeris-based pointing for rapid observation planning and updates,

Table 4.6-2. *Payload Operational Characteristics*

Science Instruments	Operational Characteristics		200 km			100 km		
			Rate (Mb/s)	Mapping Duty Cycle	Data Redux Factor	Rate (Mb/s)	Mapping Duty Cycle	Data Redux Factor
LA	Continuous Operation		0.002	100%	1	0.002	100%	1
Telecom system	Ka-band uplink with Ka-band downlink, 8 hours/day X-band uplink with Ka-band downlink, 16 hours/day		2-way Doppler			2-way Doppler		
IPR	Alternating orbits for distributed global profiles. Modes for shallow water and deep ocean searches.	Shallow Profile Mode	0.28	35%	107	0.28	35%	107
		Deep Profile Mode	0.14	45%	215	0.14	45%	215
	Full resolution target mode	Target Mode	30	–	1	30	–	1
VIRIS	Point mode, every orbit, for distributed global profiles.	Point Mode	0.1	35%	2.5	0.1	35%	2.5
	Target mode for 10 km × 10 km full spectrum images.	Target Mode	30	–	2.5	30	–	2.5
UVS	Limb viewing for stellar occultations several times per day.	Point Mode	0.01	14%	2	0.01	14%	2
INMS	Sensitive to low gas concentrations.		0.002	50%	1	0.002	50%	1
TI	Narrow profiles every orbit, for distributed global profiles.		0.009	100%	3	0.009	100%	3
NAC	Used for targeted modes in framing or pushbroom modes.		13.5	–	4	32	–	4
WAC	Provides global color and stereo maps	Color	0.27	40%	4	0.64	40%	4
	Operates every other orbit.	Panchromatic	0.07	40%	4	0.16	40%	4
MAC	Used for targeted modes.		1.4	–	4	3.2	–	4
MAG	Dual magnetometers; 10 m boom.		0.004	100%	1	0.004	100%	1
PPI	Includes ion species.		0.002	100%	1	0.002	100%	1

- Independent sequencing for individual instruments and spacecraft activities (acq and return, health, etc),
- File-based SSR and CCSDS protocols for file management and delivery,
- Autonomy for fault protection and science operations.

The Flight System is capable of continuous pointing and operation of science instruments while communicating with the Earth (via 2-axis HGA gimbal). In the Tour Science phase this is important for radio science (gravity Doppler and occultations) data collection while also collecting remote sensing data. In Europa orbit, this allows the payload to be nadir pointed continuously and monitor the local environment from a consistent attitude.

The JEO SSR is a hybrid design using a 1 Gb radiation hardened CRAM based partition for use in the Europa Science phase and a somewhat less radiation tolerant 16 Gb SDRAM partition for the Tour Science phase when higher data volume storage is needed to meet science goals.

To meet orbit maintenance needs, the orbiter is expected to perform orbit trim maneuvers one to two times per week while in Europa orbit. During the Tour Science phase, maneuvers will be less frequent except for the final pre-EOI orbits where a few maneuvers will be within days of each other.

Reaction wheel desaturations will be needed no more than every other day during all mission phases. It is expected that the frequency will be significantly less in the Interplanetary Cruise and Tour Science phases when gravity gradient torques are negligible.

4.6.4 Mission Operations System

4.6.4.1 MOS Functions

The Mission Operation System (MOS) is comprised of all hardware, software, networks, facilities, people, and processes used to operate the flight system. The MOS includes project specific elements, such as the GDS and flight teams, elements shared with other projects, like the DSN and related services, and those parts of the science teams that are used in the operations of the flight system. A high level data flow diagram showing elements of the flight system and MOS elements is shown in **Figure 4.6-1**.

The MOS functional elements include mission and science planning, sequencing and command processing, telemetry and tracking data processing, data management and archiving, science data processing, navigation, mission monitoring and flight system analysis, and infrastructure support.

Most of the MOS functions planned for the JEO use standard implementations and practices and have no unusual issues. This includes the use of CCSDS standards for information exchange among flight and mission operations system elements and the use of NASA standard information security standards (NPR 2810.1A—Security of Information Technology) to safeguard systems and information during development and operations. One MOS issue that deserves special attention is that of long term experience retention. The most challenging activities requiring the highest degree of technical flexibility occur more than 5 years after launch. While several methods for retaining domain and test knowledge will be needed, one method planned is that of regular and intensive training. Training activities will be planned at regular intervals and will include post launch training activities and ORTs for each cruise gravity assist encounter, the first Io flyby, JOI, EOI, and Europa science campaigns. Specially designed challenges and flight system anomaly resolution exercises will be needed to keep specialized knowledge fresh and accessible.

4.6.4.2 MOS Operability

The MOS design and implementation is informed by the OPFM lessons learned and OPFM Science operations concept studies (see Appendix K). Key parts of these efforts that have been incorporated are:

- Treat all system trades (spacecraft, operations, science, etc.) as mission trades to work toward best cost/risk for the overall mission (rather than optimizing an element and adding significant cost/risk to another without making the conscious trade);
- Model based engineering and state analysis tools to be used from concept development through operations;
- Spacecraft analysis tools used by mission planners and system analysts made available to science teams (early) to ensure

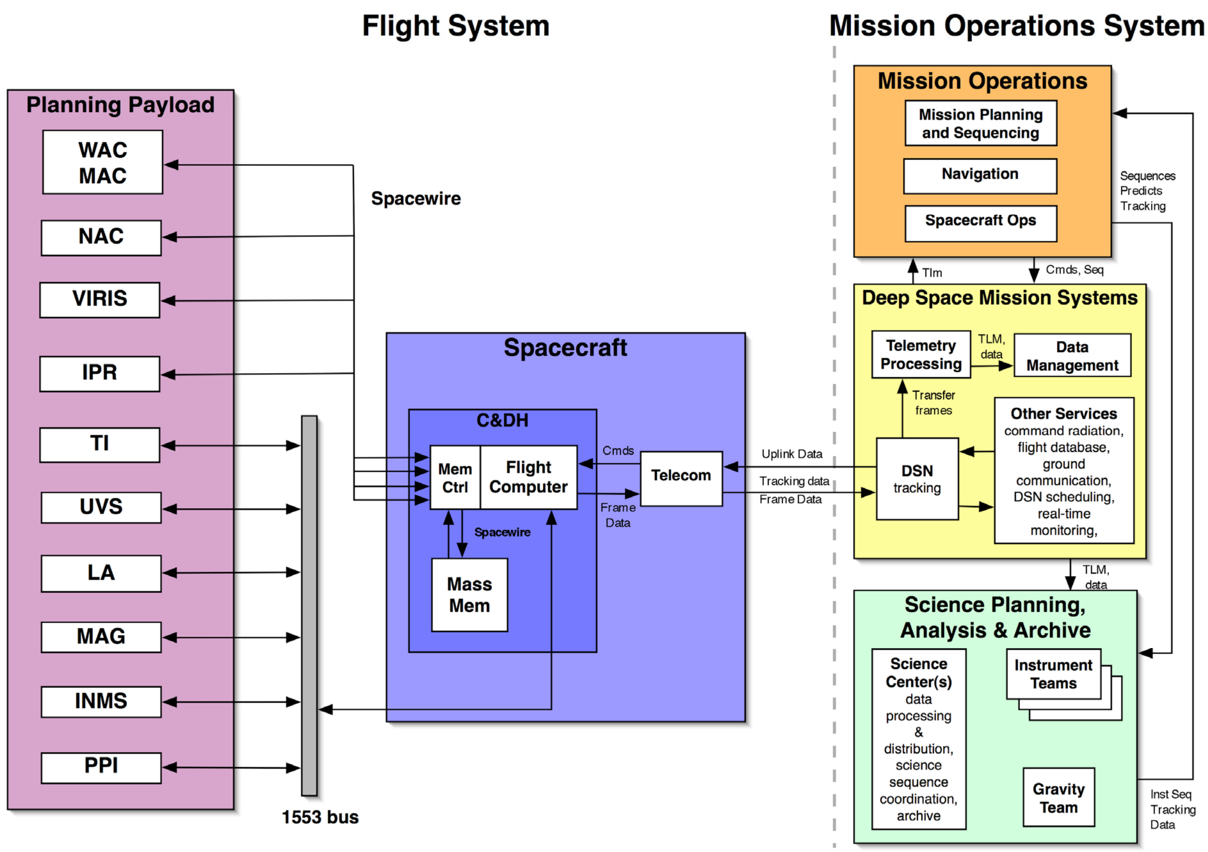


***Figure 4.6-1.** End-to-End Data Flow Diagram*

all players are using the same tools when planning;

- Science and mission planning tools to enable short (1 week) planning cycles, and update these tools throughout the mission;
- Rich online collaboration system to support remote planning and operations support;
- JPL provides a standard instrument GDS interface and tools to all instrument providers;
- Operate the spacecraft as a system and not a collection of subsystems;
- Use early cruise gravity assist flybys to test and demonstrate science and instrument interfaces and operations;
- Streamline arbitration process and collocate instrument mission planners to reduce communication delays and iterations;
- Develop planning process efficient for orbital operations and modify as necessary for tour operations;
- Implement a sequencing architecture that allows modular and parallel sequences for instrument operations, and allows non-interactive, independent development and uplink of selected commands;
- Constrain planning time, model flight constraints, allocate contentious resources (such as pointing and SSR space), develop science observation constructs for coordinated multi-instrument activities within the program's available resources;
- Post-launch maintenance to incorporate new technologies, tools and capabilities.

In addition there is expectation that emerging tools and technologies for JPL operations infrastructure and planned missions will be incorporated in the MOS to support efficient planning and operations. Some JEO investment is planned to ensure compatibility with JEO operations needs. Examples are:

- Integrated spacecraft state analysis tool that enables fewer people to safely operate the spacecraft;
- Standard instrument GDS interface;
- Planning tools to support early design and operations development.

4.6.4.3 DSN Scheduling Rationale

Similar to other deep space missions with long cruises, JEO uses economical DSN tracking in the Interplanetary phase. The planned DSN coverage is shown in **Table 4.3-4**. Weekly tracking is used to perform navigation and assess the health of the flight system. Additional tracking will be scheduled to support spacecraft and instrument calibration activities, science operations at the gravity assist flybys of Earth and Venus, and maneuvers to refine trajectory targeting before and after each flyby.

About 18 months before JOI, tracking is increased to provide additional navigation analysis and commanding support for the final preparation for JOI and the Jovian Tour. JOI approach is accompanied with significantly increased tracking and Delta-DOR tracks to ensure accurate JOI entry targeting. 70 m (or equivalent) tracking support for the JOI burn activities will be scheduled to augment the 34 m tracking to provide the best telemetry reception available at Jovian ranges.

Once in Jupiter orbit, tracking consists of daily 34 m passes to support science data collection and navigation. This routine is augmented around flybys to support the final navigation analysis and flyby science. During each flyby, tracking is augmented with 1–2 tracks of DSN 70 m antennas (or equivalent, such as 34 m arrays) to reduce science and mission risk.

One month prior to and after EOI, 34 m continuous tracking will be scheduled to support engineering and critical trajectory activities. 34 m continuous coverage will be scheduled for the remainder of the first 105-days to meet science coverage and targeting goals.

After 105 days, daily 8-hour 34 m passes will be used to support continued observations, return additional science data and support the navigation activities needed to maintain a stable orbit around Europa. This daily coverage will be continued into an extended mission should that be approved.

4.6.4.4 Data Processing and Science Planning

The rapid assessment of quick-look science data products, and rapid planning and replanning of science data collection will be needed over time spans of about 1 week. This short term activity planning cycle is needed to respond to short orbit periods late in the Jovian Tour phase, uncertain gravity field response in Europa orbit, and potential reactions to radiation induced events and degraded performance.

Recent experience from MRO and MER has shown that rapid data delivery and quick look processing as well as rapid decision making and activity planning are possible for the planning schedules needed by JEO. MRO has demonstrated the long term processes for delivering >100 Gb per day to distributed science centers. Those science centers have shown that they can quickly produce planning quality data products in one or a few days. MRO target selection processes take 3 days for nadir based targets and 1 week for complicated off-nadir coordinated targets. MRO acquires 10 times more targets per day than JEO is currently considering. MER has shown that one day turn around of science products to next day activity plans is possible over mission lifetimes as long as or longer than JEO's. The science planning tools for JEO will be developed and tested starting with demanding Europa orbit timing and complexity require–ments. Additional capabilities will be added to support flyby and Jupiter system observation needs. The required capabilities will be demonstrated in pre-launch system testing. Augmented capabilities will be added periodically based on experience from Interplanetary flybys and early Jovian tour activities.

JEO science activity planning and replanning flexibility will be needed to respond to flight system anomalies, timing errors, and non-deterministic processes. Flexibility will also be needed to respond to short term science discoveries as well, such as detected plumes and hot spots. For the most part, response to science discoveries will take the form of re-allocating target data priorities in future days to observe previously unconsidered sites.

The JEO data analysis and archiving plan provides rapid delivery of data to the science teams and scheduled delivery of products to the Planetary Data System (PDS). Depending on mission phase, daily data volume could range from 2 Gb at maximum range and a single DSN 34 m station, to more than 20 Gb for continuous tracking, shortest range, and allocation of excess link margin. The GDS will be able to keep continuous on-line access to low level data products and planning products for the entire mission. High level products are expected to expand the raw data set by at least an order of magnitude. Current storage and network capability is more than sufficient to manage the JEO data set.

Quick delivery and processing (<24 hours) of low level data products is required during the late Tour and early Europa Science phases to facilitate rapid planning and sequencing. Other mission phases will require data delivery over slightly longer periods of a few days.

The Ground Data System (GDS) will generate level-0 data products which consist of validated, assembled CFDP data units, packet streams, and channelized telemetry that includes instrument data products and engineering telemetry, navigation data, and spacecraft thermal, attitude and timing information. The GDS also delivers processed level-1 data products to the science teams. These are Experiment Data Records (EDR) consisting of instrument data products extracted from assembled packets and product data units, merged with ancillary engineering and navigation data, and catalogued.

Science teams will be able to access level-0 data within hours of Earth receipt. EDR processing will be largely automated and products will be delivered within 1–2 days.

Schedules for product delivery to the public, the scientific community and to the final PDS archive will be determined in the science AO. It is generally expected that PDS archive deliveries will be within 6 months of data receipt.

4.6.5 Jovian Tour Phase

In the Jovian Tour phase, the flight system will make routine and frequent observations of Jupiter, its satellites, and its environment. The Tour phase is divided into two science campaigns: Io Campaign and System Campaign. The JEO 30-month baseline tour trajectory enables substantial Jupiter system science in five major themes: satellite surfaces and interiors, satellite atmospheres, plasma and magnetospheres, Jupiter atmosphere, and rings, dust and small moons.

While complete assessment of all potential Jovian Tour scenarios is beyond the scope of this study, preliminary scenarios for selected flybys and assessments of potential imaging coverage and data usage for all of the satellite flybys are described in this section.

4.6.5.1 Tour Data Acquisition Scenarios

During the tour, each satellite gravity assist flyby typically happens within a day of a perijove passage. Weeks containing perijove passages and flybys have additional DSN tracking coverage scheduled. The tracking coverage supports the return of approximately 6–12 Gb per day. Non-perijove weeks allow the return of 2–4 Gb per day. The SSR can support collection and return of 17 Gb/flyby.

Flybys

Preliminary scenarios for selected flybys and for Jupiter monitoring have been developed. A timeline for the JEO mission at Jupiter is shown on **FO-11**. Satellite flybys, Jupiter monitoring and Io monitoring events are shown. Statistics for targeted flybys, non-targeted flybys and distant satellite viewing opportunities are detailed in **Table 4.6-3**. The events shown represent half of the available downlink data, leaving 50% of the downlink

Table 4.6-3. *System Science Observing Opportunities*

	Opportunities	Ranges (km)	Phase Angles (deg)	Ground Speeds (km/s)
Jupiter	33	560,000 – 1,000,000	10 – 100	
Flyby Encounters		(min. @ CA)	(±1 hr)	(peak @ CA)
Io	4	75 – 3125	15 – 168	3.8 – 9.4
Europa	6	100 – 1200	14 – 163	1.5 – 9.8
Ganymede	6	135 – 1566	10 – 161	1.9 – 6.5
Callisto	9	78 – 3219	10 – 168	1.1 – 8.4
Distant Viewing Opportunities (<500,000 km)				
Io	16	56,000 – 480,000	3 – 38	
Europa	8	81,000 – 449,000	32 – 155	
Ganymede	10	148,000 – 398,000	10 – 175	
Callisto	2	205,000 – 311,000	139 – 168	

data volume as margin for future detailed considerations of the science objectives. And while no data allocations have been made for these system science activities, the 14–28 Gb returned per week allow very large numbers of observations to be scheduled.

The JEO planning payload is intended to collect data in a close near-circular orbit of Europa. Ground speeds, altitudes, and lighting conditions are consistent in Europa orbit but vary drastically for flybys. Furthermore, to effectively use some of the instruments, flight system slews may be needed to provide the apparent ground motion (when the actual motion is too fast or too slow) needed by pushbroom style line-array detectors.

In all cases, flybys will be conducted within the relevant probability of impact requirements for planetary protection (e.g., 10^{-4} for Europa), by agreement with the NASA PPO.

The flyby scenarios are exemplified by the low altitude Io flyby (I4) as shown on **Figure 4.6-2**. A sample observation profile is shown detailing the number and timing of observations for each of the instruments. The data volume plot shows the accumulation of data in the SSR and compares it to the maximum value of 17 Gb. A margin of 3 Gb is set aside (for such things as potential opnav images, UVS aurorae observations and unique observations of the Io torus) as a preload to the analysis. This is to accommodate data acquisition outside of the closest approach (C/A) ±30-minute timespan of the analysis. The speed of the orbiter, the groundtrack speed, solar phase angle as viewed by the orbiter, and altitude above the surface are also shown. **FO-11** shows the Io example as well as example flyby scenarios for Europa, Ganymede, and Callisto.

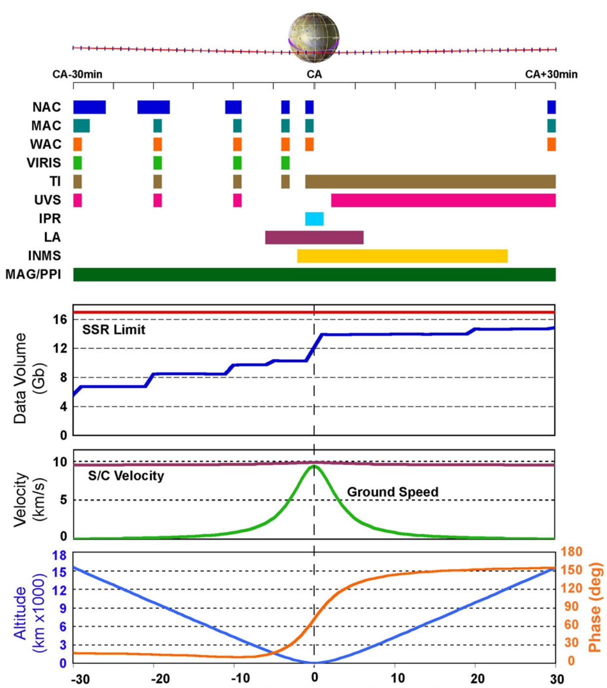


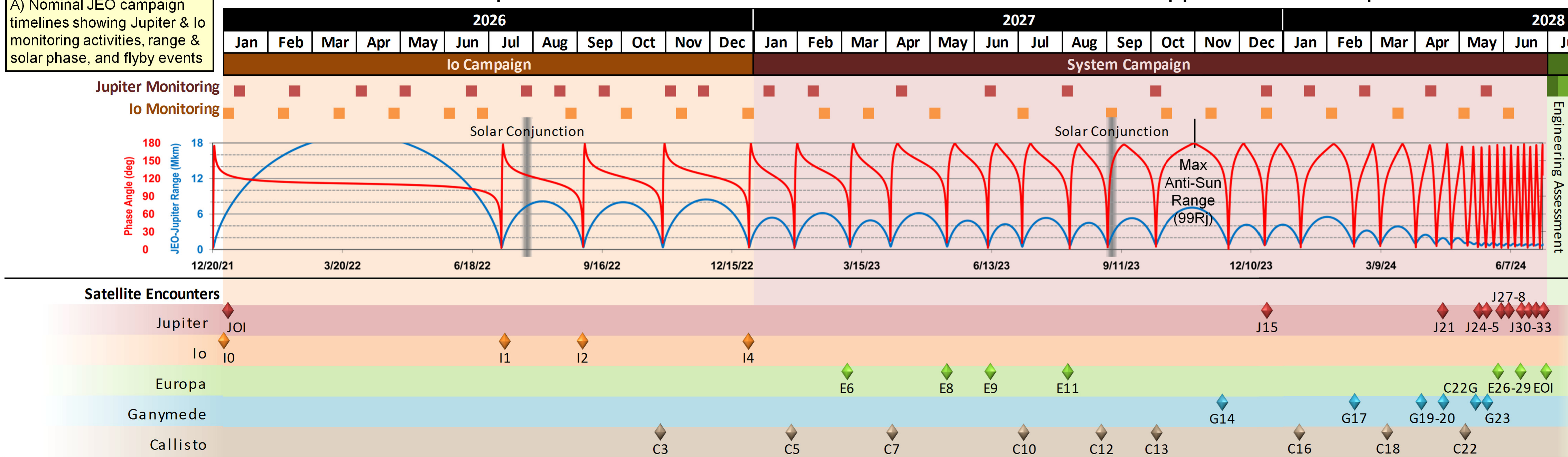
Figure 4.6-2. *Io flybys, I4 shown here, have significant data volume available for intensive investigations by all instruments. Lighting, altitudes, and ground speeds are typical for all Io flybys and most early Tour flybys.*

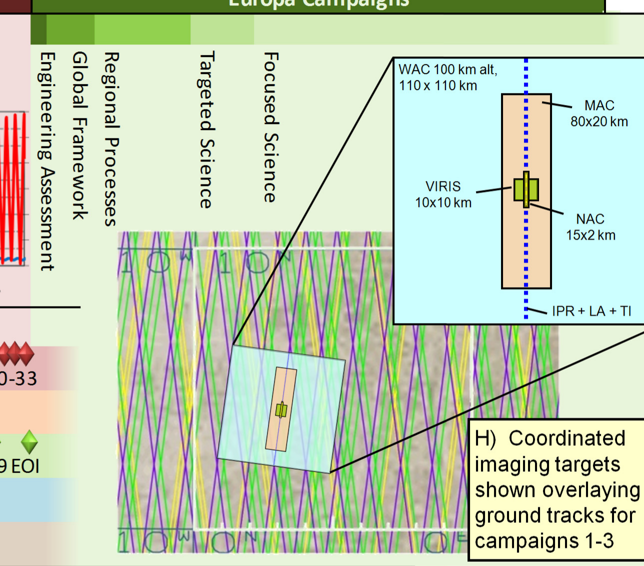
The Io example represents a notional science sequence. Early observations collect global views at moderate to low resolution. Observations closer to C/A have higher resolution but reduced extent. Because the period after the C/A is at high phase angles (in the dark) imaging observations are limited to the lit limb and thermal profiles. Within 10 minutes of C/A ground speeds are too fast for most of the imaging instruments, other than WAC and limited VIRIS observations. Near C/A the IPR will observe at full uncompressed rates for 2 minutes to sample the subsurface. The Altimeter will be operated as well for IPR processing context. WAC images will also be collected for topography context. Independently, the INMS will be operated to collect in-situ samples of plume material near C/A. The fields and particles instruments (MAG and PPI) will have been on continuously during the entire mission phase and will also collect Io data during the flyby.

The flight system will be able to point the orbiter instrument deck to Io nadir and the INMS to the ram vector at closest approach using the relatively slow reaction wheels (this avoids contaminating the INMS measurements with hydrazine exhaust). As a consequence of this, the orbiter will have reduced pointing control in the along track direction during the central 10–15 minutes of the flyby (but be nadir pointed at CA). This will result in a pointing lag with respect to the nadir tracking direction by less than 10 degrees. This constraint will only be present during the early flybys (mainly in the Io Campaign). After that the slew accelerations rates will be low enough for the orbiter to track nadir throughout the encounters.

The JEO Operational Scenario Maximizes Science Data Return and Opportunities to Explore New Discoveries

A) Nominal JEO campaign timelines showing Jupiter & Io monitoring activities, range & solar phase, and flyby events





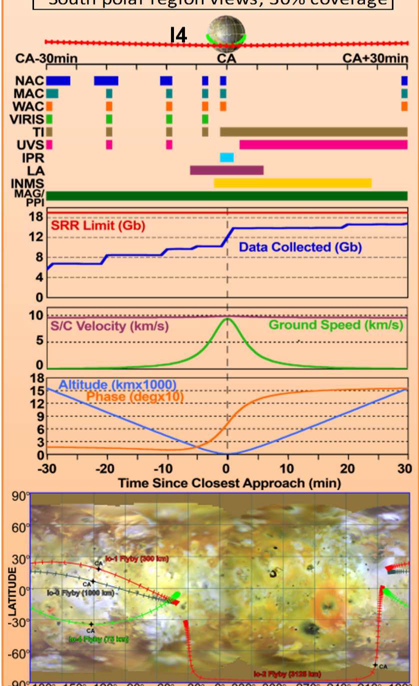
H) Coordinated imaging targets shown overlaying ground tracks for campaigns 1-3

C) I4 flyby details. Map shows the ground tracks of all flybys

Io

No. of Flybys	Closest Approach		
	Altitude (km)	Phase Angle	Ground Speed (km/s)
4	75-3125	15°-168°	3.8-9.4

Science
- In-situ plume sampling
- Sub-surface radar measurements
- South polar region views; 30% coverage

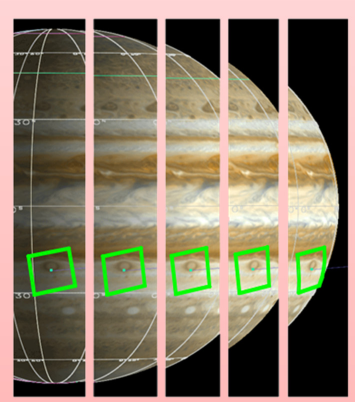


B) Jupiter monitoring example scenario shows generous capability

Jupiter Monitoring

No. of Flybys	Closest Approach		
	Altitude (km)	Phase Angle	Ground Speed (km/s)
33	56k-1000k	10°-100°	-

Science
- 3Tb Data Volume
- Jupiter & Io Monitoring Bi-weekly
- 2k-3k NAC images can be returned per we



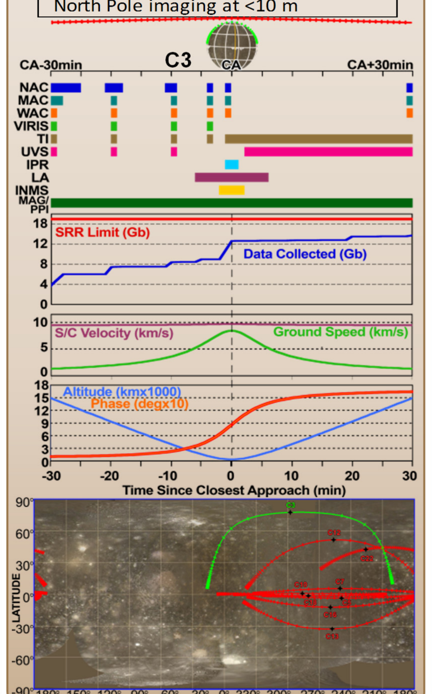
Inst.	Resolution	Data Volume	Number of Images
NAC	14 km	8 Mb	Hundreds
MAC	140 km	8 Mb	4
IRS	350 km	307 Mb	4
UVS	1400 km	25 Mb	24
TI	3500 km	0 Mb	4

F) C3 flyby details. Map shows the ground tracks of all flybys

Callisto

No. of Flybys	Closest Approach		
	Altitude (km)	Phase Angle	Ground Speed (km/s)
9	78-3219	10°-168°	1.1-8.4

Science
- 75% coverage ≤200 m
- >10,000 km for IPR & LA profiles
- North Pole imaging at <10 m

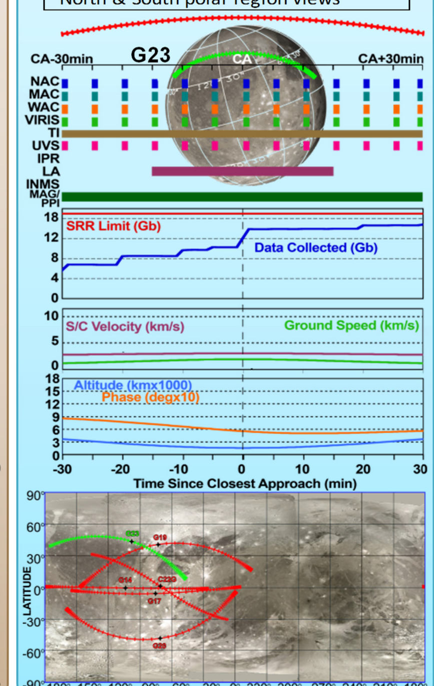


E) G23 flyby details. Map shows the ground tracks of all flybys

Ganymede

No. of Flybys	Closest Approach		
	Altitude (km)	Phase Angle	Ground Speed (km/s)
6	135-1566	10°-161°	1.9-6.5

Science
- 50% coverage ≤200 m; 10% ≤50 m
- >10,000 km for IPR & LA profiles
- North & South polar region views

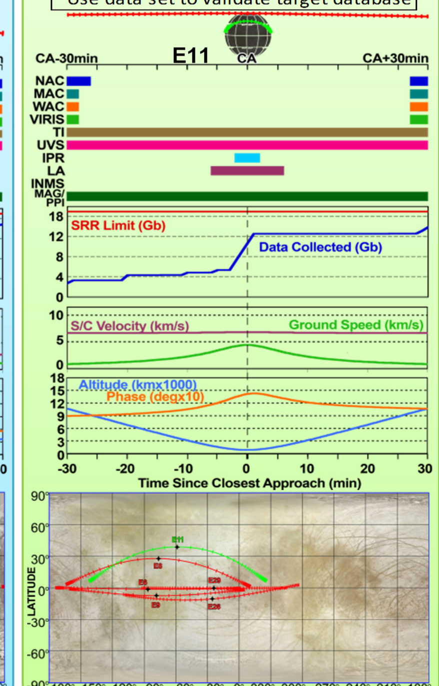


D) E11 flyby details. Map shows the ground tracks of all flybys

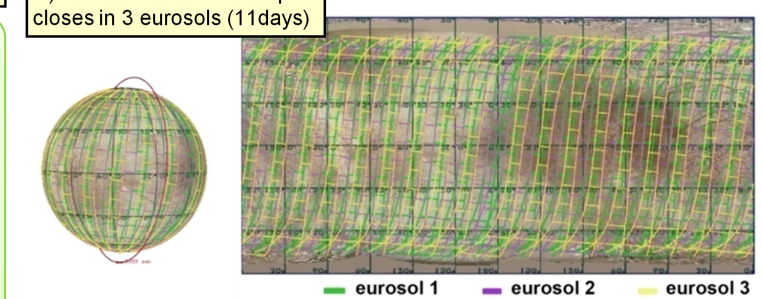
Europa

No. of Flybys	Closest Approach		
	Altitude (km)	Phase Angle	Ground Speed (km/s)
6	100-1200	14°-163°	1.5-9.8

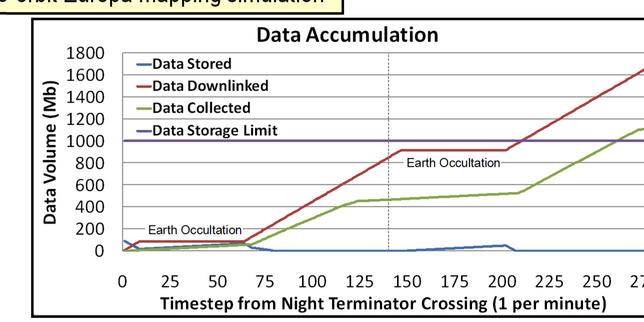
Science
- 60% mapped @ ≤200 m/pixel
- Calibrate IPR for Europa orbit science
- Use data set to validate target database



G) 200 m Global color map closes in 3 eurosols (11days)

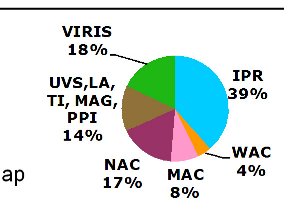


I) Two orbit Europa mapping simulation



J) Summary of Europa science phase with breakdown of data volume by instrument

Europa Science Phase
- Mapping Data Volume 1.25 Tb
- 1700 Imaging Targets
- 200 IPR targets
- 200m Global Color Map
- 200m and 100m Global Stereo Map



Figures 4.6-3 through 4.6-6 show Cartesian maps of the Galilean satellites with the flyby groundtracks from the current tour trajectory superimposed. Groundtracks shown in green represent flybys with example scenarios. Groundtracks shown in red were examined for global imaging opportunities but do not have detailed scenarios. Combined with lighting information, these indicate the extent to which the surfaces can be mapped by JEO in the baseline Tour. Figure 4.6-3 shows the groundtracks for all of the Io flybys. The groundtrack for the first Io flyby (I0) is shown in dark grey. This flyby precedes JOI by just a few hours and will allow limited science and, for this study, is assumed to have no imaging contribution. Future studies will determine whether significant science can be achieved for this encounter within risk guidelines. The start and end longitudes are similar for all groundtracks. This together with the phase angles means that global coverage will be collected mainly in one hemisphere (centered on 210 degrees West). Imaging at resolutions of <1000 m/pixel will be possible over approximately 50% of Io's surface. Pixel resolutions of <200 m for 25%, 5% for <50 m and very small (<0.01%) for <10 m are possible. This last small number is due to the very high speeds and low durations of the low altitudes needed for maximum resolutions. Two Io flybys have closest approach altitudes less than 2000 km. This allows the collection of laser altimetry and IPR data (at altitudes <1000 km). Laser altimetry will be collected for 8000 km of total track length and IPR swaths will be collected for a total of 2 minutes for a total length of 1000 km. The IPR tracks are shorter due mainly to data volume allocation limits.

Europa, Callisto, and Ganymede have a higher diversity of flyby opportunities in altitudes and phase angles and so will allow greater global coverage.

Figure 4.6-4 shows the 6 Europa flyby groundtracks on a map of Europa. The green line represents the Europa E11 flyby which is the opportunity selected for the IPR calibration. The calibration requirements were for less than 1000 km and 7 km/s and at least 6 months prior to EOI for analysis. This flyby occurs 11 months prior to EOI. Closest approach is at 866 km and the ground speed is 4.4 km/s. Closest approach is in the dark so imaging is largely global at the beginning and end of the encounter. The IPR will use 4–6 Gb of the available data volume for the IPR calibration leaving more than 10 Gb for global imaging, composition studies and studies outside of the flyby closest approach period. Taken together, the 6 Europa flybys allow 60% of Eurpopa's surface to be imaged at ≤200 m,

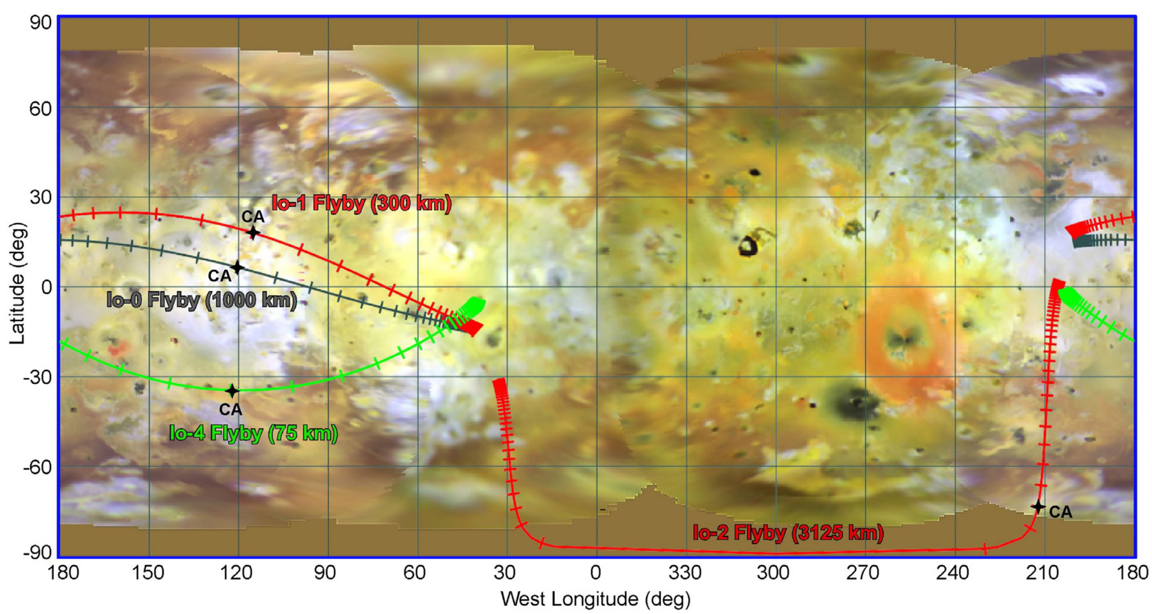


Figure 4.6-3. Io flyby geometry allows excellent viewing of one hemisphere, the South Polar region, and in-situ measurements of volcanic plumes.

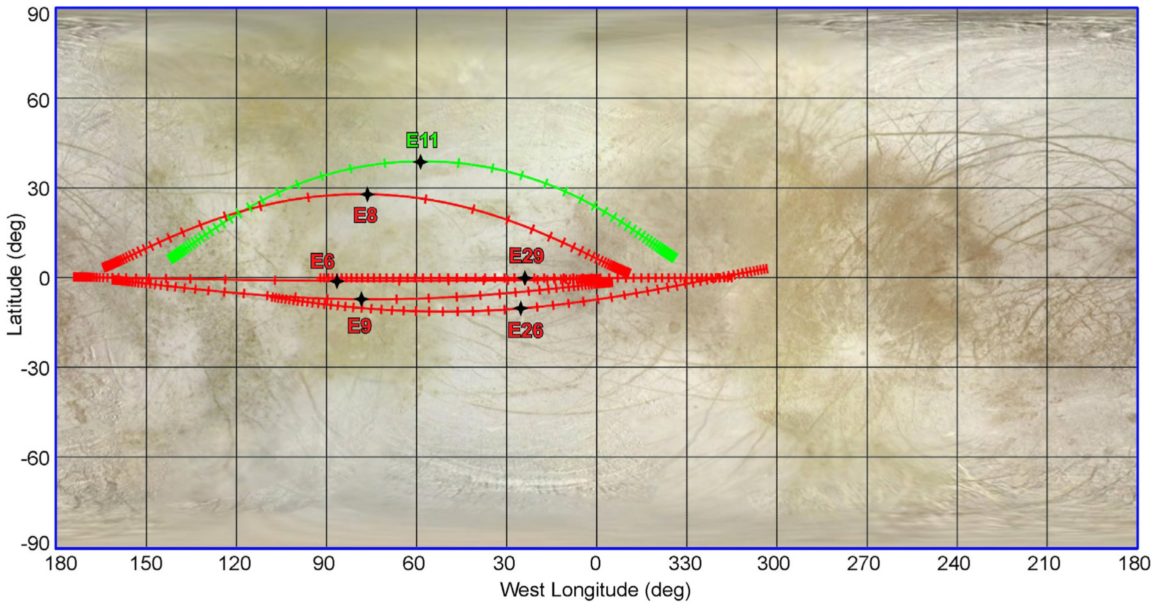


Figure 4.6-4. Europa flybys allow excellent imaging and Ice Penetrating Radar observations to calibrate instruments and prepare for Europa mapping operations.

15% at ≤50 m, and about 0.01% at ≤10 m. IPR can collect 6600 km tracks and the laser altimeter 19000 km tracks.

The 6 flybys of Ganymede are shown in **Figure 4.6-5**. The total coverage allowed by geometry and lighting is 50% at ≤200 m, 10% ≤50 m, and about 0.02% at ≤10 m. The long slow flybys near the end of the Tour (C22G and G23) allow excellent hi resolution imaging opportunities and views of both poles at incidence angles from 15–20 degrees. IPR can access 17000 km at varied latitudes suggesting the use of reduced rate IPR over most of this range. The laser altimeter will be able to measure 28000 km.

With 9 flybys, Callisto has by far the most varied and complete set of opportunities. Shown in **Figure 4.6-6**, the Callisto flybys allow 85% of the surface to be imaged at ≤1000 m, with 75% at ≤200 m. Because many

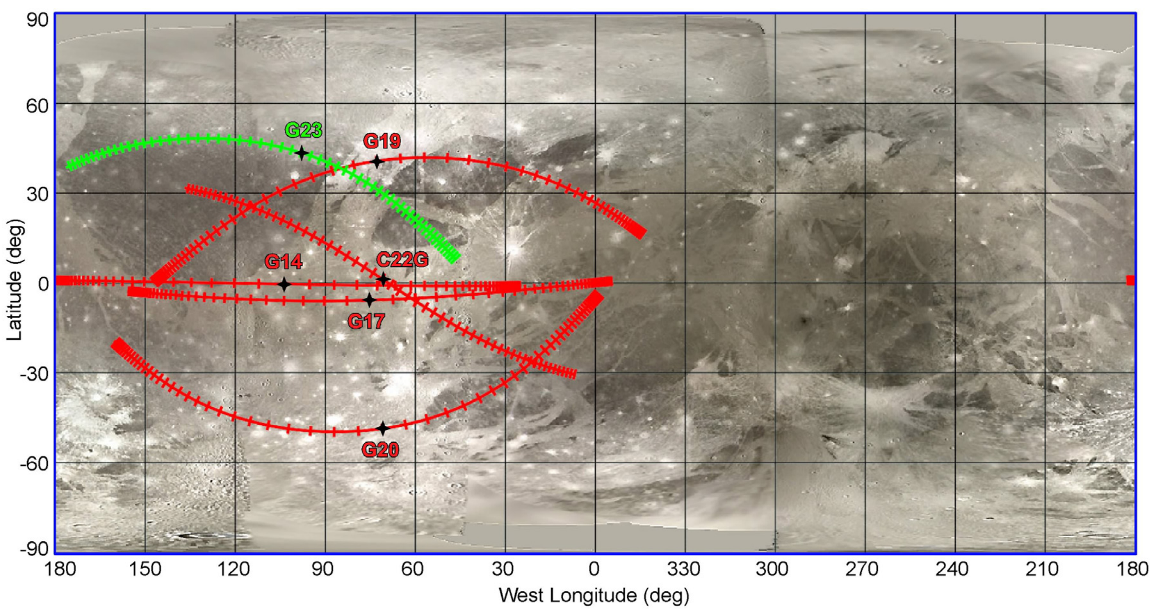


Figure 4.6-5. Ganymede flybys offer excellent imaging, composition and IPR investigations over broad regions including examination of both polar regions and high resolution at low latitudes.

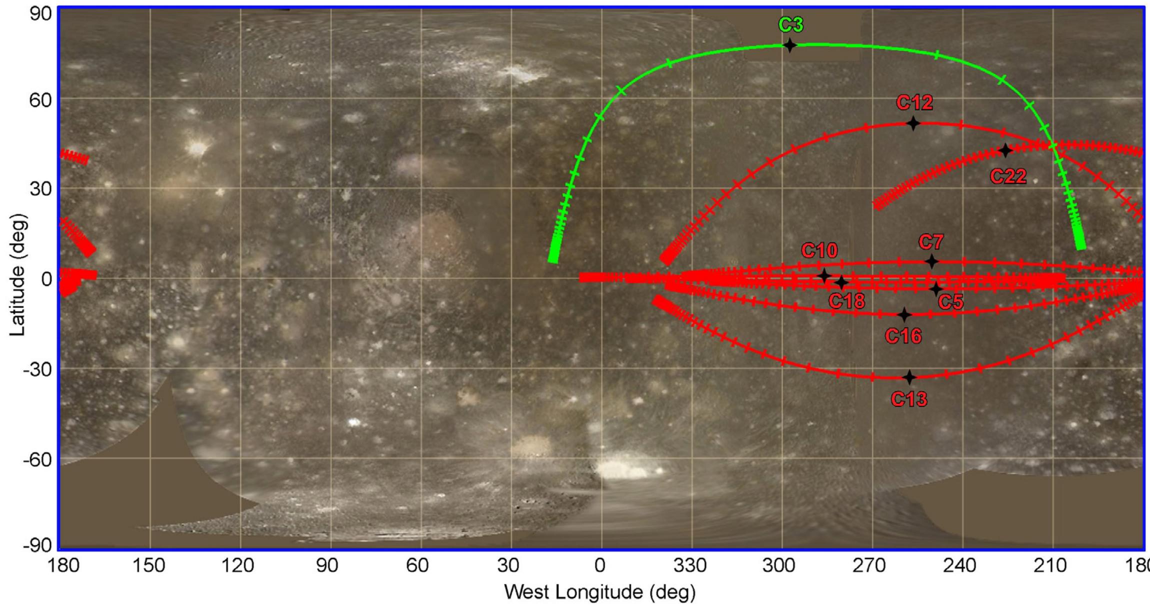
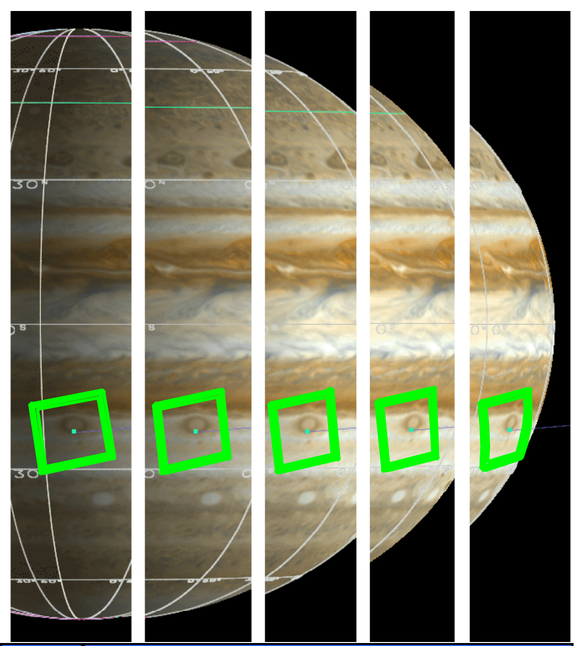


Figure 4.6-6. Callisto flybys offer highly varied observation opportunities over most of the satellite's surface.

of the closest approaches are either in the dark or at higher altitudes (above 1000 km), only about 5% can be acquired at ≤50 m and 0.01% at ≤10 m per pixel resolution. IPR and LA can achieve 15,000 tracks and 30,000 km tracks of data collection respectively. The C3 flyby includes a high latitude overflight of the north pole region.

Jupiter and Io Monitoring

High level scenario analysis shows that large numbers of monitoring images can be collected to support observations of Jupiter's atmosphere both globally with MAC, VIRIS, UVS, and TI and the periodic tracking of hundreds of features with the 9-color NAC. Because the large capacity SSR allows many observations to be collected over a short period of time, dynamic observations are possible (e.g., movies) even in conjunction with other observing activities such as Io monitoring. **Figure 4.6-7** shows an example analysis of Jupiter monitoring from 1.4 million km. This case occurs twice per Jupiter orbit and shows good sunlit viewing at a variety of close ranges and phase angles. This example shows that for ranges greater than twice perijove, observing conditions are very good for tracking dynamic features in Jupiter's atmosphere. The table included in the figure shows that basic views of Jupiter including composition data, and multicolor images of hundreds of features are



	Resolution (km)	Data Volume each (Mb)	Number of Images
NAC	14	8	Hundreds
MAC	140	9	4
IRS	350	743	4
UVS	1400	25	24
TI	3500	0.1	4

Figure 4.6-7. Jupiter monitoring example shows feature tracking. The green box represents the NAC FOV at 1.4 million km.

possible. Many of the images can be collected in the form of movies to examine dynamic structures at highest resolutions.

Io monitoring goals are, per Jupiter orbit, to collect a wide variety of data types including global maps (once per orbit), plume inventories (roughly 5 deg longitude, once per orbit), plume movies (30–40 frames) when plumes are on the limb, and images sampled over a wide variety of timescales. One full set of these images would occupy roughly ½ of the SSR and would be downlinked in a few days. Subsets of these would be collected each Jupiter orbit in combination with other activities.

Other System Science: Magnetotail, Radio Occultations, Rings, Dust and the Io Torus

No scenarios have yet been constructed for the observation of Jupiter's Rings, dust environment or the Io torus. The large variety of range and phase space options, and the large data return capability should enable vigorous investigations of these features.

Analysis of opportunities to examine the magnetotail shows the best anti-solar distance to be 99 R_j during orbit C13. Two other opportunities exist at nearly 60 R_j. The MAG and PPI experiments will collect data continuously during the Jovian Tour and Europa Science campaigns. MAG roll calibrations will be performed once or twice per month during downlink sessions. The articulated HGA allows 2-axis rotations without driving operations complexity.

While radio occultation geometry is highly sensitive to the tour trajectory, there are at least 5 opportunities for radio occultation experiments for each of the Galilean satellites and 22 for Jupiter. Radio occultation experiments will be dual frequency X-band and Ka-band with frequency stability provided by the USO.

4.6.5.2 Tour Data Return

The science data return strategy for the Jovian Tour phase is simple and repetitive. The 16+1 Gb hybrid SSR allows rapid and long term data collection at faster rates than the downlink rate. Days of downlink can be stored allowing the possibility of data retransmission in the event of a missed DSN pass, weather outage, link noise or orbiter safing.

Science observations and data downlink will largely be decoupled through the use of the gimbaled high gain antenna. Data volume will be allocated and factored into science sequences. Margins and flexible sequencing strategies will allow DSN track times to change without disrupting science observations. With time to process and space in the SSR to work with, data reduction techniques such as windowing or selective downlink become possible.

Data rates vary with Earth range, from 64 to 144 kb/s (see **Figure 4.6-8**) using standard link design methods (90% weather, 20 deg station elevation, maximum Jupiter hot body noise). For routine daily downlinks in the tour, the standard method is the baseline to save complexity and cost. The variable data rate method outlined in the next section is ideal for Europa orbit but is not desirable in the Tour phase.

Figure 4.6-9 shows the daily data volumes varying from 2 to 4 Gb for the nominal 1 track per day DSN schedule. In weeks near perijove

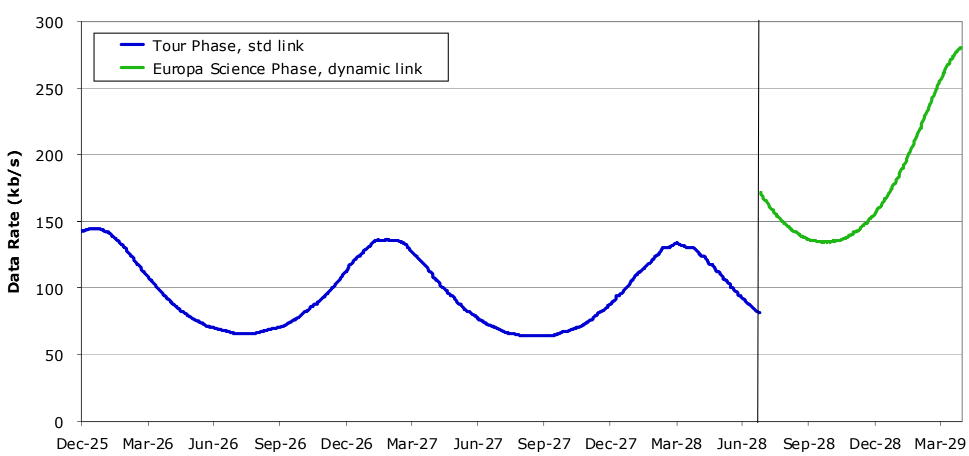


Figure 4.6-8. *Average Data Rates for 34 m DSN Stations.*

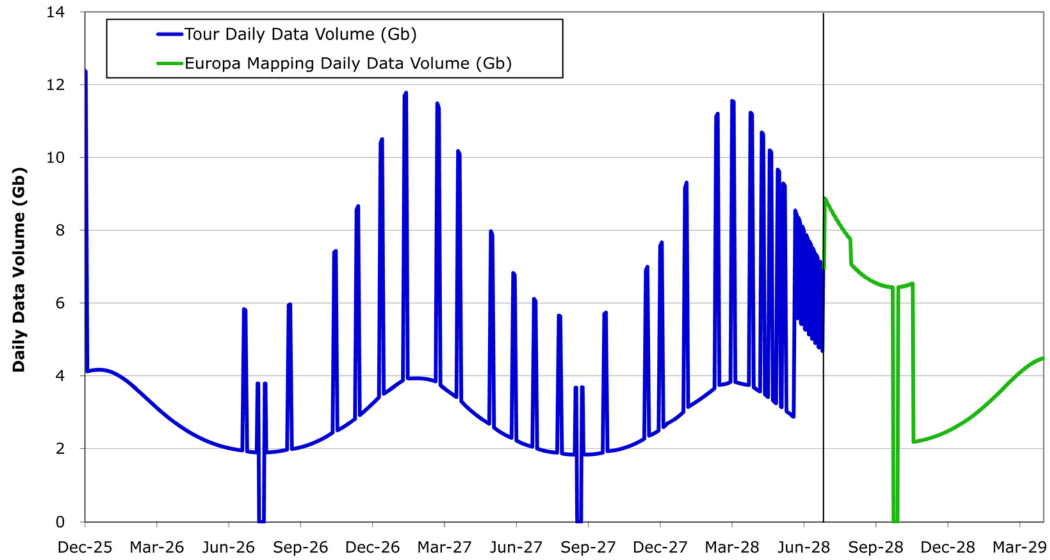


Figure 4.6-9. *Daily Data Volumes. Sharp peaks are from increased DSN tracking for flyby events. Dropouts reflect Solar Conjunction.*

and the satellite flybys, tracking will be increased to 2–3 tracks per day increasing the returned data to 6–12 Gb per day. The additional tracks will be scheduled both just before the flyby to ensure large SSR capacity for the flyby and just after the flyby to empty the SSR and accommodate Jupiter and Io monitoring observations. The data gaps in the figure represent Solar Conjunction time periods where no data return is possible.

4.6.6 Europa Science Phase

The most challenging issues driving the design and operation of the JEO mission arise from the Europa science operations scenarios. This section will describe the science data acquisition strategies and operations scenarios for the Europa Science phase.

4.6.6.1 Europa Data Acquisition Scenarios

During Europa Campaign 1, the flight system orbits at 200 km altitude for 8 eurosols (28 days), and the mission's highest priority data is acquired. During the first 4 eurosols (Phase 1A), gravity, altimetry, and magnetometry perform a first-order characterization of the ocean. The WAC attains a global color map, and the IPR searches for shallow water. During the next 4 eurosols (Phase 1B), the WAC acquires a stereo map, and the IPR performs a deep ocean search. Profile-mode observations are performed by the infrared spectrometer and the thermal instrument. Coordinated targeted observations are performed by the multiple optical remote sensing instruments, and target selection will use existing Galileo data and data obtained during the Jovian Tour flybys. Global maps obtained during this campaign will be used to select target observations in later campaigns.

Regional-scale processes are the science emphasis of Europa Campaign 2. Characterization of the gravity field during Europa Campaign 1 allows a relatively stable orbit to be selected for Europa Campaign 2, where the flight system moves to a 100 km altitude orbit for the remainder of the mission. From this distance, optical remote sensing instruments provide 2 times better spatial resolution but only half the longitudinal area coverage. The duration of the campaign is expanded to 12 eurosols (43 days) to accomplish the global mapping and profile distribution goals. Gravity, altimetry, and magnetometry improve their characterization of the ocean. The first 6 eurosols (Phase 2A) again emphasize a shallow water search by the IPR and production of a global map by the WAC, and the second 6 eurosols (Phase 2B) emphasizes a deep ocean search by the IPR and stereo mapping by the WAC. Profile-mode observations continue by the infrared and spectrometer and the thermal instrument, also now at higher spatial resolution. Global mapping at higher resolutions generates higher data rates. This leaves significantly less data volume per day for coordinated targeted observations.

Europa Campaign 3 emphasizes Targeted Processes. Targets of these synergistic observations are specific high-priority features and terrains recognized from data obtained earlier in the mission. Most of the downlink resource goes to targeted observations that occur during this campaign.

The emphasis of Europa Campaign 4 is to focus in on science discoveries achieved earlier in the mission. The principal priority is to obtain "chains" of targeted observations that attack these new discoveries and newly found priorities based on previous observations. A list of potential observation scenarios includes:

- Create a finer global and regional grid of profiling observations (IPR, VIRIS, TI), particularly in discovery areas. This would be routine mapping data collected on particular orbits;
- Continue gravity and continuous laser altimetry and fields and particles measurements;
- Collect additional coordinated target sets to investigate new discoveries and priorities and to improve coverage and characterization of candidate future landing sites;
- Collect off-nadir NAC stereo images using left/right roll-only pointing;
- Propellant permitting, plan a campaign of lower altitude operations for improved measurements (altitude depends on propellant allocation and orbit stability analysis through Europa Campaign 3);
- Monitor Io and Jupiter for several orbits, 1 to 2 times per week. Date selection gives range of resolution, phase and longitude.

Except for coordinated targeted observations, most science data collection is continuous and repetitive. Particles and magnetic field investigations (MAG and PPI) operate continuously and the LA profiles the surface continuously for the entire mission phase. The TI profiles the surface continuously for Europa Campaigns 1 and 2 and then is operated sporadically to monitor hotspots or other areas of interest. The VIRIS, in point mode, profiles the dayside of every other orbit. Every other orbit the WAC collects a swath of moderately compressed imaging data over 80% of the dayside. On alternate orbits, the IPR collects a data reduced sounding profile over 90% of the dayside surface.

The WAC images in two modes, full color (3 colors + panchromatic) and panchromatic only modes for stereo mapping coverage (with a factor of 4 difference in data rate). The WAC data will be compressed with a slightly lossy factor of 4. At 100 km WAC data rates are more than twice the rates from 200 km. The early portions of Europa Campaign 1 will collect global color images from the WAC. After completing the global map, stereo coverage at lower rates will be collected until the end of the campaign. Multiple images allow improved stereo processing.

IPR data are collected in two different modes. The shallow water search mode will be used in the first half of Europa Campaigns 1 and 2. The deep ocean search mode will be used in the second half of Europa Campaigns 1 and 2. The shallow mode collects data at 280 kb/s and the deep mode collects data at 140 kb/s.

The data volumes for the 2-orbit repetitive cycle are allocated based on coverage extent needed. Precise timing is not specified, however. This allows adjustment of the image or sounding start times to allow coverage of both polar regions. These allocations allow close spacing at high latitudes in both hemispheres providing planning margin for the WAC or for radar data processing advantages for the IPR.

The continuous and alternating orbit data collection activities represent about 2/3 of the daily average downlink data volume in Europa Campaigns 1 and 2. The data are collected at low enough rates that most of the data are downlinked in near real-time, requiring very little of the 1 Gb SSR storage capacity. The continuously operating instruments fill the SSR by about 15% during Earth occultations and that is rapidly downlinked after occultation exit. This strategy allows the remaining 1/3 of the daily data volume to be used for coordinated target observations over selected sites at Europa. Either imaging or IPR targets can be acquired at nearly any time in either orbit type.

Figure 4.6-10 shows the 2-orbit cumulative data volume usage for the instruments and the downlink. The SSR state and limits are shown to highlight minute-by-minute usage. The

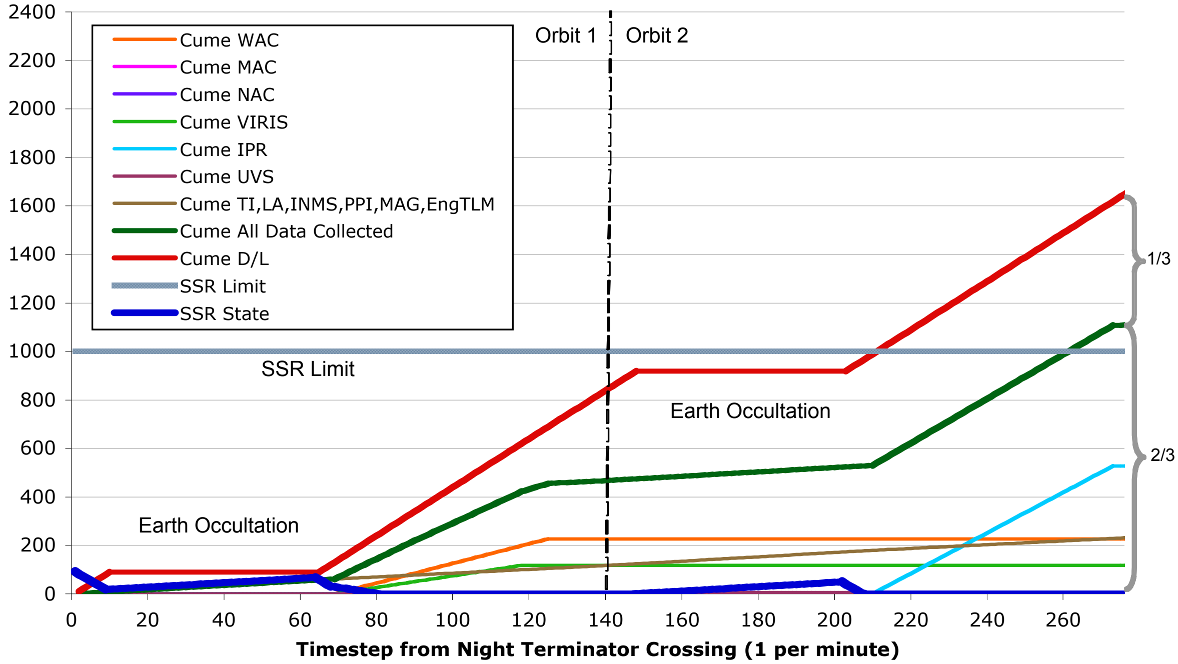


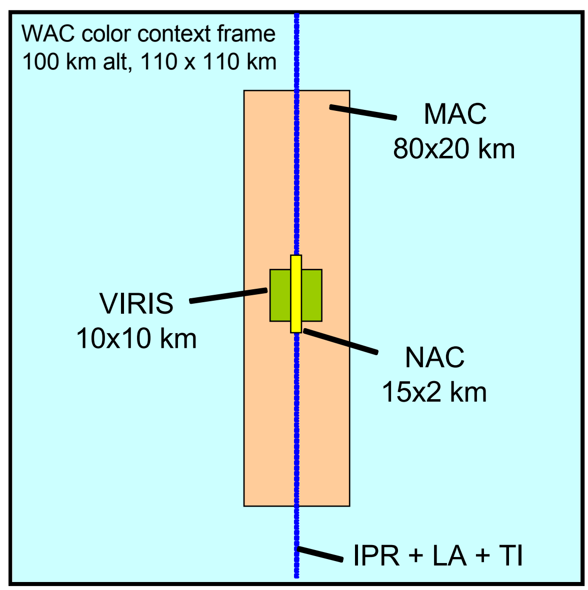
Figure 4.6-10. Cumulative data volume for a 2-orbit repeating cycle

simulation is per minute and does not account for latencies in data transfer, compression or encoding, which are assumed to be small. Estimates for occultation start/end times which include orbit period, occultation durations, DSN lockup times and ephemeris timing errors.

The example is for the beginning of Europa Campaign 1. A power profile for the same two orbit scenarios can be found in **Figure 4.4-5**.

There are two types of target data sets, coordinated target observations, and full resolution IPR. Coordinated target observations are: MAC monochromatic imaging (orange, 10 m/pixel), VIRIS imaging (green, 25 m/pixel, 700 wavelengths), NAC imaging (yellow, 1 m/ pixel), and a low-data rate IPR profile (blue, 60 seconds of data at 140 kb/s). The laser altimeter is simultaneously operating in profiling mode. Full resolution IPR data sets are based on 30 sec of data at 30 Mb/s, approaching the 1 Gb capacity of the SSR, and cannot be taken at the same time as coordinated target observations.

Figure 4.6-11 shows a view of the coordinated target observations, with scales based on a 100 km orbiter altitude. Each coordinated image represents about 290 Mb of data collected in about 1 minutes' time. The SSR holds this data until it can be downlinked



Data Volume for Coordinated Images

MAC 80x20 km	60	Mb
NAC 15x2 km	120	Mb
VIRIS 10x10km	100	Mb
IPR+LA+TI	10	Mb
Total	290	Mb

Figure 4.6-11. Coordinated Target Images

(along with the other data collected). On average, less than one target per orbit will fit in the data stream. Two coordinated targets can be collected at a time for delayed downlink.

The IPR full resolution targets are 900 Mb and only one of these can be collected at a time. More than 1900 targets of both types are expected to be returned in the Europa Science phase. This provides considerable margin over the 1000 targets required by the JJSDT.

Target acquisition will be via on-board, ephemeris driven software. The Flight System will have a shape model of Europa and an orbit ephemeris. Targeting software will calculate the precise time to image a selected site (lat, lon, alt) as it passes into the instrument field of view. Updated ephemeris files will be uplinked to the flight system as needed to maintain the desired accuracy. Lists of targets to be acquired and corresponding imaging parameters will be developed and uplinked to the flight system every few days. To speed up the selection and file development process, targets can be selected by ground software using data volume modeling and priority based selection criteria. Similar to MER and MRO science prioritization processes, targets and priorities will be selected by a subset of the Project Science Group (PSG, refer to §2.5.2.2) and placed in the target data base. New targets can be added at any time and software target lists will be reviewed by science teams before uplink.

Data reduction and compression strategies vary by instrument and by campaign. **Table 4.6-2** shows payload operational characteristics including the data rates, data reduction factors, and instrument duty cycles and data volume collected for the 2-orbit repetitive cycle and for the 200 km and 100 km orbits.

Mapping sequences will be updated and uplink products built and tested once per week. The data collection profiles and patterns (orbit repeat intervals, collection lengths, start locations, etc.) will be based on previous week's planning reflecting the adjustment of pre-arrival plans. The collection profiles will be developed from activity template menus to reduce development and verification schedules. As mapping progresses, the short planning cycle enables the adjustment of data collection profiles to avoid redundant coverage or recover observation opportunities lost due to telecom link outages, spacecraft engineering events (e.g., OTMs), or safing events. Routine engineering activities such as OTMs, reaction wheel momentum desaturation, and health and safety activities will be planned and uplinked to the orbiter on a weekly basis, coinciding with mapping sequence uploads.

Coordinated target observations are planned several times per week based on the remaining data volume resources from the weekly mapping sequences. A target data base will be maintained with prioritized target locations (lat, lon, alt, extent). Based on available data volume, SSR state, DSN schedule, ground track locations, and target priority, targets will be selected, by ground software, for one to two day planning cycles. Only targets predicted to pass under the nadir track of the orbiter will be considered for selection. Target lists will be sent to the orbiter and will be executed via ephemeris driven on-board sequencing software. The short planning duration is needed to accommodate large ephemeris errors based on poor gravity field knowledge early in the orbiting mission. The number of targets will vary with available data volume but will average fewer than one target per orbit.

4.6.6.2 Europa Science Data Return

In the Europa Science phase, data acquired by the science instruments will either be stored on the SSR or transferred directly to Earth in the downlink stream. The C&DH will prepare and/or process the science data (compression and frame encoding) then route through the SDST for downlink. All acquired data will be transmitted to the DSN. For each week during the mission, data volume estimates will be provided to the ops teams based on the scheduled DSN tracking for the period. The data volume estimates will be used to verify the science activity plans and to determine data volume availability for target selection in the coming one week period.

The SSR will function as a short term buffer for data acquired while the flight system communications are occulted by the Earth or when data is collected at aggregate rates exceeding the downlink rate. The 16 Gb SDRAM partition of the SSR is assumed, for planning purposes, to have failed due to radiation effects, by start of the Europa Science phase. For most orbits, 10–15% of the 1 Gb CRAM SSR science partition will be needed for storing data from the continuously operating instruments while in occultation. Up to once or twice per orbit, a coordinated target observation will be collected and stored in the

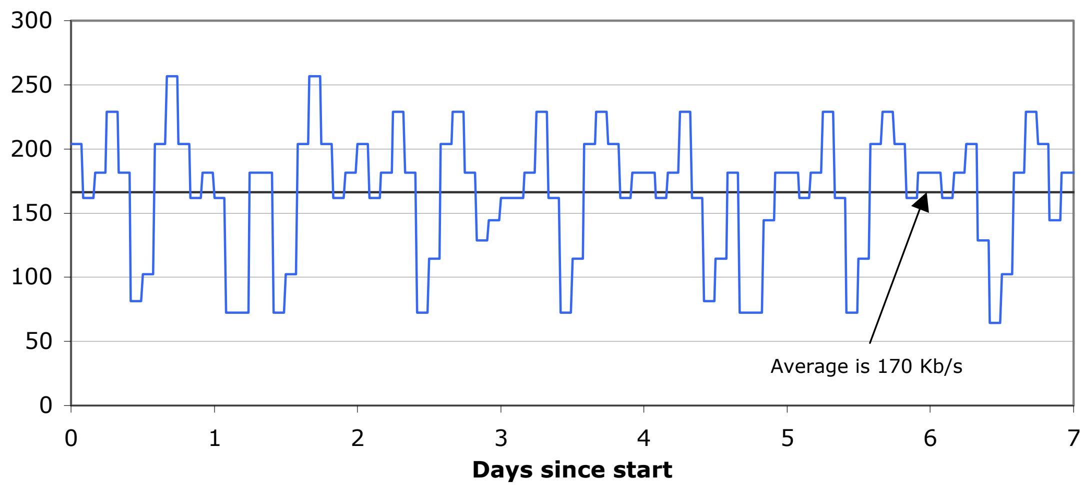


Figure 4.6-12. Orbit-to-Orbit Data Rate Variation

SSR. The target observation sizes are constrained to fit, with margin, into the SSR. The data will be queued with all other data for subsequent downlink. Buffer architectures and queuing schemes have not yet been considered. The small SSR can be used for longer term storage of very small amounts of high priority data. For the most part, data collected will be downlinked in the order it was collected. No facility for re-transmission, data editing, or for accommodating long DSN gaps is possible nor required. The science objectives are systematic and repetitive. Observations needed to achieve the science goals can be rescheduled in the event of lost downlink time. It is assumed that all data transfers, compression, encoding, and other process steps will not cause significant latencies in the data flow and therefore congestion in the SSR.

The current telecom design provides 80 kb/s to a 34 m DSN antenna at a range of 5.7 AU (at 20 deg elevation and 90% weather). Using an operational technique demonstrated by MRO and Cassini to transmit at the best achievable rate after each orbit occultation, the system takes advantage of increased elevation angles at DSN sites during a tracking pass as well as increasing rates when Europa is farthest away from Jupiter's hot body noise. These advantages increase the average data rate to 170 kb/s at 5.7 AU with an orbit-to-orbit variation from 60 kb/s to 260 kb/s. **Figure 4.6-12** shows the orbit-to-orbit variations of data rates for the first week of operations at Europa. Subsequent weeks will have a similar pattern but the increasing Earth range prior to Solar Conjunction will decrease the average rates. Rates will increase again in Europa Campaign 4. **Figure 4.6-8** shows the data rates for the Jovian Tour and Europa Science phases. **Figure 4.6-9** shows the daily data volumes available from the 34 m and 70 m stations.

4.6.6.3 Europa Science Phase Performance

The distribution of data volume resources and targets acquired are shown in **Table 4.6-4**. 1.25 Tbits of science data are collected along with nearly 1900 targeted observations, of which half are before the end of Europa Campaign 3.

Figure 4.6-13 shows the coverage of Europa during Europa Campaign 1 from the 200 km orbit. Complete color WAC coverage is obtained in the first 3 eurosols. Another complete WAC map (in panchromatic mode) to be used for stereo topography takes another 3 eurosols. Additional stereo coverage would be acquired during the two remaining eurosols to improve stereo products.

Figure 4.6-14 shows the coverage of Europa during Europa Campaign 2 from the 100 km orbit. Complete panchromatic coverage is obtained in the first 7 eurosols. Because of the significant overlap in the first 7 eurosols, stereo coverage will be complete in another 4–5 eurosols.

Ground track coverage can be used as a proxy for the coverage of the profiling instruments. **Figures 4.6-15** and **4.6-16** show the buildup of ground tracks in Europa

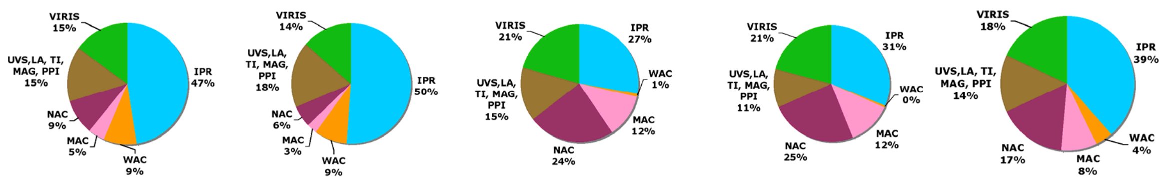
Table 4.6-4. *Summary of Data Volumes and Targets Acquired by Phase and Instrument. The pie charts show the data volume fractions for each instrument by campaign.*

	Europa Campaign 1					Europa Campaign 2					Europa Campaign 3					Europa Campaign 4					All Europa Campaigns		
Reference S/C	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	**C1 Tot Vol (Gb)**	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	**C2 Tot Vol (Gb)**	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	**C3 Tot Vol (Gb)**	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	**C4 Tot Vol (Gb)**	Total Targets	% total vol	**Total Vol (Gb)**
Data Volume	6.1	2.3			**238**	6.0	0.9			**294**	2.0	4.5			**184**	0.4	2.6			**499**			**1215**
WAC	0.74		9%		**21**	0.62		9%		**26**	0.04		1%		**1**	0.01		0%		**2**		4%	**51**
MAC		0.39	5%	13 T	**11**	0.00	0.19	3%	6 T	**8**		0.78	12%	13 T	**22**		0.37	12%	6 T	**61**	1710 T	8%	**103**
NAC		0.78	9%	13 T	**22**	0.00	0.39	6%	6 T	**17**		1.56	24%	13 T	**44**		0.75	25%	6 T	**122**	1710 T	17%	**205**
IPR	3.53	0.45	47%	1 T	**113**	3.53	0.00	51%	0 T	**150**	0.91	0.90	28%	1 T	**51**	0.05	0.90	31%	1 T	**155**	207 T	39%	**470**
VIRIS	0.61	0.65	15%	13 T	**36**	0.62	0.32	14%	6 T	**40**	0.04	1.30	21%	13 T	**38**	0.01	0.62	21%	6 T	**104**	1710 T	18%	**218**
UVS	0.03		0%		**1**	0.02		0%		**1**	0.03		1%		**1**	0.01		0%		**2**		0%	**5**
TI	0.26		3%		**7**	0.26		4%		**11**	0.05		1%		**2**	0.02		1%		**3**		2%	**23**
LA	0.17		2%		**5**	0.17		3%		**7**	0.17		3%		**5**	0.06		2%		**9**		2%	**27**
INMS	0.09		1%		**2**	0.09		1%		**4**	0.02		0%		**1**	0.01		0%		**1**		1%	**8**
PPI	0.17		2%		**5**	0.17		3%		**7**	0.17		3%		**5**	0.06		2%		**9**		2%	**27**
MAG	0.35		4%		**10**	0.35		5%		**15**	0.35		5%		**10**	0.12		4%		**19**		4%	**53**
S/C TLM	0.17		2%		**5**	0.17		3%		**7**	0.17		3%		**5**	0.06		2%		**9**		2%	**27**

[1] MAC targets are 1 minute duration (71 km/min @200 km, 78 km/min @100 km)

[2] VIRIS targets are each 400x400 pixels, 100 Mb

[3] IPR targets are each 30 Mb/s x 30 s, 900 Mb



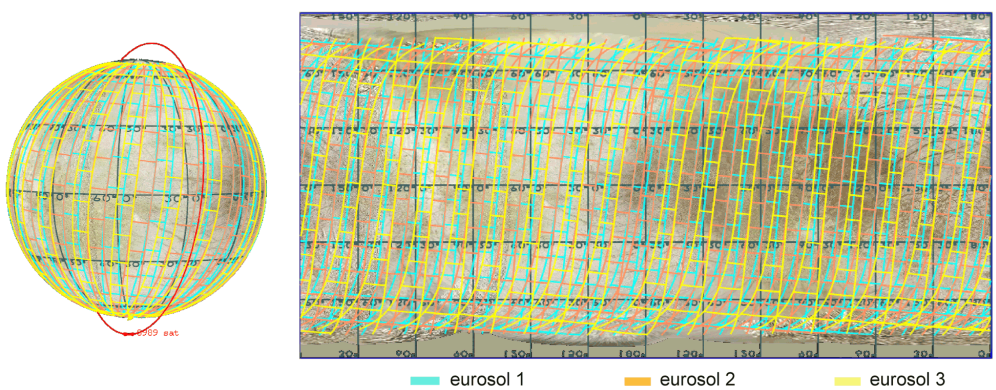


Figure 4.6-13. *WAC coverage in Europa Campaign 1*

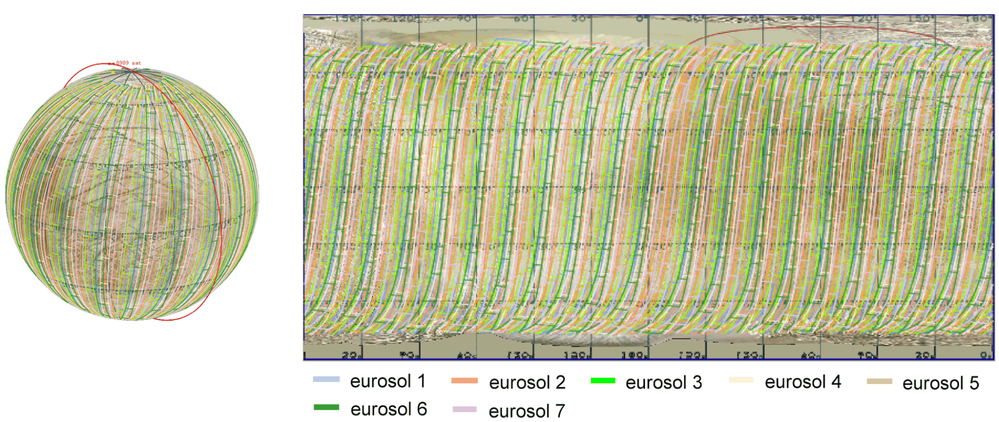


Figure 4.6-14. *WAC coverage in Europa Campaign 2*

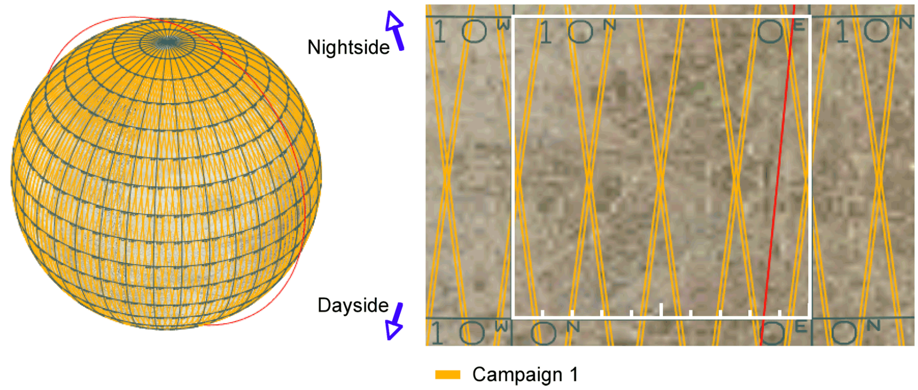


Figure 4.6-15. Ground Track coverage in Europa Campaign 1

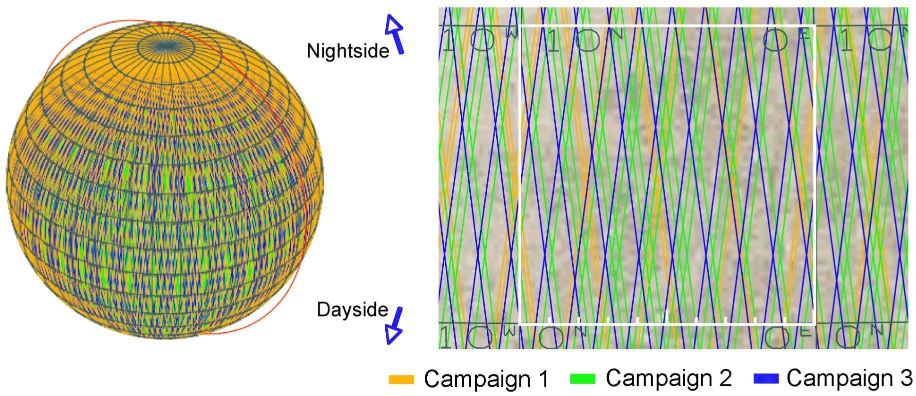


Figure 4.6-16. Ground Track coverage in Europa Campaigns 1,2,3

Campaign 1 and Europa Campaigns 1–3, respectively. The white box overlay is a 10 × 10 degree square with 1 degree tick marks to show that ground track coverage will be better than the 25 km spacing requirement at the equator by about a factor of 4 (1 deg = 27 km at Equator). IPR profiles will have half the number of ground tracks due to the alternating orbit data collection strategy. IPR tracks will exceed requirements by a factor of 4 also.

Figure 4.6-17 shows the cumulative data volume for the Jovian and Europa phases of the mission. The Jovian Tour phase returns over 3 Tb, similar to the Cassini mission data volume. The primary Europa Science phase is highlighted. The 1.25 Tb returned data volume is sufficient to meet science objectives with significant margin for collecting more targets than required and with time to respond to discoveries and augmented science questions.

4.6.7 Completed Trade Studies

Summaries of the results of key trade studies and analyses are provided here. For more details see Appendix G.

4.6.7.1 DSN Sensitivity Study

The purpose of the 34 m only DSN trade study was to consider the impacts to the baseline Europa Explorer study (2007 concept) of changing from the use of primarily 70 m DSN antennas during Europa orbital operations to the exclusive use of DSN 34 m antennas for that mission phase. The study was performed after the 2007 concept study was completed and prior to the start up of the 2008 study. X-band and X+Ka-band options were considered. The resulting recommendation to use moderate power on both X-band and Ka-band transmitters reflected the science requirement for dual frequency downlink. The 2008 study guidelines, in part informed by this trade study, were to use only 34 m DSN stations and to consider the use of Ka-band science data return. The 2008 study SDT reduced the Doppler requirement from dual frequency X+Ka-band to Ka-band only. The details of the trade study and the models used in the analysis were used to quickly determine a Ka-band only option that would meet the science needs and study guidelines.

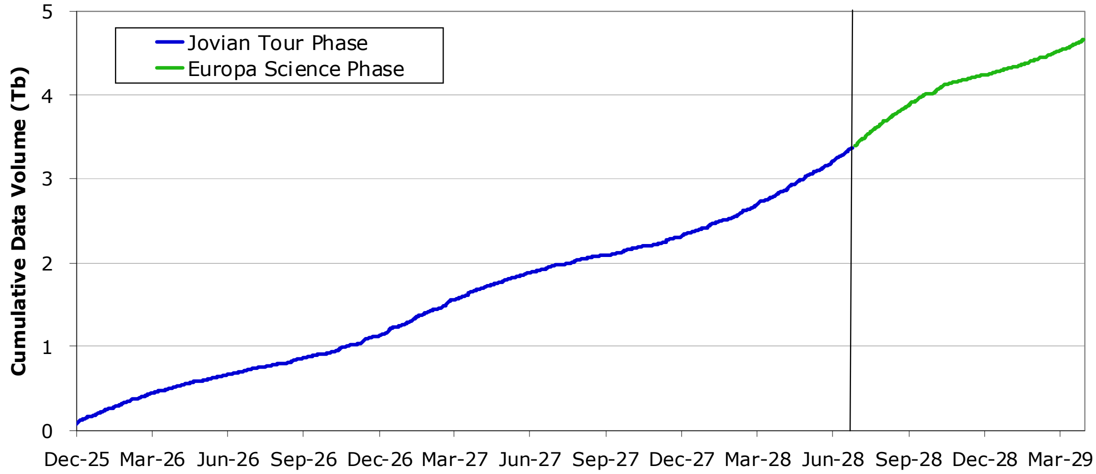


Figure 4.6-17. *Cumulative Data Volume Returned*

4.6.7.2 Mass Memory Size

Large volume, radiation hardened mass memory for Europa operations is massive and expensive. Trade studies conducted in the 2007 study showed the breakpoints for operations benefits of larger volume SSRs than those in the current baseline. The emphasis on Jovian Tour science in the 2008 study led to a trade study to find options for larger volume SSRs for the JEO mission. An option to consider a large volume CRAM based SSR (from the JSO 2007 study) was considered. Another option put forward proposed a second less radiation hardened SSR for use in the Jovian Tour phase. While the CRAM based concept was large, massive, and expensive, the second SSR brought redundant functions and overhead, complicating the system design and adding mass and cost. Finally, a hybrid SSR was proposed which added radiation tolerant SDRAM to the CRAM SSR design. SDRAM components are smaller, have higher memory density, and lower power than CRAM and so can be accommodated in the SSR without significant mass and power impacts. The demonstrated radiation dose capability does not provide sufficient reliability to baseline for use in Europa orbit but is expected to be sufficient, with additional shielding, for use in the Tour phase prior to EOI. As the SDRAM components fail due to radiation effects, the capacity of the SSR degrades to the baseline CRAM capacity needed for operating in Europa orbit.

The question of how much data volume the hybrid SSR would need for the Tour phase was the subject of an operations scenario trade study. The key considerations for the scenario were the available downlink data volume and the minimum data desired for flyby encounters. The minimum data desired for flyby operations was defined by trade studies conducted by the Europa Explorer and Jupiter System Orbiter studies in 2007. The value of 10 Gb was derived by both mission studies. For comparison, this is 2½ times greater than the Cassini SSR capacity.

The JEO telecom capability and DSN strategy provides from 14–20 Gb per week of downlink data. Due to the large memory density of SDRAM devices (1 to 2 Gb per chip), the hybrid SSR trade considered volume in units of 8 Gb and looked at volumes of 8, 16, and 24 Gbits. 16 Gb was selected as the value that is greater than the minimum needed for flyby science and is large enough to store a week's data volume.

4.6.8 Summary

The JEO mission has developed operational scenarios for both the Jovian Tour and the Europa Science mission phases. The preliminary tour scenarios show robust data volume margins and frequent opportunities to conduct the science campaigns defined by the JJSDT. Europa science scenarios continue to be robust for the delivery of the science objectives with the current planning payload and the updated 2020 mission opportunity.

The basic approach to Tour and Europa science operations remains generally unchanged from the 2007 study. The hybrid SSR enables significantly larger tour data volumes but the basic observing strategy is very similar. The Europa scenarios vary only in the updated payload. The orbiter telecom rates were tuned to the new payload and Earth range with small impact to mass and cost.

The long mission duration at Jupiter and especially at Europa enables a significant flexibility of science scenarios to achieve mission science goals and cope with radiation based anomalies, and allowed a more diverse set of measurements and investigations in the final Europa science campaigns.

4.7 Planetary Protection

4.7.1 Overview of Planetary Protection

Planetary protection (PP) requirements for Europa pose significant challenges to the mission design. The final fate of the JEO, impacting on the Europan surface, means that the mission will be classified as category III under current COSPAR and NASA policy [*COSPAR 2002*].

The approach to planetary protection compliance for the JEO mission concept can be summarized as follows:

- pre-launch sterilization to control bioburden for those areas not sterilized in-flight, and
- in-flight sterilization via radiation prior to Europa orbit insertion (EOI).

The NASA Planetary Protection Officer (PPO) has indicated support for this approach, given that the specific requirements for Europa can be met [*Conley 2006*].

4.7.2 PP Requirements

4.7.2.1 Probability of Contamination of Europa Requirement

Current PP policy [*NPR8020.12C 2005*] specifies requirements for Europa flyby, orbiter, or lander missions as follows:

“Methods…including microbial reduction, shall be applied in order to reduce the probability of inadvertent contamination of an Europan ocean to less than $1{\times}10^{-4}$ per mission. These requirements will be refined in future years, but the calculation of this probability should include a conservative estimate of poorly known parameters and address the following factors, at a minimum:

a. Microbial burden at launch.
b. Cruise survival for contaminating organisms.
c. Organism survival in the radiation environment adjacent to Europa.
d. Probability of landing on Europa.
e. The mechanisms of transport to the Europan subsurface.
f. Organism survival and proliferation before, during, and after subsurface transfer.”

4.7.2.2 Probability of Impact Requirement

In addition, there are requirements to avoid harmful contamination of any other Jovian satellites during the Jovian Tour phase of the mission.

4.7.3 PP Technical Approach

4.7.3.1 Meeting the Probability of Contamination of Europa Requirement

The probability of contamination, P_c, for a Europan mission, is dependent on the following terms [*Space Studies Board 2000*]:

- Microbial bioburden at launch (N, measurable by classical bioassay),
- Probability of cruise survival (P_{cs}, estimable, but typically a small reduction factor),
- Probability of Jovian tour survival (P_{rad}, estimable based on flight system design and radiation dose effects),
- Probability of landing on Europa (P_e, = 1 for JEO),
- Probability of transport to the Europan subsurface (P_t, an item difficult to estimate),
- Probability of organisms’ survival, dispersion and proliferation (P_g, an item difficult to estimate).

This will be interpreted for JEO as:

$$P_c = N \times P_{cs} \times P_{rad} \times P_e \times P_t \times P_g \leq 1 \times 10^{-4}$$

Based on guidance from the NASA PPO, the 1×10^{-4} requirement can be met by ensuring that the flight system has zero survivor organisms at the earliest credible encounter point for Europa, which is EOI. This approach removes many of the poorly defined/debatable/unresolvable factors in the probability relationship, which simplifies the PP requirement to a probability of contamination at EOI $P_{c[EOI]}$:

$$P_{cEOI} = N \times P_{cs} \times P_{rad} \leq 1$$

Suitably conservative figures will be utilized for P_{cs}, P_{rad}, and N:

P_{cs} and P_{rad} will be based on the spectrum of organisms present, adopting the classification system of the previously mentioned Space Studies Board, 2000 report, as implemented in the Juno planetary protection approach.

N will be obtained from a combination of direct biological measurement and accepted parametric estimates taken from the NASA policy, with subsequent reduction following sterilization processing. This will be integrated with an appropriate estimate for recontamination based on the launch environment.

For initial analysis purposes, a conservative value of 60% of Reference Jovian Tour absorbed dose is taken at EOI (see **Figure 4.5-2**), which gives >10 Mrad at the flight system surfaces (inside thermal blankets), and ~3.5 Mrad inside 15 mils aluminum.

Each hardware element will be required to demonstrate compliance with the overall flight system $P_c < 1$ requirement at EOI, by demonstrating compatibility with dry heat microbial reduction (DHMR), environmental radiation sterilization or another sterilization approach agreed and accepted by the PP subject matter expert.

DHMR is the baseline sterilizing technology, with typical planetary protection protocols having time vs. temperature profile ranging from 125°C for 5 hours to 110°C for 50 hours.

4.7.3.2 Meeting the Probability of Impact Requirement

The requirement to avoid contamination of (impact with) other Jovian satellites will be met through trajectory analysis, based on the approaches of Cassini and Juno. This includes the 10^{-4} requirement to avoid impact with Europa prior to EOI.

4.7.3.3 Interaction with the NASA Planetary Protection Office

Early formalization of the mission categorization and technical approach will be sought through the NASA PPO and the relevant peer review process. This needs to be early enough so that project can switch to an alternative (e.g., system sterilization) method early in the project at low cost penalty. This is facilitated through the inclusion of the mid-Phase B Planetary Protection review (see below). Risk associated with change in the mission PP approach as a result of this activity is carried at the project level as discussed in §4.10.3.

4.7.4 PP Implementation Overview

4.7.4.1 Flight System Design and Fabrication

In order to achieve compatibility for the flight system, it is necessary to consider dry heat sterilization compatibility in the trade studies alongside the radiation resistance. Both aspects have been considered in the Approved Parts and Materials List (APML), where a column designates the PP compliance (see §4.5.4.4).

For some hardware where there is conflict between radiation and DHMR compatibility for individual components, it may mean that the instrument is actually "distributed"—electronics and sensors physically separated on the flight system. It may influence the choice of sensor technology for some instruments, if one sensor choice is much more robust than another in this context.

The project requires that the hardware providers will:

- use Class S/MIL spec. parts for all elements for the flight system,
- identify early those instruments/components that do not currently/will not be able to comply.

In the specific case of the instrument payload, an additional mid-Phase B Planetary Protection review will be held, so that costs of developing mitigation strategies can be factored into the mission early.

At the current stage of maturity (see also §4.9.2.5), no planetary protection show-stoppers have been identified with this approach.

4.7.4.2 Assembly and Test

In the current approach, it is assumed that the option exists to maintain post-sterilization recontaminant spore density at 300/m^2 as performed for the Mars Exploration Rovers (MER) spacecraft.

It is assumed that Radioisotope Power Supplies self sterilize (e.g., per Mars Science Laboratory), propellant is filtered and that other marginal cost approaches beneficial to PP mitigation are followed (for example modification of contamination control bake-out parameters to allow bioburden reduction credit to be taken).

No specialized PP facility costs or launch vehicle costs have been assumed in this approach. It is assumed ATLO will be in standard class 100 k conditions. Requirement to work cleaner than this to manage initial bioburden (e.g., in tented class 10 k or better) will be carried as a technical risk. The detailed integration of the ATLO/PP flow will be an output from Phase A.

However, it is already anticipated that aseptic joining of flight hardware may be required during ATLO, particularly in the context of rework activities. Validation of these aseptic joining approaches will be a Phase A activity.

4.7.4.3 Flight System Launch Configuration

It is necessary that areas of the flight system not experiencing adequate levels of Jovian radiation to achieve sterility will be sterilized before or during ATLO and cleanliness maintained by protecting from recontamination prior to launch with HEPA filters (per MER/MSL) and/or biobarriers (per Phoenix).

4.7.4.4 Missions Operations

Data from the operational phase of the mission, particularly during the Jovian tour, will inform the true irradiation environment experienced by the hardware. This is accomplished by the on-board dosimeter to record the level of radiation in real-time during the JEO mission. This will give confidence that the required level of sterilization is achieved prior to EOI. Extending the pre-EOI tour to achieve a given irradiation dose for PP purposes remains a possible option.

4.8 Future Studies and Trades

4.8.1 Trajectory Opportunities

The Venus-Earth-Earth Gravity Assist (VEEGA) opportunity selected for the baseline mission is only one of a number of launch opportunities in 2020. In any given year, there are many opportunities which result in different flight times, fly-bys, delivered mass, etc. (see §5). This particular opportunity was selected due to its excellent combination of short flight time, high mass performance, and good development schedule. Program¬matic considerations will drive the ultimate selection of launch date, desired performance, and concomitantly, the interplanetary trajec¬tory. Section 5 discusses interplanetary trajec¬tory opportunities that are potential alternates and/or backups to the 2020 VEEGA.

4.8.2 Tour Optimization

Tour 08-008, selected as the baseline for this report, is a proof-of-concept. Design of the Jovian Tour has goals of reducing the duration required to get into Europa orbit and the radiation dose prior to EOI, while increasing the mass delivered to Europa and providing tour science opportunities that address the Jupiter System science objectives. Future considerations in designing the tour will include phasing of satellite encounter arrival times (e.g., adding margin around solar conjunction, and achieving the most favorable Europa orbit orientation). Future high-fidelity trajectory optimization is expected to improve the tour science opportunities (especially the amount and variety of coverage of Ganymede) while achieving reductions in radiation dose and ΔV. Designing the tour portion of the trajectory will be performed with the full science, engineering and programmatic team to ensure the optimal mission solution.

4.8.3 ASRG Accommodation Study

An ASRG-based spacecraft design requires a system level redesign. The ASRG behaves and interacts with the spacecraft significantly differently than the MMRTG. The higher efficiency by the ASRG doesn't produce enough waste heat to use for propulsion thermal control in the same way that is used for an MMRTG, and so a new thermal system is needed. The vibration and magnetic environments from the ASRG need to be analyzed and accommodated by the spacecraft. New electrical and mechanical interfaces need to be evaluated and designed in. The ASRG system itself, in particular the controller, needs to be upscreened to tolerate the radiation environment in the JEO mission. Examples of open questions still remaining on accommodating the ASRG are shown in **Table 4.4-9**.

The work performed this year on ASRG accommodation provided a starting point for these design issues. The design and characteristics of the ASRG are still evolving as the design matures. This instability and limited time and staffing resources restricted the fidelity of an ASRG-based design, especially as compared to the MMRTG-based design that JEO has developed throughout the previous studies.

NASA Headquarters has requested the Outer Planet Flagship Mission office at JPL to perform a quick study to recommend approaches for validation and qualification of the ASRG in order to support risk mitigation for the selected Outer Planet Flagship Mission. This work is on-going and will report directly to NASA Headquarters in late Fall 2008. In addition, there is a study underway to provide NASA with input on the Advanced Radioisotope Power System development by the National Research Council. Headquarters will use the output from these assessments and other information to help form the next phase of ASRG development.

As the ASRG development continues, and more accurate details of the ASRG characteristics become available over the next few years the spacecraft accommodation study will continue in more detail in order to potentially baseline it into the spacecraft design.

4.8.4 Payload On-Board Data Processing Architecture Study

The current JEO payload is notional, with instruments defined to demonstrate a viable approach to meeting the science objectives, performing in the radiation environment, and meeting planetary protection requirements. Final instrument concepts and techniques will be selected via the Announcement of Opportunity (AO) process.

To support instrument selection and the most efficient implementation of the payload, future consideration will be given to centralizing some of the on-board data processing into either the C&DH subsystem or a common payload data processing unit. The three major areas for investigation are:

- Use of a centralized instrument interface unit,
- Use of a single high-speed wavelet data compression design,
- Use of common data processing hardware for high-bandwidth optical instruments.

Centralized instrument electronics may result in savings through the use of common software and hardware and the need for fewer radiation hardened ASICs. Additionally, instruments costs may be reduced through the use of simple non-packetized communications interfaces. A trade study will explore these possible benefits and weigh them against a possible increase in overall payload complexity.

Three of the instruments presented, specifically the Camera Package, VIRIS, and NAC, are expected to implement high-speed wavelet data compression within the instrument. It is logical to explore if there are potential savings in using a single data compression scheme in place of three different designs, either through the design of a centralized data compression processor or through the dissemination of a reference data compression design. Potential savings resulting from a centralized data compression processor must be weighed against throughput and interleaving issues that may limit simultaneous instrument operation, as well as the additional costs of testing and integrating a centralized facility with the instrument payloads.

The block diagrams of the same three instruments, the Camera Package, NAC, and VIRIS (§4.2), show considerable commonality in their remote electronics in the areas of pixel processing, data buffering and spacecraft interface. Consideration will be given to implementing a common hardware design that can be configured to support the specific requirements of each instrument.

4.8.5 Execution of Risk Mitigation Plan

The Risk Mitigation Plan describes a systematic implementation approach to assuage the JEO mission development and operational risks prior to Phase A for a nominal 2020 launch. The plan spans four years, but focuses primarily on FY08 (completed) and FY09 budgets and activities. This plan will be assessed and updated upon completing early device evaluations and developing and review of the preliminary design guidelines. The plan will undergo a review at least annually to accommodate for changing radiation environment due to updated trajectory opportunity and tour optimizations. A more detailed discussion is presented in §4.5, Appendix F, and in Risk Mitigation Plan: Radiation and Planetary Protection [*Yan 2008*].

At the end of FY08, the Approved Parts and Materials List (APML) and Parts Program Requirements were released. The APML will be updated at least yearly to include any newly screened parts and materials. Efforts in FY09 will focus on completing the radiation tolerant design guidelines and methodologies and providing updates to the environment and detector model for dissemination to potential spacecraft and instrument providers. A 2nd Instrument Workshop is planned for November 2009. In the near term, the Extreme Low Dose Rate Sensitivity test will be continued as long-lead items as Pre-Phase A activities.

In the long term, a structured proof-of-concept system model, which includes identifying required input information, will be released in FY10. It will be made available to support the 3rd Instrument Workshop in May 2011 and with the release of instrument AO in November 2011. FY11 will be dedicated to completing the system model and input parameter definitions in support of the Instrument Concept Design Review in FY13.

Shielding continues to be the effective means against radiation. Besides better characterization of the radiation environment around Europa, there are planned approaches towards further reducing shield mass in Phase A. These approaches include:

- Placement of components within an enclosure (e.g., sensitive components on cards in center of stack of 6U chassis),
- Incorporating structural mass (e.g., propellant tanks) into shield model,
- Selecting less sensitive components (e.g., batteries) to shield more sensitive devices,
- Physically locating assemblies of similar rad-tolerance and using single enclosure (e.g., as used in Telecom shielding),
- Layering of shield materials (High Z and Low Z).

4.8.6 Additional Pre-Phase A Activities

A Pre-Phase A study such as this, cannot attempt to address all aspects of the design. Over the past decade, many critical areas have been addressed only to be re-assessed as time marches on and technology and priorities change. There is always refinement and analysis which can be done. The key is to understand the critical timing of effort. Pre-Phase A activities for risk reduction ensure focus on activities while the Project gets ready to start Phase A. For JEO, risk reduction efforts relate to:

- Interfacing with ESA to define and understand the integrated mission concept to allow a coordinated AO,
- Developing approach, tools and model to ensure Model Based Engineering can be efficiently used with science and engineering teams,
- Developing an integrated toolset so that efficient trajectory and radiation analyses can be completed,
- Updating the planetary protection assessment performed by Mars Exploration Rovers (upon which the JEO approach is based) and exploring additional data for supporting rationale,
- Performing specific trade studies and analyses in support of Project Information Package for AO, Science Definition Team, Headquarters requests and early challenging radiation designs (e.g., Star Tracker),
- Monitoring technology and engineering developments which may become available to enhance the current mission design (ASRG, Memory, FPGA, etc.).

In addition to risk reduction activities, there are specific project management, science and engineering activities related to gate products, concept development, and implementation approaches (partnership development). A schedule and time-phased cost estimate for these activities are presented in §4.11.6.1 and §4.11.7.2 respectively.

4.9 Technology

4.9.1 New Technology Required

There are no new technologies required to be developed for the mission as currently envisioned. Major NASA investments have been made over the past decade in the areas of radiation hardened components, development of power source technology, launch vehicle qualification, and trajectory tour design tools. Additionally, the Departments of Defense and Energy, as well as industry, have invested in technologies and developments that directly benefit the current JEO concept. The Galileo spacecraft was just beginning to return vast amounts of data about Europa in 1996. Years of additional data return as well as nearly a decade of data analysis has resulted in much better refined models and questions related to the fundamental objectives for the next mission to Europa. Many of these developments are depicted in **Foldout 12** (**FO-12**).

Engineering developments are required in most areas to adapt current designs to perform within the radiation environment and to meet the planetary protection requirements. A summary of the technology readiness review results is provided in **Table 4.9-1**.

Additionally, with the nominal launch scheduled for February 2020, Phase A would not start until 2012. Technology advancements which occur over the next several years could easily be incorporated into the design until the Preliminary Design Review in early 2015. Thus, the design is not stagnant but technology advances are not required to meet the science objectives.

4.9.2 Enhancing New Technologies and Capabilities

Although current technologies are sufficient to perform a scientifically engaging mission to Europa and meet all the science objectives, new technologies and capabilities could enhance the mission if they become available in a timeframe compatible with the mission development schedule. Examples of such technologies and capabilities include: ASRGs, memory, advanced sensors, and DSN upgrades and planetary protection developments. Many of the potential part technology advances are specifically addressed in the Risk Mitigation Plan [*Yan 2008*]. By executing this plan, there would be more advanced technology parts (FPGAs, memory, power converters, sensors, etc) characterized, pre-screened and available for instrument and electronics developers.

4.9.2.1 Radioisotope Power System (RPS)

A trade study was performed (see §4.4.5.1) between the MMRTG and the ASRG. The technically lower risk MMRTG was selected for the baseline JEO mission though adequate resources are available to incorporate the ASRG as it's currently defined. DOE and NASA are engaged in the development of the ASRG. As outlined in §4.4.5.1, there are still open issues related to using the ASRG on JEO. During the next phase of the mission development, the project team will work closely with the ASRG development team to understand how the ASRG design is evolving and to accommodate it. The trade results will be re-evaluated periodically to ensure good communication between the spacecraft development team and the ASRG development team.

4.9.2.2 Memory

The availability of space qualified non-volatile memory continues to be an issue for future missions, even those without high radiation levels. As discussed in last year's Europa Explorer Report [*Clark 2007*], Chalcogenide based RAM (CRAM) was and is still baselined for the Europa Phase of the mission. During 2008, BAE has produced and delivered its first CRAM 4 Mbit chips for flight and is in the middle of part qualification. JPL has received several devices which will be placed in radiation and reliability testing in 2009. Additionally, another manufacturer, Samsung, is investigating commercial CRAM products for consumer use. Several Samsung 512 Mbit chips were delivered to JPL where they will also undergo characterization and radiation testing during 2009.

A radiation tolerant (100–150 krad) SDRAM device is potentially available. This very dense device will also be tested in 2009. In this year's design, 16 Gbit of SDRAM is included in the SSR in addition to the rad-hard CRAM but is only assumed to be usable in the tour portion of the mission. The option to use this memory while in Europa orbit will be re-assessed as more test data becomes available.

Table 4.9-1. *Analysis of generic technologies by experts reveals no show-stoppers for meeting radiation or planetary protection requirements*

Area	Category	Mitigation	Specific issues
Embedded Materials	Radiation	Radiation insensitive materials are available, shield or replace	Pressure Transducer - investigate sensors used in Nuclear Reactors, new development or shield current sensors (mass for this already assumed)
	Planetary Protection	Heat Sterilization possible	None identified
External Materials	Radiation	Radiation insensitive materials are available, shield or replace	None identified
	Planetary Protection	Chemical wipe and vacuum/radiation sterilization in flight	None identified
Circuit Design. Electronics Parts	Radiation	Minimum allowable die level radiation hardness is 100krad, Each part within circuit will be assessed; timing and performance range will be incorporated into worst case analysis to ensure circuit functionality with rad-hard parts, testing of parts may be required to assess performance outside "specification" range for operation in radiation environment	Parts: ADCs-14 bit best available to date; Memory - some types available, may limit design choices; FPGA - not qualified yet, dictates use of ASICs
	Planetary Protection	Heat Sterilization possible	None identified
Sensors/ Detectors	Radiation	Sensor/detector performance requirements will be assessed: common mitigation approaches include cooling detector when on, warming detector when off, flexible biasing of detector, signal processing (thresholding and averaging), hardening by design and by process, removing non-essential on-chip functionality, minimizing detector volume, increasing light gathering system, folding optics and/or using quartz aperature plug, reducing performance requirements	All detectors will require specific attention and radiation mitigation techniques to insure adequate performance to end-of-mission dose and during high dose-rate observations.
	Planetary Protection	Heat sterilization or chemical sterilization during manufacturing process	Some sensor materials can be heat sterilized but may require custom heat-tolerant packaging; sterile manufacturing of some sensors may be possible
Circuit Boards	Radiation	See Embedded Materials	specific materials can be used
	Planetary Protection	Heat Sterilization possible	None identified; baseline boards can be built using materials that are compatible with DHMR or radiation sterilization
Power Source (MMRTG)	Radiation	MMRTG inherently rad hard	ASRG Controller may not have minimum die level rad hardness parts
	Planetary Protection	Naturally heat sterilized	None identified, exposed to radiation, vacuum and heat during flight

Memory Investigation for Jupiter Europa Orbiter Mission [*JPL D-48262*] documents the JEO study activities related to memory during 2008. Further developments in memory devices could further alleviate some of the current design constraints. This technology area will be closely followed so that advances which are qualified in time for insertion can be leveraged.

4.9.2.3 Advanced Sensors

There are many types of photonic sensors potentially available to work within this radiation and planetary protection environment. Special attention to the sensor selection

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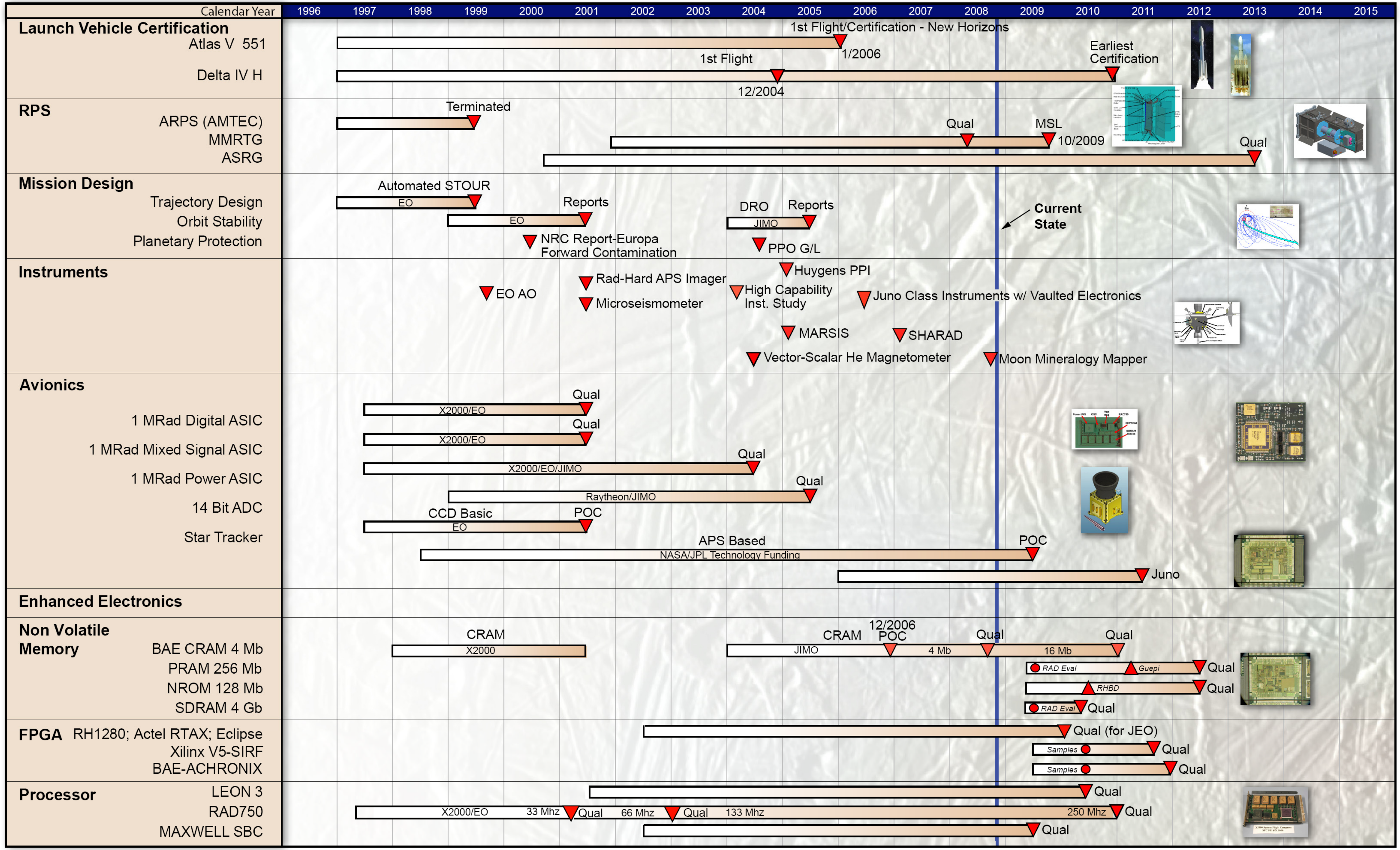
More than a decade of investment has resulted in dramatic risk reduction for Jupiter Europa Orbiter



and functionality will be required. Currently available sensors will need to have specific design implementations and features added for radiation tolerance and be fabricated on radiation-hard processing lines. Dedicated fabrication runs will be necessary with testing for each fabrication lot. Screening procedures and lot acceptance will be required. As sensor technologies advance, radiation tolerance of the underlying structures is expected to improve. Active doping, bulk material thinning, and low temperature operation techniques have been shown to improve radiation tolerance of silicon devices. CMOS-based active pixel sensors are becoming increasingly available for high-performance science imaging applications and are proving to be significantly more radiation tolerant than charge-coupled device technology. This same CMOS technology used as the read-out integrated circuit improves the total-dose tolerance of hybrid detectors. This technology (and others such as 3D detectors) are being developed and may provide additional options in the near future.

Specific sensor requirements for the instruments are difficult to assess since the instruments have not yet been selected, and satisfaction of the planetary protection requirements may end up being the larger issue. As the technology continues to mature, advances in these areas will be vigorously pursued for performance and cost savings.

A summary of the information gathered during this study regarding sensor availability can be found in the Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study Report [*JPL D-48256*], which was submitted to the sponsor under separate cover. The Detector Working Group confirmed that with careful selection, design and testing, currently identified sensors should be able to meet the science requirements identified by the JJSDT. This information is the basis for the instrument descriptions in §4.2.

4.9.2.4 DSN Upgrades

Future upgrades to the Deep Space Network (DSN) are in the planning stages. The current design assumes only the current capability of the DSN. Increased capabilities would enhance the data return rate, increasing the amount of data which could be gathered and returned every orbit, or could reduce the required on-board power for the equivalent downlink rate.

4.9.2.5 Planetary Protection Developments

Taking into account the risk management approaches of parts compatibility assessment, inclusion as a requirement in the instrument AO, additional Phase B review, and inclusion in the ATLO DTM trailblazer activity already described elsewhere in this document (§4.4.4, 4.7, 4.10.3), it is anticipated that no new planetary protection technologies are required.

However, engineering developments are planned to investigate aseptic assembly to facilitate keeping sterile surfaces clean during the assembly process. Also, current Mars Program research activities of genomic diversity may be beneficial to JEO. This research will generate an absolute knowledge of the number and types of organisms present on/in the space hardware. This may allow conservative margins applied in the NRC Space Studies Board report of 2000 for the estimation of bioburden to be eliminated resulting in a lower estimated starting bioburden count. This lower initial count would allow planetary protection compliance and schedule risk to be managed more cost-effectively. For example, the ATLO environmental cleanliness requirement may be able to be relaxed and/or the assumed radiation-sterilized bioburden count may be increased.

All planetary protection developments in the next several years will be evaluated and assessed for their impact to the baseline approach. The review inserted in Phase B will be crucial for ensuring that all aspects of the planetary protection approach are addressed and that a comprehensive approach is baselined.

4.10 Risk Assessment

The study team has identified a number of technical risks to the success of JEO mission. Each risk has been evaluated for likelihood and consequence on a scale from 1–5 and positioned on a traditional 5 × 5 risk matrix as shown in **Figure 4.10-1**. The scale used for risk assessment is described in **Table 4.10-1**, *Risk Matrix Definitions*, in accordance with JPL's *Qualitative Risk Assessment* standards as called for by NPR 7120.5D "NASA Program and Project Management Processes and Requirements." Mitigation plans have been developed for each risk and are included in the estimated mission cost. Subsequent sections give a brief discussion of each risk and the corresponding mitigation. The risk rating is given in the title of each subsection below as an ordered pair of consequence and likelihood (Risk abbreviation C, L). Section 4.11.8 discusses management strategies for these risks including specific actions taken to address cost.

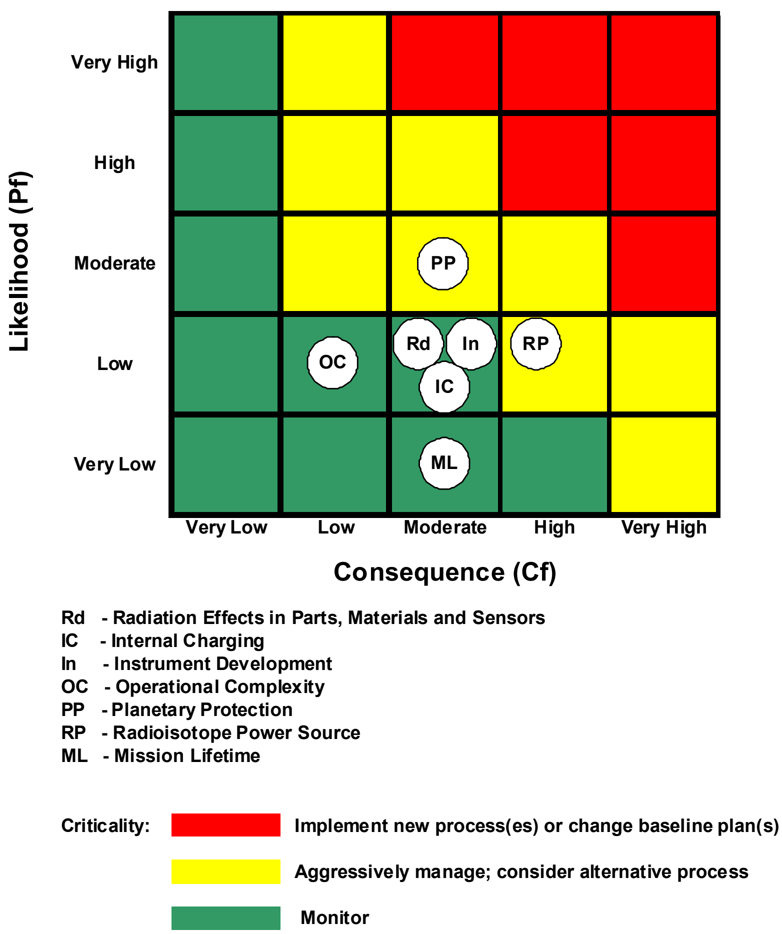


Figure 4.10-1. Jupiter Europa Orbiter risk evaluation.

4.10.1 Radiation *(Rd, IC, In)*

The overarching radiation risk has been subdivided into 3 individual risks: Effects on Parts, Materials and Sensors, Internal Charging and Instrument Development. Individually, these risks have low likelihood of creating a moderate consequence. Taken all together, these radiation-related risks become a significant risk factor for the JEO mission.

Designs for this radiation environment must be robust beyond the level normally accomplished for space flight design. It's anticipated that many of the designers working on mission systems will be inexperienced in design for such a harsh radiation environment. This inexperience may lead to unanticipated vulnerabilities in the JEO mission electronics and sensors, leading to mission degradation or failure.

Radiation effects expected in the JEO mission are (i) TID effects and SEE in electronic components, (ii) displacement damage (DD) effects in components and materials, and (iii) surface and internal charging. Since mitigations for charging issues are different than for other radiation effects, internal charging is treated as a separate risk. Since mitigation for sensors and instrument components requires early engagement of the community of instrument providers that is also treated as a separate risk. The primary risk considered here is the likelihood that component failure could have a serious impact on spacecraft functionality. The measures taken here both reduce the likelihood and the consequences of such impacts

4.10.1.1 Radiation Effects in Parts, Sensors and Materials *(Rd 3,2)*

Risk

If radiation effects in parts and materials are more severe than expected, early failures may occur resulting in loss of science. Sensors for instruments used for pointing and nav-

Table 4.10-1. *Risk Matrix Definitions.*

Scale	Consequence		Likelihood
	Mission Risk	Implementation Risk	
5	Very High: Mission failure	Very High: Overrun budget and contingency, cannot meet launch with current resources	Very High: Almost certain
4	High: Significant reduction in mission return	High: Consume all contingency, budget or schedule	High: More likely than not
3	Moderate: Moderate reduction in mission return	Moderate: Significant reduction in contingency or launch slack	Moderate: Significant likelihood
2	Low: Small reduction in mission return	Low: Small reduction in contingency or launch slack	Low: Unlikely
1	Very Low: Minimal (or no) impact to mission	Very Low: Minimal reduction in contingency or launch slack	Very Low: Very unlikely

igation—and also used in science instruments-are particularly sensitive to radiation effects. This risk results from several important sources. First, even with the use of radiation hardened parts, the project may not be able to identify some key components that will withstand the shielded environment. Test techniques used to verify component suitability may over-predict component hardness due to inadequate accounting for radiation rate or source type effects that are negligible at lower doses. Finally, unanticipated failure mechanisms may be present or may become important at high doses or at high displacement damage levels that are not of concern for missions conducted at nominal total dose exposures.

Mitigation

There has been significant effort exerted by experts to mitigate this risk over the past decade. In 2007, the study team convened several review teams to assess the particular risks in each area. The results of that review were presented in Appendix C of the 2007 EE Study Report [*Clark et al. 2007*]. As a result of those reviews, the Risk Mitigation Plan: Radiation and Planetary Protection [*JPL D-47928*] outlined in the *Clark 2007* was further developed and executed this year and is making strategic investments related to reducing the likelihood of component failure and degration, and the related radiation risk even further. A detailed description of the activities to address radiation-related risks during this study is given in §4.5. Results of that effort are reported in §4.5, Appendix F, and in the deliverable documents referenced in Appendix F. An expanded systems engineering approach focuses on graceful degradation and will reduce the consequences of any component failures in electronic parts.

4.10.1.2 Internal Charging *(IC 3,2)*

Risk

The high levels of charged particles near Europa are also a source of internal charging within flight system materials. The result of this charging is often an electrostatic discharge within the flight system that causes material damage and an electromagnetic pulse damaging to electronics. The choice of materials, the use of charge dissipating designs, and the robustness of electronic designs to internal discharge effects will greatly affect the frequency and consequence of internal discharges. If not mitigated properly, discharges resulting from internal charging may result in mission degradation or failure.

Mitigation

Mitigations for this risk include the use of rigorous design guidelines for Electrostatic Discharge and grounding. For example:

1) specifications on the maximum length of ungrounded wire length,
2) specifications on the use of necessary bleed resistors and bleed path analysis,
3) specifications on the restriction on the use of floating (e.g., ungrounded) metal area.

In addition, IC risk mitigation will include utilization of design experience from Galileo and Cassini, early testing of materials and processes to define acceptable use for a JEO mission, providing mission design guidelines in Pre-Phase A prior to release of the AO, and conducting design workshops to train designers on the environment and charging issues. Members of the JEO radiation team recently updated NASA Internal Charging guidelines [*NASA-HDBK-4002*] which has been submitted to NASA for final review. This expertise is being leveraged to continue documenting design practices for potential assembly providers for JEO.

4.10.1.3 Instrument Development *(In 3,2)*

The instruments in the planning payload are all based on mature technologies and if applied in an orbital mission in the inner solar system would represent very low risk. For JEO, however, radiation can have a detrimental impact on instrument performance. If these problems cannot be solved, or more importantly, if the solutions cannot be conveyed to instrument developers in a timely fashion, there is a risk that the science objectives of the mission will not be met.

Mitigation

The project will assign instrument interface engineers to work with each instrument provider to ensure that the spacecraft accommodates the specific instrument needs. To reduce the likelihood that the instruments do not achieve their desired specifications or run into resource and schedule problems due to radiation issues, the typical interface engineering support will be augmented for each instrument with personnel experienced in the area of radiation design. Design guidelines will be generated for the instrument teams to describe radiation constraints and to provide recommendations for design issues and parts and material selection.

Development of a knowledge base among potential instrument providers has already begun. In June 2008, an instrument workshop was held to engage the instrument provider community in a dialogue on the mission needs and potential driving requirements. Information regarding radiation and planetary protection requirements was disseminated. A website for the Outer Planets Flagship Mission (http://opfm.jpl.nasa.gov) has been established to provide a conduit for releasing information from that workshop, along with other relevant information, to anyone desiring to propose instruments. Further description of the workshop material is provided in Appendix F.

As information is available from the Risk Mitigation effort described in §4.5, it will be made available to the larger community to the maximum extent possible within ITAR and Public Release restrictions. Two workshops are planned as a part of the Pre-Phase A activity to provide further guidance and interaction between the project and the instrument community.

As a further measure to reduce the likelihood of an impact on mission science because of the time needed for instrument development, the JEO mission schedule has been augmented from that presented in the 2007 EE Study Report. This new plan provides additional time and reserves for the instrument developer and the Project to work through and understand the actual design implications for radiation and planetary protection after selection. An Instrument Concept Definition Review has been added to the project and instrument schedule along with a NASA Instrument Confirmation Review to be held prior to the system confirmation review. These will allow the project and instrument providers time to assess the instrument design and implementation plan against the stringent requirements prior to the start of Phase B. This provides risk mitigation by identifying potential instrument issues early in the project lifecycle. An additional 6 months was also added to the Phase C for the instruments to mitigate the schedule risk associated with designing for these harsh environments.

While these measures are expected to reduce the likelihood of instrument development problems and consequences of implementation risk, the mission risk will also be mitigated as a result of the robust payload for the baseline mission. Difficulties with any one instrument will only have a small impact on overall science given the rich suite of measurement capabilities

4.10.2 Operations Complexity *(OC 2,2)*

Risk

If the science and spacecraft operations planning response to faults is not flexible and capable of reconfiguration and recovery to nominal operations, some science goals might not be met within the baseline mission duration.

The concept of operations for the JEO mission includes science operations and streamlined sequence planning capable of accommodating science priorities for several instruments and science team members. If operations are not coordinated appropriately or if planning tools are not correctly designed and implemented, cost and schedule reserves may be needed to address late-breaking problems, or science may be compromised.

Mitigation

The operations concept is described in detail in §4.6 and Appendix G. The basic approach is a combination of "Cassini" and "Galileo" style tour operations and "MRO" style orbital operations. The Outer Planets Flagship Mission Science Operations Concept Study Report and Operations Lessons Learned Study Report (Appendix K) highlight recommendations to further optimize JEO operations, including the need for planning tools and coordination that is more advanced than a more traditional orbiter or flyby mission. While JEO does indeed have a long tour of the Jupiter System, including many flybys of the Galilean satellites, the layout of the instruments and the application of dual-gimbaled antenna allow for more efficient science planning and operations than on Cassini.

The instruments have been accommodated primarily for orbital operations at Europa. They, therefore, point mostly in the nadir direction, allowing concurrent scientific observations within the constraints of the power and communications systems. Rapid slews and complex changes in attitude are not required to perform multiple concurrent or serial scientific observations. Radio science, an important measurement in its own right, can be performed at these flybys without disturbing the other instruments due to the aforementioned gimbaling. Further, once the flight system achieves Europa orbit, the plan is to operate specific combinations of instruments in repetitive campaigns. Such regular operations are not possible with Cassini, whose every science operation is unique in geometry, timing, attitude and the instruments employed. The four Europa Campaigns described in detail in §4.6 are definable and repetitive. The flight system stays nadir pointed and utilizes the pointing flexibility of the HGA to continue science observations unperturbed. Furthermore, advances in the automation of command sequencing and operational planning will be applied with full affect.

Additional mitigations are to prepare science team plans and tools early, and provide sufficient opportunities for training and practice through the use of flight schools, mission simulations, operational readiness tests, and a thorough exercising of the science operations processes during Earth flybys and the Galilean satellite flybys prior to EOI. The JJSDT has developed a set of priorities and will continue to do advanced planning for various mission scenarios to allow for quick response. Detailed peer reviews of the planning and coordination process and tools will be conducted sufficiently early to allow effective implementation of the operations process.

Science operations will make use of extended fault isolation, response and recovery designs beyond current practice to prevent major loss of science in the presence of minor faults. Enhanced ground and flight system operability features (see §4.4.2.4) will be implemented to enable rapid and largely automated reconfiguration and recovery from all faults. The science ops team will practice and train during Cruise/Tour encounters.

Additional workforce was added in to Phase B–D to accommodate these risk reduction efforts including developing tools and exercising the entire science scenario chain from generation of sequence through data retrieval and archiving.

4.10.3 Planetary Protection *(PP 3,3)*

Risk

The planetary protection requirements will specify that the internal JEO flight system receive sterilization processing prior to launch to achieve specified cleanliness levels in order to avoid contamination of the Europa environment. The external spacecraft will be sterilized via the radiation exposure through the tour. If pre-launch cleanliness levels are not met, cost and schedule reserves may be required to address contamination problems late in the process, to prevent Europa contamination. A further discussion of the planetary protection requirements is found in §4.7.

Mitigation

The risk will be mitigated by development of aseptic assembly procedures, advanced planning and integration with the Assembly Test and Launch Operations (ATLO) Engineering Model and Development Test Model activities, knowledgeable peer reviews, and by providing guidance and monitoring to all subsystem and instrument contributors, to ensure that the cleanliness levels can be (and are being) met well ahead of the hardware delivery to ATLO.

The Planetary Protection (PP) activity has already started. The PP engineer is working directly with the project to ensure that issues are addressed early. The following steps have been taken:

- The approach to meeting the PP requirements via pre-launch heat and post-launch radiation sterilization has been reviewed by and tentatively approved by the NASA Headquarters Planetary Protection Officer [*Conley 2006*],
- A Planetary Protection Review is placed in mid-Phase B to review the basic approach,
- Heat sterilization of materials, detectors and electronics is included in the Risk Mitigation Plan discussed in §4.5,
- Sterilization of "boxes" on the flight system has been the mechanical implementation organization to ensure feasibility,
- $3.5 M (FY07) has been added specifically to the ATLO budget to accommodate technical and schedule issues that arise during that time.

4.10.4 Radioisotope Power Source Availability *(RPS 4,2)*

Risk

While NASA has now baselined the MMRTG for JEO, it is also developing the ASRG as the long term solution for reducing the Plutonium requirements for future planetary missions. A decision on which RPS system will be made available to JEO and is planned by NASA to occur before the start of Phase A. If that decision is delayed it will delay the system design and ultimately may have impacts on mass, power, cost and schedule. Any problems with the RPS that is selected—either in development and validation of the ASRG or in restarting the MMRTG production line—would have a serious impact on the mission since it is baselining a radioisotope power system.

Mitigation

The decision on the type of RPS (MMRTG or ASRG or both) for JEO is crucial for design of the mission starting in Phase A. The decision to use either the MMRTG or the ASRG is required in time to assure that the Phase A design correctly incorporates the design accommodation associated with either RPS. In addition, if the ASRG is selected, then well-defined and stable characteristics are required early in Phase A to allow the system designers to adequately incorporate it into the system. If the decision on type of RPS or its characteristics are not known early in Phase A, late design changes and impacts on mass, power, cost and schedule are likely. The study team will work with NASA to clearly delineate the mission requirements. However, the timing of the selection decision is not under the control of the JEO project. There is a moderate risk of either delay in the decision or problems with the selected RPS system.

JEO currently baselines 5 MMRTGs. The current design could also incorporate 5 ASRGs. These two RPS types require significantly different accommodations on the spacecraft. Margins are currently being maintained to accommodate either technology. Accordingly, the consequence of the decision, provided it is made early, is minimal to the mission and provided each RPS can deliver its specified capability. However, the development and qualification risk for ASRG and availability for MMRTG are risks with high consequences and will be outside the control of the JEO project.

Mitigation of these risks will require the project to work closely with the Program Executive at NASA Headquarters for the ASRG Development Program, to ensure that a final decision on RPS is made prior to the middle of Phase A and that the selected technology is flight qualified no later than Phase B.

4.10.5 Mission Lifetime *(ML 3,1)*

Risk

Missions designed to last 10–15 years are uncommon for deep space. Electronic parts' testing is often not extended past 5–7 years requiring extrapolation of part data to 10+ years. Real-time life testing of components is problematic for systems requiring lifetimes over 7 years. All this adds up to some risk associated with ensuring pre-launch that the design will be fully functional after 10 years.

Mitigation

High reliability is demanded to achieve the life time requirements on the electrical and mechanical parts of the system. Advanced parts screening, life testing and proper application of design margins required for long-lived missions such those used on as Voyager, New Horizons, Galileo, Cassin-Huygens, etc., are the basis for the design to ensure mission success.

Past missions to the outer solar system have dealt with this risk successfully. Though he JEO mission life is only 9 years, there is some risk associated with nearing the 10 year mission lifetime level. As a part of the 2008 Risk Mitigation activity, a set of Long Life Design Guidelines [*JPL D-48271*] were documented which is the accumulation of many decades of experience from past long lived JPL missions, These guidelines are made available to potential instrument and subsystem providers. These guidelines are described in Appendix F and included on the Review CD. All the engineering subsystems on the spacecraft will be required to review and report against the Long Life Design Guidelines as a part of their Preliminary Design Review process. The baseline mission plan includes the cost and effort of the rigorous parts program, life testing and verification and validation program required for such a long-lived mission to succeed.

Finally, a Knowledge capture and Management system, such as that implemented on New Horizons, is critical to ensure technical continuity among personnel from cradle to grave. A system such as that which was developed for New Horizons will be used on JEO.

4.11 Programmatics

The programmatic approach is structured to enable effective management and decision making.

The project management will draw from the experience in the successful design and implementation of long-life, deep-space missions such as Voyager, Galileo, Cassini, and New Horizons. Galileo and Cassini are especially relevant to the outer planets flagship mission development as they both involved major inter-center and international collaboration in development and instrumentation. The management approach outlined here is for the NASA side of EJSM. The cost estimate is for the JEO element of the mission only but does include cost for the main interfaces with ESA within the Project Management, Project System Engineering and Science elements of the WBS. For this estimate, it is assumed that all instruments are procured outright and none would be donated from foreign entities.

4.11.1 Management Approach

The complex, multi-element, architecture that is likely to be chosen for the flagship mission calls for a cohesive partnership between the entities making up the project. The management approach draws upon extensive experience from Galileo and Cassini. It follows NPR 7120.5D and incorporates NASA lessons learned.

The project approach includes: a Work Breakdown Structure (WBS), technical management processes conducted by veteran systems engineers, and integrated schedule/ cost/risk planning and management. The project will take advantage of existing infrastructure for: planning, acquisition, compliance with the National Environmental Policy Act (NEPA), compliance with export control regulations (including International Traffic in Arms Regulations), independent technical authority (as called for in NPR 7120.5D), mission assurance, ISO 9001 compliance, and earned value management (EVM).

JEO employs JPL's integrated project controls solutions to manage and control costs. Skilled business and project control professionals are deployed to projects, utilizing state of the art tools and executing processes that support the project cost, schedule and risk management requirements. Key attributes of the project controls solution are:

- The Business Manager, project focal point on all business management issues, and the project control staff lead project planners and managers in application of the most effective and efficient implementation of project control processes.
- Mature and successfully demonstrated cost and schedule tools are employed.
- Cost and schedule data are tied directly to work scope.

- "Early warning" metrics are provided monthly to key decision makers. Metrics include 1) cost and schedule variances based on the cost value of Work Performed and 2) critical path and slack analysis derived from fully integrated end to end network schedules. Each end item deliverable is scheduled with slack to a fixed receivable. Erosion of this slack value is tracked weekly and reported monthly.
- Integrated business management approach is applied to all system and instrument providers which includes relative performance measurement data integrated into total project database for a comprehensive understanding of project cost and schedule dynamics.
- Risk management processes integrated with the Liens Management process for full knowledge of Project reserve status. Early risk identification is maintained as a potential threat to project reserves. Reserve utilization decisions are made with the knowledge of risks and risk mitigation, project performance issues and increases in scope.

Requirements for project controls evolve throughout the project life cycle. Pre-Phase A and Phase A will require less support than Phases B, C and D. During Phase B, the project controls capability is established at full strength to establish all the appropriate databases and gate products required for a successful Confirmation Review. During Phase C and D, the project controls will be fully functioning with recurring performance measurement analysis and cost and schedule tracking reports. During Phases E and F, the project controls function reduces to minimal levels.

4.11.2 Organization and Decision Making

The JEO project will be led by a Project Manager (PM), who is responsible for all aspects of project development and operations. Deputy Project Managers (DPM) will be chosen from any external organizations that are delivering significant elements of the mission. Additionally, a Deputy Project Manager for Radiation will be chosen, or assigned as additional duty to an existing DPM, to coordinate and manage all aspects of the approach to managing and mitigating radiation. A Project Scientist will be appointed who will represent science interests to the Project. A representative organization chart is shown in **Figure 4.11-1**.

The Project Science Group (PSG) helps to optimize mission science return and to resolve conflicting science requirements. The PSG is led by the Project Scientist, and includes the Deputy Project Scientist, Interdisciplinary Scientists, and Team Leads. The PSG would meet regularly to coordinate on all science matters.

Decisions will be made at the lowest level possible while ensuring that a decision made in one system neither adversely affects another system nor impacts the science data return. Pursuant to NPR 7120.5D, the project will include a project-level "Communications Plan" to its list of planning documents, which will include the dissenting opinion process. This detailed plan for communication and decision-making is due in Phase B, though a draft will be completed in Phase A due to the anticipated Project complexity. The PM will be the final project authority for all decisions that cannot be resolved at lower levels. The Project Scientist will have a prominent role in arbitrating between science priorities in support of science planning for the mission. For decisions involving the quality and quantity of science data deliverables, the Project Scientist will provide concurrence.

Replacement of the PM and Project Scientist will be made only with concurrence by NASA. NASA will be promptly informed of the replacement of other key personnel. Any change in mission objective or in a mission Level 1 requirement will be made only with concurrence from the Program Executive at NASA.

4.11.2.1 Management of the Radiation Effort

The project includes a number of management and leadership positions and organizational elements that are designed to address the radiation challenges of the mission:

- Deputy Project Manager for Radiation (DPMR): reports to the Project Manager to lead all radiation activities for the project and has the authority to trade technical and programmatic resources in order to manage project risk;
- Deputy Project Systems Engineer for Radiation (DPSER): reports to the Project

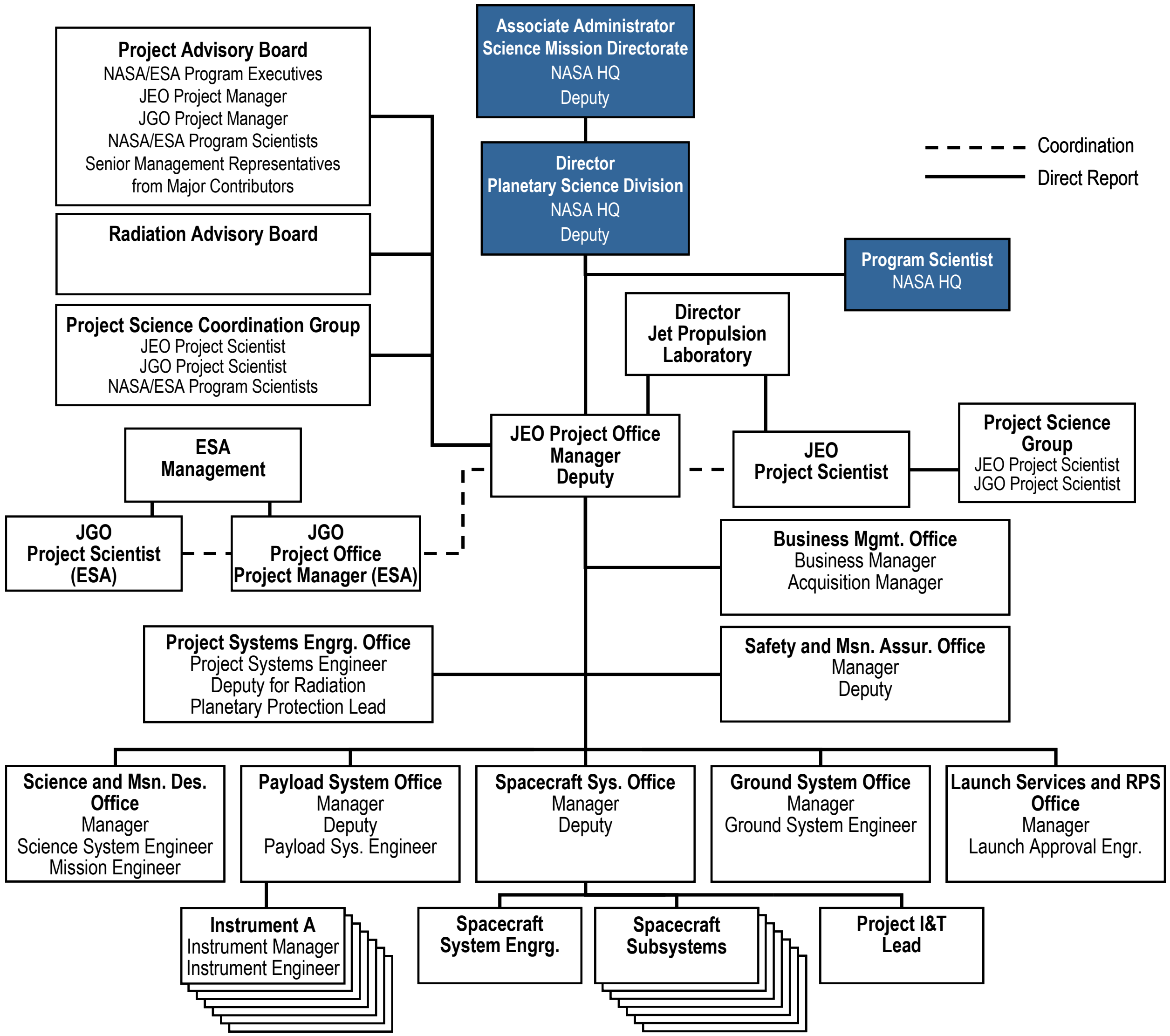


Figure 4.11-1. *Experience obtained from Galileo and Cassini can be used to provide an efficient organization which is science friendly, is pro-active in addressing key challenges and allows decisions to be made at the appropriate level.*

Systems Engineer (PSE) to lead the Radiation Systems Team comprised of systems engineers, configuration and shielding engineers, parts and materials specialists, and mission designers;

- Radiation systems engineers: at the Project, spacecraft, payload, instrument and subsystem levels, to address system issues related to environment, parts, material, shielding, fault protection and operations, with access to area experts supporting all aspects of developments including science instruments and vendor activities;
- Mission Assurance organization: engaged in Pre-Phase A to document and communicate the radiation requirements and design guidelines, to work concurrently with designers on parts, reliability analyses, and shielding and to guide systems trades;
- Radiation technical working groups: proactively work day-to-day issues such as requirements, trades, modeling, and plans;
- Radiation Advisory Board: consists of scientists and practitioners independent of the project who will periodically review the project's approach to radiation tolerant design, risks and mitigation strategies, and to advise Project Management.

4.11.2.2 Knowledge Capture

On long duration missions, personnel turnover at all levels can become an issue. Through natural progression people move on to other projects, leave for other opportunities, retire and even die. The JEO staffing plan and approach includes backup of key personnel, cross training, and continuous training throughout the life cycle of the mission to minimize loss of "corporate knowledge". Steps will be taken during the development phase to ensure that crucial technical information will be captured for use in training in Phase E. A Knowledge capture and Management (KM) system is critical to ensure technical continuity among personnel from cradle to grave. A system such as that which was developed for New Horizons will be used on JEO and documented in a Knowledge Capture Plan in Phase B.

4.11.3 Teaming

The EJSM Mission would be implemented as a joint NASA/ESA collaborative effort. The NASA portion, JEO, is planned as a JPL in-house implementation. The EJSM team would be composed of members from NASA, JPL, JHU/APL, and ESA/ESTEC that have complementary strengths as listed in **Table 4.11-1.**

It is expected that NASA will execute a Memorandum of Understanding with ESA that will cover its planned partnership on EJSM, with DOE for delivery of RPS, and with the Department of Navy, if necessary, regarding the JHU/APL participation in the EJSM project. Preliminary discussions between JPL and APL have been completed. JPL will execute a Memorandum of Agreement with JHU/APL and ESTEC subordinate to the NASA MOUs but at a more detailed level appropriate to project execution. EJSM would comply with all export laws and regulations. Technical Assistance Agreements (TAA) governing technical interchange between the project and international partners are already in place and would be maintained throughout the project development stages to facilitate required interactions.

4.11.4 Roles and Responsibilities

The PM is accountable to the NASA Program Office for the formulation and implementation of the JEO project as well as its technical, cost, and schedule performance. The PM will be responsible to the NASA Program Office. The PM will prepare and approve monthly reports to the Program Office and the NASA Management Office (NMO). All element-level management and financial reporting is through the PM. The PM is also responsible for the risk management activities of the project. The PM will be supported by a Deputy Project Manager(s), Project Scientist (PS) and Deputy PS, Project Systems Engineer (PSE), Deputy Project System Engineer for Radiation (DPSER), Mission Manager,

Table 4.11-1. *EJSM team member strengths are complementary*

Team Member	Role
JPL	JEO: Project Management, Science, System Engineering, Mission Design, Orbiter, Project I&T, and Mission Operations and Ground System
JHU/APL	JEO: Project leadership, Science, System Engineering, Hardware deliveries, Project I&T support and Mission Operations and Ground System support.
ESA/ESTEC	*JGO Implementation, EJSM Science and Instruments (ESA Member States)*

Mission Assurance Manager (MAM), Science Manager, Payload Manager, Spacecraft Manager, and Business Manager. Individuals will be appointed to these positions that have relevant experience and unique strengths with the goal of building a strong team.

The relationships within the EJSM have yet to be fully defined. They will include the support of joint or reciprocal announcements of opportunity for the instruments for both JEO and the Jupiter Ganymede Orbiter (JGO) mission that is being implemented by ESA. The JEO project management team will be responsible for oversight of those instruments and working with the JGO project to coordinate observational programs and plan for archiving data.

4.11.5 Work Breakdown Structure

The JEO Work Breakdown Structure (WBS) is structured to enable effective cost, schedule and management integration. The WBS is derived from JPL's Standard WBS Version 4 and is fully compliant with NPR 7120.5D. This WBS is a product-oriented hierarchical division of the hardware, software, services, and data required to produce end products. It is structured according to the way the work would be implemented, and reflective of the way in which project costs, schedule, technical and risk data are to be accumulated, summarized, and reported.

The top level WBS is shown **Figure 4.11-2**.

4.11.6 Schedule

The phase durations are the result of a bottoms-up integrated cost/schedule/risk assessment and draw on experience from previous flagship missions.

4.11.6.1 Pre-Phase A

Up to and including this report, many alternative concept studies have been conducted. Those studies form the basis of an assessment of alternatives that have resulted in the current mission concept and its readiness to complete Pre-Phase A. To complete Pre-Phase A, a pre-project team would be formed to refine the baseline mission concept and implementation plan in alignment with programmatic goals and objectives. This refinement, along with interactions with NASA, ESA and other potential stakeholders, would result in further definition of the mission concept and draft project-level requirements.

The Pre-Phase A activities include completion of NPR 7120.5D specified Pre-Phase A Gate Products, preparation of a Project Information Package (PIP) in support of NASA's development of an Announcement of Opportunity (AO) for instrument acquisition, and a Mission Concept Review leading to Key Decision Point (KDP) A. In addition to those activities required for transition to Phase A, the team will identify additional planning, advanced development and risk reduction tasks that, if funded, would provide a prudent and cost effective approach to early reduction of cost and schedule risk and which have the potential to reduce the estimated cost of Phase A. Primary activities would include reducing the radiation and planetary protection risks associated with instrument and spacecraft development (see §4.11.7.2). Special attention should be given to the development, selection and early design phases for the instruments. **Figure 4.11-3** provides a preliminary schedule consistent with the Pre-Phase A cost estimate provided in **Table 4.11-3**.

There has been a great deal of work done on missions to Europa that JEO builds upon. The Europa Orbiter Project and Prometheus/JIMO Program provided the first comprehensive exploration of the mission option space and led to development of technologies for coping with the radiation environment. The immediate progenitors of JEO, which uses Venus and Earth gravity assist maneuvers and chemical propulsion, are the Europa Geophysical Explorer Concept Study in 2005 and Europa Explorer in 2006 and 2007. For JEO the ability to get the instruments selected and through the first round of design updates for radiation and planetary protection is the pacing item. Since the science objectives have been vetted by the science community several times over the past few years and are highly stable, it is unlikely that significant changes would occur, nor would the response implementation be likely to change significantly as the project moves into Phase A. This is very different from previous mission concepts as they moved from Pre-Phase A into Phase A.

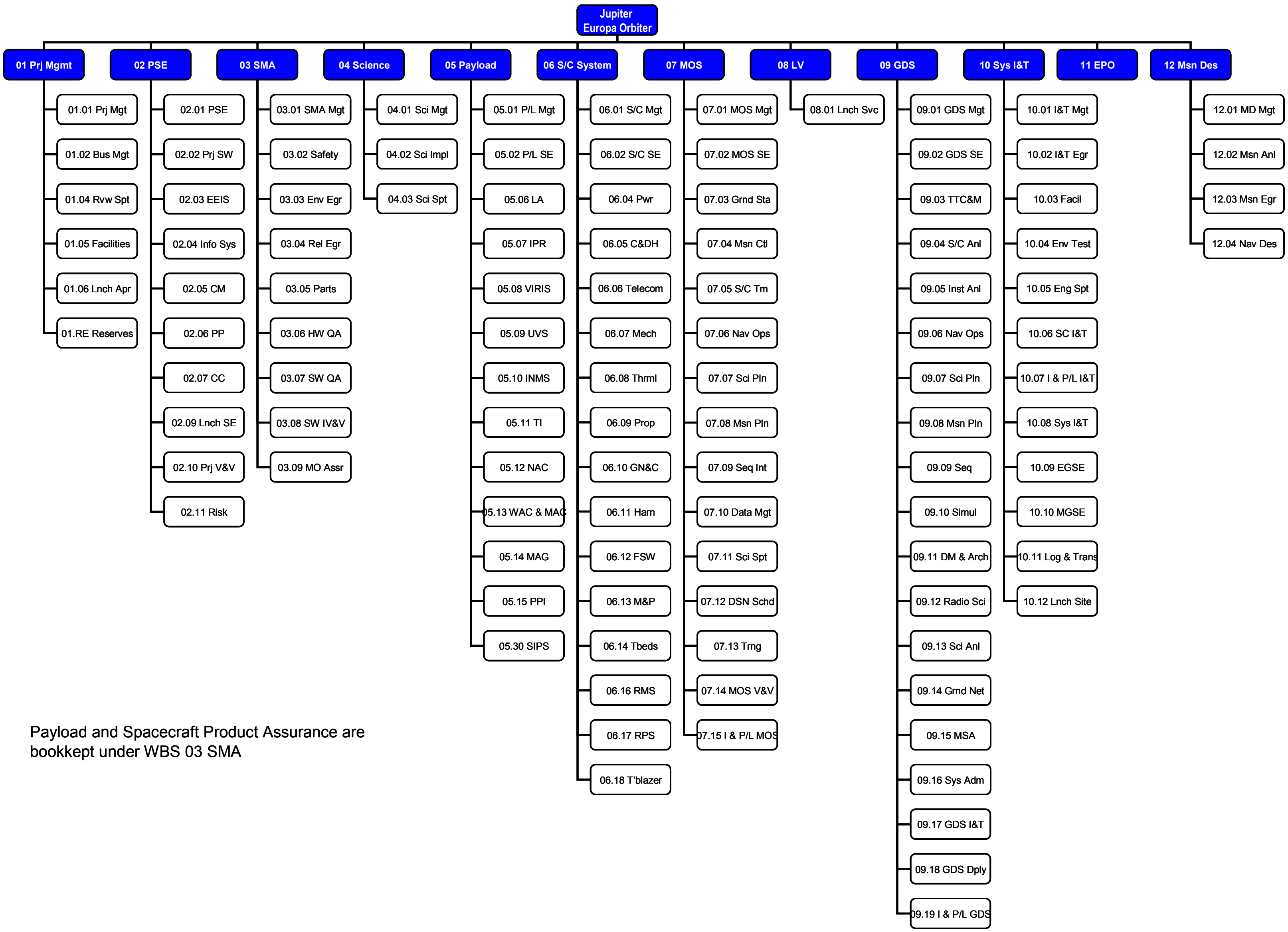


Figure 4.11-2. *JEO Work Breakdown Structure.*

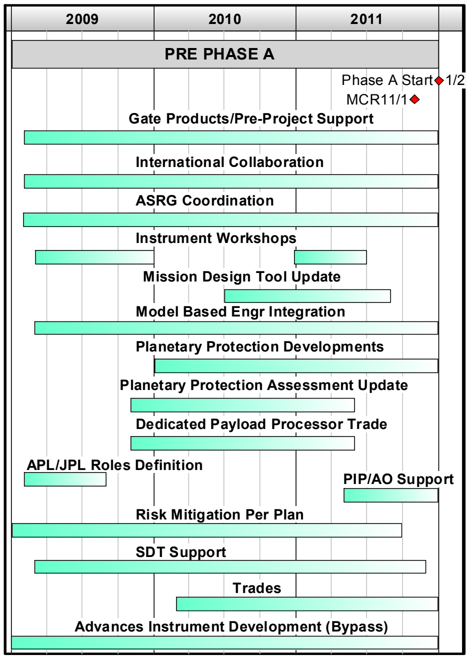


Figure 4.11-3. *Time phasing of Pre-Phase A gate products and optional planning, advanced development and risk reduction tasks.*

4.11.6.2 Phases A through F

The Phase A–F schedule reflects the total project scope of work as discrete and measurable tasks and milestones that are time phased through the use of task durations, interdependencies, and date constraints and is traceable to the WBS. To insure low risk, the schedule includes funded slack for all tasks. The top level schedule is shown in **Foldout 13 (FO-13)**.

The PM controls the project schedule, with support from a Project Schedule Analyst. An Integrated Master Schedule identifies key milestones, major reviews, and receivables/ deliverables (Rec/Dels). Funded schedule reserves shown in the Project Master Schedule for the February 2020 launch opportunity, **FO-13**, are funded at the peak burn rate, and meet or exceed JPL DPP requirements. The project utilizes an integrated cost/schedule system in Phase B, in order to fully implement an EVM baseline in Phases C/D/E. Inputs will be supplied to NASA's CADRe support contractor for reporting at major reviews. Schedule and cost estimates at completion (EAC) will be prepared at regular intervals as part of the EVM process. Major project review milestones (not all shown) are consistent with NPD 7120.5D.

Phase A - B

The length of Phases A/B (21 months-A / 20 months-B) is primarily driven by the schedule to select the instruments in response to the AO and advance the selected instruments to PDR level of maturity. In Phase A the primary tasks are completing the Gate Products required, facilitating the selection of the science instruments and completing the Instrument Concept Design Reviews (ICDR). The eight month period between instrument selection and the instrument concept design review allows instrument designers to work directly with the project personnel on issues related to radiation and planetary protection. After each instrument completes its ICDR, the Project assesses the results and presents any updates to the mission concept required to accommodate the conceptual instrument designs. This Instrument Confirmation Review allows both the project and Headquarters the opportunity to adjust implementation details if resources become an issued as a result of the payload selection. Any early work to facilitate the maturation of the instrument implementations would benefit the schedule and reduce project risk.

A milestone for a Planetary Protection decision has been inserted in Phase B. A basic approach to meeting the planetary protection requirements has been outlined and agreed to by the PPO at NASA Headquarters. This milestone is anticipated to be a review of the more detailed implementation approach including any major outstanding issues related to mission design, flight system design or operations concepts. This review may ultimately be combined with the Project PDR if it is more effective to do so.

Phase C - D

The length of Phases C/D (30 months-C/ 28 months-D) is primarily driven by the schedule to bring the flight system to launch readiness. Phase C is longer than typical due to the added time required to implement the radiation and planetary protection requirement mitigation aspects of the design. Phase D was developed using the Cassini model of I&T and has specific costs \$3.5M (FY07) associated with potential schedule impacts due to meeting planetary protection requirements.

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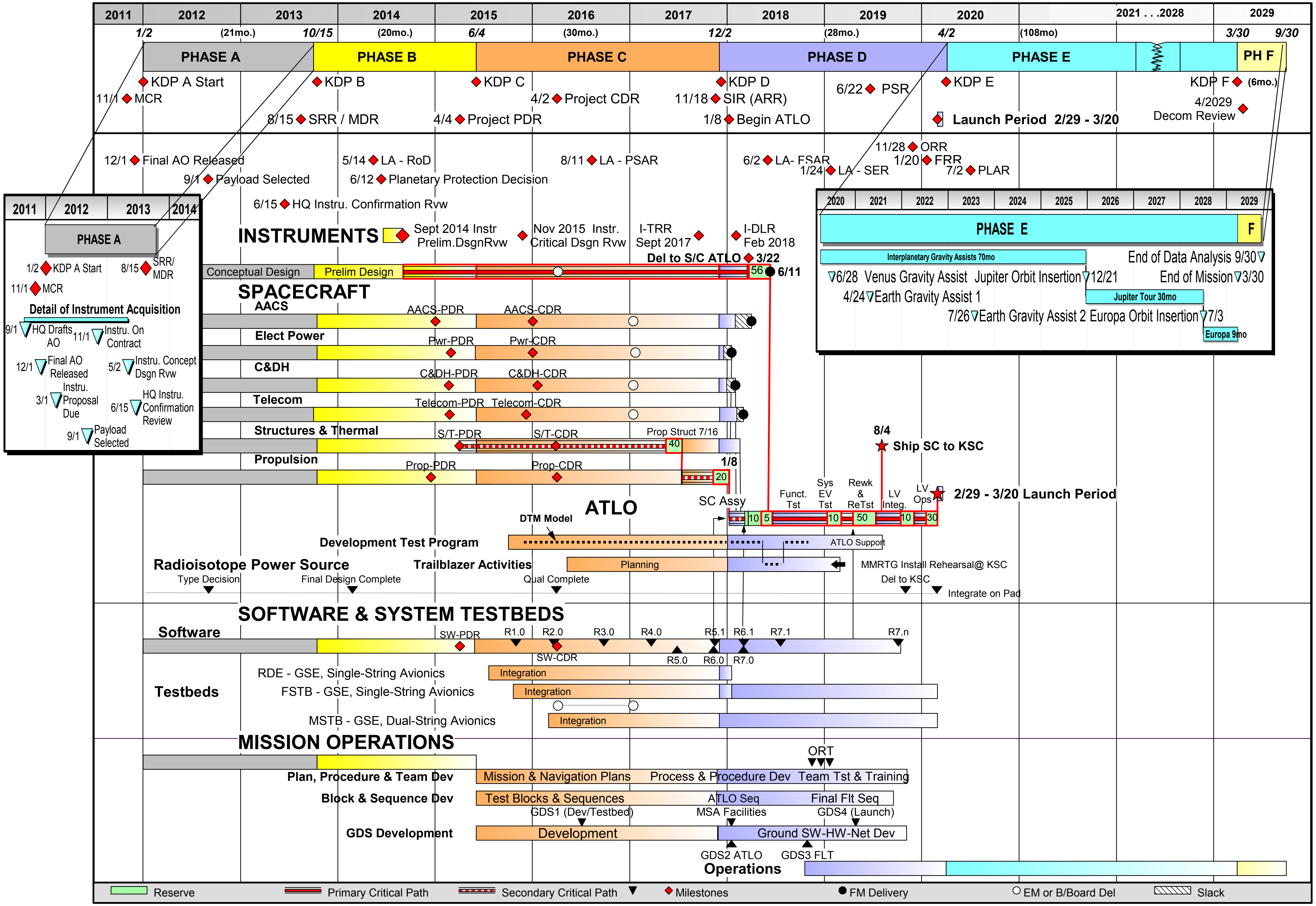
FOLDOUT 13
PROJECT MASTER SCHEDULE



A trailblazer activity is scheduled to occur at the launch facility in Phase D to ensure that the spacecraft design is compatible with the launch vehicle and facility limitations at the launch site for transporting and loading of the RPSs. This activity starts at a very low level in Phase B and continues with increasing activity until the approach to RPS installation is validated in Phase D.

Phase E - F

Phase E (108 months) is driven by the interplanetary trajectory and science requirements at Jupiter and Europa. Phase F (6 months) is structured to carry out the end-of-mission scenario and to complete data analysis and archiving.

Schedule Reserve & Critical Path

The critical path, is the instrument solicitation, development and delivery, and is shown in red in FO-13. This critical path is contingent on the release of the instrument AO. Any effort to release early design information to instrument providers would greatly mitigate the risk associated with instrument (identified Project Risk (In)) in **Figure 4.10-1** and as discussed in §4.10.1.3). Thus, early identification of parts, materials, design guidelines etc. for mitigating the radiation and planetary protection challenges would be highly effective.

Schedule reserves of 56 work-days for instrument delivery and 105 in ATLO, totaling 161 work-days or 32 weeks are available along this critical path. Later delivery of the instruments to ATLO may be possible as that schedule is firmed up in Phase A. Funded schedule reserves have been planned strategically along the critical paths as shown in the top-level schedule in **FO-13**.

There is a secondary critical path through the design of the primary structure leading into the delivery and integration of the propulsion system that is also highlighted by a red dotted line in **FO-13**. Schedule reserves of 175 work-days or 35 weeks are available along this critical path. This critical path may be mitigated somewhat during preliminary design by further de-coupling the structure from the propulsion subsystem. This will need to be worked as a part of Phase B.

4.11.7 Estimated Mission Cost

The JEO cost estimate is for the complete project life cycle from Phase A through Phase F. Pre-Phase A costs are reported separately.

4.11.7.1 Cost Estimating Methodologies

The cost estimating methodologies used to develop the JEO cost estimate are described in **Table 4.11-2.** JEO uses a hybrid methodology that includes JPL grassroots, JPL Institutional cost models, the subsystem NASA Instrument Cost Model (NICM) and percentage wrap factors derived from cost rules of thumb and cost analogies. Radioisotope power source, launch services and DSN aperture costs were provided by NASA Headquarters.

Figure 4.11-4 summarizes the cost share percentage by estimation methodology.

4.11.7.2 Pre-Phase A Costs

A preliminary time phased task and cost list is shown in **Table 4.11-3** showing an estimated Pre-phase A cost of $38M (RY). Time phasing of tasks in the Pre-Phase A schedule is driven by 1) timely completion of Gate Products, AO inputs, and reviews required for transition into Phase A, and 2) completion of additional planning, advanced development and risk reduction tasks prior to start of Phase A. The JEO project highly recommends that NASA support early definition activities for instruments. It is expected that funding will be administered through a NASA R&A program such as the Planetary Instrument Definition and Development Program (PIDDP). The costs of instrument definition and development are included in the Pre-Phase A activities and are shown in **Table 4.11-3** as a bypass item. It should be emphasized that if NASA elects not to fund the additional planning, advanced development and risk reduction tasks, the total mission cost and cost reserve plan proposed herein would be preserved; though some increased cost risks may result. Nevertheless, the funding for the Gate Products, preparation of a PIP in support of NASA's development of an AO for instrument acquisition, and a Mission Concept Review leading to KDP A would be needed. Execution of the Pre-Phase A would further reduce the risks assumed in this baseline plan.

Table 4.11-2. *Cost Estimating Methodology*

WBS Element	Description
01 Project Management	Institutional cost models. The estimate was augmented for JEO specific implementation characteristics such as additional DPM (Radiation and Project), CTM for APL subcontract, communication and planning support. WBS 01.06 Launch Approval was estimate using grassroots methodology.
02 Project System Engineering	Institutional cost models. The estimate was augmented for JEO specific implementation characteristics such as additional DPSER. WBS 02.06 Planetary Protection estimated using grassroots methodology.
03 Safety & Mission Assurance	Percentage wrap factor. Phase A–D = 5.0%, Phase E = 2.0% of CBE cost excluding RPS and LV. Includes Project level SMA and Spacecraft System product assurance. Instrument specific PA is included in the NICM estimate.
04 Science	Institutional cost model. This model was augmented per direction of Project Scientist after consultation with previous Project Scientist for Cassini and Galileo
05 Payload System	• Institutional cost models. WBS 05.01 P/L Mgmt and 05.02 P/L SE models augmented for radiation design support • NICM subsystem model was used to develop the instrument costs. Source: *NICM Version 1 -- Released December 2006*. Individual instrument cost estimates include instrument specific Management, System Engineering, Product Assurance and Integration & Test. The 50% NICM estimate was scaled for radiation and planetary protection.
06 Spacecraft System	Grassroots estimate to WBS level 4 and below. Estimates developed and reviewed by technical line line and project management organizations.
06.17 Radioisotope Power Source	Source: *RPS Cost Est for Flagship_v4*, 4/10/2007. MMRTG prices exclude qualification costs per NASA Headquarters direction.
07 Mission Operations System	Institutional cost models with tailoring due to Operations Lessons Learned Working Group recommendations.
07.03 Ground Station Tracking	DSN aperture fee estimated using *DSN Aperture Fee* tool. The *DSN Aperture Fee* tool is imbedded within the Institutional cost model for 07 Mission Operations System.
08 Launch System w/ Nuclear Support	Source: *Requirements and Ground rules for Flagship Mission Studies*, Table 1 ROM Launch Services costs for Atlas 5 and Delta IV Heavy launch vehicles. Table values reported in $FY06 and escalated to $FY07 dollars. Includes nuclear payload costs.
09 Ground Data System	Institutional cost models with tailoring due to Operations Lessons Learned Working Group recommendations.
10 Project System Integration & Test	Grassroots estimate to WBS level 4. Estimates developed and reviewed by technical line line and project management organizations.
11 Education and Public Outreach	Percentage wrap factor. Phase A = 0.5%, Phase B / D = 0.5%, and Phase E / F = 2.0% of base.
12 Mission Design	Grassroots estimate to level WBS Level 3. Estimates developed and reviewed by technical line and project management organizations.
Reserves	Reserve base excludes DSN Aperture, LV, and EPO. Phase A—10%, Phase BCD— 37%, Phase E—15%.

4.11.7.3 Baseline (and NASA-Only) LCC Estimate

The current JEO Phase A through F life-cycle cost estimate for the baseline mission concept is $3.8B (RY) $2.7B (FY07). The cost by development phase is shown in **Table 4.11-4.** Since the NASA-only mission concept is identical to the baseline mission concept, it's cost is identical.

A summary of key costing parameters for JEO is given in **Table 4.11-5**. The JEO cost estimate represents the full life cycle and conservatively assumes individual instruments instead of instrument suites. No offsets have been taken for potential domestic or foreign contributions.

4.11.7.4 Budget Reserve Strategy

Budget reserves were established using a process consistent methodology based on previous experience. As determined from the process described above, the JEO budget reserves are calculated as:

- Phase A = 10%.
- Phase B through D = at 37% per Cost Risk Subfactors.
- Phase E = 15%.

The reserves base is the current best estimate cost including RPS but excludes DSN Aperture, Launch System, and EPO.

Reserves status will be evaluated at project key decision points. Commensurately, the confidence in implementing the mission within

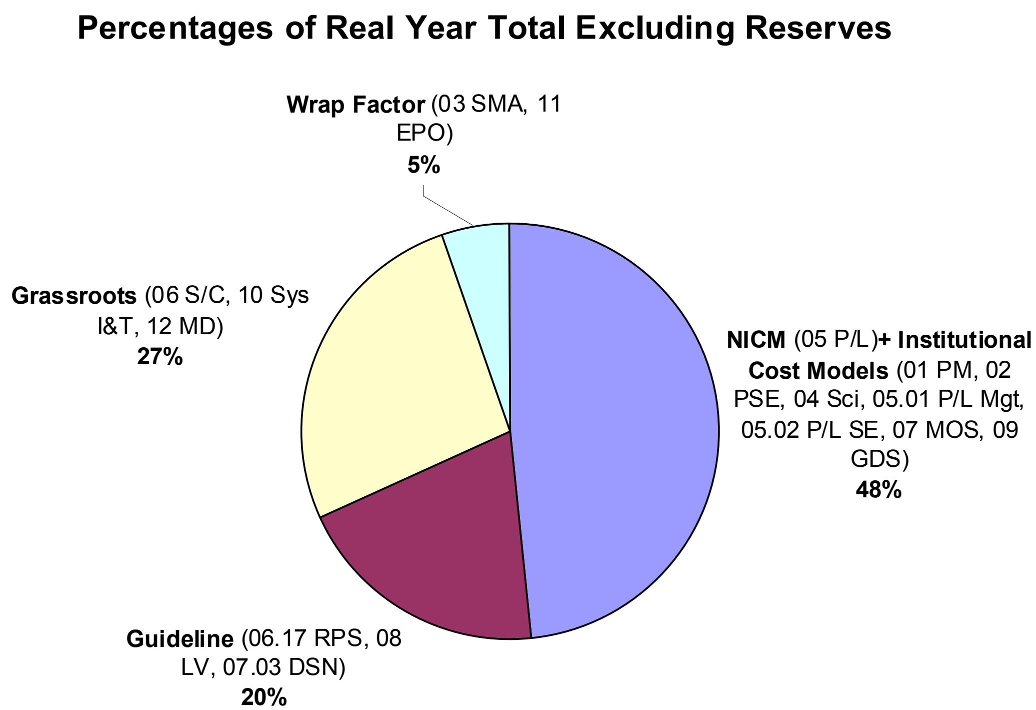


Figure 4.11-4. *Cost percentage by estimation method (excluding reserves).*

the overall estimate provided here is expected to grow.

4.11.7.5 Cost of Radiation

The cost of meeting the radiation requirements is closely coupled with the costs of meeting the planetary protection requirements for this mission. Accordingly, **Table 4.11-6** shows an estimate of the cost associated with the combined impact of the radiation and planetary protection requirements. Except for the DSN tracking cost, this entire cost delta is associated with Phases A–D. (Phase E cost impacts are difficult to discern from the base cost). Note that some costs associated with radiation and planetary protection are straightforward (rad-hard electronics, heat sterilization, additional system engineering), but some subtle aspects are the extended schedule (approximately 6 months more each in Phases B and C) as well as extra DSN time during early Europa operations. An attempt was made to capture these aspects by looking at the detailed costing, but the estimate is only approximate. For the instruments, the NICM subsystem model was run using the same masses but excluding the shield mass. Also, the instrument development cycle was reduced by 12 months (6 months each Phase B and C) and no additional factors were applied for radiation or planetary protection.

Table 4.11-3. *Cost Estimate for Pre-Phase A Gate Products ($k RY)*

	FY 2009	FY 2010	FY 2011	FY 2012	Total
Gate Products/Pre-Project Support	684	1,474	3,400	1,738	7,296
International Collaboration	287	442	725	135	1,589
ASRG Coordination	112	157	162	38	470
Instrument Workshops	133	198	307	0	638
Mission Design Tool Update	0	66	256	0	322
Model Based Engr Integration	52	150	218	59	479
Planetary Protection Developments	0	241	421	119	781
Planetary Protection Assessment Update	0	190	0	0	190
Dedicated Payload Processor Trade	0	105	109	0	215
APL/JPL Roles Definition	102	0	0	0	102
PIP/AO Support	0	0	167	183	350
Risk Mitigation Per Plan	3,224	2,875	2,556	0	8,655
SDT Support	99	454	1,404	294	2,252
Trades	0	487	846	228	1,561
Advanced Instrument Development (Bypass)	1,100	6,500	5,600	0	13,200
Total	**5,793**	**13,341**	**16,170**	**2,794**	**38,098**

Table 4.11-4. Baseline Jupiter Europa Orbiter Cost Estimate by Project Phase.

	Project Phase					Project Phase			
	A	B	C	D	Total Phase A - D ($M RY)	E	F	Total Phase A - F ($M RY)	Total Phase A - F ($M FY07)
Phase Duration (Months)	21	20	30	28	99	108	6	213	213
01 Project Management (Includes Subcontract Burden)	**13.3**	**31.2**	**46.3**	**33.8**	**124.6**	**45.4**	**1.7**	**171.7**	**122.4**
02 Project System Engineering	**5.0**	**8.8**	**19.8**	**22.0**	**55.5**			**55.5**	**41.1**
03 Safety & Mission Assurance	**2.5**	**18.1**	**57.1**	**18.8**	**96.4**	**10.2**	**0.4**	**107.0**	**81.0**
04 Science	**2.4**	**9.7**	**28.8**	**18.6**	**59.5**	**199.3**	**11.7**	**270.6**	**160.2**
05 Payload System	**5.1**	**48.3**	**429.7**	**83.9**	**567.1**			**567.1**	**437.1**
05.01 PL Mgmt	2.0	2.0	3.7	3.8	11.5			**11.5**	8.6
05.02 PL Sys Eng	3.1	5.9	6.5	6.0	21.5			**21.5**	16.3
05.06 Laser Altimeter (LA)	0.0	3.3	34.0	6.0	43.4			43.4	33.5
05.07 Ice Penetrating Radar (IPR)	0.0	9.8	101.4	18.0	129.1			129.1	99.6
05.08 Vis-IR Imaging Spectrometer (VIRIS)	0.0	6.6	68.2	12.1	86.9			86.9	67.0
05.09 UV Spectrometer (UVS)	0.0	3.4	35.3	6.3	44.9			44.9	34.7
05.10 Ion and Neutral Mass Spectrometer (INMS)	0.0	2.4	24.7	4.4	31.5			31.5	24.3
05.11 Thermal Instrument (TI)	0.0	3.0	31.1	5.5	39.6			39.6	30.5
05.12 Narrow Angle Camera (NAC)	0.0	4.2	43.4	7.7	55.2			55.2	42.6
05.13 Wide Angle & Medium Angle Camera (WAC + MAC)	0.0	4.1	42.1	7.5	53.6			53.6	41.4
05.14 Magnetometer (MAG)	0.0	1.3	13.4	2.4	17.1			17.1	13.2
05.15 Particle and Plasma Instrument (PPI)	0.0	2.4	25.2	4.5	32.1			32.1	24.8
05.30 Science Instrument Purge SS	0.0	0.0	0.7	0.0	0.7			0.7	0.6
06 Spacecraft System	**17.6**	**195.3**	**397.3**	**73.3**	**683.5**			**683.5**	**525.8**
06.01 S/C Mgmt	0.5	1.9	3.0	2.9	8.2			8.2	6.0
06.02 SC Sys Eng	0.9	9.3	16.1	5.9	32.2			32.2	24.4
06.04 Power SS	2.2	25.7	37.4	3.3	68.7			68.7	53.6
06.05 C&DH SS	0.6	61.6	41.9	1.7	105.8			105.8	84.4
06.06 Telecom SS	2.2	20.6	36.0	3.2	62.1			62.1	48.4
06.07 Mech SS	1.9	20.8	108.1	10.2	140.9			140.9	107.1
06.08 Thermal SS	0.9	3.6	9.4	5.2	19.0			19.0	14.3
06.09 Prop SS	2.4	19.5	29.3	6.8	58.0			58.0	44.9
06.10 GN&C SS	5.3	22.2	64.1	4.7	96.4			96.4	74.4
06.11 Harness	0.0	1.4	8.5	4.1	14.0			14.0	10.4
06.12 Flt SW	0.4	5.3	29.3	14.4	49.5			49.5	36.6
06.13 SC Materials & Proc	0.0	1.1	2.8	0.8	4.8			4.8	3.6
06.14 SC Testbeds	0.0	0.8	7.7	8.0	16.6			16.6	12.0
06.16 Radiation Monitoring SS	0.2	1.4	2.2	2.1	5.9			5.9	4.5
06.18 Trailblazer	0.0	0.0	1.5	0.0	1.5			1.5	1.2
07 Mission Ops Sys	**1.5**	**3.9**	**17.9**	**40.2**	**63.5**	**264.6**	**5.2**	**333.4**	**197.6**
09 Ground Data Sys	**1.0**	**3.1**	**20.9**	**28.4**	**53.4**	**28.4**	**0.8**	**82.6**	**55.8**
10 Project Sys I&T	**0.3**	**9.7**	**13.6**	**51.6**	**75.2**			**75.2**	**54.3**
11 Educ and Pub Outreach	**0.3**	**1.7**	**5.2**	**1.8**	**9.0**	**10.4**	**0.4**	**19.7**	**13.4**
12 Mission Design	**4.4**	**7.3**	**9.3**	**8.2**	**29.1**			**29.1**	**22.3**
CBE Cost	**53.3**	**337.0**	**1,045.9**	**380.6**	**1,816.8**	**558.4**	**20.1**	**2,395.3**	**1,711.1**
Reserves	**5.3**	**140.5**	**445.5**	**149.1**	**740.5**	**82.2**	**3.0**	**825.7**	**612.8**
CBE + Reserves	**58.6**	**477.6**	**1,491.5**	**529.7**	**2,557.4**	**640.6**	**23.1**	**3,221.0**	**2,323.9**
06.17 Radioisotope Power Source (5 MMRTGs)	**0.0**	**44.5**	**163.4**	**24.3**	**232.2**			**232.2**	**180.0**
07.03 Gnd Station Trckng	**0.0**	**0.0**	**0.0**	**3.4**	**3.4**	**70.5**	**0.0**	**73.9**	**43.1**
08 Launch Sys (Atlas 551 LV + Nuclear processing)	**0.0**	**0.0**	**88.5**	**178.4**	**266.9**			**266.9**	**197.1**
Total Mission Cost	**58.6**	**522.0**	**1,743.4**	**735.9**	**3,059.9**	**711.1**	**23.1**	**3,794.0**	**2,744.1**

- WBS element 05.03 Payload Product Assurance is costed under WBS element 03 Safety and Mission Assurance
- Radio Science is costed under WBS element 06.06 Telecom SS
- WBS element 06.03 Spacecraft Product Assurance is costed under WBS element 03 Safety and Mission Assurance
- WBS element 06.15 Spacecraft System I&T is costed under WBS element 10.0 Project System I&T

4.11.7.6 Cost of Planetary Protection

The cost of meeting the planetary protection requirements is closely coupled with the costs of meeting the radiation requirements for this mission.

4.11.7.7 Phase E Cost Reductions

One of the key goals of this study was to explore ways of reducing the costs of Phase E operations significantly below the level experienced in the Cassini mission. As part of the OPFM effort, a study was conducted (Appendix K: Mission Operations Lessons Learned Study For The Next Outer Planet Flagship Mission (OPFM)) to assess lessons

Table 4.11-5. Summary of Key Costing Parameters for the Jupiter Europa Orbiter

	JEO Mission Characteristic
Launch Date	February 2020
Trajectory	VEEGA
Launch Vehicle	Atlas V 551
RPS	5 MMRTGs
Instruments Quantity	11 including Radio Science
Mission Duration: Jupiter System/Europa	30 months/9 months
Reserve on Phases B–D	37%
Percentage of Cost Directly supporting Science, Instruments and instrument Operations	32%

Table 4.11-6. *Preliminary analysis shows that meeting the challenging radiation and planetary protection requirements requires an increase of approximately 25% in the estimated LCC.*

WBS Element	Estimated Radiation and Planetary Protection Cost ($MFY07)	Basis of Estimate
01 Project Management	16	1/2 Time for Deputy Project Manager dedicated to radiation issues (fully radiation related) Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (deleted months 2–7 of LoE workforce in both B and C) (combined radiation and PP)
02 Project System Engineering	6	1/2 Time of Deputy Project System Engineer dedicated to radiation issues (fully radiation related), full Planetary Protection costs(fully PP related), Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
03 Safety & Mission Assurance	32	5% on radiation specific costs plus 1% across Phase A-D on all other costs (combined radiation and PP)
04 Science	14	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
05 Payload System		
05.01 Payload Management	1	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
05.02 Payload System Engineering	8	Additional Support to Instruments + Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and pp)
05.X Instruments	183	Includes additional 6 months each in Phases B and C, extra shielding, electronics, ASIC and Detector costs
06 Spacecraft System		
06.01 S/C Management	1	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.02 Spacecraft System Engineering	6	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.03 Spacecraft Product Assurance (Included in WBS 03 SMA)		N/A
06.04 Power SS	13	Review of costs for similar aspects of JEO and TSSM (combined radiation and PP)
06.05 C&DH SS	43	Review of costs for similar aspects of JEO and TSSM (majority is Solid State Recorder which is primarily radiation related) (combined radiation and PP)
06.06 Telecom SS	8	Review of costs for similar aspects of JEO and TSSM (combined radiation and PP)
06.07 Mechanical SS	2	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.08 Thermal SS	2	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.09 Propulsion SS	1	Review of costs for similar aspects of JEO and TSSM (combined radiation and PP)
06.10 AACS SS	21	Review of costs for similar aspects of JEO and TSSM (combined radiation and PP)
06.11 Harness	1	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.12 FSW	2	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.13 SC M&P	1	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
06.14 SC Testbeds		No identified cost impact
06.16 Radiation Monitoring Subsystem	5	Full cost (fully radiation related)
06.17 Radioisotope Power Source	0	No identified cost impact
06.18 Trailblazer		No identified cost impact
07 Mission Operations System	4	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
07.03 Grnd Station Trkng	10	Additional 2 passes per day of DSN for first 105 days in Europa orbit (fully radiation related)
09 Ground Data System	4	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
10 Project System Integration & Test	4	Line item identified in PCAT for schedule for Planetary Protection (fully PP related)
11 Education and Public Outreach	0	No identified cost
12 Mission Design	4	Level of Effort Workforce: 6 months additional Phase B and 6 months additional Phase C (combined radiation and PP)
CBE Cost	**393**	
Reserves	146	37% of CBE
CBE Cost + Reserves	**539**	
08 Launch System Total (Atlas 551 LV + Nuclear processing)	**0**	No identified cost impact
Total Mission Cost	**539**	

learned from Cassini, New Horizons MRO and MESSENGER mission operations experience with the intent to improve efficiency and lower the cost of operating the next OPFM. Results from that study were incorporated in the JEO design and have dramatically reduced the complexity and therefore cost of mission operations.

In keeping with this basis, these estimates assume a modern approach to mission operations and supporting software systems similar to Cassini and MRO. Table 4.11-7 provides a comparison of JEO Phase E burdened cost estimate by year to the actual Cassini Phase E costs normalized to $M (FY07) and aligning the Cassini SOI and Europa JOI dates. JEO operations has been significantly reduced at ~$60M (FY07)/yr for the Tour (comparable to Cassini operations) compared to ~$80M (FY07)/yr for Cassini operations. This results in a planned savings of ~$20M (FY07)/yr. Further reductions are likely as more detailed analysis and planning are completed.

Still to be exploited are methods and technologies from continuing advancements, which are poised to make sizable savings in the cost of mission operations. There will be a two-decade gap between the capabilities of Cassini during development and those of JEO for the same phase. This is as large as the gap between Voyager and Cassini, which saw huge gains in productivity and capability. With the progress that has been made since Cassini, largely through continuing institutional investments, its expected that its possible to reliably streamline operations processes and improve spacecraft operability and robustness, resulting in direct reductions to staffing levels, the major component of operations cost.

The steps envisioned to enable this improvement start with new architectural methods during development that use operations scenarios and system models to more transparently specify and shape software design for both ground and flight systems. This has been demonstrated to reduce incidental complexity, producing designs that are more easily understood, and easier to validate and operate. Additional architectural support will be provided through upgraded ground system service infrastructure and middleware, as well as improvements in visualization and analysis tools, and more. Improved planning and validation tools are also available, with flight-proven success in substantially reducing costs.

Together, such capabilities enable a more consolidated and collaborative operations approach, with fewer hand-offs and translations, simpler interfaces, and better automation of routine functions. And on board, they translate into a more trouble-free spacecraft that requires less supervision, and can be used flexibly to meet the scientific objectives of the mission.

The savings to be gleaned from such an approach will require further study to quantify. Still, even modest reductions in operations cost accumulated across several years of Phase E can yield large savings compared to the investments anticipated to leverage available innovations during Phases B/C/D. With such economies readily available to this project in the time frame of its development, JEO is positioned well to achieve ambitious goals for low operations cost. An augmentation to the MOS/GDS Phase B–D costs was included in the cost estimate to attempt to capture initial costs for early development.

4.11.7.8 Descope Strategy

This mission concept provides NASA descope options to a scientifically attractive floor mission, yielding a very robust project implementation plan. In the event that demand on project reserves is higher than planned, meaningful descopes would be available to replenish reserves during the development phases. In the process of transitioning from the "core" to the "sweet spot" mission in mid-study, a list of augmentations were developed between the JJSDT and the engineering team (§4.1.5). After the baseline was developed in this process, the JJSDT re-evaluated the order in which capability would be removed from the mission until the floor mission is achieved.

Table 4.11-7. *Phase E Comparison of JEO and Cassini.*

With Reserves, Excluding DSN Aperture ($MFY07)						Aligned JEO JOI w/ Cassini SOI				
	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029
JEO Phase E	18.7	32.0	22.5	27.2	23.7	41.3	58.6	56.2	55.1	36.5
Cassini	46.3	82.2	64.8	69.4	77.0	80.1	87.6	83.9	75.7	83.7

Notes:

1. Cassini SOI = June 30, 2004 (FY 2004). FY 2004 cost includes Huygens Probe (released December 25, 2004) support.
2. JEO JOI = December 21, 2025 (FY 2026)
3. For comparison Cassini and JEO mission orbit insertions are aligned at JEO JOI.

A preliminary list of potential descopes has been identified with their associated margined mass and power, science impact and cost savings if exercised at the time of the project PDR or CDR is shown in **Table 4.11-8**. The actual descope path in going from the baseline mission to the floor mission could follow a number of sequences depending on the reason for the descope. Decisions based on risk may be different from those driven by cost or mass. Thus, an approach would be developed that quantifies the impact of each descope on the mission. This would be done in conjunction with the Project Science Group, implementation team and HQ. Once defined, impact on the mission can be traded against science, risk, schedule, and cost. This approach would be implemented by the Project System Engineering Team to ensure that optimal descope decision options are made and communicated to the sponsor, stakeholders, and team. A complete prioritized descope list and time-phased descope plan would be established in Phase B prior to confirmation and approval to proceed. Only the PM would be able to authorize descopes with the concurrence of the PS and HQ. If a level 1 requirement is effected, then HQ approval is required.

4.11.7.9 Floor Mission Costs

The floor mission is defined to take the value of the descope cost savings taken at project start. The comparison of the baseline, floor and NASA-only JEO missions are shown in **Table 4.11-9**. Note that the NASA-only mission follows the same descope process as the baseline.

4.11.7.10 Early Launch Option

As shown in §5, there is a launch opportunity in October 2018 that is very attractive. This opportunity is 17 months earlier than the nominal February 2020 launch. If NASA were to decide to launch JEO during the 2018 opportunity, the schedule could easily shift earlier by 17 months and be executable with no added project risk.

***Table 4.11-9.** Comparison between Baseline, Floor, and NASA-Only costs*

	$MRY	$MFY07
Baseline Mission	3,794	2,744
Floor	3,017	2,152
NASA Only	3,794	2,744

This would mean that the preparation of the AO (release would be 7/2010) and all Pre-Phase A activities would be compressed but would still be very feasible. No changes to the fixed year cost estimate for Phases A-F would be identifiable as the interplanetary trajectory would be the same length. In real year dollars, the cost would be lowered by 17 months of inflation.

4.11.8 Risk Assessment and Management Strategy

As a Category 1, Class A mission, JEO baselines a risk manager to assist the PM. Risk identification and assessment is part of the daily management and systems engineering process, with all team members as active participants. All technical and programmatic margins meet or exceed JPL and JHU/APL requirements and are prudent for a Pre-Phase A study.

In the event of unforeseen problems, a descope plan (outlined in §4.11.7.8) has been developed for keeping the project within cost and schedule constraints without falling below the science floor. The risk assessment, including all moderate and high risks, is summarized in §4.10. The risk management process initiated for this study contains the key aspects that would be used during formal mission formulation and development. The Risk Manager (RM) monitors the common risks associated with staffing, technology, cost, schedule, and perception. Four primary activities are performed in the risk management process:

1. Risk identification: A continuous effort to identify and document risks as they are found and to provide an estimation of the risk attributes (i.e., the consequences of failing to achieve a desired result and the likelihood of failing to achieve that result),
2. Risk analysis: An evaluation of the submitted item to determine whether or not it qualifies as a project risk and a decision about what to do with the risks, which, for important risks, includes mitigation plans,
3. Risk assessment: The process used to prioritize risks relative to each other (creation of the Risk Watch List),

Table 4.11-8. *Prioritized descopes have been discussed with the JJSDT and costs are estimated for cancellation at differing points in the project lifecycle.*

Descope Order	Descope Item	Science Impact	Mass* (kg)	Power* (W)	Approximate Cost Savings if Descope Taken* ($M FY07)			
					Proj. Start	PDR	CDR	Post Launch
1	Ka-band Up (Ka transponder req.)	Poorer gravity data for high-order gravity terms.	8	7	9	7	5	0
2	Color on the NAC	Significant losses in Jupiter and Io science	4	2	3	4	2	0
3	Energetic particle capability	Significant loss of information regarding surface weathering of Europa and other moons by particles, including source of sputtering and radiolysis; total loss of information about penetrating radiation, radiation belts of Jupiter and their variations; degradation of magnetospheric science including beams and auroral processes.	10	5	28	26	23	0
4	USO	Reduced opportunities for ionospheric and upper atmosphere studies	9	5	4	5	4	0
5	INMS	No *in situ* characterization of Europa's atmospheric species, including any sputtered organics; loss of *in situ* sensing of Io's atmosphere and torus	25	56	52	48	30	0
6	OpNav Functionality	Reduced delivery accuracy to the satellite aimpoints results in a minimum flyby altitude of 500 km imposed for safety	0	0	6	6	4	0
7	Reduce Europa Science Phase by 5.5 month	Loss of Campaign 4	5	4	24	24	24	24
8	6 Interdisciplinary scientists		0	0	19	18	17	13
9	Thermal Instrument	Loss of thermal emission maps of Europa's surface, which are key in investigating current activity.	9	9	68	65	36	0
10	UVS	Loss of sensitive Europa atmospheric measurement and plume searches, in addition to unique Ganymede/Jupiter auroral and Io torus investigations.	16	9	78	72	46	0
11	ATLAS V 551 to 541		225	0	13	13	13	0
12	Tour Phase reduced by 10mo	Loss of high latitude Ganymede and Callisto flybys results in significant degradation of interior and magnetospheric studies.	28	4	100	100	100	100
13	Hybrid SSR	Loss of data storage and return capabilities during Io and System Campaigns	3	6	71	66	1	0
14	Descope IR Capability (Reduce to 0.9 - 5 µm, with decreased spatial and spectral resolution)	Decreased spectral sensitivity hinders identification of Europa surface impurities, especially organics, and poorer spatial resolution mapping reduces correlations with geological processes and decreases the chance of identifying unique compositional end members.	19	22	50	47	40	0
15	NAC	One order of magnitude degradation in imaging resolution means loss of detailed surface characterization, including recent Europan activity and relative ages, and significant degradation of Jupiter system imaging.	22	24	67	60	35	0
	Total Savings		**383 kg**	**153 W**	**$592 M**	**$562 M**	**$379 M**	**$137 M**

* Includes all appropriate margins and reserves

4. Risk handling: Tracking and controlling risks—collecting and reporting status information about risks and their mitigation plans (where appropriate) and taking corrective action as needed (maintenance of the Risk Management Database).

Primary cost risk factor mitigations have been identified and relate to the Project Risk list (§4.10) by acronym. They fall into three primary areas:

- Instrument Development (In): The instrument AO and delivery is on the critical path. An approved parts and materials list including planetary protection (PP) and radiation characteristics (Rd) is planned in support of the AO. In addition, design guidelines (Rd, PP and IC) and provider workshops are planned. This will allow maturation of the instrument concepts prior to final selection. An additional 6 months was added to the early instrument schedule to allow for an Instrument Conceptual Design Review and Headquarters Instrument Confirmation Review to evaluate the specific mitigations for the instrument and allow project modifications if necessary.
- Radiation design (Rd): The risk is cross cutting and the cost estimate includes a Radiation System Engineer in WBS 02 Project System Engineering and additional staffing at all system engineering levels including WBS 05 Payload. The DPSER is responsible to manage all aspects of the radiation design and reports to the DPMR. It also assumes early development of parts and materials lists, and design guidelines for Radiation (Rd), Planetary Protection (PP) and Internal Charging (IC).
- Planetary Protection (PP): The risk is cross cutting and is mitigated by early attention with a review added in Phase B to confirm approach and assess implementation. This risk is also mitigated by the previous activities discussed above. The basic approach to PP is to sterilize the assemblies at the box level, use aseptic assembly procedures, and allow the radiation environment to sterilize the external surfaces. This approach has been vetted by the HQ PPO and deemed reasonable as an approach. This early review allows time for the engineering team, including instrument engineers, to determine the true feasibility of this approach. If it is deemed unworkable, then a revised approach utilizing extensive analysis may be necessary. This backup approach would be within the cost estimate for the sterilization. If, in the highly unlikely event, that full system sterilization is deemed the only approach, then the reserves proposed herein may not be enough to cover that cost and/or the proposed schedule may be unachievable.

The RM is responsible for monitoring risk management activities. The DPSER is delegated the day-to-day responsibility for mitigation of the Radiation risks. The project Planetary Protection Engineer is delegated day-to-day responsibility for the mitigation of the planetary protection risk. At the project level, risks are tracked and reported through use of a database and all moderate and high risks are carried on the Risk Watch List to facilitate communication. The PM has the ultimate responsibility for project risk. As such, a risk management process will be put in place in Pre-Phase A and will monitor progress at least weekly as mitigation of these risks is most effective early in the project. The roles of DPMR, RM, DPSER, and Payload Manager will be staffed in Pre-Phase A. The Safety and Mission Assurance organization will be utilized for independent assessment of the process.

4.11.9 NEPA Compliance and Launch Approval

Environmental review requirements will be satisfied by the completion of a mission-specific Environmental Impact Statement (EIS) for the JEO mission. In accordance with the requirements described by NPR 7120.5D, the Record of Decision (ROD) for this EIS would be finalized prior to or concurrent with Project PDR.

The JEO launch approval engineering (LAE) Plan will be completed no later than the Mission Definition Review (MDR). This plan will describe the approach for satisfying NASA's NEPA requirements for the JEO mission, and the approach for complying with the nuclear safety launch approval process described by Presidential Directive/National Security Council Memorandum #25 (PD/NSC-25) and satisfying the nuclear safety requirements of NPR 8715.3. The LAE Plan will provide a description of responsibilities, data sources, schedule, and an overall summary plan for preparing:

- A mission-specific environmental review document and supporting nuclear safety risk assessment efforts;
- Launch vehicle and flight system/mission design data requirements to support nuclear risk assessment and safety analyses in compliance with the requirements of NPR 8715.3 and the PD/NSC-25 nuclear safety launch approval process;
- Support of launch site radiological contingency planning efforts;
- Earth swing-by analysis;
- Risk communication activities and products pertaining to the NEPA process, nuclear safety and planetary protection aspects of the project.

It is anticipated that NASA HQ will initiate the JEO environmental review document development as soon as a clear definition of the baseline plan and option space has been formulated. DOE would provide a nuclear risk assessment to support the environmental review document, based upon a representative set of environments and accident scenarios compiled by the KSC/Launch Services Program working with JPL. This deliverable may be modeled after the approach used on the MSL EIS.

DOE will provide a nuclear safety analysis report (SAR) based upon NASA-provided mission-specific launch system and flight system data to support the PD/NSC-25 compliance effort. The SAR would be delivered to an ad hoc interagency nuclear safety review panel (INSRP) organized for the JEO mission. This INSRP would review the SAR's methodology and conclusions and prepare a Safety Evaluation Report (SER). Both the SER and the SAR would then be provided by NASA to EPA, DoD, and DOE for agency review. Following agency review of the documents and resolution of any outstanding issues, NASA, as the sponsoring agency, would submit a request for launch approval to the Director of the Office of Science and Technology Policy (OSTP). The Director of the OSTP would review the request for nuclear safety launch approval and either approve the launch or defer the decision to the President. Key dates and deliverables for the NEPA and nuclear safety launch approval processes are shown in **FO-13**.

As part of broader nuclear safety considerations, JEO would adopt ATLO, spacecraft, trajectory, and operations requirements that satisfy the nuclear safety requirements described by NPR 8715.3.

Development of coordinated launch site radiological contingency response plans for NASA launches is the responsibility of the launch site radiation safety organization. Comprehensive radiological contingency response plans, compliant with the National Response Plan and appropriate annexes, would be developed and put in place prior to launch as required by NPR 8715.2 and NPR 8715.3. The JEO project would support the development of plans for on-orbit contingency actions to complement these ground-based response plans.

A project-specific Risk Communication Plan will be completed no later than the Mission MDR. The Risk Communication Plan will detail the rationale, proactive strategy, process and products of communicating risk aspects of the Project, including nuclear safety and planetary protection. The communication strategy and process will comply with the approach and requirements outlined in the NASA Office of Space Science Risk Communication Plan for Deep Space Missions (1999) [*JPL D-16993*] and the JPL Risk Communication Plan, 2002 [*JPL D-24012*].

5. ALTERNATE AND BACK-UP LAUNCH OPPORTUNITIES

5.1 Interplanetary Trajectory Opportunities

There are many different combinations of gravity assists with Earth, Venus, and/or Mars that can be used to deliver a spacecraft to Jupiter. Last year's report *[EE 2007 Appendix E]* described a thorough search that was performed for trajectories from Earth to Jupiter using gravity assists at Venus, Earth, and Mars for launch dates ranging from 2015 through 2024.

5.2 Narrowing of the Launch Opportunities

Figure 5.2-1 shows the subset of the trajectory opportunities considered above which meet the following criteria:

- Launch between 2016 and 2024,
- Time-of-flight to Europa of <10.0 years (assuming a 30-month Jovian tour),
- A system margin of at least 33%.

Performance varies from trajectory opportunity to trajectory opportunity depending primarily on launch energy and ΔV (deep space and JOI). The masses are based on a conservative estimate for the 21-day launch period analysis (full launch period analysis only reflected in February 2020 launch). No adjustment is made here for the few cases which have high launch declinations. The same conservative post-JOI ΔV profile, based on Tour 08-008, is assumed for all cases.

The Atlas V 551 launch vehicle injected mass capabilities came from data on the NASA Launch Services Program Launch Vehicle Performance web site (http://elvperf.ksc.nasa.gov/elvMap/index.html).

Post-launch ΔVs are assumed to be accomplished with a high-thrust system with an I_{sp} of 323 s. (All ΔVs were assumed to be accomplished with the bi-propellant system for this backup analysis) Included are deterministic ΔVs as well as estimates of the statistical ΔVs through the end of mission.

The period of the orbit following Jupiter Orbit Insertion (JOI) is 200 days. The effect of the pre-JOI Io flyby on the JOI ΔV is conservatively estimated as a flat 200 m/s reduction for purposes of the broad search.

5.3 Resulting Trajectory Performance

Of the over 60 trajectories shown in **Figure 5.2-1,** only the most promising in terms of flight time and mass performance were selected for careful evaluation. Those with a flight time below ten years to Europa Orbit Insertion are indicated by arrows in **Figure**

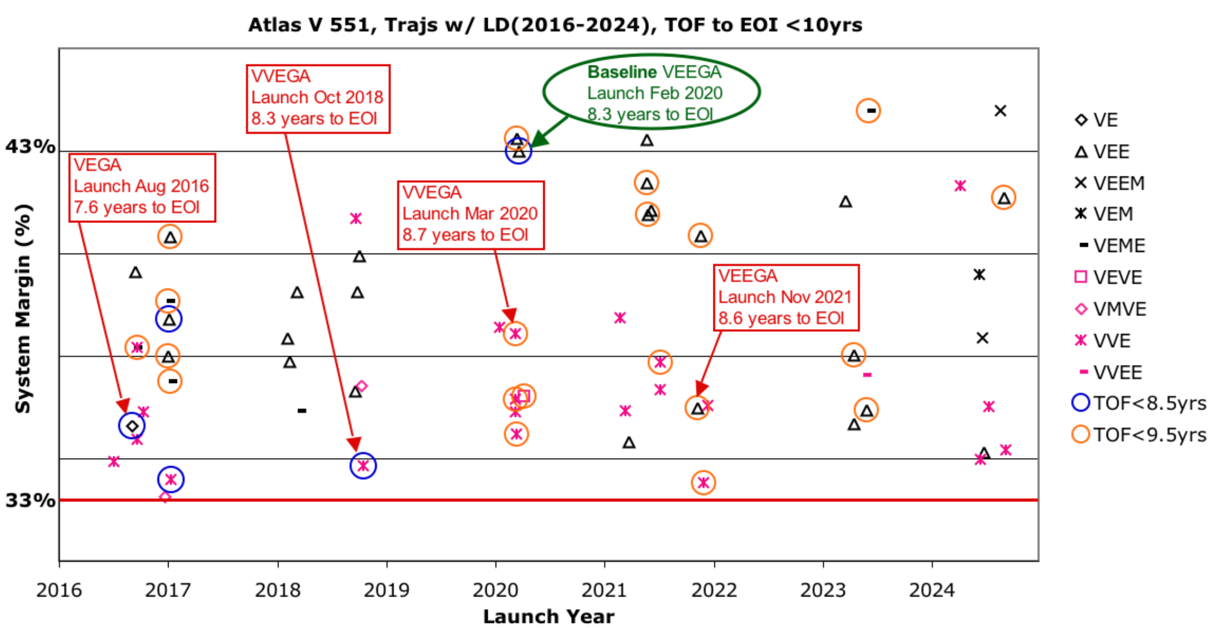


Figure 5.2-1. Hundreds of potential trajectories exist within the launch timeframe between 2015 and 2024. Those meeting the System Margin guidelines are shown here. The opportunities can be screened by evaluating them by derived "requirements" of mass, flight time and launch year resulting in the plot above. Highlighted trajectories indicate more desirable opportunities.

5.2-1 and are listed in **Table 5.3-1**, which lists, in addition, a 2019 case whose flight time is just over 10 years. Many other potentially viable trajectories exist with slightly less system mass margin than 33%. Those trajectories could be investigated further should additional system mass margin become available.

Table 5.3-1. *Comparison of Performance of the Most Promising Trajectory Opportunities from 2016 Thru 2024 indicating that many opportunities meet or exceed current margin requirements with relatively short flight times to Europa (assuming 30 months of Jupiter System Tour). The yellow highlighted opportunity is the baseline launch opportunity for 2020.*

Launch Opportunity	Flybys	TOF to EOI	Atlas V 551 Capability	System Margin (%)
August 2016	VE	7.6 yrs	4975 kg	34%
October 2018	VVE	8.3 yrs	4560 kg	33%
June 2019	VVE	10.4 yrs	4780 kg	37%
February 2020	**VEE**	**8.3 yrs**	**5040 kg**	**43%**
March 2020	VVE	8.7 yrs	4735 kg	38%
November 2021	VEE	8.6 yrs	4725 kg	35%

6. STUDY TEAM MEMBERS AND ROLES

The knowledge and experience base of an expansive team of scientists, engineers, managers, and specialists has been brought to bear on refining an international mission concept which has robust margins, feasible implementation, and excellent science value.

6.1 Team Overview

The Jupiter Europa Orbiter (JEO) study was conducted by two closely interacting teams. The NASA/ESA/JAXA-chartered Jupiter Joint Science Definition Team (JJSDT) focused on the science aspects while the JPL/APL engineering team focused on the technical and programmatic aspects of the mission concept.

There was extensive interaction between the two teams throughout the study ensuring that the science goal and objectives were feasible given the technical and programmatic constraints and approaches. A list of the team members, their affiliations and their areas of expertise are given in **Tables 6.1-1** and **6.1-2**.

The JJSDT held seven face-to-face meetings (including one in Rome, Italy and one in London, England) and weekly telecons. The JJSDT provided guidance on both the JEO and the ESA Jupiter Ganymede Orbiter (JGO). At the last meeting of the JJSDT the focus was on understanding the complementarities of JEO and JGO payloads and developing complementary and synergistic operational strategies.

The JJSDT invited specific individuals to present at the JJSDT meetings to ensure a broad input on the science and potential investigational methods (**Table 6.1-3**). Several sub-groups were formed to ensure that the efforts by the team were worked at the detailed level. The results of the working groups were then presented to the larger JJSDT and integrated into consensus JJSDT findings. Instrument leads were identified from the JJSDT members to work directly with the engineering team members to adequately define each instrument implementation to allow definition, description, performance analysis, operational scenarios and costing.

The JEO engineering team utilized technical capabilities from both JPL and APL to ensure the study resulted an implementable mission. The team held design table-top discussion enlisting experts to recommend design modifications and future work. **Table 6.1-4** documents the discussion and participants. The recommendations from these discussions were incorporated into the design or were put on the list for future work.

Interactions between the JEO and JGO study teams were primarily at the study team level although technical interchange occurred within the seven technical working groups set up by NASA and ESA. The JEO study team leader participated in the initial Concurrent Design Facility sessions for JGO as well as the outbrief. Regular telecons coordinated by the OPFM program were held with the study leader and study scientist at ESTEC as well as members of the TSSM study team.

The JPL/APL engineering team also had interactions with the ESA JGO engineering team led by Anamarija Stankov and Arno Wielders.

6.2 APL Role

Louise Prockter served as the JJSDT Deputy Study Scientist and Chris Paranicas contributed as a member of the JJSDT. Several

Table 6.1-3. *Invited talks given to the JJSDT*

Subject	Affiliation	Person
Io Science	JPL	Ashley Davies
Sub-mm Limb Sounding	JPL	Mark Allen
Gravity Anomalies at Jupiter's Satellites	UCLA	Jennifer Palguta
Micro-satellites	Aero Astro	Ray Zenick
Io Probe	National Central University, Taiwan	Wing Ip
NAC/Laser Altimeter	DLR	Juergen Oberst
Landers	JPL	Jim Shirley
Highly Integrated Payload	Cosine Research	Kraft
Europa Impactor	ARC	Tony Colaprete
Market Based Systems	JPL	Randii Wessen
Europa Impactor	UK Penetrator Consortium	Rob Gowen
Europa Impactor	JPL	Murthy Gudipati
Europa's ocean's dynamic tides	U. of Washington	Robert Tyler
Survival of Organic Compounds in Ice Ejecta	U. of Aberdeen	Stephen Bowden
EO Simulator	JPL	Kevin Hussey
Plasma science at Europa and the Jupiter System	U. of Iowa	Bill Kurth
Juno Mission status and radiation effort	JPL	Rick Grammier and Sammy Kayali
Russian Landers	IKI	Lev Zeleni

Table 6.1-4. Experts were engaged to provide recommended modifications and trade studies for 3 major subsystems.

Expert	Technical Area
Propulsion Tabletop — 4/30/08	
Duncan MacPherson (Lead)	Systems
Mark Adler	Systems
Carl Guernsey	Propulsion
Bob Rasmussen	Chief Engineer
Jim Stratton (APL)	Propulsion
Michael Trela (APL)	Propulsion
Jeff Weiss	Propulsion
Ed Wong	AACS
Paul Woodmansee	Propulsion
C&DH/Power Electronics — 5/12/08	
Randy Blue (Lead)	Avionics
Genji Arakaki	Power Systems and Packaging
Gary Bolotin	Avionics
Jeff Mellstrom	AACS/Instruments
Bob Rasmussen	Chief Engineer
Calina Seybold	MSAP systems
Greg Carr	Power Electronics

APL scientists also contributed to the review of the science sections of this report (§6.7).

On the engineering side, APL took the lead role in payload system engineering, sensor and detector evaluation, and instrument definition and analysis effort which was vital in the formulation of the instruments section of the report (§4.2). APL also led the study of Operations Lessons Learned from past missions which influenced the plan to reduce operational costs (Appendix K). They played a substantial role in project management, system engineering, risk management, radiation design.

The JPL-APL Steering Committee for Outer Planet Exploration (§6.6) played a key role in guiding the study and in the review of interim reports. There was also APL participation in the review of the technical sections of this report (§6.7)

6.3 GSFC Role

Bruce Bills' was a contributing member of the JJSDT and provided expertise in Galilean satellite geophysics.

6.4 MSFC Role

Melissa McGrath was a contributing member of the JJSDT as the lead for the Jupiter Subgroup.

6.5 ARC Role

Jeff Moore was a contributing member of the JJSDT in geology. Tony Colaprete interacted with the JJSDT regarding potential approaches to impactor science for EJSM. Mike Shafto participated in the Operations Lessons Learned Working Group and Dogan Timucin and Kevin Weaver contributed to the circuit lifetime model related to the radiation effect effort.

6.6 JPL-APL Outer Planets Steering Group

The JPL-APL Study Team interacted with and was advised by a steering group consisting of the following people:

- Chris Jones: JPL, Director for Solar System Exploration Co Chair
- John Sommerer: APL, Space Department Head: Co Chair
- John Casani, JPL Special Assistant to the Director
- Andy Cheng, APL, Chief Scientists, Space Department
- Jim Cutts, JPL: Program Manager, Outer Planet Flagship Mission Studies
- Walt Faulconer; APL, Civilian Space Business Area Executive
- Rick Grammier; JPL, Deputy Director for Solar System Exploration
- Torrence Johnson: JPL, Chief Scientist, Solar System Exploration Directorate
- Ted Mueller: APL, Civilian Space Program Area Manager
- Cheryl Reed APL: Civilian Space Program Development Manager

Table 6.1-1. *Jupiter Joint Science Definition Team*

Member	Affiliation	Expertise
US JJSDT Membership		
Ronald Greeley—Co-Chair	Arizona State University	Europa
Bob Pappalardo – Study Scientist	Jet Propulsion Laboratory	Europa and Jupiter System
Ariel Anbar	Arizona State University	Astrobiology
Bruce Bills	Goddard Space Flight Center	Geophysics
Diana Blaney	Jet Propulsion Laboratory	Composition
Don Blankenship	University of Texas	Radar/Geophysics
Phil Christensen	Arizona State University	Composition
Brad Dalton	Jet Propulsion Laboratory	Composition
Jody Deming	University of Washington	Astrobiology
Leigh Fletcher	Jet Propulsion Laboratory	Jupiter Atmosphere
Rick Greenberg	University of Arizona	Geophysics
Kevin Hand	Jet Propulsion Laboratory	Astrobiology
Amanda Hendrix	Jet Propulsion Laboratory	Satellites
Krishan Khurana	University of California Los Angeles	Fields & Particles
Tom McCord	Bear Fight Center	Composition
Melissa McGrath	Marshall Space Flight Center	Satellites
Bill Moore	University of California Los Angeles	Geophysics
Jeff Moore	Ames Research Center	Geology
Francis Nimmo	University of California Santa Cruz	Geophysics
Chris Paranicas	John Hopkins University — Applied Physics Lab	Fields & Particles
Louise Prockter	John Hopkins University — Applied Physics Lab	Geology
Jerry Schubert	University of California Los Angeles	Jupiter
David Senske	Jet Propulsion Laboratory	Satellites
Adam Showman	University of Arizona	Jupiter
Mark Showalter	SETI Institute	Rings
Mitch Sogin	Marine Biological Laboratory	Astrobiology
John Spencer	South West Research Institute	Satellites
Hunter Waite	South West Research Institute	Fields & Particles
European JJSDT Membership		
Jean-Pierre Lebreton — Co-Chair	European Space Agency	Plasma Physics
Michel Blanc — Lead-Scientist	École Polytechnique	Magnetospheres
Olga Prieto-Ballasteros	INTA	Astrobiology
Lorenzo Bruzzone	University of Trento	Radar/Geophysics
Michele Dougherty	Imperial College	Fields & Particles
Pierre Drossart	Paris Observatory	Jupiter
Olivier Grasset	University of Nantes	Geology
Hauke Huβman	German Aerospace Centre (DLR)	Geophysics
Norbert Krupp	Max Planck Institute	Fields & Particles
Frank Sohl	German Aerospace Centre (DLR)	Geophysics
Paolo Tortora	University of Bologna	Radio Science
Federico Tosi	Institute of Physics of Interplanetary Space	Origins
Ingo Mueller-Wodarg	Imperial College	Fields & Particles
Peter Wurz	University of Bern	Origins
Japan JJSDT Membership		
Masaki Fujimoto	Institute of Space and Astronautical Science / Japan Space Exploration Agency	Fields & Particles
Yasumasa Kasaba	Tohoku University	Fields & Particles
Sho Sasaki	National Astronomical Observatory of Japan	Satellites
Yukihiro Takahashi	Tohoku University	Jupiter

Member	Affiliation	Expertise
Takeshi Takashima	Institute of Space and Astronautical Science / Japan Space Exploration Agency	Fields & Particles

Table 6.1-2. Engineering Team

Member	Affiliation	Expertise
Karla Clark – NASA Study Lead	Jet Propulsion Laboratory	Project Management and Systems Engineering
Tom Magner	John Hopkins University — Applied Physics Lab	Project Management
Arden Accord	Jet Propulsion Laboratory	Assembly, Test and Launch Operations
Jim Alexander	Jet Propulsion Laboratory	Attitude and Articulation Control Subsystem
Heidi Becker	Jet Propulsion Laboratory	Sensor Design
Matthew Bennett	Jet Propulsion Laboratory	Software
Ed Blazejewski	Jet Propulsion Laboratory	Sensor Radiation Effects
John Boldt	John Hopkins University — Applied Physics Lab	Payload Engineering
Paul Bowerman	Jet Propulsion Laboratory	Circuit Reliability
Kate Coburn	Jet Propulsion Laboratory	Enterprise Support, Secretarial
Hugo Darlington	John Hopkins University — Applied Physics Lab	Narrow-Angle Camera Instrumentation
Taher Daud	Jet Propulsion Laboratory	Avionics
Ken Donahue – Student	Jet Propulsion Laboratory — Massachusetts Institute of Technology	Systems Engineering
Paul Doronila	Jet Propulsion Laboratory	Visualization
Mohamed Elghefari	Jet Propulsion Laboratory	Cost
Nayla Fernandez	Jet Propulsion Laboratory	Electronic Parts
Sarah Ferraro - Student	Jet Propulsion Laboratory — Harvey Mudd College	System Engineering
Bill Folkner	Jet Propulsion Laboratory	Radio Science Instrumentation
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6.7 Study Results Review

Elements of this study report have been reviewed extensively by independent sets of discipline specialists and by APL/JPL management as follows:

1. The Science Goal and Objectives were subjected to a review by an independent panel of planetary scientists.
2. The Science Goal and Objectives and the mission concept were presented at the following:
   - Outer Planets Assessment Group (OPAG) meeting in April 2008,
   - The Europa-Jupiter International Science Workshop, ESRIN, Frascati (Rome), Italy, April 2008,
   - Outer Planets Instrument Workshop in May 2008,
   - Asia Oceana Geosciences Society (AOGS) Conference, Busan, Koreo, June 2008,
   - Committee on Space Research meeting (COSPAR), Montreal, Canada, July 2008,
   - Saturn After Cassini Symposium, Imperial College, London, England, July 2008,
   - Europlanet, Munster, Germany, September 2008,
   - Division of Planetary Scientists meeting, Ithaca, NY, October, 2008.
3. The team has gained the support of the NASA PPO for the PP approach concept [*Conley 2006*].
4. Subsystems were subjected to focused internal reviews by JPL and APL personnel for technical validity including detailed comparison and contrasting with other flight proven subsystems.
5. The mission concept, measurement requirements, planning payload, science operational scenario, risk mitigation plans and overall approach was presented to the broad science and technical community through the conduct of an Instrument Workshop in June of 2008 and various conferences, symposiums, and workshops to communicate results and solicit external feedback.
6. The mission implementation has been reviewed by technical, management, and cost review boards and line management organizations internal to JPL and APL. This resulted in a very thorough assessment of study results that produced 100s of review item discrepancies (RIDs), all of which have been responded to in finalizing the EJSM study report.
7. The *Risk Mitigation Plan: Radiation and Planetary Protection* has been reviewed by technical experts at APL and JPL.
8. Finally, the overall concept study report was reviewed by both JPL and APL management prior to submission to NASA for independent review.

A. ACRONYMS AND ABBREVIATIONS

AACS	Attitude and Articulation Control Subsystem
A/D	Analog to Digital
ADC	Analog to Digital Converter
AFS	Andrew File System
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
APML	Approved Parts and Materials List
ARC	Ames Research Center
ARPS	Advanced Radioisotope Power System
ASI	Italian Space Agency
ASIC	Application Specific Integrated Circuit
ASRG	Advanced Stirling Radioisotope Generator
ASRG	Advanced Sterling Radioisotope Generator
ASU	Arizona State University
ATLO	Assembly, Test and Launch Operations
AU	Astronomical Unit
B	Magnetic Field Strength
BOE	Basis of Estimate
BOL	Beginning of Life
BOM	Beginning of Mission
C	Centigrade
C_3	Launch energy per unit mass; also the square of the hyperbolic excess velocity
C22	Callisto encounter number 22 (Galileo)
C&DH/FSW	Command and Data Handling/Flight Software
C&T	Command and Telemetry
CADRe	Cost Analysis Data Requirements
CAS	Cassini
CASSE	Committee on Assessing the Solar System Exploration Program
CBE	Current Best Estimate
CCAFS	Cape Canaveral Air Force Station
CCD	Charge-Coupled Device
CDF	Concurrent Design Facility
CDR	Critical Design Review
CEASE	Compact Environmental Anomaly Sensor
CEP	Critical Event Planner
CFDP	CCSDS File Delivery Protocol
cg	Center of Gravity
CHNOPS	carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur
CID	Charge Injection Device
CIMS	Collaborative Information Management System
CM	Configuration Management
CMMI	Capability Maturity Model Integration

CMOS	Complementary Metal–Oxide–Semiconductor
CO	Colorado
COMPLEX	Committee on Planetary and Lunar Exploration
ConOps	Concept of Operations
COPV	Composite Overwrapped Pressure Vessels
COSPAR	Committee on Space Research
C_{OV}	Coefficient of Variation
CP	Camera Package
CPU	Computer Processing Unit
CRAM	Chalcogenide Random Access Memory
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CSC	Computer Software Component
CTM	Contract Technical Managers
CTS	Coaxial Transfer Switch
CTX	Context Imager
CXS	Coax Transfer Switch
DAC	Digital to Analog Converter
Db	deadband
DC	Direct Current
DD	Displacement Damage
DDD	displacement damage dose
DDOR	Delta-Differential One-way Range
Deg	degree
DG	Divine-Garrett
DHMR	Dry Heat Microbial Reduction
DMOM	Deputy Mission Operations Manager
DoD	Department of Defense
DoE	Department of Energy
DOE	Department of Energy
DOR	Differential One-way Range
DPA	Destructive Physical Analysis
DPM	Deputy Project Manager
DPMR	Deputy Project Manager for Radiation
DPP	Design Practices and Principles
DPSER	Deputy Project System Engineer for Radiation
DPU	Data Processing Units
DRAM	Dynamic Random Access Memory
DRO	Distant Retrograde Orbit
DSM	Deep Space Maneuver
DSN	Deep Space Network
DTM	Development Test Model
DWG	Detector Working
ΔDOR	Delta-Differential One-way Range (same as DDOR)

ΔV-EGA	Delta Velocity – Earth Gravity Assist
EAC	Estimate at Completion
EAR	Export Administration Regulations
ECU	Electronic Control Unit
EDAC	Error Detection and Correction
EDL	Entry, Descent and Landing
EE	Europa Explorer
EEE	Electrical, Electronic and Electromechanical
EEIS	End-to-End Information System
EGA	Earth Gravity Assist
EGE	Europa Geophysical Explorer
EHF	Extremely High Frequency
EIS	Environmental Impact Statement
EJSM	Europa Jupiter System Mission
ELDRS	Enhanced Low Dose Rate Sensitivity
EM	Engineering Model
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
EO	Europa Orbiter
EOI	Europa Orbit Insertion
EOM	End of Mission
EOS-MLS	Earth Observing System-Microwave Limb Sounder
EPA	Environmental Protection Agency
EPD	Energetic Particle Detector
EPINS	Electronic Parts Information System
EPO	Education and Public Outreach
ERD	Environmental Requirements Document
ESA	European Space Agency
ESD	Electrostatic Discharge
ESSP	Europa Surface Science Package
EUV	Extreme Ultraviolet
eV	electron Volt
EVA	extreme value analysis
EVM	Earned Value Management
FC	Flight Controllers
Fe-RAM	Ferroelectric-random access memory
FEP	Fluorinated Ethylene Propylene
FER	Frame Error Rate
FET	Field-Effect Transistor
FMECA	Failure Modes Effect and Criticality Analysis
FO	Foldout
FOV	Field of View
FPGA	Field Programmable Gate Array
FPP	Flight Project Practices

FSS	Fine Sun Sensor
FSW	Flight Software
FUV	Far Ultraviolet
FWHM	Full Width at Half Maximum
G	Giga
Gb	Gigabit
G/L	Guidelines
G&C	Guidance and Control
GCMS	gas chromatography and mass spectrometer
GDS	Ground Data System
G-G	Gravity Gradient
GGA	Ganymede Gravity Assist
GIRE	Galileo Interim Radiation Electron
GNC	Guidance, Navigation and Control
GOI	Ganymede Orbit Insertion
GPHS	General Purpose Heat Source
GRACE	Gravity Recovery And Climate Experiment
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
GTO	Geosynchronous Transfer Orbit
HEPA	High Efficiency Particulate Air
HGA	High Gain Antenna
HiRISE	High Resolution Imaging Science Experiment
HIFI	Heterodyne Instrument for the FarInfrared
HQ	Headquarters
HQA	Hardware Quality Assurance
hr	hour
HRSC	High Resolution Stereo Camera
HST	Hubble Space Telescope
HW	hardware
H/W	hardware
Hz	Hertz
I&T	Integration and Test
IC	Internal Charging
ICD	Interface Control Documents
IDP	Instrument Data Package
IESD	Internal Electrostatic Discharge
IFOV	Instantaneous Field of View
IML	Icy Moons Lander
IMU	Inertial Measurement Unit
InD	Instrument Development
INMS	Ion Neutral Mass Spectrometer
INSRP	Interagency Nuclear Safety Review Panel

IO	Instrument Operations
IONET	IP Operational Network; *also* Interoperability Network
IPR	Ice-Penetrating Radar
IR	Infrared
IRS	Infrared Spectrometer
IRU	Inertial Reference Units
ISI	Integral Systems, Inc.
ISO	International Standards Organization
IT	Information Technology
ITAR	International Tariff And Trace Regulation
ITL	Integrated Test Laboratory
IV&V	Independent Verification and Validation
J	Joule
JAXA	Japanese Aerospace Exploration Agency
JEDI	Juno Energetic-particle Detector Instrument
JEO	Jupiter Europa Orbiter
JGA	Jupiter Gravity Assist
JGO	Jupiter Ganymede Orbiter
JHU/APL	Johns Hopkins University Applied Physics Laboratory
JIMO	Jupiter Icy Moons Orbiter
JJSDT	Joint Jupiter Science Definition Team
JMI	Jovian Moon Impactor
JMO	Jupiter Magnetospheric Orbiter
JOI	Jupiter Orbit Insertion
JPL	Jet Propulsion Laboratory
JSO	Jupiter System Observer
JURAP	Joint Users Review Allocation Planning
JWST	James Webb Space Telescope
k	kilo
K	Kelvin
KaT	Ka-band Transponder
keV	kilo-Electron Volt
km	kilometer
KSC	Kennedy Space Center
L	Magnetic Shell Parameter
LA	Laser Altimeter
LA	Launch Approval
LAE	Launch Approval Engineering
LANL	Los Alamos National Laboratory
LED	Light Emitting Diode
LEOP	Launch and Early Operations
LGA	Low Gain Antenna
LILT	Low Intensity Low Temperature

LL	Lessons Learned
LMSS	Long-Range Imager
LOLA	Lunar Orbiter Laser Altimeter
LORRI	Long Range Reconnaissance Imager
LOS	Line of Sight
LROC	Lunar Reconnaissance Orbiter Camera
LRS	Little Red Spot
LV	Launch Vehicle
LVA	Launch Vehicle Adapter
LVDS	Low-Voltage Differential Signaling
LVPS	Low voltage power supply
m	meter
m	milli
µ	micro
M	Million (Mega)
M^3	Moon Mineralogy Mapper
MAC	Medium-Angle Camera (Descoped payload)
MAC	Medium-Angle Stereo Camera (Baseline payload)
MAG	Magnetometer
MAGIC	MSAP Analog GNC Interface Card
MAM	Mission Assurance Manager
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding
Mb	Megabit
mbar	millibar
MCR	Mission Concept Review
MCS	Mars Climate Sounder
MD	Maryland
MDAS	Mission Data Analysis System
MDIS	Mercury Dual Imaging System
MDR	Mission Definition Review
MEL	Mass (Master) Equipment List
MER	Mars Exploration Rover
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MeV	Mega- Electron Volt
MEV	Maximum Expected Value
MGA	Medium Gain Antenna
MGSS	Multi-mission Ground System Services
MHD	Magnetohydrodynamics
MHz	Megahertz
MLI	Multi-layer Insulation
MMR	Monthly Management Review
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator

MOC	Mars Orbiter Camera
MOI	Mercury Orbit Insertion
MOLA	Mars Orbiter Laser Altimeter
MOM	Mission Operations Manager
MOPS	Mission Operations
MOS	Mission Operation System
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
M&P	Materials and Processes
MPI	Magnetometer & Plasma Instrument
MPV	Maximum Possible Value
MREU	MSAP Remote Engineering Unit
MRB	Materials Review Board
MRO	Mars Reconnaissance Orbiter
MSAP	Multi-Mission Spacecraft Architectural Platform
MSIA	MSAP System Interface Assembly
MSL	Mars Science Laboratory
MSO	Mars Science Orbiter
MSS	Mission Support & Services
MSTB	Mission System Testbed
MTIF	MSAP Telecom Interface
MVPS	Medium voltage power supply
n	nano
N	Newton
NAC	Narrow-Angle Camera
NASA	National Aeronautics and Space Administration
Nav	Navigation
NEAR	Near Earth Asteroid Rendezvous
NEPA	National Environmental Protection Agency
NEPP	NASA Electronics Parts Program
NH	New Horizons
NICM	NASA Instrument Cost Model
NIMS	Near Infrared Mapping Spectrometer
NIR	Near Infrared
NLR	NEAR Laser Rangefinder
NMO	NASA Management Office
NPG	NASA Procedures and Guidelines
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPR	NASA Program Requirement
NRC	National Research Council
NSP	NASA’s 2007 Science Plan
NSPAR	Non-standard Part Approval Request
nT	nanoTesla
NTO	Nitrogen Tetroxide

NUV	Near Ultraviolet
NVM	Non-volatile Memory
OBB	On-board Blocks
OMEGA	Observatoire pour la Mineralogy, l'Eau, les Glaces et l'Activité
OPAG	Outer Planets Assessment Group
OPF	Outer Planets Flagship
OPFM	Outer Planets Flagship Mission
OpSc	Science Operations
ORNL	Oak Ridge National Laboratory
ORS	Optical Remote Sensing
ORT	Operational Readiness Test
OSTP	Office of Science and Technology Policy
OTM	Orbital Trim Maneuver
OTM	Orbit Trim Maneuver
PA	Plutonium Availability
PAM	Power Assembly
PCB	Parts Control Board
PCU	Power Converter Unit
PDMS	Product Data Management System
PDR	Preliminary Design Review
PDU	Power Distribution Unit
PEEK	Polyether-ether Ketone
PEL	Power Equipment List
PEPSSI	Pluto Particle Spectrometer Science Investigation
PFM	Proto-Flight Models
P/FR	Problem/failure reports
PI	Principal Investigator
PIDDP	Planetary Instrument Definition and Development Program
PIND	Particle Impact Noise Detection
PLAS	Plasma Instrument
PM	Project Manager
PMCM	Parametric Mission Cost Model
PMD	Propellant Management Device
POC	Proof of Concept
POM	Payload Operations Manager
PP	Planetary Protection
PPI	Particle and Plasma Instrument
PPO	Planetary Protection Office(r)
PPR	Parts Program Requirements
PRM	Perijove Raising Maneuver
PS	Project Scientist
PSE	Project System Engineer
PSG	Project Science Group

PSO	Primary Science Orbit
PSP	Primary Science Phase
PSRD	Project System Requirements Document
QA	Quality Assurance
QPSK	Quadrature-Phase-Shift Keying
QQO	Quasi-Quadrennial Oscillation
Qual	Qualification
RadE	Radiation Environment
RADFET	Radiation Sensing Field Effect Transistor
RadPSM	Radiation Effects in Parts, Sensors, and Materials
RAM	Random Access Memory
RAM	Responsibility Assignment Matrix
RARB	Resource Allocation Review Board
RBSP	Radiation Belt Storm Probes
RDF	Radiation Design Factor
REX	Radio Science Experiment
RFA	Request for Action
RFP	Request for Proposal
RGA	Residual Gas Analysis
RHU	Radioisotope Heater Unit
R_j	Jovian radii
RLAT	Radiation Lot Acceptance Test(ing)
RMS	Radiation Monitoring Subsystem
ROD	Record of Decision
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPS	Radioisotope Power Source
RS	Radio Science
RSE	Radiation System Engineer
RTG	Radioisotope Thermoelectric Generator
RTI	Real Time Interrupt
RTOF	Reflection Time of Flight
RW	Reaction Wheels
RWA	Reaction Wheel Assembly
s	second
S	Siemens
SAIC	Science Applications International Corporation
SAR	Safety Analysis Report
S&M	Structures and Mechanisms
S/C	Spacecraft
SCO	Spacecraft Operations
SDC	Student Dust Counter
SDRAM	Synchronous Dynamic Random-Access Memory
SDST	Small Deep Space Transponder

SDT	Science Definition Team
sec	second
SEE	Single Event Effects
SEL	Single Event Latch-up
SEP	Solar Electric Propulsion
SER	Safety Evaluation Report
SEU	Single Event Upset
SHARAD	Shallow (Subsurface) Radar
SIRU	Space Inertial Reference Unit
SMA	Safety & Mission Assurance
SMD	Science Mission Directorate
SNL	Sandia National Laboratory
SNR	Signal to Noise Ratio
SOC	Science Operations Center
SOHO	Solar and Heliospheric Observatory
SONOS	Silicon Oxide Nitride Oxide Semiconductor
SP	Science & Uplink
SPF	Single Point Failure
SRAM	Static Random Access Memory
SRR	System Requirements Review
SRU	Stellar Reference Unit
SS	Subsystem
SSD	Solid State Drives
SSER	Solar System Exploration Roadmap
SSES	Solar System Exploration Survey
SSI	Solid State Imager
SSPA	Solid State Power Amplifier
SSR	Solid State Recorder
SSR	System Safety Review
ST	Star Tracker
ST5	Space Technology 5
STOUR	Satellite Tour (trajectory software)
SW	software
S/W	software
SWAP	Solar Winds and Plasma (spectrometer)
SWRI	Southwest Research Institute
T	Tera-
T	Tesla
TAA	Technical Assistance Agreements
Tb	Terabit
TBD	To Be Determined
TCM	Trajectory Correction Maneuver
TCS	Thermal Control Subsystem

TDI	Time-Delay Integration
THEMIS	Thermal Emission Imaging System
TI	Thermal Instrument
TID	Total Ionizing Dose
TLM	Telemetry
TMC	Technical, Management, and Cost
TVC	Thrust Vector Control
TWG	Technical Working Group
TWTA	Traveling Wave Tube Amplifier
UCLA	University of California Los Angeles
UHF	Ultra-high Frequency
ULO	Uplink Operations
U of A	University of Arizona
U of Col	University of Colorado
U of H	University of Houston
USO	Ultra-Stable Oscillator
UTJ	Ultra Triple Junction
UTMC	United Technologies Microelectronics Center, Inc
UV	Ultraviolet
UVS	Ultraviolet Spectrometer
UVIS	(Cassini) Ultraviolet Imaging Spectrometer
V&V	Verification and Validation
VDE	Valve Drive Electronics
VEEGA	Venus-Earth-Earth Gravity Assist
VGA	Venus Gravity Assist
VIMS	Visible and Infrared Mapping Spectrometer
VIR	Visible-IR
VIRIS	Visible-IR Imaging Spectrometer
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
VIS	Visible
VRHU	Variable Radioisotope Heater Unit
VSE	Vision for Space Exploration
WAC	Wide-Angle Camera
WBS	Work Breakdown Structure
WCA	Worst Case Analysis
WCD	Worst Case Datasheet
WM	Work Months
WTS	Waveguide Transfer Switch
WWW	World Wide Web
WY	Work Year
YAG	Yttrium Aluminum Garnet
yr	year
§	Section

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B. REFERENCES

Abramov, O. and Spencer, J. (2008), Numerical modeling of endogenic thermal anomalies on Europa, *Icarus* 195(1):378–385.

Alvarellos, J. L. et al. (2008), Transfer of mass from Io to Europa and beyond due to cometary impacts, *Icarus,* 194(2), 636–646.

Anderson, J. D., Lau E. L., Sjogren W. L., Schubert G., and Moore W. B. (1996), Gravitational constraints on the internal structure of Ganymede. *Nature* 384(6609):541–543.

Anderson, J. D. et al. (1997), Europa gravity field determination from a proposed Galileo extended mission, *5th Europa Ocean Conference,* Conference paper, San Juan Capistrano Research Institute, San Juan Capistrano, CA.

Anderson, J. D. et al. (1998a), Europa's differentiated internal structure: Inferences from four Galileo encounters, *Science*, 281:2019–2022.

Anderson, J. D., Schubert G., Jacobson R. A., Lau E. L., Moore W. B., and Sjogren W. L. (1998b), Distribution of rock, metals, and ices on Callisto, *Science* 280:1573–1576.

Anderson, J. D., Jacobson R. A., Lau E. L., Moore W. B., and Schubert G. (2001), Io's gravity field and interior structure, *J. Geophys. Res.* 106(E12):32963-32970.

Anderson, J. D., Schubert G., Jacobson R. A., Lau E. L., Moore W. B., and Palguta J. L. (2004), Discovery of mass anomalies on Ganymede, *Science* 305(5686):989–991.

Atkinson, D. (1989), Measurement of the Planetary Wind Fields by Doppler Monitoring of an Atmospheric Entry Vehicle, PhD Dissertation, Washington State University.

Baines, K. H. et al. (2002), Fresh ammonia ice clouds in Jupiter. I—Spectroscopic identification, spatial distribution, and dynamical implications, *Icarus,* 159(1), 74–94.

Balsiger, H., Altwegg, K., Arijs, E., Bertaux, J.-L., Berthelier, J.-J., Block, B., Bochsler, P., Carignan, G., Duvet, L., Eberhardt, P., Fiethe, B., Fischer, J., Lisk, L., Fuselier, S., Ghielmetti, A., Gliem, F., Gombosi, T., Illiano, M., Koch, T., Koop, E., Korth, A., Lange, K., Lauche, H., Livi, S., Loose, A., Magoncelli, T., Mazelle, C., Mildner, M., Neefs, E., Nevejans, D., Reme, H., Sauvaud, J., Scherer, S., Schoenemann, A., Shelley, E., Waite, J., Westermann, C., Wilken, B., Woch, J. Wollnik, H., Wurz, P., and Young, D. (2007), ROSINA: Rosetta Orbiter Spectrometer for Ion and Neutral Analysis, *Space Science Review* 128:745–801.

Baross, J. A. and S. E. Hoffmann (1985), Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life, *Origins of Life* 15(4):327–345.

Baross, J. A., M. O. Schrenk, and J. A. Huber (2007), Limits of carbon life on Earth and elsewhere. *Planets and Life: The Emerging Science of Astrobiology*, W. T. Sullivan and J. A. Baross, eds., Cambridge University Press, 275–291.

Becker, H., Miyahira, T., and Johnston, A. (2003), The Influence of Structural Characteristics on the Response of Silicon Avalanche Photodiodes to Proton Irradiation, *IEEE Transactions on Nuclear Science* 50(6).

Bell, J. F. (1992), Charge-coupled device imaging spectroscopy of Mars 2. Results and Implications for Martian Ferric mineralogy, *Icarus* 100(2):575–597.

Bibring, J., Langevin, Y., Gendrin, A., Gondet, B., Poulet, F., Berthe, M., Soufflot, A., Arvidson, R., Mangold, N., Mustard, J. et al. (2005), Mars Surface Diversity as Revealed by the OMEGA/Mars Express Observations, *Science* 307(5715):1576–1581, doi: 10.1126/science.1108806.

Bibring, J.-P., Squyres S. W., and Arvidson R. E. (2006), Merging views on Mars, *Science* 29:1899–1901.

Billings, S. E. and S. A. Kattenhorn (2005), The great thickness debate: Ice shell thickness models for Europa and comparisons with estimates based on flexure at ridges, *Icarus* 177:397–412.

Bills, B. G. (2005), Free and forced obliquities of the Galilean satellites of Jupiter, *Icarus*, 175:233–247.

Bills, B. G. and F. G. Lemoine (1995), Gravitational and topography isotropy of the Earth, Moon, Mars, and Venus, *J. Geophys. Res*., 100:26275–26295.

Bills, B. G. and F. Nimmo (2008), Forced obliquity and moment of inertia of Titan, *Icarus* 196:293–297.

Blanc, M. et al. (2007), *Laplace: A Mission to Europa and the Jupiter System for ESA's Cosmic Vision Programme,* <http://jupiter-europa.cesr.fr>.

Boldt, J. et al. (2008), *Assessment of Radiation Effects on Detectors and Key Optical Components*, JPL Internal Document D-48256.

Borucki W. J. and Williams M. A. (1986), Lightning in the Jovian water cloud, *J.Geophys. Res.* 91:9893–9903, (ISSN 0148-0227).

Broadfoot, A., Belton, M., Takacs, P., Sandel, B., Shemansky, D., Holberg, J., Ajello, J., Atreya, S., Donahue, T., Moos, H. et al. (1979), Extreme Ultraviolet Observations from Voyager 1 Encounter with Jupiter. *Science* 204(4396):979–982.

Brown, M. E. (2001), Potassium in Europa's atmosphere, *Icarus*, 151:190–195.

Brown, M. E. and Hill R. E. (1996), Discovery of an extended sodium atmosphere around Europa, *Nature* 380:229–231.

Brunetto, R. et al. (2005) Reflectance and transmittance spectra (2.2–2.4μm) of ion irradiated frozen methanol, *Icarus* 175:226–232.

Burns, J. A., M. R. Showalter, D. P. Hamilton, P. D. Nicholson, I. de Pater, M. Ockert-Bell, and P. Thomas (1999), The formation of Jupiter's faint rings, *Science* 284:1146–1150.

Burns, J. A., D. P. Simonelli, M. R. Showalter, D. P. Hamilton, C. C. Porco, H. Throop, and L. W. Esposito (2004), Jupiter's Ring-Moon System. *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, ed., Cambridge University Press, 241–262.

Canup R. M. and Ward W. R. (2002), Formation of the Galilean satellites: Conditions of accretion, *The Astronomical Journal* 124(6):3404–3423.

Carlson, R. W. (1999), A Tenuous Carbon Dioxide Atmosphere on Jupiter's Moon Callisto, *Science* 283:820–821.

Carlson, R. W. (2001), Spatial distribution of carbon dioxide, hydrogen peroxide, and sulfuric acid on Europa, *Bull. Amer. Astron. Soc.* 33:1125.

Carlson, R. W. et al. (1999a), Hydrogen Peroxide on the Surface of Europa, *Science* 283:2062–2064.

Carlson, R. W., R. E. Johnson, and M. S. Anderson (1999b), Sulfuric Acid on Europa and the Radiolytic Sulfur Cycle, *Science* 286(5437):97–99.

Carlson, R. W. et al. (2002), Sulfuric acid production on Europa: the radiolysis of sulfur in water ice, *Icarus* 157:456–463.

Carlson, R. W. et al. (2005), Distribution of hydrated sulfuric acid on Europa, *Icarus* 177:461–471.

Carlson, R. W. et al. (2008, in press), Europa's Surface Composition, *Europa,* Pappalardo, McKinnon, and Khurana, eds., University of Arizona Press.

Carr, M. H. et al. (1998a), Evidence for a subsurface ocean on Europa, *Nature* 391: 363–365.

Carr, M. H., McEwen A. S., Howard K. A., Chuang F. C., Thomas P., Schuster P., Oberst J., Neukum G., and Schubert G. (1998b), Mountains and calderas on Io: Possible implications for lithosphere structure and magma generation, *Icarus* 135:146-165.

Cassen, P., S. J. Peale, and R. T. Reynolds (1979), Is there liquid water on Europa? *Geophys. Res. Lett.* 6:731–734.

Cassen, P. M., S. J. Peale, and R. T. Reynolds (1982), Structure and thermal evolution of the Galilean satellites, in *Satellites of Jupiter* (D. Morrison, ed.), University of Arizona Press, Tucson, 93–128.

Cassidy, T. A. et al. (2008), Simulation of Na D emission near Europa during eclipse, *J. Geophys. Res.* 113(E2), doi:10.1029/2007 JE002955.

Cavanaugh, J., Smith, J., Sun, X., Bartels, S., Bartels, A., Ramos-Izquierdo, L., Krebs, D., McGarry, J., Trunzo, R., Novo-Gradac, A., Britt, J., Karsh, J., Katz, R., Lukemire, A., Szymkiewicz, R., Berry, D., Swinski, J., Neumann, G., Zuber, M., and Smith, D. (2007), The Mercury Laser Altimeter

Instrument for the MESSENGER Mission, *Space Science Review* 131:451–479.

Cheng, A. F., Simon-Miller A. A., Weaver H. A., Baines K. H., Orton G. S., Yanamandra-Fisher P. A., Mousis O., Pantin E., Vanzi L., Fletcher L. N., Spencer J. R., Stern S. A., Clarke J. T., Mutchler M. J., and Noll K. S. (2008), Changing characteristics of Jupiter's little red spot, Astro. J. 135:2446–2452.

Cheng, K. S. et al. (1986), Energetic Radiation from Rapidly Spinning Pulsars. 1. Outer Magnetosphere Gaps, *Astrophysical J.* 300:500–521.

Christensen, P. R. et al. (2001), Mars Global Surveyor Thermal Emission Spectrometer Experiment: Investigation Description and Surface Science Results, *J. Geophys. Res.* 106(E10):23823–23871.

Chyba, C. F. (2000), Energy for microbial life on Europa, *Nature* 403:381–382.

Chyba, C. F. and C. B. Phillips (2001), Possible Ecosystems and the Search for Life on Europa, *Proc. Natl. Acad. Sci. U.S.A.* 98:801–804.

Chyba, C. F., S. J. Ostro, and B. C. Edwards (1998), Radar detectability of a subsurface ocean on Europa, *Icarus*, 134, 292–302.

Chyba, C. F. et al. (1999), Europa and Titan: Preliminary recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System. *Lunar Planet. Sci. Conf.*, *XXX*, abstract #1537, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Clark, K. et al. (2006), *2006 Europa Explorer Study Report*, JPL Internal Document D-34054.

Clark, K. et al. (2006), *2006 Europa Explorer Radiation Issue Report*, JPL Internal Document D-34103.

Clark, K., R. Greeley, R. Pappalardo, and C. Jones (2007), *2007 Europa Explorer Mission Study: Final Report*, JPL Internal Document D-38502.

Clark, K. et al. (2007), *2007 Europa Explorer Mission Study Report: Final Report*, JPL Internal Document D-41283.

Clark, R. and T. McCord (1980), The Galilean Satellites: New near-infrared spectral reflectance measurements (0.65–25μm) and a 0.325–5 μm Summary, *Icarus* 41:323.

Clark, R. N. (1983), Spectral properties of mixtures of montmorillonite and dark grains- Implications for remote sensing minerals containing chemically and physically absorbed water, *J. Geophys. Res.* 88:10635–10644.

Clark, R. N., Fanale F.P., and Zent A. P. (1983), Kinetics of ice grain growth: implications for remote sensing of planetary surfaces, *Proc. Lunar Planet. Sci. XIV*, 120–121.

Clark, R., Fanale, F., and Zent, A. (1983), Frost grain size metamorphism: Implications for remote sensing of planetary surfaces, *Icarus* 56(2):233–245.

Clark, R. N. et al. (2005), Compositional maps of Saturn's moon Phoebe from imaging spectroscopy, *Nature* 435:66–69.

Cleve, J. E. Van, Pappalardo, R. T., Spencer, J. R. (1999), Thermal Palimpsests on Europa: How to Detect Sites of Current Activity, *Lunar Planet. Sci.* 32.

Colaprete, T. personal communication

Cole, T., Boies, M., El-Dinary, A., and Cheng, A. (1997), The Near-Earth Asteroid Rendezvous Laser Altimeter, *Space Science Reviews*, 82:217–253.

COMPLEX, Committee on Planetary and Lunar Exploration (1999), National Research Council, *A Science Strategy for the Exploration of Europa*, National Academy Press, Washington, DC.

Comstock, R. L., and B. G. Bills (2003), A solar system survey of forced librations in longitude, *J. Geophys. Res.* 108, doi: 10.1029/ 2003JE002100.

Constable, S. and C. Constable (2004), Observing geomagnetic induction in magnetic satellite measurements and associated implications for mantle conductivity, *Geochemistry, Geophysics, Geosystems* 5:Q01006, doi:10.1029/ 2003GC000634.

Cooper, J. F. et al. (2001), Energetic ion and electron irradiation of the icy Galilean satellites, *Icarus* 149:133–159.

Crowley, J. K. (1991), Visible and near-infrared (0.4–2.5μm) reflectance spectra of playa evaporite minerals, *J. Geophys. Res.* 96: 16231–16240.

Cruikshank, D. P. et al. (2007), Surface Composition of Hyperion, *Nature* 448:54–56.

Dalton, J. B. (2000), Constraints on the surface composition of Jupiter's moon Europa based on laboratory and spacecraft data, Ph.D. dissertation, University of Colorado, Boulder.

Dalton, J. B. (2007), Linear Mixture Modeling of Europa's Non-Ice Material Using Cryogenic Laboratory Spectroscopy, *Geophys. Res. Lett.* 34:21205.

Dalton, J. B. and R. N. Clark (1998), Laboratory spectra of Europa candidate materials at cryogenic temperatures, *Bull. Am. Astron. Soc.* 30:1081.

Dalton, J. B. and R. N. Clark (1999), Observational constraints on Europa's surface composition from Galileo NIMS data, *Proc. Lunar Planet. Sci. Conf. XXX*, 2064.

Dalton, J. B. et al. (2003), Near-infrared detection of potential evidence for microscopic organisms on Europa, *Astrobiology* 3:3, 505–529.

Dalton, J. B. et al. (2005), Spectral Comparison of Heavily Hydrated Salts to Disrupted Terrains on Europa, *Icarus* 177:472–490.

Delamere, P.A., Steffl A. J., and Bagenal F. (2004), Modeling temporal variability of plasma conditions in the Io torus during the Cassini era, *J. Geophys. Res.*, 109:A10216.

Del Genio, A. D., Barbara J. M., Ferrier J., Ingersoll A.P., West R. A., Vasavada A. R., Spitale J., and Porco C. C. (2007), Saturn eddy momentum fluxes and convection: First estimates from Cassini images, *Icarus* 189:479–492.

Delitsky, M. L. and A. L. Lane (1997), Chemical schemes for surface modification of icy satellites: A road map, *J. Geophys. Res.* 102(E7):16385–16390.

Delitsky, M. L. and A. L. Lane (1998), Ice chemistry on the Galilean Satellites, *J. Geophys. Res.* 103(E13):31391–31403.

Deming, J. W. (2002), Psychrophiles and polar regions, *Current Opinion in Microbiology* 5(3) :301–309.

Des Marais, D. et al. (2003). The NASA astrobiology roadmap, *Astrobiology*, 3, 219–235.

Domingue, D. L. and A. L. Lane (1997), IUE's view of Callisto: Detection of an SO_2 absorption correlated to possible torus neutral wind alterations, *Geophys. Res. Lett.* 24(9):1143.

Eckhardt, D. H. (1981), Theory of the libration of the Moon, *Earth, Moon and Planets* 25(1):3–49, doi:10.1007/BF00911807.

Ehlmann, B., Mustard, J., Fassett, C., Schon, S., Head III, J., Des Marais, D., Grant, J., and Murchie, S. (2008), Clay minerals in delta deposits and organic preservation potential on Mars, *Nature Geoscience* 1(6):355.

Eluszkiewicz, J. (2004), Dim prospects for radar detection of Europa's ocean, *Icarus*, 170, 234–236.

ESA (2005), *Cosmic Vision: Space Science for Europe 2015–2025,* ESA Brochure BR-247, ESA Publ. Div., ESTEC, Noordwijk, The Netherlands.

Fanale, F. P. et al. (1999), Galileo's multiinstrument spectral view of Europa's surface composition, *Icarus* 139:179–188.

Figueredo, P. H. et al. (2003), Locating Potential Biosignatures on Europa from Surface Geology Observations, *Astrobiology* 3:(4)851–4861.

Figueredo, P. H. and R. Greeley (2004), Resurfacing history of Europa from pole-to-pole geological mapping, *Icarus* 167:287–312.

Fink, U. and Sill, G. T. (1982), *The Infrared Spectral Properties of Frozen Volatiles, Comets* (L. L. Wilkening, Ed.), Univ. of Arizona Press, Tucson, 164–202.

Foote, M., Krueger, T., Schofield, J., McCleese, D., McCamm, T., Jones, E., and Dickie, M. (2003), Space Science Applications of Thermopile Detector Arrays, *Quantum Sensing: Evolution and Revolution from Past to Future, Proceedings of SPIE*, 4999.

Gaidos, E. J., K. H. Nealson, and J. L. Kirschvink (1999), Life in Ice-Covered Oceans, *Science* 284:1631–1633.

Garrett, H. B., I. Jun, J. M. Ratliff, R. W. Evans, G. A. Clough, and R. E. McEntire

(2003), Galileo interim radiation electron model, JPL Publication 03-006.

Geissler, P. E. et al. (1998), Evolution of lineaments on Europa: Clues from Galileo multispectral imaging observations, *Icarus* 135:107–126.

Greeley, R., Thelig E., and Christensen P. (1984), The Mauna Loa sulfur flow as an analog to secondary sulfur flows on Io, *Icarus* 60:189–199.

Greeley, R. et al. (2004), Geology of Europa, in *Jupiter: The Planet, Satellites, and Magnetosphere,* F. Bagenal, T. E. Dowling, and W. B. McKinnon, eds., Cambridge: Cambridge University Press, 329–362.

Greenberg, R. (2005), *Europa, the Ocean Moon,* New York: Springer-Praxis.

Greenberg, R. and Geissler P. (2002), Europa's dynamic icy crust, *Meteoritics & Planetary Science* 37:1685–1711.

Greenberg, R., P. Geissler, B. R. Tufts, and G. V. Hoppa (2000), Habitability of Europa's crust: The role of tidal-tectonic processes, *J. Geophys. Res.*, 105, 17551–17562.

Greenberg, R., Hoppa G. V., Tufts B. R., Geissler P. Riley J., and Kadel S. (1999), Chaos on Europa, *Icarus* 141:263–286.

Greenberg, R. and P. Geissler (2002), Europa's dynamic icy crust, An invited review, *Meteoritics and Planetary Science* 37:1685–1711.

Grundy, W., Buratti, B., Cheng, A., Emery, J., Lunsford, A., McKinnon, W., Moore, J., Newman, S., Olkin, C., Reuter, D. et al. (2007), New Horizons Mapping of Europa and Ganymede, *Science* 318(5848):234.

Hall, D. T., Strobel D. F., Feldman P. D., McGrath M. A., and Weaver H. A. (1995), Detection of an oxygen atmosphere on Jupiter's moon Europa, *Nature* 373:677–679.

Hall, D. T., Feldman P. D., McGrath M. A., and Strobel D. F. (1998), The far-ultraviolet oxygen airglow of Europa and Ganymede, *Astrophys. J.* 499:475–481.

Hairston, A., Stobie, J., and Tinkler, R. (2006), Advanced Readout Integrated Circuit Signal Processing, *Infrared Technology and Applications XXXII, Proceedings of SPIE*, 6206.

Hamilton, D. and Krüger, H. (2008), The sculpting of Jupiter's gossamer rings by its shadow, *Nature* 453(7191):72.

Hand, K. P. (2007), On the Physics and Chemistry of the Ice Shell and Sub-surface Ocean of Europa, Ph.D. Thesis, Stanford University.

Hand, K. P. and C. F. Chyba (2007), Empirical constraints on the salinity of the europan ocean and implications for a thin ice shell, *Icarus* 189(2):424–438, doi: 10.1016/j.icarus.2007.02.002

Hansen, C. J. et al. (2006), Encleadus' water vapor plume, *Science* 311:1422–1425.

Hansen, C. J., L. Esposito, J. Colwell, A. Hendrix, B. Meinke, and I. Stewart (2008), New occultation observation of Enceladus' plume, *Proc. Lunar Planet. Sci. XXXIX*, 1391:2014.

Hansen, G. and T. B. McCord (2003), Amorphous and crystalline ice on the Galilean satellites: A balance between thermal and radiolytic processes, *J. Geophys. Res.* 109(E1) , doi: 10.1029/2003JE002149.

Hansen, G. and T. B. McCord (2004), Amorphous and crystalline ice on the Galilean Satellites: A balance between thermal and radiolytic processes, *J. Geophys. Res*., 109, E01012, doi:10.1029/2003JE002149.

Hansen and McCord (2008), Widespread CO_2 and other non-ice compounds on the anti-Jovian and trailing sides of Europa from Galileo/NIMS observations, *Geophys. Res. Lett.*, 35:L01202, doi:10.1029/2007GL031748.

Hartle, R. E. and R. Killen (2006), Measuring pickup ions to characterize the surfaces and exospheres of planetary bodies: Applications to the Moon, *Geophys. Res. Lett.* 33:5201, doi:10.1029/2005GL024520.

Head, J. W. and R. T. Pappalardo (1999), Brine mobilization during lithospheric heating on Europa: Implications for formation of chaos terrain, lenticula texture, and color variations, *J. Geophys. Res.* 104(E11):27143–27155.

Hendrix, A., Barth, C., Hord, C., and Lane, A. (1998), Europa: Disk-Resolved Ultraviolet Measurements Using the Galileo

Ultraviolet Spectrometer, *Icarus* 135(1):79–94.

Hendrix, A. R. et al. (1999), Ganymede's ozone-like absorber: Observations by the Galileo ultraviolet spectrometer, *J. Geophys. Res*. 104:14169–14178.

Hendrix, A. R. and C. J. Hansen (2008), Iapetus: New Results from Cassini UVIS, *Lunar and Planetary Institute Conference Abstracts* 39:2200.

Henschel, H., Köhn, O., Schmidt, H., Bawirzanski, E., and Landers, A. (1994), Optical Fibres for High Radiation Dose Environments, *IEEE Transactions on Nuclear Science*, 41(3).

Herzberg, G. (1991), *Molecular Spectra and Molecular Structure: Infrared and Raman of Polyatomic Molecules* (Krieger Pub Co, 1991) ISBN-10: 0894642693.

Hibbitts, C. A., Klemaszewski J. E., McCord T. B., Hansen G. B., and Greeley R. (2002), CO_2-rich impact craters on Callisto, *J. Geophys. Res.*, 107(E10):5084.

Hibbits, C. A., J. Szanyi, and T. B. McCord (2004), Carbon dioxide in the surfaces of the icy satellites, *Bull. Amer. Astron. Soc.* 36 #24.05.

Hoppa, G. V. et al. (1999), Formation of cycloidal features on Europa, *Science*, 285: 1899–1902.

Horanyi, M., Morfill, G., and Grün, E. (1993), Mechanism for the acceleration and ejection of dust grains from Jupiter's magnetosphere, *Nature* 363:144–146, doi:10.1038/363144a0.

Hudson, R. L. and M. H. Moore (1998), Infrared study of Ion-Irradiated Water-Ice mixtures with Hydrocarbons relevant to comets, *Icarus* 136(2):518–527.

Hunt, G. R. et al. (1971a), Visible and near-infrared spectra of minerals and rocks: III. Oxides and hydroxides, *Modern Geology* 2:195–205.

Hunt, G. R. et al. (1971b), Visible and near-infrared spectra of minerals and rocks: IV. Sulphides and sulphates, *Modern Geology* 3:1–14.

Hussmann, H., Sohl F., and Spohn T. (2006), Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects, *Icarus* 185:258–273.

Hussman, H. and T. Spohn (2004), Thermal-orbital evolution of Io and Europa, *Icarus* 171:391–410.

Hussman, H., T. Spohn, and K. Wieczerkowski (2002), Thermal equilibrium states of Europa's ice shell: implications for internal ocean thickness and surface heat flow, *Icarus* 156:143–151.

Ingersoll, A. P., Dowling T. E., Gierasch P. J., Orton G. S., Read P. L., Sánchez-Lavega A., Showman A. P., Simon-Miller A. A., and Vasavada A. R. (2004), Dynamics of Jupiter's atmosphere, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge. 105–128.

Jaeger, W. L., Turtle E. P., Keszthelyi L. P., Radebaugh J., McEwen A. S., and Pappalardo R. T. (2003), Orogenic tectonism on Io, *J. Geophys. Res.*, 108(E8), 5093, doi:10.1029/2002JE001946.

Janesick, J., Elliott, T., and Tower, J. (July 2008), CMOS Detectors: Scientific Monolithic CMOS Imagers Come of Age, *Laser World Focus*.

JIMO SDT, Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) (2004), NASA, Washington, D.C., 2004. <http://www.lpi.usra.edu/opag/resources.html>.

Johnson, R. E. (1998), Sputtering and desorption from icy surfaces, *Solar System Ices,* B. Schmitt, C. de Bergh, and M. Festou, eds., Kluwer, Dordrecht, The Netherlands, 303–334.

Johnson, R. E. and T. I. Quickenden (1997), Radiolysis and photolysis of low-temperature ice, *J. Geophys. Res.* 102:10985–10996.

Johnson, R. E., R. M. Killen, J. H. Waite, and W. S. Lewis (1998), Europa's surface composition and sputter-produced iono–sphere, *Geophys. Res. Lett.* 25(17):3257–3260.

Johnson, R. E., F. Leblanc, B. V. Yakshinskiy, and T. E. Madey (2002), Energy Distributions for desorption of sodium and potassium from ice: The Na/K ratio at Europa, *Icarus* 156:136–142.

Johnson, R. E., F. Leblanc, B. V. Yakshinskiy and T. E. Madey (2002), Energy Distributions for desorption of sodium and potassium from ice: The Na/K ratio at Europa, *Icarus* 156:136–142.

Johnson, R. E., R. W. Carlson, J. F. Cooper, C/ Paranicas, M. H. Moore, and M. Wong, Radiation Effects on the Surfaces of the Galilean Satellites (2004), in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, W. B. McKinnon, and T. E. Dowling (Eds.), Cambridge Univ. Press, 485–512.

Johnson, R. E., Killen R. M., Waite J. H., and Lewis W. S. (1998), Europa's surface composition and sputter-produced ionosphere, *Geophys. Res. Lett.* 25(17):3257–3260.

Johnson, T. V. (2005), Geology of the icy satellites, *Space Sci. Rev.*, 116, 401–420.

Johnston, A. (2001), Proton Displacement Damage in Light-Emitting and Laser Diodes, *IEEE Transactions on Nuclear Science,* 48(5).

Jun, I. et al. (2002), Monte Carlo simulations of the Galileo energetic particle detector, *Nuclear Instruments & Methods in Physics Research A* 490:465–475.

Jun, I. et al. (2005), Statistics of the variations of the high-energy electron population between 7 and 28 jovian radii as measured by the Galileo spacecraft, *Icarus* 178:386–394.

Kargel, J. S. et al. (2000), Europa's crust and ocean: Origin, composition, and the prospects for life, *Icarus* 148:226–265.

Kasting, J. F., D. P. Whitmire, and R. T. Reynolds (1993), Habitable Zones around Main Sequence Star, *Icarus* 101:108–128.

Kelley, D. S., Karson, J. A., Fruh-Green, G. L., Yoerger, D. R., Shank, T. M., Butterfield, D. A., Hayes, J. M., Schrenk, M. O., Olson, E. J., Proskurowski, G., Jakuba, M., Bradley, A., Larson, B., Ludwig, K., Glickson, D., Buckman, K., Bradley, A. S., Brazelton, W. J., Roe, K., Elend, M. J., Delacour, A., Bernasconi, S. M., Lilley, M. D., Baross, J. A., Summons, R. T., and Sylva, S. P. (2005). A serpentinite-hosted ecosystem: The Lost City hydrothermal field. *Science* 307(5714):1428–1434.

Keszthelyi, L., Jaeger, W., Turtle, E., Milazzo, M., and Radebaugh, J. (2004), A post-Galileo view of Io's interior, *Icarus* 169(1):271–286.

Khurana, K. K. et al. (1998), Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto, *Nature* 395:777–780.

Khurana, K. K., M. G. Kivelson, and C. T. Russell (2002), Searching for liquid water in Europa by using surface observations, *Astrobiology J.*, 2:93–103.

Khurana, K., Pappalardo R. T., Murphy N., and Denk T. (2007), The origin of Ganymede's polar caps, *Icarus* 191(1):193–202.

Kivelson, M. G., K. K. Khurana, C. T. Russell, R. J. Walker, J. Warnecke, F. V. Coroniti, C. Polanskey, D. J. Southwood, and C. Schubert (1996), Discovery of Ganymede's magnetic field by the Galileo spacecraft, *Nature* 384:537.

Kivelson, M. G., Khurana K. K., Stevenson D. J., Bennett L., Joy S., Russell C. T., Walker R. J., and Polanskey C. (1999), Europa and Callisto: induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, 104:4609–4625.

Kivelson, M. G., K. K. Khurana, C. T. Russell, M. Volwerk, R. J. Walker, and C. Zimmer (2000), Galileo magnetometer measurements: A stronger case for a subsurface ocean at Europa, *Science* 289:1340–1343.

Kivelson, M. G., Khurana K. K., and Volwerk M. (2002), The permanent and inductive magnetic moments of Ganymede, *Icarus* 157(2):507–522.

Kivelson, M. G., F. Bagenal, W. S. Kurth, F. M. Neubauer, C. Paranicas, and J. Saur (2004), Magnetospheric interactions with satellites, in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, W. B. McKinnon, and T. E. Dowling (Eds.),, Cambridge Univ. Press, 513–536.

Klaasen, K., Clary, M., and Janesick, J. (1984), Charge-Coupled Device Television Camera for NASA's Galileo Mission to Jupiter, *Optical Engineering* 23:334–342.

Kliore, A. J., Hinson D. P., Flasar F. M., Nagy A. F., and Cravens T. E. (1997), The ionosphere of Europa from Galileo radio occultations, *Science* 277:355–358.

Kliore, A. J., Anabtawi A., and Nagy A. F. (2001a), The ionospheres of Europa, Ganymede, and Callisto, *EOS*, Abstract #P12B-0506, B506.

Kliore, A. J., Anabtawi A., Nagy A. F., and Galileo Radio Propagation Science Team (2001b), The ionospheres of Ganymede and Callisto from Galileo radio occultation's. *BAAS* 33:1084.

Kliore, A. J., A. Anabtawi, R. G. Herrera, S. W. Asmar, A. F. Nagy, D. P. Hinson, and F. M. Flasar (2002), Ionosphere of Callisto from Galileo radio occultation observations, *J. Geophys. Res. (Space Physics)* 107(A11):SIA19-1, doi 10.1029/ 2002JA009365.

Konopliv, A. S., Yoder, C. F., Standish, E. M., Yuan, D-N., Sjogren, W. L. (2006), A Global Solution for the Mars Static and Seasonal Gravity, Mars Orientation, Phobos and Deimos Masses, and Mars Ephemeris, *Icarus* 182(1):23–50.

Krembs, C., J. W. Deming, and H. Eicken (2008, submitted), Effects of exopolymeric substances on microstructure and salt retention in sea ice, *Mar Ecol Prog Ser.*

Kuiper, G. P. (1957), Infrared Observations of planets and satellites, *Astronomical Journal* 62:295.

Kwok, J., L. Prockter, D. Senske, and C. Jones (2007), *Jupiter System Observer Mission Study: Final Report*, JPL Internal Document D-41284.

Lane, A. L. et al. (1981), Evidence for Sulphur Implantation in Europa's UV absorption band, *Nature* 292:38–39.

Leblanc, F., Johnson, R. E., Brown, M. E., (2002), Europa's Sodium Atmosphere: An Ocean Source? *Icarus* 159(1):132–144

LeBlanc, F. et al. (2005), Origins of Europa Na cloud and torus, *Icarus* 178(2):367–385.

Lee, S., R. T. Pappalardo, and N. C. Makris (2005), Mechanics of tidally driven fractures in Europa's ice shell, *Icarus* 177:367–379.

Leovy, C. B., A. J. Friedson, and G. S. Orton (1991), The quasiquadrennial oscillation of Jupiter's equatorial stratosphere, *Nature* 354:380–382.

Liang, M.-C., Lane B. F., Pappalardo R. T., Allen M., and Yung Y. L. (2005), Atmosphere of Callisto, *J. Geophys. Res.*, 110(E02003), doi:10.1029/2004JE002322.

Lipps, J. H. and S. Rieboldt (2005), Habitats and taphonomy of Europa, *Icarus* 177:515–527.

Little, B., Anger C. D., Ingersoll A. P., Vasavada A. R., Senske D. A., Breneman H. H., Borucki W. J., and the Galileo SSI Team (1999), Galileo images of lightning on Jupiter, *Icarus* 142(2):306–323.

Long Life Design Guidelines, JPL D-48271.

Lopes, R. M. C. and D. A. Williams (2005), Io after Galileo, *Reports on Progress in Physics* 68:303–340.

Lopes, R. M. and Spencer J. R. (2007), *Io After Galileo: A New View of Jupiter's Volcanic Moon*, Cambridge University Press, Cambridge.

Lorenz, R. D., Stiles B. W., Kirk R. L., Allison M. D., Persi del Marmo P., Iess L., Lunine J. I., Ostro S. J., and Hensley S. (2008), Titan's rotation reveals an internal ocean and changing zonal winds, *Science* 319:1649–1651.

Luthcke, S. B. et al. (2002), Enhanced geolocation of spaceborne laser altimeter surface returns: parameter calibration from the simultaneous reduction of altimeter range and navigation tracking data, *J. Geodynamics* 34:447–475.

Luthcke, S. B. et al. (2005), Reduction of ICES at systematic geolocation errors and the impact on ice sheet elevation change detection, *Geophys. Res. Lett.* 32(L21S05), doi:10.1029/2005GL023689.

Luttrell, K. and D. Sandwell (2006), Strength of the lithosphere of the Galilean satellites, *Icarus* 183:159–167.

Marchis, F., de Pater, I., Davies, A., Roe, H., Fusco, T., Mignant, D., Descamps, P., Macintosh, B., and Prang´e, R. (2002), High-Resolution Keck Adaptive Optics Imaging of Violent Volcanic Activity on Io, *Icarus* 160(1):124–131

Marion, G. M. et al. (2003), The Search for Life on Europa: Limiting Environmental

Factors, Potential Habitats, and Earth Analogues, *Astrobiology* 3(4):785–811.

Matson, D. L., J. C. Castillo, J. Lunine, and T. V. Johnson (2007), Enceladus' plume: Compositional evidence for a hot interior, *Icarus* 187(2):569–573.

Mauk, B. H., Mitchell D. G., Krimigis S. M., Roelof E. C., and Paranicas C. (2003), Energetic neutral atoms form a trans-Europa gas torus at Jupiter, *Nature* 421(6926):920–922.

McCollom, T. M. (1999), Methanogenesis as a potential source of chemical energy for primary biomass production by autotrophic organisms in hydrothermal systems on Europa, *J. Geophys. Res.* 104:30729–30742.

McCord, T. B. (2000), Surface composition reveals icy Galilean satellites' past, *EOS Trans. Amer. Geophys. U.* 81(19):209, doi:10.1029/1000EO00141.

McCord, T. B. et al. (1997), Organics and other Molecules in the Surfaces of Callisto and Ganymede, *Science* 278:271–275.

McCord, T. B. et al. (1998a), Salts on Europa's surface detected by Galileo's near infrared mapping spectrometer, *Science* 280:1242.

McCord, T. B. et al. (1998b), Non-water-ice constituents in the surface material of the icy Galilean satellites from the Galileo near-infrared mapping spectrometer investigation, *J. Geophys. Res.* 103(E4): 8603–8626, doi:10.1029/1098JE00788.

McCord, T. B. et al. (1999), Hydrated salt minerals on Europa's surface from the Galileo near-infrared mapping spectrometer (NIMS) investigation, *J. Geophys. Res.* 104:11827–11851.

McCord, T. B., G. B. Hansen, and C. A. Hibbitts (2001a), Hydrated salt minerals on Ganymede's surface: Evidence of an ocean below, *Science* 292:1523–1525.

McCord, T. B. et al. (2001b), Thermal and radiation stability of the hydrated salt minerals epsomite, mirabilite, and natron under Europa environmental conditions, *J. Geophys. Res*. 106(E2):3311–3320.

McCord, T. B. et al. (2002), Brines exposed to Europa surface conditions. *J. Geophys. Res.* 107:5004.

McEwen, A. S., Keszthelyi L. P., Lopes R., Schenk P. M., Spencer J. R. (2004), The Lithosphere and Surface of Io, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.) Cambridge University Press, Cambridge, 307–328.

McGrath, M. A., E. Lellouch, D. F. Strobel, P. D. Feldman, and R. E. Johnson (2004), Satellite atmospheres, *Jupiter: The Planet, Satellites and Magnetosphere,* F. Bagenal et al., eds., Cambridge University Press, 457–483.

McKay, C. (2008), An Approach to Searching for Life on Mars, Europa, and Enceladus, *Space Science Reviews* 135(1):49–54.

McKay, C. and Smith, H. (2005), Possibilities for methanogenic life in liquid methane on the surface of Titan, *Icarus* 178(1):274–276.

McKinnon, W. B. (1999), Convective instability in Europa's floating ice shell, *Geophys. Res. Lett.*, 26:951–954.

McKinnon, W. B. (2005), Radar Sounding of Convecting Ice Shells in the Presence of Convection: Application to Europa, Ganymede, and Callisto, *LPI Workshop on Radar Investigations of Planetary and Terrestrial Environments*, Feb. 7–10, 2005, Houston, Texas, abstract no. 6039.

McKinnon, W. B. and M. Gurnis (1999), On initiation of convection in Europa's floating ice shell (and the existence of the ocean below), in *Lunar and Planetary Science XXX*, Abstract #2058. Lunar and Planetary Institute, Houston (CD-ROM).

McKinnon, W. B. and Parmentier E. M. (1986), Ganymede and Callisto, in *Satellites of Jupiter* (D. Morrison, ed.), Univ. of Arizona Press, Tucson, 718–763.

McKinnon, W. B. and M. E. Zolensky (2003), Sulfate Content of Europa's Ocean and Shell: Evolutionary Considerations and some Geological and Astrobiological Implications, *Astrobiology* 3(4):879-897.

Memory Investigation for Jupiter Europa Orbiter Mission, JPL Internal Document D-48262

Miller, S. L. and L. E. Orgel (1974), *The origins of life on the earth*, Englewood Cliffs, New Jersey: Prentice-Hall.

Moersch, J. et al. (1997), What happened to Cerberus? Telescopically observed thermophysical properties of the Martian surface, *Mars Telescopic Observations Workshop II,Lunar and Planetary Science* Technical Report 97-03.

Monnard, P.-A. et al. (2002), Influence of ionic solutes on self-assembly and polymerization processes related to early forms of life: Implications for a prebiotic qaueous medium, *Astrobiology* 2:213–219.

Moore, J. C., Reid, A. P., Kipfstuhl, J. (1994), Microphysical and Electrical Properties of Marine Ice and its Relationship to Meteoric and Sea Ice, *J. Geophys. Res.* 99:5171–5180.

Moore, J. M. and 25 colleagues (2001), Impact features on Europa: Results of the Galileo Europa Mission (GEM), *Icarus* 151:93–111.

Moore, J. M. and 11 colleagues (2004), Callisto, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 397–426.

Moore, J. M., Schenk, P. M., Bruesch, L. S., Asphaug, E., and McKinnon, W. B. (2004), Large impact features on middle-sized icy satellites, *Icarus* 171(2):421–443.

Moore and Pappalardo 2008 Titan: Callisto With Weather, Eos Trans AGU

Moore, M. (1984), Studies of proton-irradiated SO_2 at low temperatures: Implications for Io, *Icarus* 59:114.

Moore, M. H. and R. L. Hudson (2003), Infrared study of ion-irradiated N_2-dominated ices relevant to Triton and Pluto: Formation of HCN and HNC, *Icarus* 161(2):486–500.

Moore, W. B. and G. Schubert (2000), The tidal response of Europa, *Icarus* 147:317–319.

Moore, W. B. (2001), The thermal state of Io, *Icarus* 154:548–550.

Moore, W. B. (2006), Thermal equilibrium in Europa's ice shell, *Icarus*, 180, 141–146.

Moroz, V. I. (1965), Infrared Spectrophotometry of the Moon and the Galilean Satellites of Jupiter, *Soviet Astronomy* 9:999 and *AZh* 42:1287.

Moses, J. I., Fouchet T., Yelle R. V., Friedson A. J., Orton S. G., Beard B., Drossart P., Gladstone G. R., Kostiuk T., and Livengood T. A. (2004), The stratosphere of Jupiter, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 129–158.

Mosqueira, I. and Estrada P. R. (2003), Formation of the regular satellites of giant planets in an extended gaseous nebula I: subnebula model and accretion of satellites, *Icarus* 163(1):198–231.

Mustard, J., Murchie, S., Pelkey, S., Ehlmann, B., Milliken, R., Grant, J., Bibring, J., Poulet, F., Bishop, J., Dobrea, E., et al. (2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, *Nature* 454(7202):305.

NASA (2004), *The Vision for Space Exploration*, NASA NP-2004-01-334-HQ.

NASA (2006), *Solar System Exploration Roadmap.* NASA Science Mission Directorate, http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf.

NASA (2007), *Science Plan for NASA's Science Mission Directorate* 2007-2016, http://science.hq.nasa.gov/strategy.

NASA (1999),, *Avoiding Problems Caused By Spacecraft On-Orbit Internal Charging Effects, NASA-HDBK-4002.*

Nash, D. B., Yoder C. F., Carr M. H., Gradie J., and Hunten D. M. (1986), Io, in *Satellites of Jupiter* (D. Morrison, ed.), Univ. of Arizona Press, Tucson, 629–688.

Nash, D. and Howell, R. (1989). Hydrogen Sulfide on Io: Evidence from Telescopic and Laboratory Infrared Spectra, *Science* 244(4903):454–457.

Nealson, K. H. (1997), The limits of life on Earth and searching for life on Mars, *Journal of Geophysical Research* 102: 23675–23686.

Neubauer, F. (1998), Planetary science: Oceans inside Jupiter's moons, *Nature* 395:749–751.

Neumann, G. A. et al. (2001), Crossover analysis of Mars Orbiter Laser Altimeter data, *J. Geophys. Res.* 106:23753–23768.

Newhall, X X and J. G. Williams (1997), Estimation of the lunar physical librations, *Celestial Mechanics* 66:21–30.

Nimmo, F., B. Giese, and R. T. Pappalardo (2003), Estimates of Europa's ice shell thickness from elastically supported topography, *Geophys. Res. Lett.* 30(5):1233, doi:10.1029/2003GL016660.

Nimmo, F., Pappalardo, R., and Cuzzi, J. (2007), Observational and Theoretical Constraints on Plume Activity at Europa, *American Geophysical Union, Fall Meeting 2007*, abstract# P51E-05.

Nimmo, F., J. R. Spencer, R. T. Pappalardo, and M. E. Mullen (2007), A shear-heating mechanism for the generation of vapour plumes and high heat fluxes on Saturn's moon Enceladus, *Nature* 447:289–291.

Noll, K. S., H. A. Weaver, and A. M. Gonnella (1995), The Albedo spectrum of Europa from 2200 to 3300, *J. Geophys. Res.* 100:19057–19060.

Nozawa, H., Misawa H., Takahashi S., Morioka A., Okana S., and Sood R. (2005) Relationship between the Jovian magnetospheric plasma and Io torus emission, *Geophys. Res. Letts*. 32(L11101), doi:10.1029/2005GL022759.

NSP, NASA Science Plan (2007), *Science Plan for NASA's Science Mission Directorate,* <http://science.hq.nasa.gov/strategy>.

O'Brien, H., Brown, P., Beek, T., Carr, C., Cupido, E., and Oddy, T. (2007), A Radiation Tolerant Digital Fluxgate Magnetometer, *Measurement Science and Technology*, 18:3645–3650.

Ockert-Bell, M., J. A. Burns, I. J. Daubar, P. C. Thomas, M. J. S. Belton, and K. P. Klaasen (1999), The structure of Jupiter's ring system as revealed by the Galileo imaging experiment, *Icarus* 138:188–213.

Ojakangas, G. W., D. J. Stevenson (1989), Thermal state of an ice shell on Europa, *Icarus* 81:220–241.

OPAG, Outer Planets Assessment Group (2006), *Scientific Goals and Pathways for Exploration of the Outer Solar System,* <http://www.lpi.usra.edu/opag>.

OPFM Science Operations Concept Study Report (2008), JPL D-46870.

O'Reilly, T. C. and Davies G. F. (1981), Magma transport of heat on Io—A mechanism allowing a thick lithosphere, *Geophys. Res. Lett.* 8:313–316.

Orlando, T. M. et al. (2005), The chemical nature of Europa surface material and the relation to a sub-surface ocean, *Icarus* 177:528–533, doi:10.1016/j.icarus.2005.05.009.

Outer Planet Flagship Missions (Europa and Titan Orbiters) Parts Program Requirements, JPL Internal Document D-47664.

Paczkowski et al. (2008), Outer Planets Flagship Mission Science Operations Concept Study Report, JPL Internal Document D-46870.

Palguta, J., Anderson J. D., Schubert G., and Moore W. B. (2006), Mass Anomalies on Ganymede, *Icarus* 180:428–441.

Pappalardo, R. and Sullivan, R. (1996), Evidence for Separation across a Gray Band on Europa, *Icarus* 123(2):557–567.

Pappalardo, R. T. et al. (1998), Geological evidence for solid-state convection in Europa's ice shell, *Nature,* 391, 365.

Pappalardo, R. T., et al. (1998), Grooved terrain on Ganymede: First results from Galileo high-resolution imaging, *Icarus* 135:276-302.

Pappalardo, R. T. et al. (1999), Does Europa have a subsurface ocean? Evaluation of the geological evidence, *J. Geophys. Res,* 104:24015–24056.

Pappalardo, R. T. and A. C. Barr (2004), Origin of domes on Europa: The role of thermally induced compositional buoyancy, *Geophys. Res. Lett.* 31:L01701, doi:10.1029/2003GL019202.

Pappalardo, R. T., Collins G. C., Head III J. W., Helfenstein P., McCord T. B., Moore J. M., Procktor L. M., Schenk P. M., and Spencer J. R. (2004). Geology of Ganymede, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 363–396.

Pappalardo, R. (2006), Europa Science Objectives, NAI Europa Focus Group (Report to OPAG), http://www.lpi.usra.edu/opag/may_06_meeting/agenda.html.

Paranicas, C., Mauk, B., Ratliff, J., Cohen, C., and Johnson, R. (2002), The ion environment near Europa and its role in surface energetics, *Geophysical Research Letters* 29(5):18–1.

Paranicas, C., B. H. Mauk, K. Khurana, I. Jun, H. Garrett, N. Krupp, and E. Roussos (2007), Europa's near-surface radiation environment, *Geophys. Res. Lett.* 34, L15103, doi:10.1029/2007GL030834.

Parish, A. (1989), Development of Algorithms for On-Focal Plane Gamma Circumvention and Time Delay Integration, *Twenty-Third Asilomar Conference on Signals, Systems and Computers*.

Parkinson, W. D (1983), *Introduction to Geomagnetism*, Scottish Academic Press Ltd., Edinburgh, 308–340.

Parkinson, C., Liang, M., Yung, Y., and Kirschivnk, J. (2008), Habitability of Enceladus: Planetary Conditions for Life, *Origins of Life and Evolution of Biospheres* 38(4):355–369.

Parmentier, E. M., Squyres S. W., Head J. W., and Allison M. L. (1982), The tectonics of Ganymede, *Nature* 295:290–293.

Peale, S. J. (1976), Orbital resonances in the solar system, *Ann. Rev. Astron. Astrophys.* 14:215–246.

Pierazzo, E. and C. F. Chyba (2002), Cometary delivery of biogenic elements to Europa, *Icarus* 157(1):120–127.

Pilcher, C. B., S. T. Ridgway, and T. B. McCord (1972), Galilean Satellites, *J. Geophys. Res.* 103:31391–31403.

Porco, C. et al. (2003), Cassini imaging of Jupiter's atmosphere, satellites and rings, *Science* 299:1541–1547.

Porco, C. C., Helfenstein, P., Thomas, P. C. T., Ingersoll, A. P., Wisdom, J., West, R., Neukum, G., Denk, T., Wagner, R., Roatsch, T., Kieffer, S. Turtle, E., McEwen, A., Johnson, T. V., Rathbun, J.,Veverka, J., Wilson, D., Perry, J., Spitale, J., Brahic, A., Burns, J. A., DelGenio, A. D., Dones, L., Murray, C. D., and Squyres, S. (2006), Cassini Observes the Active South Pole of Enceladus, *Science* 311(5766):1393–1401.

Potter et al. (2005), Prockter, L. M., J. W. Head III, R. T. Pappalardo, J. G. Patel, R. J. Sullivan, A. E. Clifton, B. Giese, R. Wagner, and G. Neukum (2002), Morphology of Europan bands at high resolution: A mid-ocean ridge-type rift mechanism, *J. Geophys. Res.*, 107, doi:10.1029/2000JE001458.

Prockter, L. M. and 13 colleagues (1998), Dark Terrain on Ganymede: Geological Mapping and Interpretation of Galileo Regio at High Resolution, *Icarus* 135(1):317–344.

Prockter, L. M., Head J. W., Pappalardo R. T., Sullivan R. J., Clifton A. E., Giese B., Wagner R., and Neukum G. (2002), Morphology of Europan bands at high resolution: A mid-ocean ridge-type rift mechanism, *J. Geophys. Res.*, 107(E5): 5028, doi:10.1029/2000JE001458.

Prockter, L. M., Pappalardo R. T., and Nimmo F. (2005), A shear heating origin for ridges on Triton, *Geophys. Res. Lett.*, 32:L14202, doi:10.1029/2005GL022832.

Riley, J., G. V. Hoppa, R. Greenberg, B. R. Tufts, and P. Geissler (2000), Distribution of chaotic terrain on Europa, *J. Geophys. Res.* 105(E9):22599–22616, doi:10.1029/1999 JE001164.

Risk Reduction Plan (2008), JPL D-47928.

Rose, T., Hopkins, M., and Fields, R. (September 1995), Characterization and Control of Gamma and Proton Radiation Effects on the Performance of Nd:YAG and ND:YLF Lasers, *IEEE Journal of Quantum Electronics,* 31(9).

Rothschild, L. and Mancinelli, R. (2001), Life in extreme environments, *Nature* 409(6823):1092–1101.

Rowlands, D. D. et al. (1999), The use of laser altimetry in the orbit and attitude determination of Mars Global Surveyor, *Geophys. Res. Lett.*, *26*, 1191–1194.

Sagan, C., Thompson W. R., Carlson R., Gurnett D., and Hord C. (1993), A search for life on Earth from the Galileo spacecraft, *Nature* 365:715–721.

Salyk, C., A. P. Ingersoll, J. Lorre, A. Vasavada, and A. D. Del Genio (2006), Interaction between eddies and mean flow in Jupiter's atmosphere: Analysis of Cassini imaging data, *Icarus* 185:430–442.

Sanchez-Lavega, A. and 24 colleagues (2008), Depth of a strong jovian jet from a planetary-scale disturbance driven by storms, *Nature* 451:437–440.

Sarid, A. R., Greenberg R., Hoppa G. V., Hurford T. A. Tufts B. R., and Geissler P. (2002), Polar wander and surface convergence of Europa's ice shell: Evidence from a survey of strike-slip displacement, *Icarus* 158:24–41.

Schenk, P. M. and Bulmer M. H. (1998), Origin of mountains on Io by thrust faulting and large-scale mass movements, *Science* 279(5356):1514.

Schenk, P. M., C. R. Chapman, K. Zahnle, J. M. Moore (2004), Ages and interiors: The cratering record of the Galilean satellites, in: *Jupiter: The Planet, Satellites, and Magnetosphere* (F. Bagenal et al., eds.), Cambridge Univ. Press, Cambridge, 427–457.

Schenk, P. and Pappalardo, R. (2004), Topographic variations in chaos on Europa: Implications for diapiric formation, *Geophys. Res. Lett.* 31(10.1029).

Schilling, N., K. K. Khurana, and M. G. Kivelson (2004), Limits on an intrinsic dipole moment in Europa, *J. Geophys. Res*. 109:E05006.

Schilling, N., Neubauer, F. M., Saur, J. (2007), Time-varying Interaction of Europa with the Jovian Magnetosphere: Constraints on the Conductivity of Europa's Subsurface Ocean, *Icarus* 192(1):41–55.

Schubert, G., Zhang K., Kivelson M. G., and Anderson J. D. (1996), The magnetic field and internal structure of Ganymede, *Nature* 384(6609):544–545.

Schubert, G., J. D. Anderson, T. Spohn, and W. B. McKinnon (2004), Interior composition, structure and dynamics of the Galilean satellites, *Jupiter: The Planet, Satellites and Magnetosphere,* F. Bagenal et al., eds., Cambridge University Press, 1:281–306.

Schulze-Makuch, D. and Grinspoon, D. H. (2005), Biologically enhanced energy and carbon cycling on Titan? *Geochimica et Cosmochimica Acta*, 69(10):A528–A528.

Seas, A., Li S., Stephen, M., Novo-Gradac, A-M., Kashem, N., Vasilyev, A., Troupaki, E., Chen, S., and Rosanova, A. (2007), Development and Vacuum Life Test of a Diode-Pumped Cr:Nd:YAG Laser (Heritage Laser) for Space Applications, Conference on Lasers and Electro-Optics.

Shematovich, V. I., R. E. Johnson, J. F. Cooper, and M. C. Wong (2005), Surface-bounded atmosphere of Europa, *Icarus* 173(2):480–498.

Shoemaker E. M., Lucchitta B. K., Plescia J. B., Squyres S. W., and Wilhelms D. E. (1982), The geology of Ganymede, in *Satellites of Jupiter* (D. Morrison, ed.), Univ. of Arizona Press, Tucson, 435–520.

Showalter, M. R., A. F. Cheng, H. A. Weaver, S. A. Stern, J. R. Spencer, H. B. Throop, E. M. Birath, D. Rose, and J. M. Moore (2007), Clump detections and limits on moons in Jupiter's ring system, *Science* 318(5848):232–234.

Showalter, M., de Pater, I., Verbanac, G., Hamilton, D., and Burns, J. (2008), Properties and dynamics of Jupiter's gossamer rings from Galileo, Voyager, Hubble and Keck images, *Icarus* 195(1):361–377.

Showman, A. P.; Stevenson, D. M. R. (1997), Coupled orbital and thermal evolution of Ganymede, *Icarus* 129(2):367–383, doi:10.1006/icar.1997.5778.

Showman, A. P. and Malhotra R. (1999), The Galilean satellites, *Science* 286:77–84.

Showman, A. P., I. Mosqueira, and J. W. Head (2004), On the resurfacing of Ganymede by liquid-water volcanism, *Icarus* 172:625–640.

Simon-Miller, A., Conrath, B., Gierasch, P., Orton, G., Achterberg, R., Flasar, F., and Fisher, B. (2006), Jupiter's atmospheric temperatures: From Voyager IRIS to Cassini CIRS, *Icarus* 180(1):98–112.

Simon-Miller, A. A., Chanover N. L., Orton G. S., Sussman M., and Karkoschka E. (2006), Jupiter's white oval turns red, *Icarus* 185:558–562.

Smythe, W. D. et al. (1998), Galileo NIMS measurements of the absorption bands at 4.03 and 4.25 microns in distant observations of Europa, *Amer. Astronom. Soc.* 30:1448.

Smyth, W. H. and M. L. Marconi (2006), Europa's atmosphere, gas tori, and magnetospheric implications, *Icarus* 181(2):510–526.

Spencer, J. R., Tamppari L. K., Martin T. Z., and Travis L. D. (1999), Temperatures on Europa from Galileo PPR: Nighttime thermal anomalies, *Science* 284:1514–1516.

Spencer, J. R. and W. M. Calvin (2002), Condensed O_2 on Europa and Callisto, *Astron. J.* 124(6):3400–3403.

Spencer J. R. et al. (2005), Mid-Infrared detection of large longitudinal asymmetries in Io's SO_2 atmosphere, *Icarus* 176(2):283–304.

Spencer J. R. et al. (2006), Cassini Encounters Enceladus: Background and the Discovery of a South Polar Hot Spot, *Science* 311(5766):1401–1405.

Spencer, J., Stern, S., Cheng, A., Weaver, H., Reuter, D., Retherford, K., Lunsford, A., Moore, J., Abramov, O., Lopes, R. et al. (2007), Io Volcanism Seen by New Horizons: A Major Eruption of the Tvashtar Volcano, *Science* 318(5848):240.

Squyres, S. W. et al. (1983), Liquid water and active resurfacing on Europa, *Nature* 301:225–226.

SSB (1999), *A Science Strategy for the Exploration of Europa,* Space Studies Board, National Research Council, National Academy Press, Washington D.C.

SSB (2003), *New Frontiers in the Solar System: an Integrated Exploration Strategy*, Space Studies Board, National Research Council, National Academy Press, Washington D.C.

SSB (Committee on Assessing the Solar System Exploration Program) (2007), *Grading NASA's Solar System Exploration Program: A Midterm Review*, Space Studies Board, National Academies Press.

SSER, Solar System Exploration Roadmap (2006), NASA Science Mission Directorate. http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf

SSES, Solar System Exploration Survey (2003), Space Studies Board, National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, National Academy Press, Washington, D.C.

Steffl, A. J., Delamere P. A., and Bagenal F. (2004), Cassini UVIS observations of the Io plasma torus I: Initial results, *Icarus* 172:78–90.

Steffl, A. J., Delamere P. A., and Bagenal F. (2006), Cassini UVIS observations of the Io plasma torus III: Observations of temporal and azimuthal variability, *Icarus* 180:124–140.

Steffl, A. J., Delamere P. A., and Bagenal F. (2008) Cassini UVIS observations of the Io plasma torus IV: Modeling temporal and azimuthal variability, *Icarus* 194:153–165.

Stern, S. A. and McKinnon W. B. (2000), Triton's surface age and impactor population revisited in light of Kuiper Belt fluxes: Evidence for small Kuiper Belt objects and recent geological activity, *Astron. J.* 119:945–952.

Stofan, E., Elachi, C., Lunine, J., Lorenz, R., Stiles, B., Mitchell, K., Ostro, S., Soderblom, L., Wood, C., Zebker, H. et al. (2007), The lakes of Titan, *Nature* , 445(7123):29–30.

Strobel, D. F., J. Saur, P. D. Feldman, and M. A. McGrath (2002), Hubble Space Telescope Space Telescope Imaging Spectrograph Search for an Atmosphere on Callisto: A Jovian Unipolar Inductor, *The Astrophysical Journal*, 581, L51–L54.

Sullivan, R., R. Greeley, K. Homan, J. Klemaszewski, M. J. S. Belton, M. H. Carr, C. R. Chapman, R. Tufts, J. W. Head III, R. Pappalardo, J. Moore, P. Thomas and the Galileo Imaging Team (1998), Episodic plate separation and fracture infill on the surface of Europa, *Nature* 391:371–373.

Sullivan, R. J. et al. (1999), Does Europa have a subsurface ocean? Evaluation of the geological evidence, *J. Geophys. Res.* 104(E10).

Takahashi, S., H. Misawa, H. Nozawa, A. Morioka, S. Okano, and R. Sood (2005), Dynamic features of Io's extended sodium distributions, *Icarus*, 178:346–359.

Tantino, Dan (2008), *ASRG User ICD*, Lockheed Martin 9121C001299 (export controlled information).

Taylor, F. W., Atreya S. K., Encrenaz T., Hunten D. M., Irwin P. J. G., and Owen T. C. (2004), The composition of the atmosphere of Jupiter, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 59–78.

Thomas, N., F. Bagenal, T. W. Hill, and J. K. Wilson (2004), The Io neutral clouds and plasma torus, in *Jupiter: The Planet, Satellites and Magnetosphere*, F. Bagenal, W. B. McKinnon, and T. E. Dowling (Eds.), Cambridge Univ. Press, 561–591.

Tobie, G., Grasset O., Lunine J. I., Mocquet A., and Sotin C. (2005), Titan's internal structure inferred from a coupled thermal-orbital model, *Icarus* 175:496–502.

Tsang, T., and Radeka, V. (July 1995), Electro-optical Modulators in Particle Detectors, *Review of Science Instrumentation*, Vol, 66, No. 7.

Tufts, B. R., R. Greenberg, G. Hoppa, and P. Geissler (2000), Lithospheric dilation on Europa, *Icarus*, 146:75–97.

Turtle, E. P. and 12 colleagues (2001), Mountains on Io: High-resolution Galileo observations, initial interpretations, and formation models, *J. Geophys Res.* 106(E12):33175–33200.

Valavanoglou, A., Oberst, M., Magnes, W., Hauer, H., Neubauer, H., Baumjohann, W., and Falkner, P. (2007), Magnetometer Front-End ASIC (MFA), *Geophysical Research Abstracts*, 9.

Van Cleve, J., Pappalardo, R., and Spencer, J. (1999)., Thermal Palimpsests on Europa: How to Detect Sites of Current Activity, *30th Annual Lunar and Planetary Science Conference,* March 15–29, 1999, Houston, Texas, abstract.

van Herwaadren, A. (2001), Low-Cost Satellite Attitude Control Sensors Based on Integrated Detector Arrays, *IEEE Transactions on Instrumentation and Measurement*, 50(6).

Vasavada, A. R. and Showman A. (2005), Jovian atmospheric dynamics: an update after Galileo and Cassini, *Reports on Progress in Physics* 68(8):1935–1996.

Veeder, G. J., Matson D. L., Johnson T. V., Davies A. G., and Blaney D. L. (2004), The polar contribution to the heat flow of Io, *Icarus* 169(1):264–270.

Vincent, M. et al. (2000), Jupiter's polar regions in the ultraviolet as imaged by HST/WFPC2: Auroral-aligned features and zonal motions, *Icarus*, 143:205–222.

Vogt, S. S., Butler R. P., Marcy G. W., Fischer D. A., Henry G. W., Wright J. T., Johnson J. A. (2005), Five new multi-component planetary systems, *Astrophysical J.* 632: 638–658.

Volwerk, M. et al. (2001), Wave activity in Europa's wake: Implications for ion pickup, *J. Geophys. Res.* 106(A11):26,033–26,048.

VSE, The Vision for Space Exploration, President's Commission on Implementation of United Spates Space Exploration Policy (2004), *A Journey to Inspire, Innovate, and Discover*, Washington, DC.

Wackett, L. P., A. G. Dodge, and L. B. M. Ellis (2004), Microbial genomics and the periodic table, *Appl Environ. Microbio.* 70:647–655.

Wahr, J. M. et al. (2006), Tides on Europa, and the thickness of Europa's icy shell, *J. Geophys. Res.* 111, doi:10.1029/ 2006JE002729.

Waite, J. H. et al. (2006), Cassini Ion Neutral Mass Spectrometer: Encleadus Plume Composition and Structure, *Science* 311:1419–1422.

Ward, W. R. (1975), Past orientation of the lunar spin axis, *Science* 189:377–379.

Wessen, R. R. and D. Porter (1998), Market-Based Approaches for Controlling Space Mission Costs: The Cassini Resource Exchange, *Journal of Reduced Mission Operations Costs,* 1:1, 9–25.

Wessen, R. R. and D. Porter (2000), Market-Based Systems for Instrument Development and Science Planning, *Journal of Reduced Mission Operations Costs,* 1:2, 119–132.

West, R. A., Baines K. H., Friedson A. J., Banfield D., Ragent B., and Taylor R. W. (2004), Jovian clouds and haze, in *Jupiter:*

The Planet, Satellites and Magnetosphere (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 79-104.

Wienbruch U. and Spohn, T. (1995), A Self Sustained Magnetic Field on Io? *Planetary and Space Science* 43(9):1045–1057.

Willis, P. B. (2006), *Materials Survivability and Selection for Nuclear Powered Missions: Final Report,* JPL Internal Document D-34098.

Wu, X. P. et al. (2001), Probing Europa's hidden ocean from tidal effects on orbital dynamics, *Geophys. Res. Lett.* 28:2245–2248.

Yan, T-Y. et al. (2008), *Risk Mitigation Plan: Radiation and Planetary Protection*, JPL Internal Document D-47928.

Yelle, R. V. and S. Miller (2004), Jupiter's thermosphere and ionosphere, in *Jupiter: The Planet, Satellites and Magnetosphere* (F. Bagenal, T. Dowling, and W. McKinnon, eds.), Cambridge Univ. Press, Cambridge, 185–218.

Yoder C. F. and Peale S. J. (1981), The tides of Io, *Icarus* 47:1–35.

Yoder, C. F. et al. (1981), Tidal variations of Earth rotation, *J. Geophys. Res.*, 86:881–891.

Zahnle, K., L. Dones, and H. F. Levison (1998), Cratering rates in the Galilean Satellites, *Icarus* 136:202–222.

Zahnle, K., Alvarellos, J. L., Dobrovolskis, A., and Hamill, P. (2007), Secondary and sesquinary craters on Europa, *Icarus* 194(2):660–674, doi:10.1016/j.icarus.2007.10.024.

Zimmer, C., K. K. Khurana, and M. G. Kivelson (2000), Subsurface oceans on Europa and Callisto: Constraints from Galileo magnetometer observations, *Icarus* 147:329–347.

Zolotov, M. Y. and E. L. Shock (2004), A model for low-temperature biogeochemistry of sulfur, carbon, and iron on Europa, *J. Geophys. Res.* 109:E06003, doi:2003JE 002194.

Zolotov, M. Y. and J. S. Kargel (2008, in press), Chemical composition of Europa's ice shell, ocean, and underlying rocks, *Europa*, University of Arizona Press series on Space Science.

Zombeck, M., (1982), *Handbook of Space Astronomy and Astrophysics*, Cambridge University Press, 230.

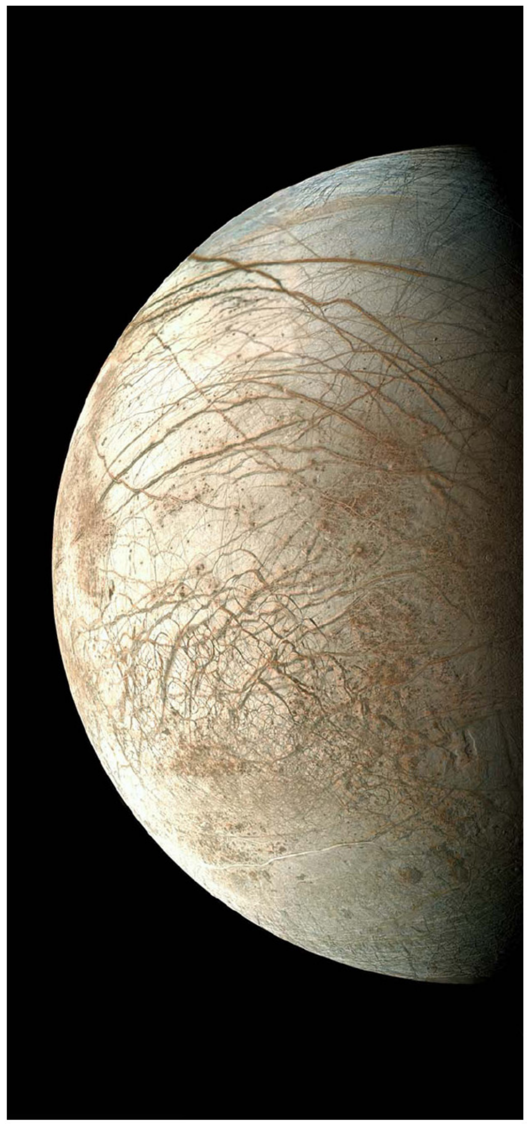
Zuber, M. T. et al. (1992), The Mars Observer Laser Altimeter investigation, *J. Geophys. Res.* 97:7781–7797.

C. PREVIOUS MISSION STUDIES

- JPL Publication 08-1, Assessment of Alternative Europa Mission Architectures

JPL Publication 08-1

Assessment of Alternative Europa Mission Architectures



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January 2008

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The work was performed by JPL's Solar System Exploration Directorate and supported by the JPL Strategic Studies program.

Table of Contents

1. Executive Summary

The purpose of this study was to assess the science merit, technical risk and qualitative assessment of relative cost of alternative architectural implementations as applied to a first dedicated mission to Europa. The objective was accomplished through an examination of mission concepts resulting from previous and ongoing studies. Key architectural elements that were considered include moon orbiters, flybys (single flybys like New Horizons and multiple flybys similar to the ongoing Jupiter System Observer study), sample return and *in situ* landers and penetrators.

Science merit was assessed relative to the 2007 Europa Explorer (EE) Science Definition Team (SDT) science objectives, which focus on global characterization. An orbital remote observation type of mission is a natural fit to global characterization rather than the single location of a lander or limited coverage of a few, even many, flybys. The most recent 2007 EE Flagship study concluded that a dedicated moon orbiter would be the lowest cost and risk architecture that would fully achieve all of the science objectives identified by the SDT. This is consistent with the conclusions of previous studies.

An examination of multiple and single flyby missions indicates poor science value when compared to a dedicated moon orbiter. A single flyby mission would yield very little in terms of Priority 1 science objectives. A spacecraft in orbit around Jupiter that makes multiple flybys past Europa, similar to the recently defined Jupiter System Observer mission with more than 6 low-altitude (100–200 km) flybys of Europa, would provide significant science for some of the key objectives; however, it falls short of achieving most top-priority science objectives. Because flyby missions would not be in orbit around Europa and thus spend much less time in the near vicinity of Europa, even the most favorable implementation would accomplish less than 50% of the Priority 1 science objectives.

While landers have the potential to return significant new science from Europa's surface, the science results would be limited to only a single site. As a result, a lander-only mission falls far short of achieving Priority 1 science objectives. In addition, due to the uncertainties in today's limited understanding of Europa's surface features, a first dedicated mission at Europa consisting only of a single lander would be characterized as having high risk. Data from a predecessor Europa orbiter would greatly reduce the risk for subsequent implementation of an *in situ* mission.

The combination of a dedicated moon orbiter and a lander would clearly provide more science return than an orbiter alone, but it would require more resources (fiscal and possibly technical) than are currently anticipated to be practical in the near future.

The study concludes that a dedicated moon orbiter would provide the greatest science value at lowest risk and cost for a first dedicated mission to Europa. This conclusion is consistent with the conclusions of previous studies.

2. Background

Over the last decade there have been a number of mission and system studies that have defined science objectives, mission architectures and implementation approaches applicable to a dedicated mission at Europa. Over that period of time, variations in the programmatic and technical environments have significantly influenced the results. For example, the Europa Orbiter (EO) study of 2001 had a severe pressure on cost and flight time. This resulted in a ~$1.2B mission with less than 30 kg of science instrumentation delivered by a direct Earth-to-Jupiter trajectory into Europa orbit. This was followed in the 2002–2005 timeframe with a focus on breakthrough capability for solar system exploration (i.e., nuclear electric propulsion and power) and expanded goals for Jupiter system science (multiple destinations: Ganymede, Callisto, Europa). This resulted in the Phase A conceptual design of a nuclear electric Jupiter Icy Moons Orbiter (JIMO) mission that was estimated to cost greater than $10B. In the current era, following the success of Cassini/Huygens, serious consideration is being given to preparing for the next outer planet flagship mission in a fiscally constrained environment. Current Flagship Mission studies have targeted a total mission cost in the $2–3B range. This assessment of alternative architecture options was undertaken to ensure that the science value of a Europa flagship mission would be maximized relative to the currently defined science objectives at an acceptable level of risk.

The approach to assessing alternatives has been to review what has been learned to date from past studies and evaluate those results in context of the currently evolved science objectives and programmatic/technical constraints. The 2007 EE science objectives resulted from over a decade of community input and debate. The resulting objectives focus on understanding the global aspects of Europa.

The balance of this report provides an historical summary of previous studies as well as an assessment of alternative Europa mission architectures. A summary of conclusions is provided at the end of this document.

3. Summary of Historical Europa Mission Concept Studies

In the last decade (spanning from April 1996 to present) more than a dozen Europa Mission concepts have been studied at JPL to varying degrees. They are listed in chronological order in Table 1. Brief highlights and references from those studies are included. This section provides a summary of the studies in this table.

Table 1: Historical Europa Mission Studies

Study Name	Power Source	Key Features	Ref
Europa Orbiter (1996)	RPS, Solar	Series of studies by Team X of simple, low-cost Europa orbiter mission. Looked at solar and RTG options	1
Europa Orbiter; Pluto S/C Option Study (1996)	RPS, Solar	Study to look at adopting new technologies being used on then-current Pluto mission study. Included RTG, AMTEC and solar options	2
Europa Sample Return (1996)	Solar	Study for potential Discovery proposal to fly Stardust-type capture and return of sample blasted from Europa surface by small impactor.	3

Study Name	Power Source	Key Features	Ref
Europa Orbiter, All Solar (1997)	Solar	Delta-V Earth Gravity Assist trajectory, Titan IV (SRMU)/Centaur, payload 42 kg	4
Europa Orbiter, All Solar (1998 IOM)	Solar	Revisit of 1997 All Solar study. Venus-Earth-Earth Gravity Assist (VEEGA) trajectory, STS/IUS, payload 20 kg, mass margin −15 kg, solar array 235 kg	5
Europa Orbiter (2001)	RPS	Direct trajectory, science payload 27 kg	6
Europa Orbiter Alternative Missions Study (2001)	RPS	Various trajectories, many options	7
Europa Orbiter Competitive (2002)	RPS	Look at low cost Europa orbiter mission for potential New Frontiers proposal	8
Jupiter Icy Moons Tour (2002)	Reactor	Flagship Mission, science payload 490 kg	9
Non-Fission Icy Moons Tour (2002)	RPS	Two S/C mission to all Galilean satellites, science payload 273 kg, plus two landers (Callisto and Ganymede)	10
Jupiter Icy Moons Orbiter (2005)	Reactor	Flagship Mission, science payload 1,500 kg	11
Europa Geophysical Explorer (2005)	RPS	VEEGA trajectory, science payload 153 kg plus additional margin 853 kg (additional 853 kg probably too optimistic, ~340 kg is a more likely figure)	12
Europa Explorer (2006)	RPS	VEEGA trajectory, science payload 180 kg plus unallocated margin of 340 kg	13
Europa Explorer Solar Array Feasibility Study (2006)	Solar	Attempt at an all-solar implementation of Europa Explorer science mission; found to be not practical.	14
Enhanced Europa Geophysical Explorer (2006)	RPS	Broad architectural assessment for single orbiter. VEEGA trajectory, science payload 150 kg plus additional margin 340 to 1200 kg (additional margin due to advanced RPS, larger LV and later launch dates)	15
2007 Europa Explorer Flagship Study	RPS	NASA-funded flagship study. Numerous architectures considered with focus on single orbiter. VEEGA trajectory, ~205 kg science payload (includes contingency), mass margins 982 kg including 185 kg “unallocated” margin	16
2007 Solar Europa Feasibility Study	Solar	Investigation of an all-solar implementation of Europa Explorer science mission; focused on achieving floor science objectives of 2007 EE Study.	17

3.1 Europa Orbiter (1996)

This represents the first study performed by Team X to investigate a mission to Europa. The initial study was performed in April of 1996 aimed at developing a very simple, single instrument (radar) mission to orbit Europa. Options explored included solar power and use of one half of a General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS RTG) to meet low power requirements (less than 150W). A series of updates to the original study were performed through May of 1996, ending up with design using one full GPHS RTG and incorporating technologies assumed for a concurrent Pluto mission study. Further options were investigated including benefits of Solar Electric Propulsion (SEP) (not found to be of significant value).

3.2 Europa Orbiter; Pluto S/C Option Study (1996)

The purpose of this study was to further develop the Europa mission concept using the then-current Pluto spacecraft hardware design, taking full advantage of the advanced technologies being considered for that mission. Three design options were investigated: one using a single GPHS RTG, one using the Alkalai Metal Thermoelectric Converter (AMTEC) RPS then in development, and a solar option.

3.3 Europa Sample Return (1996)

This study evaluated a possible candidate for a Discovery-class mission that would use the Stardust spacecraft architecture to capture and return a surface sample from Europa. The concept would have delivered a projectile to the surface of Europa to eject a plume through which the spacecraft would fly at ~ 50 km altitude, capturing plume particles in aerogel for return to Earth. Mission duration was estimated to be ~10 years. The mission was envisioned to be solar powered, using a “hibernation” mode to conserve power at large sun ranges.

3.4 Europa Orbiter, All Solar (1997)

This study was performed by Team X in 1997 to develop a point design for an all-solar mission to Europa. The study looked at a launch in late 2004 on a Titan IV launch vehicle followed by a 4.6-year flight to Jupiter using an Earth gravity assist. Wet mass for this concept was 3530 kg, leaving a margin of 1952 kg for launch on the Titan IV. Payload mass was 42 kg (including a 15-kg surface package). Solar arrays were estimated at 159 kg.

3.5 Europa Orbiter, All Solar (1998 IOM)

This IOM reassessed the feasibility of designing an all-solar mission to Europa. The work revisited the previous study performed by Team X in June 1997 by reexamining some spacecraft assumptions and by considering the possible use of a Shuttle with an Inertial Upper Stage. The combination of these two assumptions with the Team X study conclusions resulted in some increased performance as compared to the Team X conclusion but not nearly enough to change the ultimate conclusion that a Titan IVB launch vehicle would be required to attempt the mission without using an RPS for a power source. Launch date for this reanalysis was October 2005. Launch mass was decreased to 2925 kg and payload allocation was reduced to 20 kg. Solar array mass was sized to accommodate 135 W of extra heater power to avoid the need for Radioisotope Heater Units (RHUs). Even with the reduced capability and lower flight system wet mass, the study was not able to achieve a positive margin for launch on the Shuttle.

3.6 Europa Orbiter (2001)

This was the first rigorously developed point design for a Europa mission. The development effort spanned several years and resulted in a Radioisotope Power System (RPS)-based flight system design (Figure 1) constrained to a direct Earth-Jupiter trajectory. The science mission duration of 30 days in Europa orbit was determined by the SDT to be the minimum time required to meet the science objectives. This concept accommodated a modest science payload of 27 kg. Wet mass of this design was~1790 kg and power was to have been provided by two GPHS RTGs. Driving science requirements included the category 1A objectives defined by the SDT:

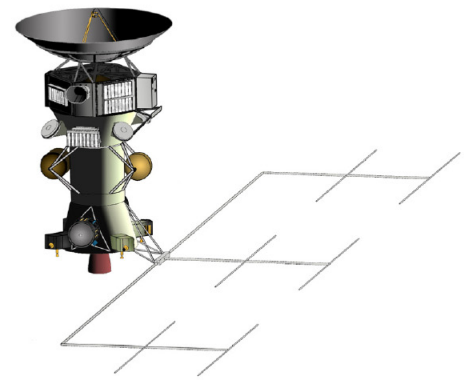

Figure 1. 2001 Europa Orbiter Flight System.

- Determine the presence or absence of a subsurface ocean
- Characterize the 3D distribution of any subsurface liquid water and its overlying ice layers
- Understand the formation of surface features, including sites of recent or current activity, and identify candidate sites for future lander missions

The work performed in this study provided insights into the issues associated with implementation of Europa missions, including a full assessment of the radiation environment and technologies for accommodating operations in that environment.

3.7 Europa Orbiter Alternative Missions Study (2001)

This report assessed alternative approaches to the EO mission in an effort to investigate lower cost options. Primary trades investigated included; an assessment of trajectory options including both direct and indirect trajectories, flight system trades between the EO baseline and minimum mass implementations, and endgame science mission options at Europa including an assessment of orbiters and flyby missions. Mission architectures were developed that addressed subsets of the full EO science objectives based on temporal or spatial observations. Alternative architectures resulted in some cost savings, but at the expense of full science.

3.8 Europa Orbiter Competitive (2002)

This study investigated the possibility of developing a simple, low-cost (less than $1B) mission to Europa that could potentially be developed as a New Frontiers proposal. The mission was envisioned to use a single GPHS RTG for power and had a limited payload of six instruments: a radar and a five-element Europa Integrated Science package totaling ~17 kg. Mission length was 30 days in orbit.

3.9 Jupiter Icy Moons Tour (JIMT) Studies (2002)

Three mission concepts were studied by independent teams: A reactor-powered mission employing a single launch vehicle to deliver the flight system to space, a second reactor-powered option employing multiple launches to low-Earth orbit (LEO) and using on-orbit assembly techniques to construct the final flight system, and a third non-reactor–powered option consisting of one or more flight systems to meet the same science objectives. All mission studies were completed as directed.

3.9.1 Reactor Options

The reactor options fall into a unique category. They would utilize nuclear fission power systems and advanced ion propulsion to enable exploration of multiple targets in a single mission. These studies also offered greatly enhanced science payload mass and power. The single launch option of the JIMT study had a science payload allocation of 490 kg and a total flight system launch mass of 21,000 kg. It would have been delivered to LEO by a single Delta-IVH launch vehicle, from which point it would have activated its nuclear electric propulsion (NEP) system to spiral out to its Jupiter trajectory. The on-orbit assembly option was similar to the single launch option, but would have launched the fuel tank and science module first on a heavy Evolved Expendable Launch Vehicle (EELV), to be followed by a shuttle launch of the power and propulsion module which would have been mated to the previously launched elements in LEO. Large solar arrays were to be used to provide solar-electric propulsion for the initial spiral-out from LEO. Total launch mass of this option would be about 23,000 kg with a payload allocation of 500 kg.

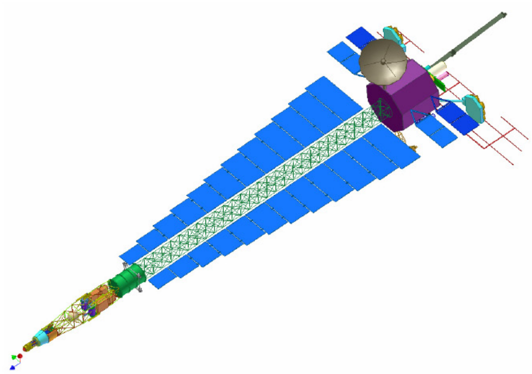

Figure 2. JIMT Single Launch Option.

3.9.2 Non-Reactor Option

The non-reactor JIMT team was asked to create a mission concept that (a) would achieve, as a minimum, the Europa Orbiter Level 1 science objectives at Europa, Ganymede and Callisto, (b) could be implemented for launch by the end of the decade, (c) would cost not more than \$4.5B, and (d) could be implemented without use of fission power. A large number of possible mission architectures was quickly reduced to five options for further study:

1. Jupiter orbital flotilla consisting of three identical spacecraft in orbit around Jupiter with multiple flybys of the three ice moons.
2. Icy moon flotilla consisting of a dedicated orbiter to each of the three icy moons.
3. Single large cruiser that would sequentially orbit each of the three icy moons for several weeks before moving on to the next.
4. Dual identical cruisers that would sequentially orbit each of two of the moons.
5. SEP/Radioisotope Electric Propulsion (REP) mother ship that would deliver a dedicated orbiter to each of the icy moons.

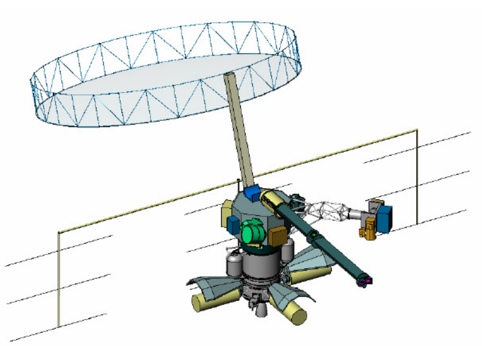

Figure 3. Non-Fission Option Orbital Configuration.

The fourth option was chosen for development in the study. Dual, identical twin spacecraft (Fig. 3) would be deployed to the Jovian system to provide full redundancy for Europa. Cruiser 1 would be deployed to Callisto first, for 12 weeks of detailed mapping and deployment of a small lander. It would then be flown into orbit around Europa for Europa science and end of mission. Cruiser 2 would be deployed to Ganymede into a 10-week mapping orbit, then into orbit around Io for its end of mission. Redundancy for Europa would be provided by phasing Cruiser 2 flight time to allow diversion to Europa in event of problems with Cruiser 1.

The flight system design took advantage of existing and a few high-value new technologies to lower mission risk and cost. A 100-kW SEP system (beginning of life power) with NASA Evolutionary Xenon Thrusters and Square Rigger Photovoltaic solar arrays was baselined. The Science Mission Module would use radiation-hard avionics and three 250-W advanced RPSs. A sixteen-instrument, 273-kg payload was accommodated on each spacecraft. One 132-kg lander was also carried on each spacecraft for delivery to Callisto and Ganymede. Landers each carried six instruments.

3.10 Jupiter Icy Moons Orbiter (JIMO)

The JIMO project mission and flight system designs evolved directly from the single launch option of the JIMT study. Requirements expanded over the course of this study and both the flight system and payload allocation grew. The payload allocation for JIMO (Fig. 4) was 1,500 kg and the total launch mass was more than 36,000 kg. While the capabilities of the JIMO flight system would have revolutionized the approach to outer planets science missions, the estimated cost of developing the project was deemed too large; the programmatic priorities changed at Headquarters, and, after successfully completing Phase A, further effort was indefinitely deferred. For this reason the Jupiter Icy Moons studies will not be included in further assessments contained in this report.

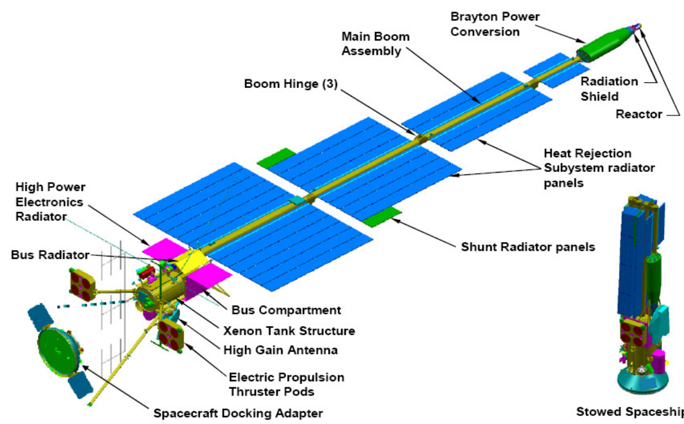

Figure 4. JIMO Configuration.

3.11 Europa Geophysical Explorer (2005)

The Europa Geophysical Explorer (EGE) study, funded by NASA's Planetary Program Support task and the NASA RPS Mission Systems Engineering Office, returned to the concepts of inner solar system gravity assists and conventional chemical propulsion for a mission to Europa, using radioisotope power in the form of the newly developed RPSs. This study made use of a Venus-Earth-Earth Gravity Assist (VEEGA) trajectory to increase delivered mass over previous studies, resulting in a launch mass capability of ~7230 kg using a Delta IVH launch vehicle. A payload allocation of 150 kg was baselined. The payload was sufficient to meet all newly defined science objectives in a Europa orbital mission phase of 30 days.

3.12 Europa Explorer (2006)

The EE study, which was internally funded by JPL, involved a detailed analysis of a Europa orbital mission. It took advantage of recent technology developments and additional knowledge gained from past studies to develop a highly capable mission aimed at meeting current science objectives for Europa. This study developed a flight system (Fig. 5) with a wet mass of 6988 kg. Science payload allocation was ~180 kg, with an additional 340 kg "unallocated mass" potentially available for a lander or other science payload. The orbital phase of the mission was extended to 90 days in collaboration with the science team. The improvements over past study results were made achievable by significant advances in radiation-hardened component technologies, now-proven larger launch capabilities and well-established gravity assist trajectory options, and better characterized radiation environment around Europa. The concept relies on traditional chemical propulsion system (similar to Cassini and Galileo), Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs - as are to be employed by Mars Science Laboratory) and a real-time continuous data downlink.

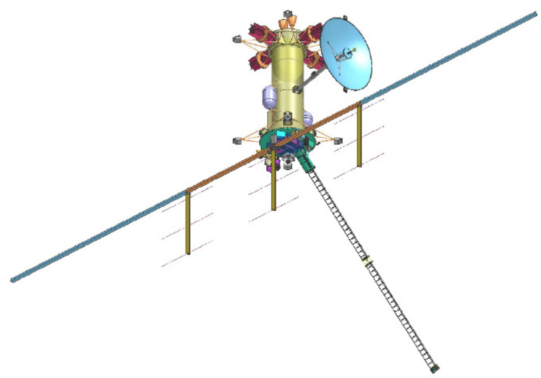

Figure 5. EE Orbital Configuration.

3.13 Enhanced Europa Geophysical Explorer (2006)

The Enhanced Europa Geophysical Explorer (EEGE) study was performed in 2006 to update the original EGE concept and assess the mass impacts associated with using different existing and advanced radioisotope power systems. Also studied were the mass implications associated with choosing different launch dates, interplanetary trajectories, and launch vehicles. The output was a detailed trade space analysis that could be used to assess the enabling and potentially cost-saving capabilities of using advanced RPS systems for a Europa mission. As expected, mass and power gains were realized when using the most advanced RPSs and most capable launch vehicles. EEGE was funded by NASA's RPS office.

3.14 Europa Explorer Solar Array Feasibility Study (2006)

This study, which was internally funded by JPL, evaluated the potential for replicating the EE 2006 science mission using solar power instead of RPSs. The study looked at the issues involved with the use of solar arrays in the Europa environment, considering radiation degradation and low solar intensity. The very large size of the arrays needed to accommodate Europa eclipses and the large gimbals and reaction wheels needed for this implementation led to the conclusion that this approach was not practical within the EE mission orbital constraints.

3.15 Europa Explorer Flagship Study (2007)

The NASA-commissioned 2007 EE Flagship Study has recently been completed. For this study NASA appointed an SDT to develop science objectives in light of the advances in understanding made by the JIMO SDT and refined by subsequent studies and science advisory groups. A further development of the mission and flight system developed in the EE 2006 study, it accommodated 205 kg of science payload (maintaining 185 kg of unallocated margin) while refining the design (lower telecom power and sequencing of instruments) to allow reduction in the number of MMRTGs from eight to six. This study looked at a baseline implementation, achieving all of the objectives of the Europa SDT, and a floor mission that would achieve many of the SDT objectives at a lower total mission cost. Results were thoroughly reviewed by NASA-appointed independent science and technical, management and cost panels.

3.16 Solar-Powered Europa Orbiter Design Study (2007)

In parallel with the 2007 EE Study, a solar-powered Europa Orbiter Design Study, which was internally funded by JPL, was carried out to take another look at the possibility of using solar arrays to provide power to a Europa mission (Fig. 6). This fairly high-level study directly addressed the issues raised by the 2006 EE solar study by changing the science orbit at Europa to one with continuous illumination, thus greatly reducing the excess solar array area needed to accommodate frequent eclipses and enabling a configuration with fixed solar arrays. A single-session Team X study was performed to evaluate the feasibility of such a mission that could accommodate the floor science objectives as defined by the 2007 EE SDT. Preliminary results indicate that such a mission might be viable and warrants further study.

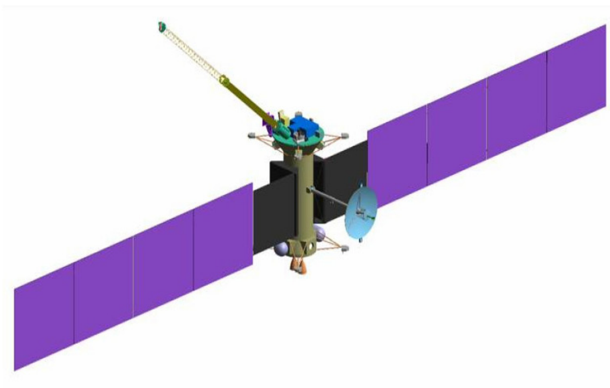

Figure 6. Solar Powered Europa Concept.

3.17 Europa Lander Studies

In addition to the orbital missions studied over the last decade a number of studies have been carried out to investigate designs for Europa landers. These studies have looked at a wide range of capabilities ranging from simple penetrators to very capable landers with cryobots and submarine vehicles capable of exploring the Europan ocean. A summary of the design parameters for some of these past studies is presented in Table 2.

None of the Europa mission studies ended up baselining a lander vehicle as part of their mission architecture. Each mission study concluded that the accommodation of a Europa landed package of some form would provide significant science above that required to meet the science objectives. The reluctance to baseline such a package has come from a combination of the estimated cost and risk impact that such an auxiliary element would have on the overall mission.

3.18 Science Goals and Objectives

The mission and spacecraft conceptual designs for exploration of Europa have significantly progressed over the years in detail and maturity. In parallel, the Europa science goals and objectives have evolved into a more comprehensive set of Priority 1 Objectives. Over the last decade several key advisory groups have considered and recommended sets of science objectives

Table 2. Past Europa Lander Studies (ref. 18).

Study title	Wet	Dry	Propellant	Landing	Power
Europa Lander (Baseline, 1997)	886 kg	338 kg	549 kg	Soft	AMTEC RPS
Europa Lander (Microtech, 1997)	828 kg	279 kg	549 kg	Soft	AMTEC RPS
Europa Pathfinder (2001)	221 kg	Solid Propulsion		Airbag	Battery + RHU
Europa Lander (1999)	487 kg	228 kg	259 kg	Soft	AMTEC RPS
Europa Lander + Cyobot+ Submarine (1998)	1502 kg	646 kg	856 kg	Soft	AMTEC RPS
Scout Lander (2000)	3451 kg	1502.1 kg	2340.2 kg	Multi	AMTEC ARPS
Europa Impactor (2000)	4×7kg	N/A	N/A	Impactor	Battery
Cadmus (Ga Tech, 2004)	558 kg	248 kg	310 kg	Soft	MMRTG
EGReSS (Ga Tech, 2004)	1575 kg	440 kg	1135 kg	Soft	MMRTG
JuIcy (Ga Tech, 2004)	1211 kg	511 kg	700 kg	Soft	Undefined RTG
Europa Surface Science Package (2004)	379 kg	44 kg	143 kg	Soft	Modified RTG
Jupiter Icy Moons Lander (2006)	390 kg	362 kg	22 kg	Soft	Battery

for the exploration of Europa (Table 3). The lineage of Europa science objectives traces back to the EO SDT, whose "Group 1" (highest priority) and "Group 2" (second priority) objectives were subsequently endorsed by the NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System, and then by the National Research Council's Solar System Exploration Survey ("Planetary Science Decadal Survey"). The Decadal Survey explicitly stated that a flagship-class mission should address both the Europa Orbiter Group 1 and Group 2 objectives, in addition to Jupiter system science during its Jupiter orbiting phase.

Subsequent to the recommendations of the Decadal Survey, the JIMO SDT expanded the scope of Europa objectives and included additional objectives relevant to the whole Jupiter system. Following NASA's indefinite postponement of the ambitious JIMO mission, the Outer Planets Assessment Group honed the objectives for Europa exploration. These objectives were iterated by the Europa Focus Group of the NASA Astrobiology Institute, and then codified by OPAG [2006] in its Scientific Goals and Pathways document. This codification was subsequently reflected in the 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate. The EE 2007 SDT reviewed and updated the 2006 objectives and relative priorities for use in their study. It is these Europa objectives that form the basis of the latest EE mission studies.

Table 3. Heritage of Europa Science Objectives.

Committee	Report Title	Ref.
Europa Orbiter Science Definition Team	Europa Orbiter Mission and Project Description	19
Committee on Planetary and Lunar Exploration (COMPLEX)	A Science Strategy for the Exploration of Europa	20
NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System	Europa and Titan: Preliminary Recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System	21
Solar System Exploration ("Planetary Science Decadal") Survey	New Frontiers in the Solar System: An Integrated Exploration Strategy	22
Jupiter Icy Moons Orbiter (JIMO) Science Definition Team	Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO)	23
Europa Focus Group of the NASA Astrobiology Institute	Europa Science Objectives	24
Outer Planets Assessment Group (OPAG)	Scientific Goals and Pathways for Exploration of the Outer Solar System	25
NASA Solar System Exploration Strategic Roadmap Committee	2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate	26
Europa Explorer 2007 Science Definition Team	2007 Europa Explorer Mission Study: Final Report	16

4. Assessment of Alternative Europa Mission Architectures

In the course of studying concepts for missions to Europa a number of candidate architectures have been considered, as shown in Figure 7. These include both single-element and multiple-element types. Single-element missions might consist of an orbiter around Europa, a Jupiter orbiter that makes multiple close passes by Europa during its mission, or a single flyby spacecraft, as in the Voyager and New Horizons missions. Architectures involving a single capable lander-only mission delivered by a simple cruise stage and communicating directly to Earth have not been studied yet in detail, for reasons given later in this section. Multiple-element missions might add a lander to an orbiter or flyby spacecraft, with the lander design ranging from a fully instrumented soft lander, to a more limited hard lander, to a simple impactor; multiple orbiting platforms might also be possible, maybe even sample return missions, but they have not been studied in detail, again for reasons given later in this section. One platform type, an aerial vehicle (e.g., a balloon), is rejected after only cursory consideration. The Europan atmosphere is so tenuous it is difficult even to *detect* with all but the most sensitive of instruments. Its mass density is orders of magnitude too small to cause detectable aerodynamic drag on orbiting spacecraft or impactors, let alone support any kind of aerial vehicle, so it need not be considered.

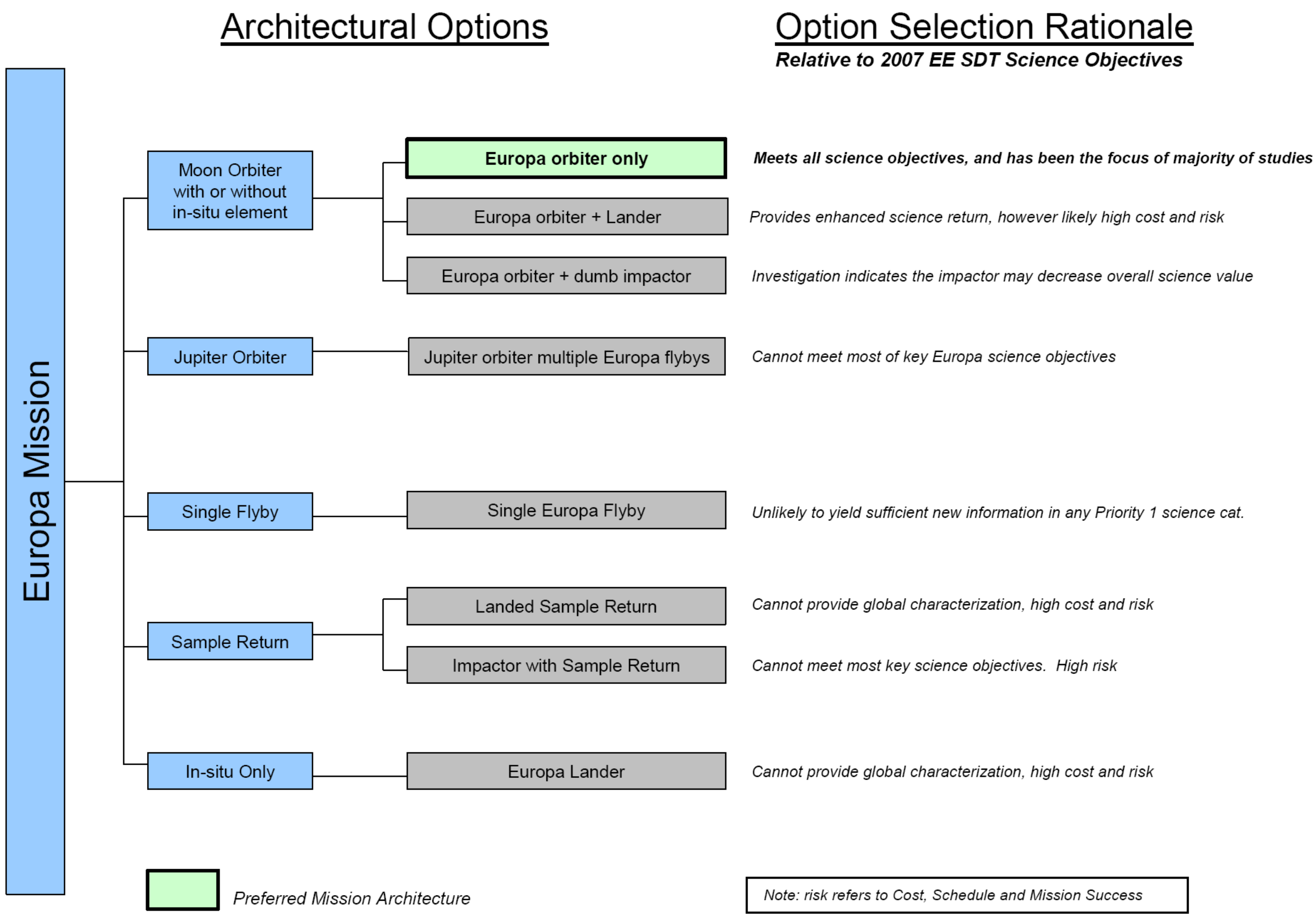

Figure 7. Architecture Options.

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Previous studies have examined all these applicable options, with varying science objectives and in greatly varying levels of detail. Reviewing the implications of these architectures in light of current Europa science objectives, as summarized in Table 4 [16], and considering technological readiness, cost and risk, the choice of optimal mission architecture quickly narrows to a dedicated Europa orbiter mission. The EE mission concept, such a dedicated orbiter mission, fully addresses all of the science objectives defined by the 2007 EE SDT and has been the focus of most of the recent studies for Europa exploration. The remainder of this section addresses the characteristics of the multiple-element architectures, and then the alternative single-element architectures, that make them less attractive than the single-orbiter-only option for a first dedicated mission to Europa. Further assessment would need to be done to address the impact of planetary protection requirements on mission cost, design, mass, and schedule for landers and sample return missions, as this study does not address planetary protection considerations.

Table 4. Architectures considered and rated against the Priority 1 Europa Science Objectives. ***(after Pappalardo et al., 2007)***

	A. Ocean	B. Ice	C. Chemistry	D. Geology	E. External Environment
Europa Explorer	5	5	5	5	5
Europa Explorer + Simple Lander	6	6	6	6	5
Europa Multiple Fly-bys	2	2	2	3	3
Capable Lander (No Orbiter)	3	2	4	2	1

NOTES:
- Multiple fly-bys means a dedicated Europa fly-by mission.
- Orbiter + lander implies a simple lander, carrying a seismometer, imager, composition experiment.
- Capable Lander is stand-alone (no orbiter), modeled after the Europa Astrobiology Lander.

6	Exceeds science objectives.
5	Fully addresses all science objectives.
4	Addresses most science objectives.
3	Addresses some science objectives.
2	May address partial science objectives.
1	Touches on science objectives.
0	Does not address science objectives.

4.1 Moon Orbiter, Plus Lander or "Dumb" Impactor

The addition of a simple instrumented lander to a Europa orbiter mission would provide even greater science return, exceeding the EE SDT's science objectives in all but one category [16] (see Table 4, row 2). Such a mission architecture would enable global remote sensing with ground truth for at least one site on the surface, and science measurements not possible from an orbiter. Given the likelihood of significant Europan tidal flexing, levels of seismic activity should be of sufficient magnitude that *in situ* measurements would provide unique geophysical insight into the subsurface and interior. Although costs have not been accurately modeled for any landed systems, the EE study determined that the cost for an orbiter with even a simple soft lander would likely exceed the expected resources available [16]. Moreover, the inferred low technology readiness of a simple hard lander, especially one landing on a surface whose topography is not well characterized, suggests a high risk to schedule and cost.

Multiple design teams have concluded that the only practical means of reducing the risk of safe landing on Europa, in a time frame consistent with implementation of the lander, is high-resolution imaging characterization of the surface, especially potential landing sites, from a precursor orbiter mission. Imaging of the candidate landing sites from an orbiter that delivers the lander is not useful, since the new information is not available for the design of the lander, and there is no guarantee that an orbiter with a lander designed for specific surface characteristics will find any scientifically interesting area, or any area at all, with those characteristics. It is an appropriate role for an orbiter mission to provide the information that enables subsequent lander missions with acceptable levels of risk.

A simple "dumb" impactor added to a Europa orbiter or flyby mission could allow remote measurement of elemental composition from the impact flash, and would excavate material from the shallow subsurface that might not have been radiolytically processed, for remote analysis later. However, a preliminary assessment by the EE team of the impact energies for reasonable masses and velocities suggest that the crater formed would be too small to yield significant compositional measurements, and might be too small to locate [16]. Instruments optimized for the Europa Priority 1 science objectives are different from the specialized instrumentation needed to observe an impact flash and plume, implying additional cost and/or the loss of other science.

4.2 Multiple Moon-Orbiting Platforms

Multiple orbiting platforms, in the form of an orbiting subsatellite deployed from a primary orbiting spacecraft, have several avenues for augmenting the science from a single orbiter, but would have significant impact on the resources available for the primary orbiter. At Europa, as elsewhere, simultaneous measurements from multiple spacecraft improve magnetospheric investigations. But according to the EE SDT, the greatest science gain would stem from formation-flying gravity measurements [16] as done by the GRACE mission at Earth [27]. Such investigations would primarily target the high-degree and -order (short spatial scale) gravity field components. But the measurable tidal signal of an internal Europan ocean is low-order (degree 2), and the most likely sources of non-isostatically–compensated gravity field anomalies are sufficiently deep, below the icy shell and ocean, that the higher-order signal levels would be quite feeble at orbital altitudes. Thus, the science gain from such a subsatellite would be limited. But the impact on resources for the primary orbiter would be substantial: the subsatellite would have to duplicate many of the subsystems of the primary orbiter, such as power, attitude determination and control, communications, command and control, etc., in addition to the subsatellite's payload. Resources devoted to the subsatellite, especially mass and cost, would subtract from those available to the primary orbiter and its payload. The EE SDT determined that a subsatellite's science did not justify the added cost and complexity [16].

4.3 Multiple Flybys

A Jupiter orbiter with multiple close flybys of Europa could provide significant science return to address some of the key science objectives for Europa. However, important measurements related to the ocean and other objectives cannot be achieved except from orbit. A flyby mission cannot provide 1) gravity and altimetry data of the requisite accuracy measured at appropriate phases of the tidal cycle, addressing the ocean objective; 2) significant areal coverage by an ice-penetrating radar for the ice shell objective; 3) global and targeted spectral imaging coverage at high resolution for the chemistry and geology objectives; and 4) sufficient temporal and spatial coverage for the external environment objective [16]. The Jupiter System Observer (JSO) flagship mission concept, studied by another team in parallel with the 2007 EE study, would do Europa science in the multiple-flyby fashion, with a many-flyby tour of the Galilean satellites that would include 6 or more Europa flybys. The 2007 EE SDT reviewed the JSO approach's performance in achieving its Europa science objectives and concluded that JSO would do a "poor" job, addressing less than 50% of the high-priority objectives.

Some have wondered if a Juno-like spacecraft and mission could perform Europa flyby science. But the JSO mission would provide far better science than would a Juno-like mission. To provide the best science possible by keeping encounter velocities low, the JSO mission concept's orbit would be fairly narrowly constrained to Jupiter's equatorial plane, with only small excursions to adjust flyby geometries. Of the many JSO flybys, the best for science occur in low-eccentricity orbits with low flyby V-infinities. The Juno mission's highly eccentric polar orbit [28] will be much less amenable to satellite science. It is such an orbit that will keep Juno's radiation dose relatively low for the first 20 (or so) orbits, despite a perijove within about 1.1 Jovian radii. Near perijove, that orbit will thread an axially aligned, roughly cylindrical "clear zone" between the planet and the inside edge of the main radiation belts, then recross the equatorial plane well outside the roughly toroidal ("doughnut-shaped") radiation belts. Jupiter's oblateness, notably the large J_2 component of its gravity field, will cause the eccentric polar orbit's line of apsides to rotate with each perijove pass, such that eventually the "long sides" of the ellipse will pass briefly near each of the Galilean satellites. But the flyby V-infinities for such an approach to Europa will be far greater than would be for JSO, more than 20 km/s compared to JSO's less than 10 km/s. Attempting to decrease the flyby velocities by rotating the Juno orbit into the equatorial plane would thwart the "threading" approach and result in radiation fluxes even greater than JSO would receive during its orbit insertion maneuver, just inside Io's orbit. The Juno spacecraft is not designed to survive this increased radiation level. For multiple reasons, the Juno approach is not suitable for a Europa mission.

4.4 Single Flyby

The single-flyby option was dismissed from further consideration because it is unlikely to yield significant new information in *any* of the highest-priority Europa science objective categories. This conclusion is consistent with a similar conclusion by the "Billion Dollar Box" study [29] of potential missions to Saturnian icy satellites Titan and Enceladus. The general conclusion that it is difficult to justify a single-flyby mission at a satellite already visited multiple times by a well-instrumented spacecraft orbiting the satellite's primary would not be a surprise. In the case of Europa, multiple Galileo flybys "raise the bar" for significant science there.

4.5 Stand-Alone Lander

A large stand-alone lander carrying a full suite of instruments for surface science could provide significant new results for Europa, especially if it were long-lived (more than 5 eurosols or 18 days). While the science return from a capable surface lander could be high, a lander would characterize only one location on Europa, which would not necessarily be representative of the satellite as a whole. At the current stage of Europa exploration, science priorities focus on global characterization, which would not be provided by a lander at a single location. Thus, a capable lander without a supporting orbiter does not address the Europa Explorer SDT's science objectives well. Moreover, the technology readiness of such a lander is quite low, and the surface topography of Europa is unknown at scales of concern to landers, posing significant problems for a safe landing. A capable lander is anticipated to have a high risk and cost.

4.6 Sample Return

Planetary scientists have emphasized for decades the benefits of bringing samples of extra-terrestrial materials to Earth, where the full power and flexibility of huge ground-based laboratories can be brought to bear on the analyses of the samples. The role of the Apollo samples in unraveling the origin of Earth's moon is a prime example. But despite the potential paradigm-altering science return, sample return missions to outer solar system destinations must contend with three significant hurdles: long mission durations for a round-trip to a distant location; risk that the required samples might not be collected or delivered to a useful location such as a curation facility on Earth; and high cost. Note that these are common challenges, and a specific mission could also face other challenges.

The proposed Europa Ice Clipper [30] mission is a sample return mission concept based on an interesting variation on the single flyby spacecraft. In this architecture a flyby spacecraft would release an impactor on approach to Europa. The impactor would create a crater and plume of debris through which the spacecraft would fly, collecting debris samples as it passes through. The samples would then be returned to Earth. While such a mission has the potential for returning unique results, it has problems with both science value and technical risk: it can address only a limited number of Europa science objectives at a single impact site, and is generally considered high risk for a number of reasons, including a low probability of obtaining an acceptable sample coupled with extremely demanding navigation requirements. The closer to Europa's surface the sample collecting spacecraft flies in an effort to increase the (small) chance of acquiring a usable sample, the tighter are the navigation requirements to prevent a catastrophic impact of the spacecraft on Europa's surface.

A more "conventional" landed sample return mission, one that places a soft-lander on the surface to collect and document samples, suffers greatly from the mission duration and cost problems. Compared to the Ice Clipper architecture, the landed sample return mission involves much more delta-V and thus more mass, time, and cost, and a much more complex flight system that is far more costly. A previous study by Woodcock [31], and preliminary results of a current study by some of this study's authors [32], of the utility of the proposed Ares launch vehicles for solar system exploration indicate that launching a landed outer solar system sample return mission appears to be a job for an Ares V launch vehicle, with an anticipated unit cost over $1B. It is clear that this type of sample return mission would far exceed the fiscal resources expected to be available for a flagship mission in the relatively near future.

4.7 Most Appropriate Architecture

A single Europa orbiter with no lander, impactor, or subsatellite is the architecture of choice for a first dedicated mission to Europa, since it fully addresses the science objectives at the lowest risk and cost, and since it provides the information needed to enable a future Europa lander with acceptable risk.

5. Conclusions

The objective of this study, *to assess the science merit, technical risk and qualitative assessment of relative cost of alternative architectural implementations as applied to a first dedicated mission to Europa,* was accomplished by 1) reviewing results from previous and current studies and 2) examining alternative architectural options relative to the science objectives defined by the 2007 EE SDT. This report summarizes a number of Europa mission and system concepts studied over the last decade as well as the results from assessing alternative architectural options in light of current science requirements. Based on this work, the study arrived at the following conclusions:

1. A dedicated orbiter mission to Europa provides the greatest science value (as measured by the 2007 EE SDT science objectives) at lowest risk. This conclusion is consistent with the conclusions of previous studies.

2. Varying programmatic constraints and evolving prioritization of science objectives affected the details of studies over the last decade but not the high-level conclusions.

6. References

[1] "Europa Orbiter", Team X Final Report, July 12, 1996. (JPL internal document)

[2] "Europa Orbiter, Pluto Spacecraft Option", Team X Final Report, July 12, 1996. (JPL internal document)

[3] "Europa Sample Return", Team X Final Report, June 25, 1996. (JPL internal document)

[4] "Europa Orbiter, All Solar," Advanced Projects Design Team (Team X), Final Report, 2 June 1997. (JPL internal document)

[5] Europa All-Solar Revisit, JPL IOM 311.1/98-5, May 29, 1998NS. (JPL internal document)

[6] Europa Orbiter Overview 7-9-01 (ppt). (JPL internal document)

[7] Europa Orbiter Alternative Missions Study, JPL Advanced Mission Studies Office, 8-15-01. (JPL internal document)

[8] "Europa Orbiter Competitive", Team X Final Report, October, 2002. (JPL internal document)

[9] Jovian Icy Moons Tour Mission Studies, Final Report, February 28, 2003. (JPL internal document)

[10] Nuclear Systems Initiative (NSI) Jovian Icy Moon Tour Mission Study Non-Fission Dual Cruisers to the Jovian Moons Flight System, January 27, 2003.

[11] Prometheus Project Final Report, Doc No. 982-R120461, October 1, 2005. (JPL internal document)

[12] (a) Europa Geophysical Explorer Mission Concept Study, JPL internal document D-32355, September 30, 2005 (b)Europa Explorer Design Team Report, JPL internal document D-34109, April 27, 2006.

[13] Europa Explorer Study Report, JPL internal document D-34054, March 10, 2006.

[14] Europa Explorer Solar Array Feasibility Report, August 30, 2006. (JPL internal document)

[15] Enhanced Europa Geophysical Explorer Study (EEGE) utilizing Advanced Radioisotope Power System, October 2006. (JPL internal document)

[16] 2007 Europa Explorer Mission Study: Final Report, JPL internal document D-41283, 1 November, 2007. Cleared for external release.

[17] Solar-Powered Europa Orbiter Design Study (2007), JPL internal document D-40344, September 28, 2007. Cleared for external release as JPL Pub 08-2, January 2008.

[18] Europa Surface Science Package Feasibility Assessment, JPL internal document D-30050, September, 2004.

[19] NASA AO: 99-OSS-04, Europa Orbiter Mission and Project Description, 1999.

[20] COMPLEX, Committee on Planetary and Lunar Exploration (1999), National Research Council, *A Science Strategy for the Exploration of Europa*, National Academy Press, Washington, DC.

[21] Chyba, C. F., W. B. McKinnon, A. Coustenis, R. E. Johnson, R. L. Kovach, K. Khurana, R. Lorenz, T. B. McCord, G. D. McDonald, R. T. Pappalardo, M. Race, and R. Thomson (1999), Europa and Titan: Preliminary recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System. *Lunar Planet. Sci. Conf.*, *XXX*, abstract #1537, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

[22] SSES, Solar System Exploration Survey (2003), Space Studies Board, National Research Council, New Frontiers in the Solar System: An Integrated Exploration Strategy, National Academy Press, Washington, D.C.

[23] JIMO SDT, Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) (2004), NASA, Washington, D.C., 2004. <http://www.lpi.usra.edu/opag/resources.html>

[24] Pappalardo, R. (2006), Europa Science Objectives, NAI Europa Focus Group (Report to OPAG), <http://www.lpi.usra.edu/opag/may_06_meeting/agenda.html>.

[25] OPAG, Outer Planets Assessment Group (2006), Scientific Goals and Pathways for Exploration of the Outer Solar System, <http://www.lpi.usra.edu/opag>.

[26] SSER, Solar System Exploration Roadmap (2006), NASA Science Mission Directorate. <http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf>

[27] NASA, "Gravity Recovery and Climate Experiment", Science@NASA website, <http://science.hq.nasa.gov/missions/satellite_19.htm>

[28] Matousek, Steve, "The Juno New Frontiers Mission", *Acta Astronautica*, Volume 61, Issue 10, November 2007, Pages 932–939.

[29] Reh, K. R. et al., Titan and Enceladus $1B Mission Feasibility Study, Prepared for NASA's Planetary Sciences Division, Performed at JPL, Final Report JPL D-37401B posted on the OPAG website: <http://www.lpi.usra.edu/opag/announcements.html> as "$1B Box Studies", January 30 (2007).

[30] "Europa Ice Clipper Summary", excerpt from 1997 Discovery Proposal, posted on the Astrobiology Web site: <http://www.astrobiology.com/europa/clipper/index.html>

[31] Woodcock, G., Ares Report, Prepared for David B. Smith (Boeing Company), PowerPoint presentation, December 13 (2007).

[32] "Ares V: Application to Solar System Scientific Exploration", JPL D-41883, December 12, 2007. Cleared for external release as JPL Pub 08-3.

7. Glossary

AMTEC	Alkali Metal Thermal to Electric Converter
ARPS	Advanced Radioisotope Power Systems
BOL	Beginning of Life
COMPLEX	Committee on Planetary and Lunar Exploration
Delta IVH	Delta IV Heavy
Delta-V	Delta Velocity
EDL	Entry, Descent and Landing
EE	Europa Explorer
EEGE	Enhanced Europa Geophysical Explorer
EGE	Europa Geophysical Explorer
EIS	Europa Integrated Science package
EO	Europa Orbiter
GPHS	General Purpose Heat Source
GRACE	Gravity Recovery and Climate Experiment
IUS	Inertial Upper Stage
JIMO	Jupiter Icy Moons Orbiter
JIMT	Jupiter Icy Moons Tour
JSO	Jupiter System Observer
LEO	Low Earth Orbit
LV	Launch Vehicle
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NEP	Nuclear Electric Propulsion
NEXT	NASA Evolutionary Xenon Thruster
NSI	Nuclear Systems Initiative
OPAG	Outer Planets Assessment Group
REP	Radioisotope Electric Propulsion
RHU	Radioisotope Heater Unit
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generator
S/C	Spacecraft
SDT	Science Definition Team
SEP	Solar Electric Propulsion
SMM	Science Mission Module
SRMU	Solid Rocket Motor Upgrade
STS	Space Transportation System (Space Shuttle)
Team X	JPL's Advanced Projects Design Team (concurrent engineering)
VEEGA	Venus Earth Earth Gravity Assist

8. Europa Quick-Look Statistics

Discovery	Jan 7, 1610 by Galileo Galilei
Diameter (km)	3,138
Mass (kg)	4.8e22 kg
Mass (Earth = 1)	0.0083021
Surface Gravity (Earth = 1)	0.135
Mean Distance from Jupiter (km)	670,900
Mean Distance From Jupiter (Rj)	9.5
Mean Distance from Sun (AU)	5.203
Orbital period (days)	3.551181
Rotational period (days)	3.551181
Density (gm/cm^3)	3.01
Orbit Eccentricity	0.009
Orbit Inclination (degrees)	0.470
Orbit Speed (km/s):	13.74
Escape velocity (km/s)	2.02
Visual Albedo	0.64
Surface Composition	Water Ice

http://www2.jpl.nasa.gov/galileo/europa/

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D. COST DETAIL

Details not available for public release.

FO-14A and FO-14B details not available for public release.

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E. FLIGHT SYSTEM DESIGN SUPPORTING DETAIL

Details not available for public release.

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F. RADIATION DESIGN SUPPORTING DETAIL

F.1 Fact Sheet

F.2 List of FY08 Deliverables and Summary Descriptions

F.3 Roadmap to Design Guidelines

F.4 Jupiter Europa Orbiter Radiation and Planetary Protection Design Tutorials

F.5 APML Format and Sample Worst Case Datasheet

F.1 Fact Sheet

Radiation Facts About the Jupiter Europa Orbiter (JEO) Mission

Spacecraft to Jupiter's inner magnetosphere must use a combination of natural and man-made radiation mitigation strategies to operate successfully over many years.

What is the radiation environment like near Europa's orbit?

Like Earth's Van Allen radiation belts, Jupiter's intense belts of ions and electrons are spatially confined in a torus encircling the planet. The greatest threat to spacecraft systems are the ions and electrons in the hundreds of keV to tens of MeV energy range. Analyses of the inner regions of Jupiter's magnetosphere have shown that these particles have fairly consistent intensities over time [1]. Storm-like and other disruptive transient events have been observed to occur. Storms caused, for instance, by changes at the sun and throughout the heliosphere can perturb the magnetosphere greatly. However, the data from Galileo indicate that these events do not affect the overall fluence significantly. Therefore, the total dose to the spacecraft in the inner region is predictable.

How do we ensure the instruments will operate?

JPL has accumulated years of experience in designing instruments and ensuring their operations near Jupiter. To date there have been seven flybys of Jupiter by spacecraft (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini, and New Horizons) as well as an orbiter, Galileo. The project has developed a reference model to estimate the effects of that planet's radiation environment on different instruments and spacecraft systems. In FY'08, a Detector Working Group was formed to assess the susceptibility of notional instruments under the harsh radiation environment. A scientific quality image has been demonstrated under simulated heavy radiation conditions.

What are the natural forms of radiation mitigation?

The easiest way to lessen the total dose is to limit the amount of time in the belts themselves. Galileo employed an orbit that included a low perijove for satellite flybys and a large apojove. Even so, it spent many weeks in the radiation belts: the first encounter was with Io on Dec. 7, 1995 and the last was with Amalthea on Nov. 5, 2002. Juno will spend some time on the magnetic field lines connecting to the radiation belts, but will travel mostly on polar field lines, (which map outside the belts), and at low Jovian altitude, essentially under the belts.

Europa is situated well inside the electron radiation belt; thus, simply avoiding the belts is not an option for JEO. JEO would orbit Jupiter for 2.5 to 3 years prior to inserting into Europan orbit and would receive a radiation dose similar to that of the Galileo orbiter. Also like Galileo, the dose accumulates most rapidly in the regions closest to Jupiter, near the orbits of Io and Europa.

The Divine and Garrett model, with the GIRE update [2], is the standard model used to estimate the radiation dose a spacecraft receives during its lifetime. Using the model, a Total Ionizing Dose (TID) can be computed, given the spacecraft trajectory through the environment. (Experience with Galileo indicates that this model probably overestimates the total dose.) Although other types of radiation effects, such as single event upsets, can transiently affect functionality, we are focusing on TID because its accumulation influences mission feasibility.

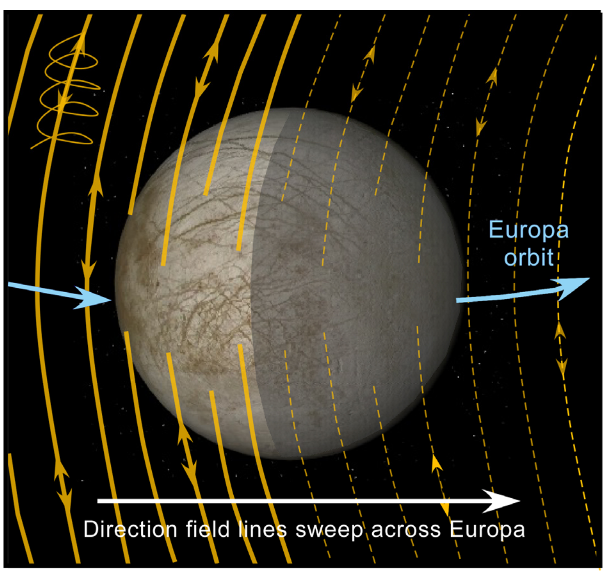


Figure 1. Energy is deposited into Europa's trailing hemisphere as plasma overtakes the moon. The depleted field lines result in an energy-dependent "shadow" lowering the radiation environment on Europa's leading hemisphere.

GIRE is a global model not intended to account for strategies such as shielding of the spacecraft by the moon itself, which has always been done to mitigate the total dose predicted. The protection afforded to the spacecraft by a moon can be quite substantial in a low altitude orbit as seen by considering the dimensions: R_E = 1560 km and R_{SC} = 100–200 km. Since the spacecraft would be in orbit for months, this correction to the TID is critical. Our best estimate to date of the "radiation shadow" cast by Europa (Fig. 1) involves the following principles. In considering dose, energetic electrons penetrate deepest into materials and as they slow, they emit photons (bremsstrahlung, or "braking" radiation) that deposit energy even deeper. Electrons are therefore hard to shield out except by using a lot of heavy material on the spacecraft. But near Europa, electrons travel with high velocities along magnetic field lines (in the north/south direction at Europa) and very slowly in the perpendicular directions. Therefore, electrons spiraling up and down the field lines hit Europa as soon as the field lines come into contact with it. Energetic electrons are therefore heavily lost near the equatorial trailing hemisphere of the moon leaving flux tubes very depleted of these electrons over much of Europa's surface. This creates a kind of shadow; the exact dimensions of which depend on electron energy. The **JEO would spend about *half its time in this shadow*** and so ***would experience significantly less radiation*** than it would receive in free space [3]. In summary, the moon would provide a great deal of the shielding that would otherwise be needed on the spacecraft itself.

What does this mean for JEO total dose?

Analysis of total mission radiation dose including the Europa shadowing effect results in a TID estimate of 2.9 Mrad behind 100 mils of Al (Fig. 2) and in a high confidence level that the spacecraft would be fully functional at 1 year. This approach was peer reviewed by non-project personnel in six separate reviews in 2007 and was endorsed and updated per inputs from specialists [4].

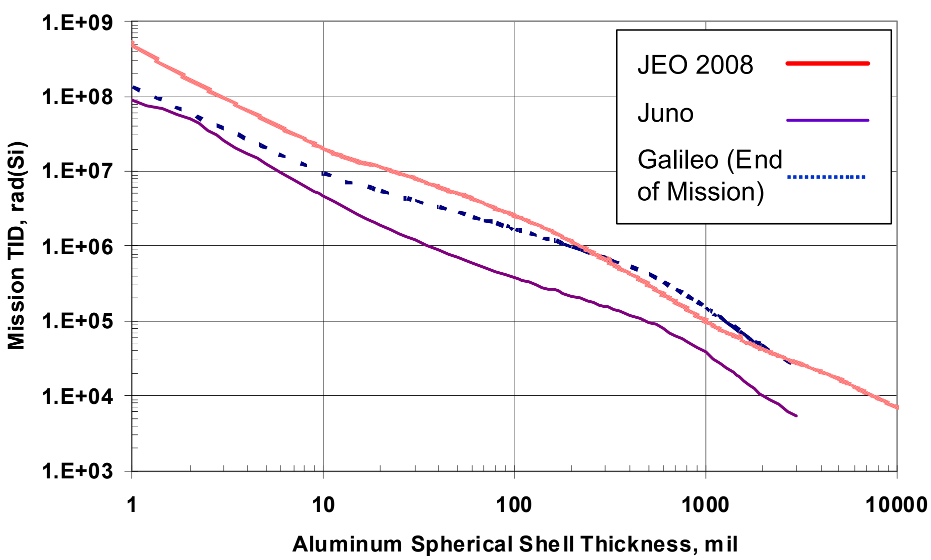


Figure 2. Estimated Total Mission Ionizing Dose vs. Shell (Al) Thickness — Estimated dose depth curves for Juno, Galileo, and Jupiter Europa Orbiter indicate that the estimated Galileo actual experience is close to the expected design environment for the primary Jupiter Europa Orbiter mission.

How do we shield for this?

A thick enclosure of material (usually chosen for high density for packaging efficiency) can shield components (sensor heads, electronics, materials, etc.) from the harmful effects of the radiation environment. Conservative JPL design practices dictate that components are shielded such that they “see” only one-half the part capability.

What is the shielding strategy and how does it compare with that of Juno and Galileo?

JEO handles the radiation environment using a combination of radiation-hardened parts and key component shielding. Juno uses non-hardened, or “radiation-soft” parts (10–50 krad), and a single large “vault” (~160 kg of tantalum and aluminum shielding) designed to reduce the environment at the electronics to one-half the part capability.

Using the Juno approach for JEO, which expects approximately 5 times the TID, would require an inordinate amount of mass. In contrast, the primary radiation-mitigation strategy for JEO is to use more radiation-hard parts (100–1000 krad). In addition, instead of a single vault, JEO uses multiple enclosures where the shielding is tailored for specific part capability, resulting in a manageable total of ~180 kg of tungsten/copper shielding. This JEO approach is similar to Galileo’s.

Are the needed rad-hard parts available now?

Yes, key parts are available and have required heritage. Recent advances in electronics for military and nuclear applications have made many parts available from 100 – 1000 krad(Si). High Speed PWM chips up to 1 MRad(Si) are commercially available. They were developed under the NASA Mars Exploration Program in partnership with JHU/APL. Radiation hardened ASICs have been flight qualified and flown. Other key components such as processors, memory, detectors, bus interface chips, and ADCs are available from 300 krad to 1 Mrad from many qualified commercial vendors.

What help is going to be available?

The project would develop and provide design guidelines and other information for prospective suppliers of components, including instruments which would be required to operate in the harsh radiation environment. Additionally, the project is testing, assessing, and compiling radiation data on high-profile parts; detectors, sensors, microprocessors, memory, FPGAs/ASICs, interface parts, ADCs/DACs, and power converters would be included in an Approved Parts and Materials List to be initially released in Fall 2008.

References:

[1] Europa Explorer Radiation Issue Report, JPL D-34103, April 4, 2006.

[2] Garrett, H.B., I. Jun, J.M. Ratliff, R.W. Evans, G.A. Clough, and R.E. McEntire, Galileo interim radiation electron model, JPL Publication 03-006 (2003).

[3] Paranicas, C., B.H. Mauk, K. Khurana, I. Jun, H. Garrett, N. Krupp, and E. Roussos, Europa’s near-surface radiation environment, *Geophys. Res. Lett.*, 34, L15103, doi:10.1029/2007GL030834 (2007).

[4] 2007 Europa Explorer Mission Study Report: Final Report, JPL D-41283, dated November 1, 2007 (especially Appendix C—Radiation Assessment Report which describes Peer Reviews conducted in 2007).

F.2 List of FY08 Reports and Descriptions

WBS	Report Title	Reference Number	Summary Description
0.0	EJSM Risk Mitigation Plan: Radiation and Planetary Protection	JPL D-47928	This document describes a four-year plan targeted towards mitigating the development and operational risk posed to the spacecraft and instruments of the JEO. The plan will facilitate trades among mission lifetime, mass and power requirements, while meeting science objectives and reducing lifecycle cost. This plan is based on the approach and strategy outlined in the 2007 Europa Explorer (EE) Mission Study Report. It also factors in the recommendations of the 2007 NASA Science, Technical, Management and Cost (TMC) Review team and includes compliance with NASA Planetary Protection (PP) requirements that were established based on recommendations set by the Committee on Space Research (COSPAR).
1.0	JEO Circuit Lifetime Model - Final Report for FY-08	IOM# 5133-08-013	The document expands circuit lifetime modeling effort started in FY-07 to include variation in part performance and correlates reliability with circuit performance. Organizational interfaces are identified and discussed. The plan for completing the circuit lifetime modeling task is explained, and progress to-date noted. Specific recommendations for inclusion in the FY-09 circuit modeling effort are presented, predicated upon insights from the FY-08 activities.
	Final Report for 2008 JEO System Radiation Lifetime Report	IOM# 313-08-055	This document continues the FY07 investigation of the JEO lifetime expectancy due to TID effects. This year's approach uses the enumeration of expected circuits based on the mass equipment List (MEL) as well as the MEL specified TID hardness. The study incorporates probabilistic TID hardness models of circuits and probabilistic characterization of the TID accumulation in Europa orbit to derive life expectancy curves for JEO mission based on the FY08 referenced radiation environment. The study also discusses future work to be performed to enhance the fidelity and credibility of the model results.
2.0	Jupiter Europa Orbiter Radiation Environment for the T08-008 Trajectory	IOM# 5132-08-041	This document provides the radiation environments for the JEO 2008 study. The 2008 mission trajectory results in the total ionizing dose (TID) of 2.8 Mrad (Si) behind a 100-mil aluminum shielding (RDF=1).
3.0	JEO Designing Circuits and Systems for Single Event Effects	JPL D-33338	This document discusses the effects of single energetic particles in space on microelectronic and optoelectronic devices. Examples are provided of the complex responses of advanced microelectronics, including functional interrupts that disrupt the basic way in which devices respond to electrical signals. Various circuit and system design approaches are included.
	OPFM ASIC via FPGA Guideline with Addendum on Europa ASIC Process Flow	JPL D-48347	This document describes the combined process of designing the complex digital logic in ASICs rather than FPGAs in order for the spacecraft electronics to survive the extreme radiation environment for the JEO mission. However, FPGAs have considerable advantages over ASICs in verification and validation. They can be programmed early on with the final or intermediate design and extensively tested on breadboards and in the system. It is recommended a combined process is used with the design started on an FPGA and finishing on an ASIC. This document also provides guidelines for the logic design, which will make the FPGA and ASIC sufficiently alike such that the FPGA is a good representation of the ASIC.
	JEO FY08 WCA Task Final Report	IOM# 5133-08-012	This report documents the work performed in FY08 towards developing a less conservative, and more accurate, process to assure circuit functionality under mission extreme conditions. Work started in FY08 included a review of Worst Case Analysis (WCA) methodologies and design efforts on several circuits representative of those that would be flown on JEO that will be analyzed and built and TID tested to check where margins and processes can be adjusted.
	Introduction to Space Radiation Effects on Materials	JPL D-48274	This presentation provides a brief description of the Europa environment, a survey of known radiation effects in materials, a discussion of current deficiencies and an approach to obtaining meaningful test results.
	OPFM Long Life Design Guidelines	JPL D-48271	This document provides guidelines that will enhance the lifetime of flight electronics in a JEO mission in the engineering subsystems such as C&DH, Power, and Telecom, as also in the science payload. Measures to extend lifetime vs. radiation and other life-limiting effects are considered. All phases of mission design are addressed, from requirements capture through operations.

WBS	Report Title	Reference Number	Summary Description
4.0	JEO Radiation Design Guidelines	JPL D-48258	This document provides guidelines and recommendations to support the design of space avionics in a high radiation JEO environment. It is targeted at the major locations of spacecraft flight electronics: in the engineering subsystems C&DH, Power, and Telecom, as well as in the science payload. All phases of avionics development are addressed, including architecture, fault tolerant systems engineering, parts selection, design & reliability analyses, simulation and support equipment, and test.
	Assessment of Radiation Effects on Science and Engineering Detectors for the JEO Mission Study	JPL D-48256	This document summarizes the findings of the JEO Detector Working Group (DWG). The JEO DWG was chartered to assess the radiation susceptibility of the photonic detector and key component technologies required by the notional JEO science planning payload and the spacecraft stellar reference sensor system. The DWG assessed the impact of total dose on component survivability as well as the impact of transient noise effects.
5.0	OPFM Test Method for Enhanced Low Dose Rate Damage (ELDRS) Effects in Integrated Circuits	JPL D-33339	This document describes a new approach for dealing with enhanced damage at low dose rate. It is applicable to missions to the outer planets that have radiation requirements that are so high that it is impractical to do the tests at the very low rates used for more conventional missions.
	Memory Investigation for JEO Mission	JPL D-48262	This document summarizes the devices and technologies considered for use in the spacecraft data recorder, testing and evaluation performed to date, and makes a recommendation for further study.
	Juno/Europa Extended Radiation Testing - FY08 Task Report	IOM# 5144-08-33	This document summarizes results of extended Juno tests to obtain higher dose levels data in support of the high radiation environments for the JEO mission. Present standard test methods are cost and schedule prohibitive. This data can be used to verify accelerated test methods, identify or eliminate candidate devices/ processes and provide statistical data for evaluation of worst case design parameter methods.
	FPGA Use for Europa Mission – FY08 Task Report	IOM# 5141-08-99	This document examines several candidate FPGAs that could be considered for Europa instruments. The JEO mission is considering the possible use of FPGAs for instruments. This report presents the results of a trade study and analysis of current and near term FPGA devices for application to possible Europa instruments. The focus of this trade study is on technology related issues, both reliability and radiation.
	Power Conversion Approach for the JEO Mission	IOM# 5144-08-32	This document explores the power converter / load regulation requirements options for the Outer Planets programs at JPL. The goal is to project forward the driving requirements, and explore the potential design space. Surveys include the design options available, the available electrical parts, and their qualification status. Based on the observed gaps, uncertainties, and risks, additional risk reduction tasks are identified.
6.0	Outer Planet Flagship Missions (Europa and Titan Orbiters): Parts Program Requirements (PPR)	JPL D-47664	This document establishes the baseline Electrical, Electronic and Electromechanical (EEE) Parts Program Requirements (PPR) for Outer Planet Flagship Missions, encompassing both the Europa and Titan orbiters. The EEE parts program requirements apply to both internal and external organizations to JPL, supplying EEE parts used in flight hardware. All Flight Hardware contractors, including Payload Instrument providers, are required to submit their Parts Program Implementation Plan to PPM for review and approval.
	JEO Total Dose and Displacement Damage Design Guideline	JPL D-33337	This document provides the background required to interpret the effects of total dose and displacement damage on electronic and optoelectronic parts on the proposed mission to Europa. The guideline describes the conventional approach using worst-case parameters that incorporate the effects of temperature, aging, and radiation damage, along with a new statistical approach that is less conservative.
	Approved Parts and Material List for OPFM	IOM# 5143-08-079	This document is the Outer Planet Flagship Mission (OPFM) Approved Parts and Materials List (APML). The APML will be used as the selection source of EEE parts and Materials. Every approved part listed on the APML will meet the applicable reliability, quality, and radiation requirements of OPFM Parts Program Requirements (PPR). Due to the higher levels of total dose radiation expected for the Europa mission, the APML will specify the acceptability of parts at 4 radiation levels, 3 pertaining to Europa mission (100, 300, and 1000Krads) and 1 pertaining for the Titan mission (50Krads)

WBS	Tutorial Title	Reference Number
2.0	Overview of Jovian Environment	Presented at 1st OPFM Instrument Workshop
	Characterisitics of Radiation Environments: Europa Orbiter	
	Planetary Protection for OPFM	
3.0	Space Radiation Effects on Microelectronics	
6.0	Radiation Effects on Materials: Europa Environment	
2.0	Shielding Design Considerations: Europa Orbiter	
	Spacecraft Charging Effects	
1.0	Mission Lifetime Model	
6.0	Introduction to Space Radiation Effects on Materials	JPL D-48274

F.3 Roadmap to Design Guidelines

F.3.1 Overview

This document provides an overall summary of the way in which radiation-hardened circuits are designed, along with the role that various documents prepared for the JEO mission provide the necessary information to implement successful designs. **Figure F.3-1** provides a general summary of the methodology, along with the relevant documents.

Operational Requirements. The first step is to establish the operational requirements for the particular circuit or subsystem. For example, some circuits may be needed only during the cruise phase, not during the exploration phase when the spacecraft first enters the high radiation environment. In other cases, the requirements for circuit or subsystem operation may state that operation is only required for part of the exploration phase, effectively lowering the radiation requirement compared to circuits that need to function for the entire mission.

Another important part of the operational requirements is establishing the bias and power conditions for various parts of the mission, which affect SEE as well as total dose. For example, a circuit that was unpowered for the lengthy cruise phase could tolerate a larger probability for catastrophic SEU effects, such as latchup or SEGR, compared to a circuit that was powered for the entire mission.

Radiation Requirements. Shielding is an important part of the Europa mission. It is

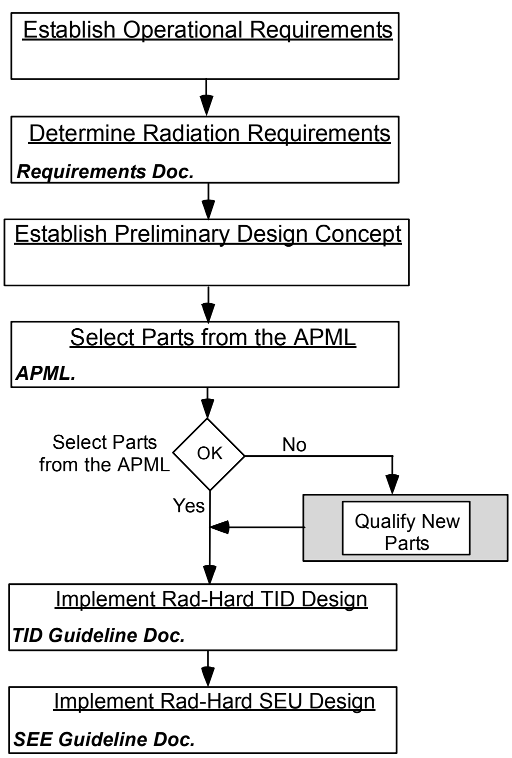


***Figure F.3-1.** Simplified flow chart for the main steps involved in designing circuits and systems for the Europa Orbiter.*

anticipated that the total dose requirements will be different for various locations within the spacecraft, which will include thick "vaults" to enclose some of the critical circuitry. The radiation requirements document will provide the information that is necessary in this step.

Preliminary Design Concept. In nearly all cases a successful circuit design begins with an overall concept of the circuit, including its basic function, interface and power requirements, and the types of components that are needed. Special design methods such as error detection and correction are usually included at this stage.

Parts Selection. The Approved Parts and Materials List (APML) provides a list of approved parts that will meet the specific requirements for radiation and reliability. Every approved part listed on the APML will meet the applicable reliability, quality, and radiation requirements specified in JPL D-47664, *Outer Planet Flagship Mission Parts Program Requirements*. It is strongly recommended, that all of the parts used for the design are selected from the APML. In exceptional cases it may be necessary to include new parts, as shown by the branch to the right of the flow chart. Although this is a simple concept, qualification of new parts is extremely expensive and time consuming, and is strongly discouraged.

Design for Total Dose and Displacement Damage. The most difficult environment for the Europa Orbiter is total dose, which is much higher than for typical missions. Designing for this environment requires careful consideration of all of the component parameters that will be degraded by radiation to ensure that the circuit will still function. In principle this is straightforward as long as the parameters of the devices used in the design are only moderately affected by radiation damage. In practice, this is much more difficult. JPL D-33337, *Total Dose and Displacement Damage Design Guideline*, describes the mechanisms and part degradation considerations in detail, and is a valuable tool for implementing hardened designs.

Design for SEE Hardness. The single-event upset problem is important, but the environment for Europa is not that different from other deep space mission. The main technical problem is that of understanding the rather complicated way in which modern integrated circuits can be affected by SEE. JPL D-33338, *Designing Circuits and Systems for Single-Event Effects*, summarizes those effects, and also includes some important considerations in testing and qualifying devices for the SEE environment.

Design Verification. Although it is not included in the flow chart, the final step in the design process is that of verifying that the design will meet the overall requirements for the mission. Several steps are involved in that process, including a failure modes and effects analysis, along with the documentation to verify that the circuit design has fully considered the effects of radiation damage, temperature, and aging.

F.3.2 Operational Requirements

Although it appears obvious, establishing the operational requirements for specific circuits and subsystems is a critical first step. It is vitally important for the JEO mission because the mechanisms for radiation damage, SEE response, and long-term reliability are affected by the way that components are used within the system. The first question is whether the circuit or subsystem must work over the entire mission length, and whether the parts (and any redundant circuits that may be included) are powered during the entire mission.

The second question is to establish the impact of circuit failure, and whether there are alternative ways of overcoming circuit failure that still allow the overall system to meet requirements.

The third question is whether the operation and use conditions of the circuit can be changed during the mission to deal with radiation effects or reliability issues. This can include system or subsystem solutions, such as the implementation of error-detection-and-correction; temporarily removing power to clear a function error from SEU; or temporarily removing power to promote recovery of radiation damage. It is important to determine and document these requirements before starting the circuit design process.

F.3.3 Radiation Requirements

Radiation requirements will be provided in an overall document that determines the radiation levels for specific regions with the spacecraft. The initial plan is to define three different regions with different amounts of shielding, resulting in nominal radiation levels of 100 krad, 300 krad, and 1 Mrad. However, there will be other regions, such as detectors, where different radiation levels will be likely.

Another factor in the radiation requirements is the on-board nuclear power source, which produces high-energy neutrons and gamma rays. These particles are very difficult to shield, and will impact the electronic continually, starting with pre-launch date when the power source is integrated into the spacecraft. The intensity of the particles emitted by the power source will depend on the distance between the power source and the electronics. Thus, the specific location of the electronics on the spacecraft must be known in order to add that radiation component to that of the natural space environment.

Part of the design process is to summarize the effects of the natural environment, the nuclear power source environment, and the amount of shielding that was assumed to arrive at final requirements for a specific circuit or subsystem.

F.3.4 Preliminary Design Concept

The initial design concept is a partial step towards circuit design. We need to use a broad definition of concept, recognizing that the radiation environment is so severe that some designs may depend on using system solutions, not just circuit design. Although part selection is the next step in the overall process, the initial design concept must include a list of the types of parts that are needed in the final design, along with their radiation susceptibility.

The best approach is to simply design the circuit to be robust to the radiation environment. This is possible for designs that require only very hard digital parts, but it may be impossible for circuits that require complex analog functions, or that involve low-level signals.

Traditional system solutions such as EDAC are important, but we may have to come up with more innovative ways to deal with the very high total dose levels for the mission. For example, the high leakage current from radiation damage in some CMOS circuits will anneal over time periods of a few weeks if they are placed in standby, or with power removed. In such cases it may be possible to alternate the operation of a digital circuit between two different modules, switching the operation between them in a way that takes advantage of annealing.

Another concept that could be useful is that of placing circuits that cannot meet the final requirements in small “pods” with local heaters. The heaters could be used to raise the temperature of the sensitive circuits to about 100ºC for approximately 24 hours, annealing the damage.

There are many possible approaches for the specific design as well as mitigation. The initial design concept should clearly define the circuit function, the initial list of part types, and the specific ways in which damage can be mitigated before starting the final design.

F.3.5 Parts Selection

In most cases it should be possible to implement a circuit design with the components that are on the Approved Parts and Material List (APML). Exceptions are strongly discouraged because of the difficulty of qualifying parts.

Permanent Damage. The parameters for parts on the APML will show parametric changes for three total dose levels. The APML will also flag conditions where more extreme changes will occur, as well as the maximum total dose level for use of a specific part type.

Although the APML will include displacement damage from the natural space environment, it will not include the effects of neutrons from the internal radioactive power sources. The circuit designer will have to add those effects, which will depend on the specific location of the circuit within the spacecraft.

The parameters on the APML will only incorporate a limited set of conditions. For example, transistor gain degradation will only be specified at specific collector currents (e.g., 1, 10, 50, and 100 mA), and the designer must interpolate between the values provided if the specific design uses different currents. The same situation applies to linear integrated circuits, where the parameters of the circuit are only tabulated for a specific set of values (e.g., ±5 V and ±15 V). Power supply conditions are even more complex for voltage regulators because the voltage between the “raw” input and regulated output can be as high as 40 V.

SEE Hardness. The APML is less transparent for SEE effects. The complexity of SEE responses, which is discussed in the SEE Guideline Document, includes multiple-bit upsets, functional interrupts, and stuck bits. The designer has to recognize the importance of those effects in implementing the design. Although the APML identifies parts that are susceptible to SEE effects, it is up to the designer to realize how they will impact the design.

The APML also identifies parts that meet the requirements for catastrophic SEE effects. Part applications must meet applicable derating requirements in order to ensure that catastrophic SEE effects do not happen.

New Components. As pointed out earlier, the use of components that are not in the APML is very strongly discouraged. Unless the components are produced by a hardened manufacturer, a lengthy and costly qualification process will be required, including radiation testing. It will take considerable resources, and at least six months, to complete the evaluation of the devices and verify that they are acceptable for Europa. This approach will be necessary for some specialized components, particularly optoelectronic devices, but will only be required in unusual cases for more conventional components.

F.3.6 Design for Total Dose and Displacement Damage

Designing for this environment requires careful consideration of all of the component parameters that will be degraded by radiation. JPL D-33337, *Total Dose and Displacement Damage Design Guideline*, describes the mechanisms and part degradation considerations in detail.

F.3.7 Design for SEE Hardness

The main technical problem is that of understanding the rather complicated way JPL D-33338, *Designing Circuits and Systems for Single-Event Effects*, summarizes the effects in which modern integrated circuits can be affected by SEE. This document also includes some important considerations in testing and qualifying devices for the SEE environment.

Basic SEU Phenomena

Relatively few integrated circuits are immune from SEE effects. Non-catastrophic effects for digital circuits include single and multiple bit upset, functional interrupt, and stuck bits (these do not recover, but are usually lumped with the other basic SEU effects).

We also have to be concerned about transients from linear integrated circuits. Nearly all linear circuits, including voltage regulators, will produce transients when they are exposed to heavy ions in space.

The challenges for the circuit designer are first to thoroughly understand the meaning of these effects and how they are influenced by application conditions, and second to design the circuit so that the overall circuit function can tolerate these effects. There is no basic "formula" for doing this. Basic integrated circuit functions such as transients from a comparator are easy to deal with, but the complex functional interrupt signatures for a processor or other digital circuit are far more difficult.

In many cases a system solution where the error is detected, triggering a set of responses that can correct for the malfunction, is the best approach. However, it can be difficult to verify that system solutions will actually work without considerable testing and analysis.

Catastrophic Effects

Latchup is difficult to deal with in space systems. However, we expect that most circuits on the APML will either be immune to latchup, or will have such a low probability that latchup will not be a concern, provided that the part is applied within the range of voltages where the latchup immunity has been verified. As discussed in the SEE Guideline Document, the use of current monitoring and power shutdown to allow the use of latchup-prone devices is not recommended. Gate rupture and burnout are relatively straight-forward for parts on the APML.

F.3.8 Summary

This brief document provides a bridge between the more comprehensive guideline documents that were developed for Europa and the design process. It outlines the basic steps in the process, although it does not include the important final step, which is to verify and document the analyses and tests that verify that the specific circuit will meet the requirements for Europa.

This document emphasizes the risk and cost involved in using parts that are not included in the APML, and strongly discourages the use of non-standard parts, a theme that was also emphasized in the other documents.

One topic that was not included was the use of a statistical design methodology in lieu of the standard design approach, using worst-case parameters and circuit conditions. We expect that the statistical design methodology will be applied to some circuits used on the Europa Orbiter in order to avoid the extreme conservatism that is inherent when worst-case conditions are assumed. Statistical design was discussed in the Total Dose and Displacement Damage Guideline document, but many details have to be worked out before it can actually be implemented.

F.4 Jupiter Europa Orbiter Radiation and Planetary Protection Design Tutorials

The JPL OPFM office conducted an Instrument Workshop June 3–5, 2008 in Monrovia, California. Over 150 participants attended the three-day event.

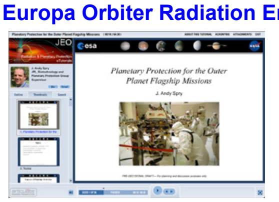
Eight sessions of the workshop were dedicated to providing tutorial material to potential instrument providers. The sessions focused on design issues related to instrument design in anticipation of and preparation for the release of the Announcement of Opportunity.

The following are screen shots of the recorded presentations provided as part of the tutorial. They are included in the disk as part of the FY08 deliverables.

Environmental Challenges in the Jovian System

Overview of the Jovian Environment

The Jupiter Europa Orbiter Radiation Environment



Planetary Protection for OPFM

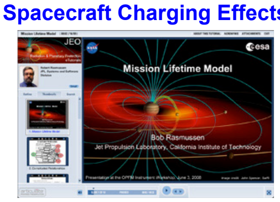
Jupiter Europa Orbiter Parts & Materials Challenges: Survivability Selection, & Testing

Radiation Effects on Microelectronics

Radiation Effects on Materials

Shielding Design Considerations

Spacecraft Charging Effects



Mission Lifetime Model

F.5 APML Format and Sample Worst Case Datasheet

Item #	Descriptor	Device Category	Device Type	Generic Part No.	PKG	MFG	Part Description	Flight Part #	Parts Status	SEL/ SEGR/ SEB	SEU	SET	SEFI	DD	50K	100K	300K	1000K	NSPAR Number	Planetary Protection	Comments/Recommendations
1	U	Linear Device	Line RCVR	26C32	FP16	Intersil	LINE RECEIVER, QUAD DIFFERENTIAL, RAD HARD	5962F9568901VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
2	U	Linear Device	Line DRVR	26CLV31	FP16	Intersil	RS422 driver	5962F9666302VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
3	U	Linear Device	Line RCVR	26CLV32	FP16	Intersil	RS422 Receiver	5962F9568902VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
4	U	Linear Device	Line DRVR	26CT31	FP16	Intersil	LINE DRIVER, QUAD DIFFERENTIAL	5962F9563201VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
5	U	Linear Device	Line RCVR	26CT32	FP16	Intersil	LINE RECEIVER, QUAD DIFFERENTIAL	5962F9563101VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T			
6	U	Digital Device	Memory	28F256LVQLE	FP28	Aeroflex	PROM, 32K X 8-BIT, 3.3 V, 65 NS ACCESS TIME	5962H0151704VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	A/WCD			
7	U	Digital Device	Logic, NOT	4049UB	FP16	Intersil	IC, HEX INVERTER BUFFER	5692R9663601VXC	A	A	A	S	A	A	A/WCD	A/WCD	T	N			
8	U	Digital Device	Logic NAND	4093B	FP14	Intersil	IC, Quad 2-Input Nand Gate, Schmitt Trigger	5962R9664101VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N			
9	U	Digital Device	Multivibrators	4098B	FP16	Intersil	IC, Dual Monostable Multivibrator	5962R9661401VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N			
10	U	Digital Device	Logic, NOT	54AC05	FP14	NSC	HEX INVERTER, WITH OPEN-DRAIN OUTPUT	5962R9059001SDA	A	A	S	A	A	A	A/WCD	A/WCD	N	N			
11	U	Digital Device	Line DRVR	54ACS244	FP20	Aeroflex	BUFFER/DRIVER, OCTAL, NONINVERTING, WITH 3-STATE OUTPUTS	5962H9657001VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	A/WCD			
12	U	Digital Device	D Flip Flop	54ACTS74	FP14	Aeroflex	IC, FLIP-FLOP, D-TYPE, DUAL, W/PRESET AND CLEAR AND TTL-COMPATIBLE INPUTS, ENHANCED	5962H9653502VXA	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	A/WCD			

Part Variation Worksheet for Worst Case Analysis

Program name	EUROPA		
Part Number(s)	5962H0151704 Rev C	Lot date code effective dates:	06 June 2006 - -
Generic part type	28F256LVQLE		
Description	32K x 8 bit Radiation Hardened PROM	SEU ≥ 40MeV, SEL ≥ 110MeV	

Conditions of use:	Min Temp (°C):	-20	Max Temp (°C):	60	
	Radiation Dose (K rad):	1000	Service Life (months):	78	
	Shelf Life Max Temp (°C):	25	Shelf Life (months):	24	

Parameter:	Standby Current		**Symbol:**	I_{DDSB}			
Nominal Value:		**Units:** mA		CE not = V_{DD}-0.25V, V_{IL}= V_{SS}+ 0.25V			
	Deterministic variation		**Random variation**				
	Min	**Max**	**(+/-) %**		**Data Source**	**Notes**	
Initial		0.25	1.00			mil spec	min is est
Low temp.		0.00	0.00			mil spec	included in initial
High temp.		0.00	0.00			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1MEG
End-of-life		-0.03	0.12			est	

Worst Case Minimum: 0.220 mA **Worst Case Maximum:** 1.120 mA

Parameter:	Operating Supply Current		**Symbol:**	I_{DDOP1}	V_{IL}=0.2V, freq= 15.4MHz, V_{IH}=3.0V		
Nominal Value:		**Units:** mA		CMOS inputs (Iout=0)			
	Deterministic variation		**Random variation**				
	Min	**Max**	**(+/-) %**		**Data Source**	**Notes**	
Initial		12.50	50.0			mil spec	min is est
Low temp.		0.0	0.0			mil spec	included in initial
High temp.		0.0	0.0			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1MEG
End-of-life		-0.75	3.01			est	

Worst Case Minimum: 11.747 mA **Worst Case Maximum:** 53.011 mA

Parameter:	Output voltage high		**Symbol:**	V_{OH1}	Vdd= 3.3V max		
Nominal Value:		**Units:** volts		I_{OH}=-100uA			
	Deterministic variation		**Random variation**				
	Min	**Max**	**(+/-) %**		**Data Source**	**Notes**	
Initial		3.15	3.30			mil spec	
Low temp.		0.00	0.00			mil spec	included in initial
High temp.		0.00	0.00			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1 MEG
End-of-life		-0.12	0.00			est	

Worst Case Minimum: 3.030 VOLTS **Worst Case Maximum:** 3.30 VOLTS

Parameter:	Output voltage high		**Symbol:**	V_{OH2}	Vdd= 3.3V max		
Nominal Value:		**Units:** volts		I_{OH}=-1mA			
	Deterministic variation		**Random variation**				
	Min	**Max**	**(+/-) %**		**Data Source**	**Notes**	
Initial		2.85	3.300			mil spec	
Low temp.		0.00	0.000			mil spec	included in initial
High temp.		0.00	0.000			mil spec	included in initial
Radiation		0.00	0.000			mil spec	up to 1 MEG
End-of-life		-0.12	0.000			est	

Worst Case Minimum: 2.730 volts **Worst Case Maximum:** 3.300 volts

Part Variation Worksheet for Worst Case Analysis

Program name	EUROPA		
Part Number(s)	5962H0151704 Rev C	Lot date code effective dates:	06 June 2006 - -
Generic part type	28F256LVQLE		
Description	32K x 8 bit Radiation Hardened PROM	SEU ≥ 40MeV, SEL ≥ 110MeV	

Conditions of use:	Min Temp (°C):	-20	Max Temp (°C):	60
	Radiation Dose (K rad):	1000	Service Life (months):	78
	Shelf Life Max Temp (°C):	25	Shelf Life (months):	24

Parameter:	Voltage Output Low		**Symbol:**	V_{OL1}	V_{DD}=3.0V max	
Nominal Value:	0.0	**Units:** V		I_{OL} = 100uA	V_{SS}=0V	
	Deterministic variation		**Random variation**			
	Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial	0.00	0.050			mil spec	
Low temp.	0.00	0.000			mil spec	included in initial
High temp.	0.00	0.000			mil spec	included in initial
Radiation	0.00	0.000			mil spec	up to 1 MEG
End-of-life	0.00	0.000		0.006	est	

Worst Case Minimum: 0.000 V **Worst Case Maximum:** 0.056 V

Parameter:	Voltage Output Low		**Symbol:**	V_{OL2}	V_{DD}=3.0V max	
Nominal Value:	0.1	**Units:** V		I_{OL} = 1mA	V_{SS}=0V	
	Deterministic variation		**Random variation**			
	Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial	0.00	0.100			mil spec	
Low temp.	0.00	0.000			mil spec	included in initial
High temp.	0.00	0.000			mil spec	included in initial
Radiation	0.00	0.000			mil spec	up to 1 MEG
End-of-life	0.00	0.000		0.012	est	

Worst Case Minimum: 0.000 V **Worst Case Maximum:** 0.112 V

Parameter:	Read Cycle Time		**Symbol:**	t_{AVAV}		
Nominal Value:		**Units:** nS				
	Deterministic variation		**Random variation**			
	Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial	65.00	n/a			mil spec	
Low temp.	0.00	0.00			mil spec	included in initial
High temp.	0.00	0.00			mil spec	included in initial
Radiation	0.00	0.00			mil spec	up to 1 MEG
End-of-life	-0.78	0.00			est	

Worst Case Minimum: 64.217 nS **Worst Case Maximum:** n/a nS

Parameter:	Read Access Time		**Symbol:**	t_{AVQV}		
Nominal Value:		**Units:** nS				
	Deterministic variation		**Random variation**			
	Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial	0.00	65.00			mil spec	
Low temp.	0.00	0.00			mil spec	included in initial
High temp.	0.00	0.00			mil spec	included in initial
Radiation	0.00	0.00			mil spec	up to 1 MEG
End-of-life	0.00	0.78			est	

Worst Case Minimum: 0.000 nS **Worst Case Maximum:** 65.78 nS

Part Variation Worksheet for Worst Case Analysis

Program name	EUROPA		
Part Number(s)	5962H0151704 Rev C	Lot date code effective dates:	06 June 2006 - -
Generic part type	28F256LVQLE		
Description	32K x 8 bit Radiation Hardened PROM	SEU ≥ 40MeV, SEL ≥ 110MeV	

Conditions of use:	Min Temp (°C):	-20	Max Temp (°C):	60
	Radiation Dose (K rad):	1000	Service Life (months):	78
	Shelf Life Max Temp (°C):	25	Shelf Life (months):	24

Parameter:	Chip Enable (not) Access Time			**Symbol:**	t_{ELQV}		
Nominal Value:		**Units:**	nS				
	Deterministic variation			**Random variation**			
		Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial		0.00	65.00			mil spec	
Low temp.		0.00	0.00			mil spec	included in initial
High temp.		0.00	0.00			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1 MEG
End-of-life		0.00	0.78			est	

Worst Case Minimum: 0.000 nS **Worst Case Maximum:** 65.78 nS

Parameter:	Output Enable (not) Access Time			**Symbol:**	t_{GLQV}		
Nominal Value:		**Units:**	nS				
	Deterministic variation			**Random variation**			
		Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial		0.00	35.00			mil spec	
Low temp.		0.00	0.00			mil spec	included in initial
High temp.		0.00	0.00			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1 MEG
End-of-life		0.00	0.42			est	

Worst Case Minimum: 0.000 nS **Worst Case Maximum:** 35.42 nS

Parameter:	output enable (not) three state time			**Symbol:**	t_{GHQZ}		
Nominal Value:		**Units:**	nS				
	Deterministic variation			**Random variation**			
		Min	**Max**		**(+/-) %**	**Data Source**	**Notes**
Initial		0.00	35.00			mil spec	
Low temp.		0.00	0.00			mil spec	included in initial
High temp.		0.00	0.00			mil spec	included in initial
Radiation		0.00	0.00			mil spec	up to 1 MEG
End-of-life		0.00	0.42			est	

Worst Case Minimum: 0.000 nS **Worst Case Maximum:** 35.4216 nS

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G. OPERATIONS SCENARIO ANALYSIS

G.1 Introduction

The purpose of Appendix G of the Jupiter Europa Orbiter (JEO) study report is to document the work and methods used to develop the operations scenarios for the JEO study and describe detailed operations context for several aspects of the mission. The key conclusions and summary descriptions of the baseline data acquisition and return scenarios for the Jupiter system and Europa science scenarios are included in the main body of the report. Tool and methodology descriptions and some key analysis results for the Europa science scenarios and preliminary Jupiter system tour scenarios are described in this appendix. Context descriptions including mission operations system architecture and DSN scheduling methods are also provided.

G.2 Study Approach

The development of the operations scenarios was a central part of the JEO Mission Concept Study from the start. The development was an interactive collaboration among the members of the Joint Jupiter Science Definition Team (JJSDT) and engineers from the JEO study team. The engineering team members were Rob Lock, Greg Welz, Grace Tan-Wang, Tracy van Houten, Ken Hibbard, Kenny Donahue, and Joe Neelon.

The starting point for the operations scenarios development was the work done in the previous studies (2006 and 2007) since most of the key elements of the mission, including science payload, mission design, and flight system design, were similar to those from the 2007 study. The 2007 study developed detailed operations scenarios for the Europa Science phase but did not develop detailed operations scenarios for Jovian Tour science. The results of the 2007 study directly supported the operations scenario development and can be found in [*Clark et al. 2007*].

Working in concert with the JJSDT, and in parallel with the JJSDT's development of the science value matrix, key mission capabilities and constraints were examined and challenged. Science goals were discussed and options were considered for data collection scenarios.

Based on the current planning payload, flight system design and trajectory, the current study re-analyzed Europa Science phase scenarios for Europa Campaigns 1–3. As before, Europa Campaign 4 scenarios will be developed both based on results of the first 3 campaigns but also from investigation requirements developed in future studies.

The Jovian Tour scenarios in this study were derived from Tour analysis from the 2007 study. The current 30-month Tour trajectory and the addition of Io flybys were new but did not alter the constraints on flyby dynamics from the previous study. Example flyby scenarios were developed for each Galilean satellite as well as for a Jupiter monitoring example.

G.3 Mission Operations System Architecture Context

The description of the mission operations system architecture in this appendix is intended to provide detailed information for the mission operations system elements, ground data system elements, and the DSN scheduling rationale aspects of the mission not presented in the main body of the report. The descriptions of the mission design and flight system design are provided in §4 of the report and are not repeated here.

The Mission Operation System (MOS) is comprised of all hardware, software, networks, facilities, people, and processes used to operate the flight system. The MOS includes project specific elements, such as the GDS and flight teams, elements shared with other projects, like the DSN and related services, and those parts of the science teams that are used in the operations of the flight system.

The descriptions herein are generic for JPL missions of the scope of JEO and were used for cost estimation purposes. They are included for here for context.

The DSN scheduling rationale is described for all phases of the mission and is used for mission cost analysis and for Jupiter system tour and Europa science data return scenarios.

G.3.1 Mission Operations System

The mission operations system is illustrated in **Figure G.3-1**, and is made up of the people, processes, software, and hardware necessary to successfully operate the mission. This figure shows the three major elements that make up the ground system, the NASA wide common services and capabilities provided through the

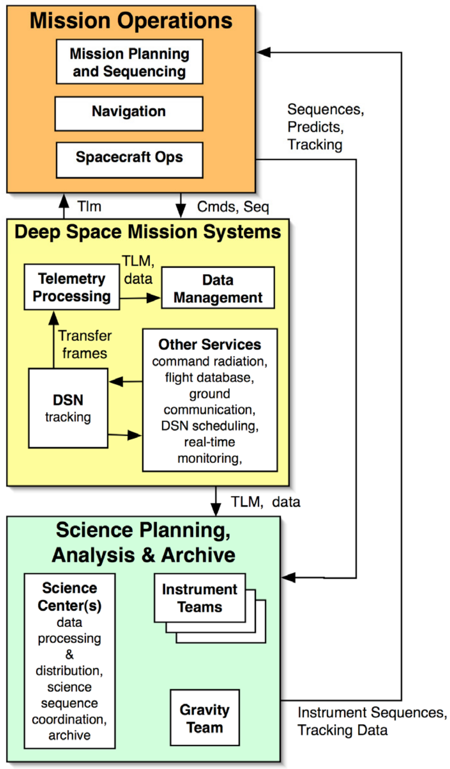


Figure G.3-1. Mission Operations System Data Flow Diagram

DSMS; the project specific MOS with its underlying ground data system; and the science support elements.

G.3.1.1 Deep Space Mission System

The DSMS handles the communication interface between the flight and ground systems. DSMS includes the DSN, the underlying interconnecting ground network, and the related services. The services support initial processing of the telemetry and the related data management and distribution of the telemetry data to specific interfaces, such as the science processing organization and spacecraft analysis teams.

The DSN will perform all tracking for this mission, starting shortly after launch. For launch support up through final injection burn the tracking system will consist of NASA Ground Network 9–12 m X-band ground stations used to support launches from Cape Canaveral Florida. The actual stations used depend significantly on the ascent trajectory. Shortly after launch, the DSN tracking profile will be as shown in **Table G.3-1**. The DSN currently consists of three complexes (Goldstone, USA; Canberra, Australia; Madrid, Spain), each with several 34 m stations and one 70 m station.

A note on 70 m station usage. Per study guidelines, JEO does not require 70 m stations for science data return. Tracking resources with equivalent performance at X-band are required for engineering support of critical or high value activities during the mission. These resources are needed for limited periods of hours or days.

In addition to the DSN, DSMS also provides services for working with the DSN. These services include telemetry processing and distribution, commanding, real-time monitoring and control, scheduling, and ground communications infrastructure. The telemetry services will take the bit-stream as received at the DSN stations and convert it to level 0 formats (as the data appeared on the flight system prior to transmission). The telemetry system also performs additional processing to separate the instruments data from the spacecraft data, store the data in the project database for non-real-time analysis, and distribute telemetry data to the appropriate customers. The command service takes the command files generated by the MOS and radiates them to the flight system. The real-time monitoring and control team, also known as the mission control team, act as the interface between the mission and the DSN operations, and provide ongoing monitoring of the telemetry being received and of the command radiation activities, ensuring timely responses to problems in communications. Scheduling services ensure the project is able to get the DSN tracking resources needed routinely and for emergencies and are key to resolving conflicts with other missions over the limited resources of the DSN. Finally a critical, but often overlooked service is the ground communications network support. This final service provides as a minimum the communications between JPL and each of the DSN complexes and voicenets used by the project. More frequently this service is also extended to implement and support remote science or spacecraft operation centers. A key part of this support are network system administrators that ensure the continued functioning of the network, network security, and voice communications.

G.3.1.2 Project Specific MOS Elements

Key project specific elements of the MOS include: infrastructure support, spacecraft operations and analysis, navigation support, mission planning and sequence development, science instrument operations and planning, and training. **Figure G.3-2** shows the functions and flow of products among the MOS elements in the project.

The infrastructure support includes the system administrators, software developers, and supporting hardware. Prior to launch the multi-mission Ground Data System (GDS) is adapted across all elements of the ground system to handle the mission specific functions and requirements. In addition, after launch the underlying multi-mission GDS undergoes periodic revision, about every 18 months, changes to the GDS will need to be made and tested as needed by supporting programmers. Typically every 3 to 4 years the GDS computers and related hardware will need to be replenished to ensure that the hardware and operating systems support will be available during flight operations.

Spacecraft operations teams monitor spacecraft health and develop sequences for the spacecraft. The spacecraft system engineers generate all commands and sequences for engineering activities (e.g., telecommunications sessions, propulsive maneuvers, flight software maintenance) and support analysis needed for science activities such as pointing predicts and memory management. Spacecraft system engineers also perform general spacecraft health analysis and trending. The spacecraft subsystem engineers participate in fault diagnosis, anomaly resolution, and prediction of future behavior, and sequence development and review.

The navigation team performs trajectory analysis and design and performs the orbit determination and trajectory analysis for the flight system using DSN RF data and, if needed, on-board imaging data (opnav). The navigation team also coordinates with instrument and spacecraft teams to implement planned propulsive maneuvers and reaction wheel de-saturation burns, predict flyby geometry and timing parameters, assist in Doppler data processing for radio science investigations, and plan future mission phase trajectories.

Mission planning is an ongoing function for the life of the mission and involves the cross-project coordination, planning and analysis of

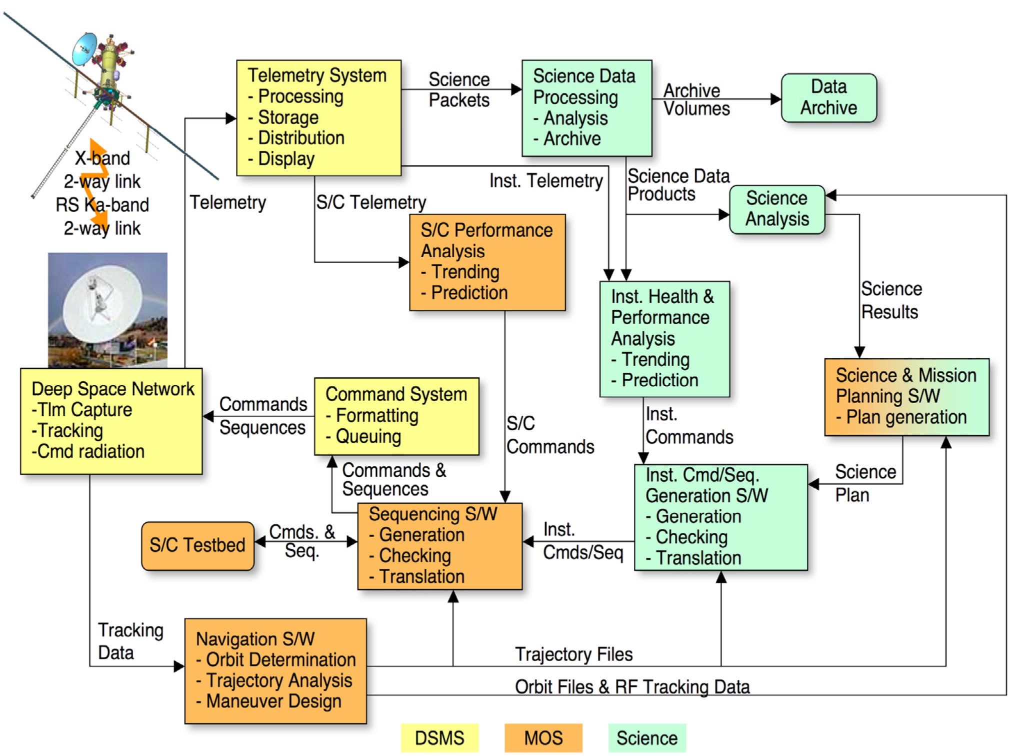


Figure G.3-2. *MOS Function and Product Flow Diagram* the trajectory design, mission timelines, and the major activities during each of the mission phases. This is performed with membership across the project including support from spacecraft, navigation, instrument and science teams. Once the flight system is operational, mission planning coordinates the refining of trajectories and activities to compensate for changing plans and evolving flight system characteristics, and to fine-tune specific events such as flybys, checkouts and instrument calibrations.

Instrument operations teams working with science teams provide instrument health monitoring and trending, instrument command sequence development, coordination of science plans within instrument teams, and coordination across instrument and spacecraft teams for major activities.

Training activities are required to maintain personnel skill levels and to prepare for mission operations. Activity planning, uplink product generation, flight and ground system software updates and testing, operations rehearsals and Operation Readiness Tests (ORT) support personnel training and readiness. These activities validate procedures and prepare the teams for upcoming critical events. During ATLO, missions typically conduct ORTs and other test and training activities for launch, the first major maneuver, and for any mission critical event that could cause a loss of mission if done incorrectly. For the long duration of JEO, mission skill retention issues will necessitate periodic training. Team training activities will be planned at regular intervals and will include post launch training activities and ORTs for each of the gravity assist encounters, the first Io flyby, JOI, Europa approach, EOI, and Europa mapping campaigns.

Sequences will be developed by many teams and, for some sequences, will be centrally integrated and tested. The spacecraft team develops all engineering sequences for the spacecraft based on the mission plan, inputs from navigation, and the results of subsystem analysis and trends. The instrument operations teams create sequences for each instrument based on mission plans and science observation plans, coordinating with other instrument teams and the spacecraft team to ensure proper sharing of resources. Many routine science and engineering sequences will be developed and uplinked independently. First time events, critical events, and complex interdependent activities will be integrated and tested prior to uplink. All sequences are checked for format, syntax and flight rule violations prior to uplink.

For the Europa Science phase, science teams perform quick analysis of the returned science products within hours of data receipt. The quick analysis products will be used to support near term data collection strategies and to guide the longer-range observation plan updates. Science analysis for the Jovian Tour phase will occur within timing guidelines provided by NASA.

The rapid assessment of quick-look science data products, and rapid planning and replanning of science data collection will be needed over time spans of about 1 week. This short term activity planning cycle is needed to respond to short orbit periods late in the Jovian Tour phase, uncertain gravity field response in Europa orbit, and potential reactions to radiation induced events and degraded performance.

Recent experience from MRO and MER has shown that rapid data delivery and quick look processing as well as rapid decision making and activity planning are possible for the planning schedules needed by JEO. MRO has demonstrated the long term processes for delivering >100 Gb per day to distributed science centers. Those science centers have shown that they can quickly produce planning quality data products in one or a few days. MRO target selection processes take 3 days for nadir based targets and 1 week for complicated off-nadir coordinated targets. MRO acquires 10 times more targets per day than JEO is currently considering. MER has shown that one day turn around of science products to next day activity plans is possible over mission lifetimes as long as or longer than JEO's. The science planning tools for JEO will be developed and tested starting with demanding Europa orbit timing and complexity requirements. Additional capabilities will be added to support flyby and Jupiter system observation needs. The required capabilities will be demonstrated in pre-launch system testing. Augmented capabilities will be added periodically based on experience from

Interplanetary flybys and early Jovian tour activities.

JEO science activity planning and replanning flexibility will be needed to respond to flight system anomalies, timing errors, and non-deterministic processes. Flexibility will also be needed to respond to short term science discoveries as well, such as detected plumes and hot spots. For the most part, response to science discoveries will take the form of re-allocating target data priorities in future days to observe previously unconsidered sites.

The JEO data analysis and archiving plan provides rapid delivery of data to the science teams and scheduled delivery of products to the Planetary Data System (PDS). Depending on mission phase, daily data volume could range from 2 Gb at maximum range and a single DSN 34 m station, to more than 20 Gb for continuous tracking, shortest range, and allocation of excess link margin. The GDS will be able to keep continuous on-line access to low level data products and planning products for the entire mission. High level products are expected to expand the raw data set by at least an order of magnitude. Current storage and network capability is more than sufficient to manage the JEO data set.

Quick delivery and processing (<24 hours) of low level data products is required during the late Tour and early Europa Science phases to facilitate rapid planning and sequencing. Other mission phases will require data delivery over slightly longer periods of a few days.

The Ground Data System (GDS) will generate level-0 data products which consist of validated, assembled CFDP data units, packet streams, and channelized telemetry that includes instrument data products and engineering telemetry, navigation data, and spacecraft thermal, attitude and timing information. The GDS also delivers processed level-1 data products to the science teams. These are Experiment Data Records (EDR) consisting of instrument data products extracted from assembled packets and product data units, merged with ancillary engineering and navigation data, and catalogued.

Science teams will be able to access level-0 data within hours of Earth receipt. EDR processing will be largely automated and products will be delivered within 1–2 days.

Schedules for product delivery to the public, the scientific community and to the final PDS archive will be determined in the science AO. It is generally expected that PDS archive deliveries will be within 6 months of data receipt. The project science working group (PSG) leads science teams in setting up the overall science observation plan that will be used for the development and operation of the mission. Science observation planning is likely to evolve over the life of the mission as conditions change and spacecraft and instrument health change.

Instrument operations teams bridge the science teams and spacecraft operations. The science teams provide the direction for what the instrument observations are to be based on the mission and science plans. The spacecraft team provides the information on the spacecraft state and attitude, resources available, and any potential conflicts that may be encountered. The instrument operations team ensures that all instrument sequences meet science goals, are fully integrated, tested and successfully uplinked to the flight system.

G.3.2 DSN Scheduling Rationale

The amount of tracking for this mission is significant due to the duration of the mission and the science volumes collected at Europa. The duration of 9 years is illustrated in the JEO mission phase timeline in **Figure G.3-3**. The DSN tracking profile used for the current trajectory is summarized in **Table G.3-1**. The profile, like the trajectory, is notional and provided to demonstrate the proof-of-concept. Both will change and evolve over the course of project development.

Launch and Early Operations

Immediately after launch is an intense month of flight system deployment, checkout, and critical maneuvers. This period will use round-the-clock tracking by the DSN 34 m subnet at X-band to support the commanding, flight system telemetry, and RF navigation data needed for these tasks. During this phase the flight system developers are monitoring the deployments and performing their final in space tests and handing the flight system over to the flight team. The navigation team compares the actual launch performance versus the predicted, reviews RF data and alters the maneuver design to ensure the flight

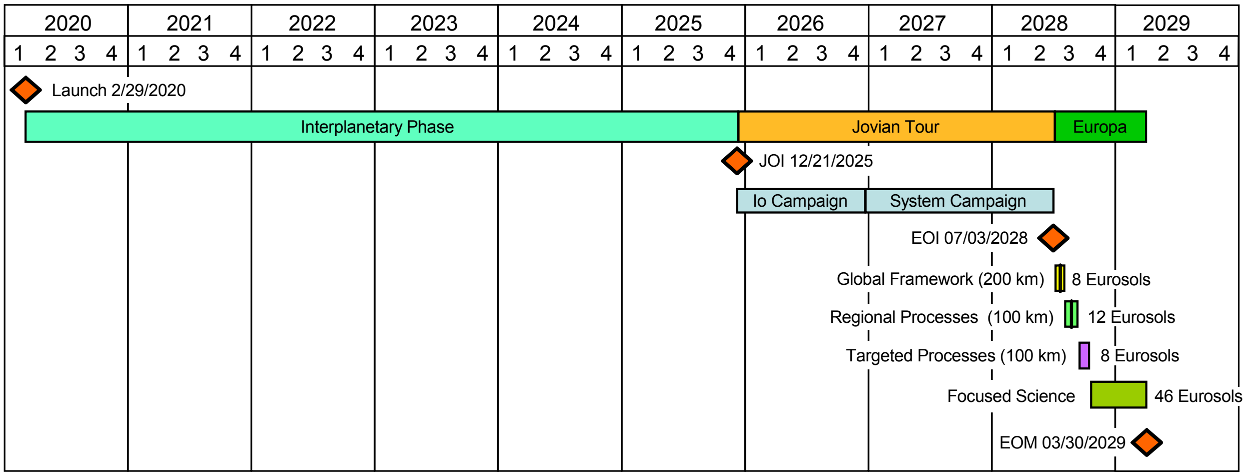


Figure G.3-3. *JEO Mission Phase Timeline*

system will achieve the planned trajectory that will take it to Jupiter.

Interplanetary Cruise

The long duration of cruise drives the tracking to be economical and still ensure safe delivery to Jupiter orbit. For the first year, three passes per week would provide the necessary tracking needed for navigation analysis and flight system characterization activities. For gravity assists or maneuvers the tracking will be augmented around the event to provide at least twenty 8-hour passes for the 2 weeks surrounding the event. Venus and Earth Fly-bys will be used to test science and instrument operating procedures, to provide training opportunities, and as early preparation for the Jovian tour. After the first year, tracking can generally be decreased to one or two 8-hour passes per week with annual weeklong intensive spacecraft and instrument health checks, to ensure long term health and safety of the flight system. These health checks usually require 1 week of daily 8-hour passes. Though not explicitly called out, ΔDOR tracks. will be scheduled periodically and prior to planet and satellite encounters.

About 18 months before JOI, tracking frequency is increased to handle the operational needs for JOI and the tour. This tracking will be used for flight software loads and provide RF tracking data to support increased orbit determination and trajectory analysis work for JOI, as well as some early Jovian system science. Approach to JOI is accompanied by significantly increased tracking including ΔDOR. At the time of JOI, 70 m or equivalent tracking support will be used to augment 34 m tracking to provide the best reception available at burn attitudes.

Jovian Tour

Once in Jupiter orbit, tracking is scheduled for daily 8-hour 34 m passes, intended to support Jovian system science data collection and navigation. This routine is augmented around fly-bys to support navigation tracking and increased science. During each fly-by, tracking is augmented with DSN 70 m or equivalent antennas to ensure flight system safety, minimum engineering telemetry, and timely navigation data.

Europa Science

The Jovian Tour ends with Europa orbit insertion. Once in orbit, DSN tracking is increased to continuous 34 m tracking for 105 days to maximize science return. Focused Europa science will continue for an additional 9 months with tracking reduced to one 34 m track per day.

In addition to the instrument based science observations, Europa gravity science will be performed during first 9 months in Europa orbit using the radio science capabilities of the flight system and DSN. Gravity science will use coherent, two-way Ka and X-band Doppler data. Most 34 m stations can support the coherent X-band up and X or Ka-band down Doppler data. Ka-up/Ka-down Doppler data currently require Goldstone's 34 m BWG, DSS-25, with the only Ka-band transmitter in the DSN. Additional Ka-band uplink stations are under study by the DSN and ESA tracking networks.

Table G.3-1. Planned DSN coverage as a function of Mission Phase

DSN Coverage					
Description	**Subnet**	**Year**	**Hours/ track**	**Tracks/ week**	**Duration (weeks)**
Interplanetary Phase Feb 2020 to Dec 2025					
Launch and Early Operations: Begins with the launch countdown. Activities include initial acquisition by the DSN, checkout and deployment of all critical flight system systems and a major maneuver to clean-up trajectory errors from launch vehicle injection				Feb 2020 30 day duration	
Launch to L+30	34BWG	2020	8	21	4
Cruise: Activities include science instrument calibrations, Venus and Earth gravity assist flyby science operations, trajectory correction maneuvers, and operations readiness testing.				March 2020 to December 2024	
Maneuvers & VEEGA	34BWG	2020–2024	8	10	11
Annual health checks	34BWG	2020–2024	8	7	4
EH&H + Nav (through VEEGA)	34BWG	2020–2024	8	3	41
EH&H + Nav (till JOI – 12m)	34BWG	2020–2024	8	1	235
Jupiter Approach: Activities include final preparations, training, and ORTs for all mission elements in preparation for JOI and Jovian moon flybys, and an optical navigation campaign to determine satellite ephermerides prior to pre-JOI Ganymede flyby.				January 2025 to JOI (Dec 2025)	
EH&H + Nav (till JOI – 2m)	34BWG	2024-2025	8	3	41
JOI Approach Heavy tracking**	34BWG	2025	8	21	3
JOI Approach Light tracking**	34BWG	2025	8	14	3
JOI	34BWG	2025	8	20	2*
Jovian System Tour Jan 2026 to Jul 2028					
The phase is characterized by continuous science observations of the Jovian system and multiple (20+) flybys of major Jovian satellites. The final month of the phase is dedicated to targeting maneuvers in preparation for EOI and actual EOI and .				JOI to EOI (Jan 2026 – Jul 2028)	
Jupiter System Science	34BWG	2026–2028	8	7	99
Fly-by Prep & Science (25 Flybys)	34BWG	2026–2028	8	14	40*
EOI	34BWG	2028	8	21	2*
Initial Europa Orbital Science Jul 2028 to Oct 2028					
Begins after achieving the primary science orbit and continues for 6 day engineering assessment period plus 28 Eurosols (99 days). All high priority science goals are achieved in this phase.				Jul 2028– Oct 2028 (105 days)	
Europa Mapping + Ka-band RS	34BWG	2028	8	21	15
Focused Europa Science Oct 2028 to Mar 2029					
Begins after the initial Europa science has ended and continues for 6 months. This phase is characterized by specific targeted science and new campaign types.				Nov 2028 – March 2029	
Europa mapping + Ka-band Radio Science	34BWG	2028-2029	8	7	26
Extended Europa Science Apr 2029+					
Begins after the end of the primary mission. End date is dependent on negotiated funding period, flight system health, and remaining propellants.				April 2029 +	
Extended Orbital Science	34	2029+	8	7	+
*Coverage by both 34m and 70m antennas during this time span. **DDOR tracking would be used during approach and as needed during cruise, not called out separately.					

G.4 Scenario Analyses

The 2007 EE study developed detailed science data acquisition scenarios for the Europa mapping phases and developed feasibility level scenarios for a low priority Tour phase.

The current study applies the Europa science scenarios directly, with relatively minor updates for the specific planning payload, launch date, phase durations, and the use of Ka-band and 34 m DSN stations for primary science data return. Preliminary Tour science scenarios have been developed from the feasibility level analysis from the previous study. The addition of a 16 Gb SDRAM partition to the 1 Gb CRAM science partition in the SSR enables considerable science improvements for the Jovian Tour.

Tour science benefits by the ability to collect large volumes of data near flyby events and downlinking over subsequent days. This strategy allows much of the data to remain on the SSR until space is needed days or weeks later to store new Jupiter system science data.

For the Europa science phase, the SDRAM partition is assumed to have failed due to radiation effects and the 1 Gb CRAM science partition is the only available mass memory for Europa mapping operations. As before, simple proven operating constraints allow significant data return with a limited memory allocation. These constraints are:

- Downlink all data on the orbit collected
- Collect data mainly during downlink sessions
- Preclude mass memory allocations for data retransmission
- Schedule continuous DSN 34 m tracking

These operations constraints remove consideration for data retransmission, discontinuous DSN coverage, and prioritizing and queuing of data products. On the other hand, on-the-fly data reduction, compression, processing, packetization and management can still be accommodated and is necessary in most cases. Analysis based on these recommendations showed that mass memory allocations of significantly less than one Gbit could be used while allowing considerable flexibility in data collection among instruments.

The simulation tool used for scenario analysis was adapted from the tool used last year by adding a power model to the data flow model. The tool simulates, at one minute intervals, data flow and power usage over a two orbit timeframe. The simulation models data collection for each instrument, data storage in the SSR, downlink rate, observation timing and data volume. Instrument and telecom on times are used to model power usage and battery state of charge. Power modeling results are not included in this appendix as the model is used to check tht scenarios work without violating power constraints. Power plots for key scenarios are included in §4.4.2.7.4 (System-Level Power Summary). This enables detailed scenarios to be developed and tested for the Europa science phase. Two-orbit scenarios have been developed for each Europa science campaign and the results aggregated to show the data volume distribution for the entire Europa science phase. The long term performance is used to validate science value metrics and mission achievement.

The tool was modified only slightly to test data collection strategies for the Tour phase as well. The tool was exercised for several flybys typical of the variations found in the tour trajectory. A one-hour timeframe was simulated for each flyby. Observation times and durations for each instrument were determined and the data flow and power usage was estimated. Coverage analysis was performed separately using SOAP, an orbit analysis tool, to determine coverage performance of the flyby. The example was extrapolated across all flybys and a coarse estimate of total science coverage of each satellite was generated.

G.4.1 Jupiter System Science Analysis

The Jupiter system science opportunities exist as a result of the trajectory needed to minimize the required ΔV for EOI and constrain total radiation dose to less than 2.9 MRad. The trajectory gradually reduces the flight system's orbital energy through 30 months of gravity assist flyby maneuvers at Io, Europa, Ganymede, and Callisto. While not fully optimized, where possible, science goals were incorporated into the trajectory. The resulting trajectory contains encounters with Io, Europa, Ganymede, and Callisto that can be considered typical for such trajectories. It is very likely that future studies will be able to design science optimized targeted and non-targeted encounters for a small penalty of ΔV, radiation dose, and/or trip time.

The following analysis is representative of the types of geometries that could be used for observing during a Tour. The analysis is a preliminary look at typical geometries and how they might be used with the JEO planning payload to survey Jupiter and the Jovian satellite system. Each gravity assist flyby typically happens within a day or two of a Jupiter closest approach (perijove). **Figure G.4-1** provides an overview of observing opportunities in the Tour phase. It includes JEO range to Jupiter, solar phase angle, daily data volumes (per track), and a notional timeline of Jupiter and Io Monitoring events that are coordinated with the satellite flyby encounters. JEO's ability to collect tour science is determined by the planning payload, on-board data storage space, downlink rate,

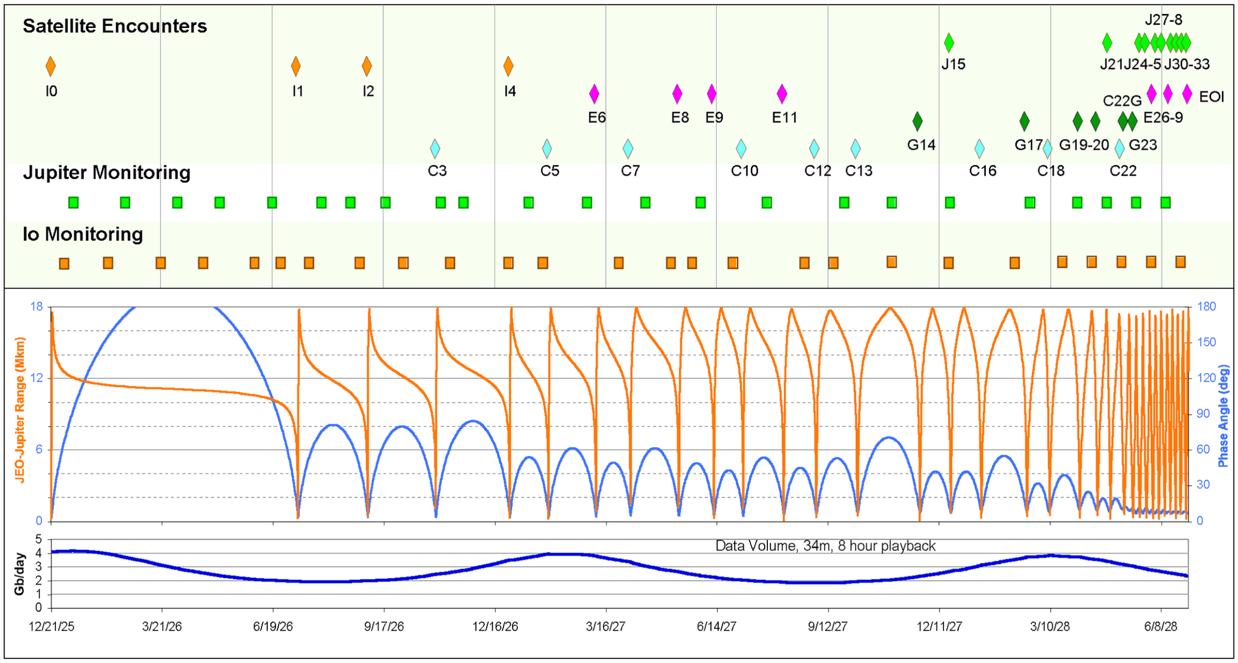


Figure G.4-1. Overview of the observation opportunities for the Tour Phase. The tour range and solar phase angle, daily data volumes, and observing opportunities are shown.

and DSN time. Gravity assist flybys have additional DSN 34 m tracking coverage scheduled, to increase data volume returned and navigation accuracy during an encounter. While the data volume is increased, the close ranges and high resolutions occur over such a short time period that on-board data storage becomes the most significant limiting constraint.

Around any given satellite encounter, the range to the surface will be less than 10,000 km for about 1 to 3 hours depending on the range and relative speed of the flight system to the target. At 10,000 km the narrow angle camera (NAC), for example will get 100 m/pixel resolution, similar to the WAC in a 100 km Europa orbit. **Figure G.4-2** shows the pixel resolution vs range for the three imaging payloads.

During the closest approach portions of the encounter, where ranges of less than 10,000 km occur, the hybrid SSR can support collection and return of around 14 Gb (with 2–3 Gb set aside for other observations not involving closest approach. These might include opnav images (<0.1 Gb), UVS aurorae observations, or stellar occultation experiments. In a week where a satellite flyby or perijove occurs, the tracking coverage and associated telecom rates typically support downlink of 10–30 Gb for the entire week.

In addition to the data volume that can be collected during the flyby, the remaining downlink data volume capacity over the week can be divided between non-targeted observations (between 10,000 and 100,000 km), Jupiter monitoring opportunities, distant viewing opportunities to observe other satellites at ranges of between 100,000 and 500,000 km, where NAC can get resolutions of 1–5 km/pixel. "Non-targeted" means that they are geometrically opportunistic and have

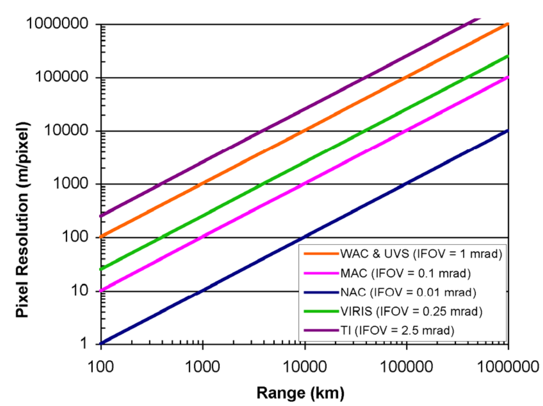


Figure G.4-2. Pixel Resolution as a Function of Range

Table G.4-1. *System Science Observing Opportunities*

	Opportunities	Ranges (km)	Phase Angles (deg)	Ground Speeds (km/s)
Jupiter	33	363,000 – 1,000,000	0 – 165	
Flyby Encounters		(min. @ CA)	(±1 hr)	(peak @ CA)
Io	4	75 – 3125	15 – 168	3.8 – 9.4
Europa	6	100 – 1200	14 – 163	1.5 – 9.8
Ganymede	6	135 – 1566	12 – 149	1.9 – 6.5
Callisto	9	78-3219	10 – 168	1.1 – 8.4
Distant Viewing Opportunities (<500,000 km)				
Io	16	56,000 – 480,000	3 – 177	
Europa	8	81,000 – 449,000	32 – 157	
Ganymede	10	148,000 – 398,000	10 – 175	
Callisto	2	205,000 – 311,000	139 – 168	

no impact on the vehicle flight path.

Table G.4-1 summarizes the number and characteristics of the Jupiter observing opportunities, gravity assist encounters, and not-targeted observing opportunities during the tour.

Jupiter System Opportunities

Jupiter monitoring opportunities are well distributed across the Tour, facilitating observation of changing phenomena that span the length of the 30-month tour. Jupiter observing opportunities at less than 1 million km occur on every orbit whether there is a satellite encounter or not. **Table G.4-2** summarizes the characteristics of 33 Jupiter opportunities during the tour that have range less than one million km. The table shows values for closest approach. Ranges near this value on either side will have varied phase angles. Monitoring observations wll have a large variation in lighting conditions at pixel scales less than 15 km.

Planned DSN coverage allows about 3.4 Tb to be downlinked during the tour. Of this, about one quarter is focused on flyby scenarios. During the rest of the tour the data volume capability will be used to downlink data for investigations supporting Jupiter and Io monitoring, non-targeted and distant viewing opportunities of major and minor satellites, and extended studies of the rings, dust, and Io torus.

Figure G.4-3 shows an example trajectory for orbit J15, which has no satellite flyby and can be used for a variety of system science purposes. The flight time from perijove at 0.66 million km to 1.5 million km on either side is ±40 hours. For this period NAC pixel resolution is less than 15 km. 28 Gb of observation data can be collected and returned using the extra tracks planned for perijove and flyby events 16 Gb more can be stored for later. Put in perspective, this is sufficient to collect over 3500 noiselessly compressed NAC images. Phase angles for Jupiter and the inner bodies vary by ±100 degrees, Jupiter rotates 8 times, and Io rotates nearly twice during this perijove passage.

The large data volume can support observations of Jupiter's atmosphere both globally with MAC, VIRIS, UVS, and TI and the periodic tracking of hundreds of features with the 9-color NAC. Because the large capacity SSR allows many observations to be collected over a short period of time, dynamic observations are possible (e.g., movies) even in conjunction with other observing activities such as Io monitoring. **Figure G.4-4** shows an example analysis of Jupiter monitoring from 1.4 million km. This case occurs twice per Jupiter orbit and shows good sunlit viewing at

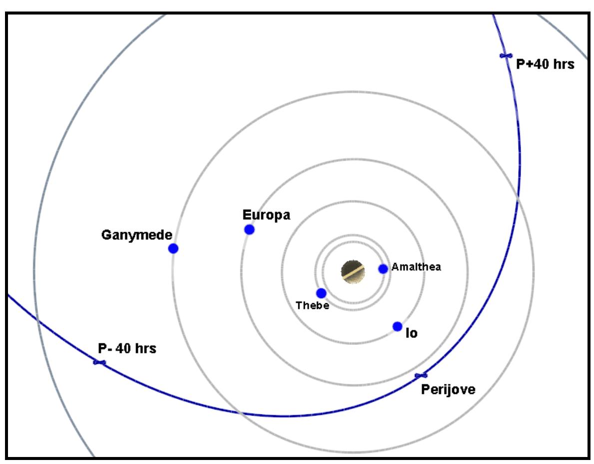


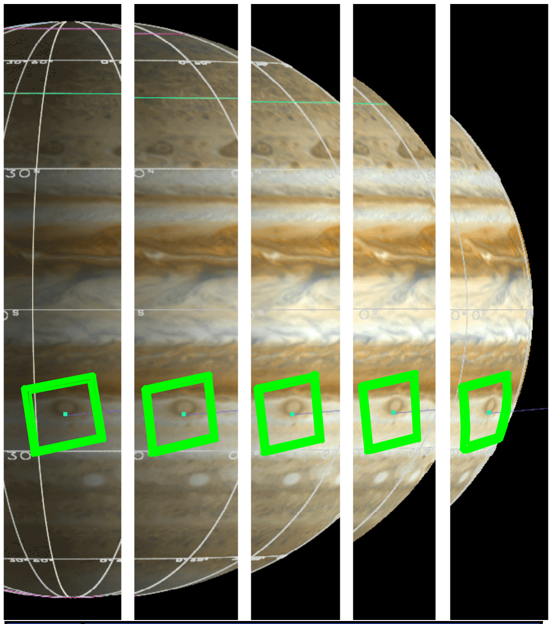
Figure G.4-3. *Example System Science orbit J15. Jupiter ranges less than 1.5 million km persist for ±40 hours around perijove. NAC pixel resolution is 6.6 to 15 km during this period.*

***Table G.4-2**. Summary of opportunities to observe Jupiter at less than 1 million km*

Date	Closest Approach Range (km)	Closest Approach Latitude (deg)	Closest Approach W. Longitude (deg)	S/C Speed wrt Jupiter (km/s)	Phase Angle Sun-body-S/C (deg)
12/21/25	368857	-4.7	125.8	26.6	77.2
7/9/29	364110	-5.6	290.2	25.8	64.0
9/4/26	362384	-5.2	253.4	25.9	59.8
10/29/29	362384	-5.2	358.0	25.9	55.4
12/28/26	364903	-0.2	294.4	25.5	54.9
1/28/27	416291	0.0	2.8	23.9	47.8
3/7/27	416291	0.0	340.8	23.9	44.7
4/5/27	499262	-0.4	333.5	21.7	31.0
5/14/27	499262	-0.4	199.3	21.7	27.9
6/11/27	487514	0.1	78.4	21.7	22.5
7/5/27	479754	0.0	202.1	21.8	18.4
8/7/27	597594	0.1	149.9	19.5	26.0
9/2/27	682519	-3.9	2.2	18.1	13.8
10/5/27	804674	-0.5	231.7	16.8	0.8
11/25/27	733746	-0.5	7.3	17.1	8.9
12/20/27	733746	-0.5	63.5	17.1	7.0
1/14/28	893806	0.7	72.4	15.6	9.2
2/20/28	893806	0.7	145.6	15.6	11.9
3/9/28	810108	0.4	67.0	15.8	30.1
4/2/28	980379	0.2	279.9	14.4	16.5
4/16/28	917908	4.1	293.7	14.2	35.6
4/27/28	829434	0.2	145.4	14.6	57.3
5/13/28	889146	-5.9	74.9	12.9	147.4
5/18/28	666418	-0.3	271.1	15.5	163.6
5/24/28	666391	-0.3	357.3	15.4	163.1
5/29/28	664593	-0.3	72.5	15.8	161.6
6/2/28	655186	-0.4	9.4	15.2	131.9
6/7/28	660102	-0.4	160.5	15.1	131.4
6/12/28	662761	-0.5	298.0	15.6	126.1
6/16/28	656832	-0.4	156.2	14.8	93.4
6/20/28	660536	-0.4	253.1	14.7	93.1
6/24/28	663697	-0.4	2.5	14.7	92.7
6/29/28	664869	-0.4	121.5	14.6	92.5

a variety of close ranges and phase angles. This example shows that for ranges greater than twice perijove, observing conditions are very good for tracking dynamic features in Jupiter's atmosphere. The table included in the figure shows that basic views of Jupiter including composition data, and multicolor images of hundreds of features are possible for the 8 Gb assumed for the case study. Many of the images can be collected in the form of movies to examine dynamic structures at highest resolutions.

Io monitoring goals are, per Jupiter orbit, to collect a wide variety of data types including global maps (once per orbit), plume inventories (roughly 5 deg longitude, once per orbit), plume movies (30–40 frames) when plumes are on the limb, and images sampled over a wide variety of timescales. One full set of these images would occupy roughly ½ of the SSR and would be downlinked in a few days. Subsets of these would be collected each Jupiter orbit in combination with other activities.



	Resolution (km)	Data Volume each (Mb)	Number of Images
NAC	14	8	Hundreds*
MAC	140	9	4
IRS	350	743	4
UVS	1400	25	24
TI	3500	0.1	4

Figure G.4-4. *Jupiter monitoring example shows feature tracking. The green box represents the NAC FOV at 1.4 million km.*

Non-Targeted and Distant Viewing Opportunities

Non-targeted encounters are opportunities to observe satellites in the Jupiter system at less than 100,000 km range. This is a traditional range for trajectory design processes. For ranges between 100,000 km and 500,000 km, the term distant viewing opportunity will be used. The details of distant viewing opportunities for Amalthea, Io, Europa, Ganymede, Callisto, and Thebe are shown below in **Tables G.4-3** through **G.4-4**. None of these opportunities are specifically targeted in the mission design and the timing and number of encounters can be adjusted for a small cost in ΔV. Amalthea and Thebe are listed as surrogates for near Jupiter system science objectives such as small bodies, dust, and rings.

Flyby Opportunities

Several preliminary analyses were conducted to explore the usefulness of JEO planning payloads during gravity assist flybys or encounters. The JEO planning payload is intended to collect data in a low altitude, near-circular orbit of Europa where ground speed, altitude and lighting conditions are very similar orbit-to-orbit. In the tour, however, ground speeds, altitudes, and lighting conditions vary drastically through each encounter. For most encounters, these conditions are within reasonable limits for the types of instruments in the planning payload. To effectively use some of the instruments, flight system slews may be needed.

The WAC, MAC, NAC, TI and UVS operate in pushbroom modes while in Europa orbit. For all but the NAC, which has a framing mode, the orbiter and the trajectory need to provide apparent ground motion at the appropriate range of speeds. Combined with range, ground speed indicates pixel speed, which in turn determines the pixel integration time needed.

Slew rates and accelerations needed to track nadir were evaluated for each flyby in the Jovian Tour. Except for closest approach for the highest speed, lowest altitude flybys in the Io campaign, most of the flybys offer pixel rates and integrations times within a factor of 2 of those in Europa orbit.

A flyby example scenario was developed for each of the Galilean satellites. They were selected to show the range of values for altitude, ground speed, latitude, and lighting conditions. For each flyby example, a preliminary observation profile was selected based on altitude and FOV to collect as much information as possible within the geometric constraints of the flyby. Based on the example flybys, all of the flyby encounters were assessed for imaging coverage area at resolutions of ≤1000 m, ≤200 m, ≤50 m, ≤10 m, and for total length of track achievable for IPR swaths and laser altimeter profiles.

Constraints for these observation types were IPR <1000 km altitude and 7 km/s ground speed, laser altimeter <2000 km. INMS was included when altitudes were less than 500 km for conservative planning.

The large SSR and battery capacity and co-boresighted instruments allows observations to be made independently of one another. Power profiles were reviewed to ensure viability of observation profiles. SSR data accumulation

***Table G.4-3.** Summary of Io and Europa distant viewing opportunities at <500,000 km*

Satellite	Date	Closest Approach Range (km)	Closest Approach Latitude (deg)	Closest Approach W. Longitude (deg)	S/C Speed wrt Jupiter (km/s)	Phase Angle Sun-body-S/C (deg)
Io	10/29/26	185428	-17.2	276.7	17.4	37.5
Io	7/5/27	56378	0.3	183.8	4.5	16.1
Io	11/25/27	314690	-1.3	175.3	0.2	17.5
Io	12/20/27	325128	-1.2	192.5	0.4	13.3
Io	2/20/28	479870	1.2	174.5	1.9	2.9
Io	4/27/28	426998	0.3	172.3	3.0	32.7
Io	5/30/28	457575	0.7	170.7	6.0	98.0
Io	6/2/28	329663	-0.6	194.1	3.9	47.7
Io	6/8/28	270300	-0.5	169.4	2.8	176.9
Io	6/13/28	414202	0.6	175.9	5.8	115.7
Io	6/16/28	262378	-1.0	171.9	3.1	147.4
Io	6/19/28	329366	0.3	189.7	4.3	5.2
Io	6/22/28	432866	0.9	181.0	6.0	83.0
Io	6/25/28	348942	-0.1	171.8	4.7	159.4
Io	6/28/28	257160	-0.7	186.9	2.9	52.2
Io	7/1/28	411265	0.9	185.0	5.7	54.3
Europa	12/21/25	333968	7.6	71.7	20.5	77.9
Europa	7/9/26	208392	-17.8	56.8	8.8	107.7
Europa	9/4/26	312022	-8.1	8.6	11.9	111.6
Europa	4/5/27	80816	-0.9	57.8	7.6	155.7
Europa	11/25/27	430744	-1.1	278.2	11.6	31.5
Europa	12/20/27	449089	-1.0	279.8	12.0	33.1
Europa	5/18/28	321826	1.2	82.3	8.5	157.5
Europa	5/19/28	303020	-2.6	156.2	2.9	59.2

***Table G.4-4.** Summary of Ganymede and Callisto distant viewing opportunities at <500,000 km*

Satellite	Date	Closest Approach Range (km)	Closest Approach Latitude (deg)	Closest Approach W. Longitude (deg)	S/C Speed wrt Jupiter (km/s)	Phase Angle Sun-body-S/C (deg)
Ganymede	1/27/27	166610	2.9	78.2	12.4	36.8
Ganymede	3/8/27	148112	-3.2	96.5	9.0	128.3
Ganymede	4/5/27	246137	-0.2	81.4	7.3	143.1
Ganymede	7/4/27	364319	0.9	296.8	5.9	174.6
Ganymede	10/5/27	398482	0.0	83.7	11.0	12.8
Ganymede	1/13/28	383388	2.6	87.3	9.5	10.4
Ganymede	5/17/28	276216	1.5	329.4	1.9	66.9
Ganymede	6/4/28	213545	2.3	39.2	0.3	44.1
Ganymede	6/17/28	343162	-0.3	14.2	2.4	15.2
Ganymede	6/28/28	339740	0.2	351.3	2.4	155.5
Callisto	8/9/27	205190	-7.7	103.3	6.3	139.4
Callisto	11/23/27	311118	0.1	269.1	5.8	168.3

was also determined to show that observation profiles fit within flight system limits.

Table G.4-6 summarizes the dates and geometry of the flyby encounters. In total there are 3 Io, 6 Europa, 6 Ganymede, and 9 Callisto encounters between JOI and EOI. Details of these encounters with potential for science observations are provided including latitude and longitude, closest approach altitude, ground speed, and lighting phase angle. Also shown is an assessment of each flyby for imaging and IPR observing and for global imaging coverage at pixel scales of 200m along with the longitude ranges accessible by those flybys.

Figures G.4-5 through **G.4-8** show example flyby scenarios for encounters of Io, Europa, Ganymede, and Callisto.

The Io example scenario shown in **Figure G.4-5** is for the I4 flyby. It is typical of all 4 Io

Table G.4-5. *Summary of of Amalthea and Thebe distant viewing opportunities at <500,000 km*

Satellite	Date	Closest Approach Range (km)	Closest Approach Latitude (deg)	Closest Approach W. Longitude (deg)	S/C Speed wrt Jupiter (km/s)	Phase Angle Sun-body-S/C (deg)
Amalthea	12/21/25	412555	1.4	192.8	6.8	6.5
Amalthea	12/21/25	498502	-2.5	164.9	9.5	168.5
Amalthea	7/9/26	289674	-3.7	165.4	4.2	129.3
Amalthea	9/3/26	358515	1.4	191.1	7.1	19.9
Amalthea	10/29/26	183059	-2.6	179.9	2.4	48.2
Amalthea	12/27/26	269291	0.1	189.0	3.5	6.1
Amalthea	1/28/27	422167	0.2	188.8	8.0	28.9
Amalthea	1/28/27	441010	-0.3	167.5	8.5	126.8
Amalthea	3/8/27	359687	-0.2	168.0	6.3	110.7
Amalthea	4/5/27	321477	-0.2	180.1	4.9	20.0
Amalthea	5/14/27	405191	0.0	171.2	7.1	79.4
Amalthea	6/11/27	495988	0.2	186.8	9.3	50.0
Amalthea	6/11/27	395464	-0.1	171.1	7.2	75.8
Amalthea	7/5/27	331262	0.1	183.4	5.5	16.5
Amalthea	5/18/28	497089	-0.1	177.4	11.3	171.5
Amalthea	5/24/28	497546	-0.1	177.3	11.3	171.4
Amalthea	6/2/28	497918	0.0	179.8	11.7	91.9
Amalthea	6/3/28	484984	0.0	177.5	11.5	159.1
Amalthea	6/7/28	478639	0.0	178.6	11.3	126.1
Amalthea	6/16/28	487907	0.0	179.2	11.9	59.5
Amalthea	6/16/28	485840	-0.1	177.7	11.9	124.8
Amalthea	6/20/28	478837	0.0	178.5	11.7	90.2
Amalthea	6/24/28	497880	0.0	179.2	12.1	54.7
Amalthea	6/25/28	489078	-0.1	177.8	11.9	118.5
Amalthea	6/29/28	484675	0.0	178.6	11.8	81.3
Thebe	7/9/26	237715	-8.6	147.6	0.8	129.2
Thebe	9/4/26	299411	-5.8	145.3	1.9	140.1
Thebe	12/27/26	359148	1.4	211.9	4.8	33.7
Thebe	1/28/27	198283	-0.3	180.6	0.7	48.2
Thebe	3/7/27	199300	-1.1	176.2	0.5	55.5
Thebe	4/5/27	416731	-0.7	161.6	5.7	95.3
Thebe	5/14/27	405642	-0.1	161.3	5.1	91.0
Thebe	6/11/27	333439	0.3	163.4	3.5	72.9
Thebe	7/5/27	260757	0.4	174.3	1.9	34.5
Thebe	8/7/27	384490	0.8	174.7	4.4	44.0
Thebe	9/2/27	469372	-1.9	176.4	6.1	27.6
Thebe	5/18/28	462324	0.0	184.7	8.7	132.6
Thebe	5/23/28	476669	0.1	185.6	8.9	121.4
Thebe	5/29/28	493464	0.2	186.3	9.2	111.5
Thebe	6/2/28	436196	-0.4	182.9	8.5	111.6
Thebe	6/7/28	440785	-0.5	182.8	8.6	111.3
Thebe	6/12/28	447482	-0.5	182.9	8.7	107.9
Thebe	6/16/28	432607	-0.2	181.3	8.8	82.0
Thebe	6/17/28	498041	-0.9	177.8	10.3	171.3
Thebe	6/20/28	452127	0.2	182.6	9.3	54.3
Thebe	6/21/28	466696	-1.0	178.3	9.5	147.0
Thebe	6/24/28	485172	0.5	183.3	10.1	27.6
Thebe	6/25/28	444851	-0.8	179.3	9.0	118.0
Thebe	6/29/28	439952	-0.5	180.9	8.9	86.3

flybys. Spacecraft velocities and ground speeds are near 10 km/s requiring high spacecraft rates and accelerations to maintain nadir pointing for imaging, radar and altimeter observations. The flybys have well lit approach views and dark departure views and allow global scale imaging at the same longitudes, achieving about 20% of Io coverage at resolutions better than 200 m/pixel.

For I4, the 75 km periapsis altitude flies over potential plumes in the Amirani region. This enables the use of the INMS for in-situ sampling and analysis of plume materials. The INMS must be placed in a velocity vector orientation (this is the incoming direction for plume molecules), and the IPR and laser altimeter must be placed in a nadir direction at closest approach. The orbiter reaction wheels are not powerful enough to deliver the high angular accelerations needed to keep up with the nadir pointing vector. To ensure the INMS, IPR and LA are pointed correctly at closest approach, the orbiter will "fall behind" the nadir vector by a few degrees prior to closest

Table G.4-6. *Summary of the dates and geometry of the flyby encounters. The I0 encounter at JOI is not used for science.*

Orbit Identifier	Date	Time of CA (UTC)	Gnd Speed @ CA (km/s)	Alt (km)	Lat, W-Lon @ C/A	Phase @ -1 hr	Comments	Cvg ≤200m (%)	Cvg ≤200m (from/to Long)
I1	26/07/09	6:18:39	8.995	300	18 / 115	19	Good Imaging, too fast for hi-res, fair IPR	~20%	150-260
I2	26/09/03	21:00:55	3.832	3125	-74 / 213	16	Good Imaging (much overlap with I1), No IPR, Good S Pole views (lit half <50m)	~20%	150-260
C3	26/10/30	20:52:06	8.444	362	78 / 298	10	Good imaging, good polar view (~800m res at N pole), fair IPR	~20%	320-60
I4	26/12/27	21:25:17	9.425	75	-35 / 123	19	Good Imaging, too fast for hi-res, fair IPR, INMS opp'y	~20%	150-260
C5	27/01/26	16:41:09	4.751	2101	-4 / 249	71	Fair imaging, poor IPR, lowest alts in dark	<10%	120-180
E6	27/03/08	8:37:13	9.828	215	-1 / 87	54	Good Imaging, fair IPR	~20%	220-260,300-30
C7	27/04/03	3:42:42	7.608	315	6 / 250	80	Fair imaging, good IPR, lowest alts in dark	<10%	110-170, 0-30
E8	27/05/14	13:23:32	8.16	231	28 / 76	77	Fair imaging, good IPR, lowest alts in dark	~20%	180-220, 300-360
E9	27/06/11	23:08:52	5.26	1197	-7 / 78	83	Fair imaging (much overlap with E8), good IPR, lowest alts in dark	~20%	180-220, 300-360
C10	27/07/07	7:58:51	7.014	289	1 / 286	44	Good imaging (esp Hi res), Good IPR	~20%	240-270, 300-60
E11	27/08/07	14:34:36	4.418	866	39 / 58	85	IPR Calibration, fair imaging, lowest alts in dark	~15%	270-330, 160-190
C12	27/08/31	12:20:36	7.025	175	52 / 257	91	Good IPR (context from C10), poor imaging (dark)	<10%	300-345
C13	27/10/03	21:24:59	7.318	78	-33 / 258	98	Good IPR (context from C10), poor imaging (dark), INMS opp'y	<10%	345-30
G14	27/11/24	17:02:44	6.549	315	0 / 104	75	Good IPR. Good low to high res imaging.	~10%	30-80, 120-210
C16	28/01/12	1:20:34	5.757	407	-12 / 259	107	Good IPR (context from C10), poor imaging (dark)	<10%	130-150
G17	28/02/20	20:04:04	5.906	143	-6 / 75	125	Good IPR, Good low res imaging, poor hi-res.	~10%	140-210
C18	28/03/11	18:51:15	3.593	1283	-1 / 280	93	Fully lit, great for imaging, not IPR	~50%	180 - 360
G19	28/04/03	11:05:16	4.635	135	41 / 73	132	Good IPR. Good low to moderate res imaging. Poor hi-res.	~10%	120-210
G20	28/04/17	18:30:23	4.09	454	-49 / 71	149	Good IPR, Good low res imaging. Poor hi-res.	~10%	120-210
C22	28/05/03	0:43:30	1.106	3219	43 / 226	150	Long Slow FB, good N hemisphere views, great for imaging, not IPR	~50%	220 - 10
C22G	28/05/07	21:13:30	2.708	600	1 / 71	133	Long Slow FB. View of S Pole at 19 deg incidence angle. Good IPR	~20%	40-60, 90-220
G23	28/05/15	0:54:27	1.944	1566	44 / 98	99	Long Slow FB. View of N Pole at 15 deg incidence angle. Good imaging, not IPR	~30%	40-220
E26	28/05/29	13:12:33	2.435	100	-10 / 25	55	Long slow FB, good imaging, good IPR	~15%	250-350, 50-80
E29	28/06/12	9:48:28	1.508	633	0 / 24	14	Long slow FB, good imaging, good IPR	~30%	210-360

approach and then "lead" the nadir vector after closest approach. Near closest approach, orbiter pointing will be close enough to permit INMS, IPR and LA observations. Ground speeds will be very high, however, so NAC, MAC, and VIRIS integration times will be very short.

The observation schedule collects global and regional imaging data from all imaging instruments on inbound leg of the trajectory and allows investigations with the TI and the UVS on the outbound leg. The MAG and PPI will operate continuously during the mission phase and so will be on for the flyby as well.

The Europa example scenario is for the E11 flyby and is shown in **Figure G.4-6**. The IPR calibration is planned for the E11 flyby. The altitude is less than 1000 km, 7 km/s, a earlier than six months prior to EOI as required by the SDT. The altitude is between 866 km and 1000 km for the four minutes full rate IPR observations. Periapsis is in the dark for most of the low altitudes of this flyby. Imaging is primarily global and regional

The Ganymede example scenario is G23 and is representative of a late Tour flyby. The scenario summary is shown in **Figure G.4-7**. It

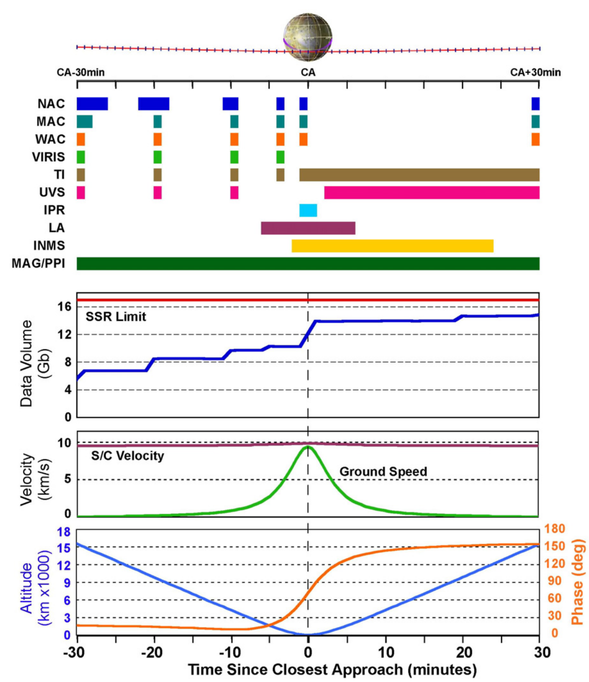


Figure G.4-5. *Io Example Flyby, I4, includes instrument observation schedule, data volume collection profile, S/C velocity, groundspeed, altitude, and solar phase angle*

is a relatively high altitude, low velocity flyby and has the entire trajectory in well lit

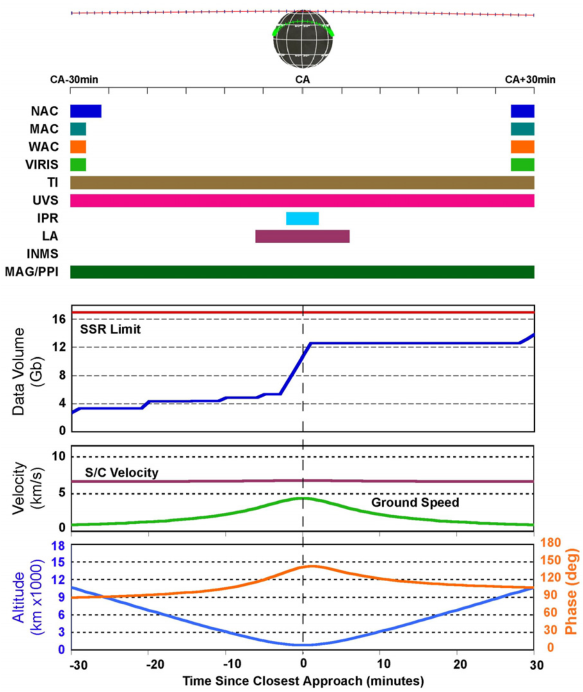


Figure G.4-6. Europa Example Flyby, E11, includes instrument observation schedule, data volume collection profile, S/C velocity, groundspeed, altitude, and solar phase angle

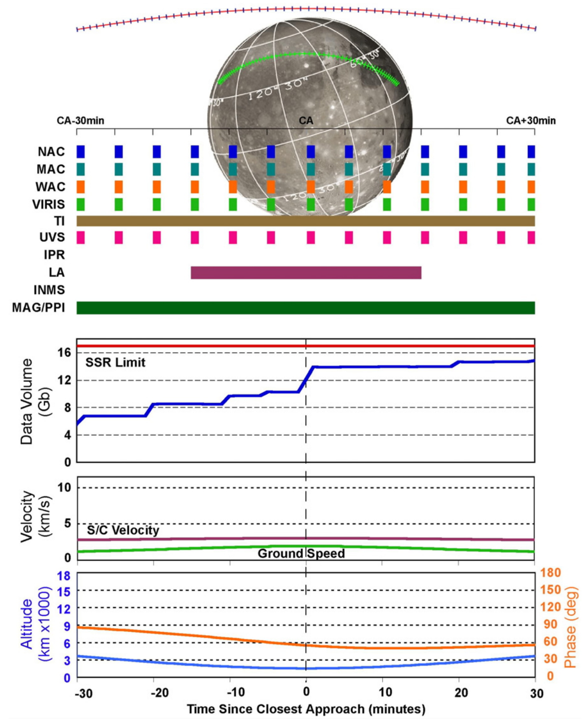


Figure G.4-7. Ganymede Example Flyby, E23, includes instrument observation schedule, data volume collection profile, S/C velocity, groundspeed, altitude, and solar phase angle

conditions. The altitudes are too high for IPR or INMS observations but do well for altimetry and all types of imaging. The latitudes covered give very good views of the northern hemisphere and a low incidence angle view of the North Pole.

The Callisto flyby, C3, is the example shown in **Figure G.4-8**. This encounter flies over the extreme northern hemisphere, coming within a few hundred kilometers of the North Pole. Regional imaging can cover the lit half of the North at resolutions between 100 and 200 m with 10 m imaging at targeted sites. The scenario includes IPR and INMS observations to stress the power profile and data volumes.

Flyby Coverage Performance

The flyby encounter ground tracks have been mapped onto cylindrical projection Cartesian maps of each satellite to show where and when each flyby provides access for observing. **Figures G.4-9** through **G.4-12** show the ground tracks. Ground tracks in green are the ones highlighted by example scenarios. The closest approach point for each flyby is shown as a black diamond on each ground track.

The Io map shown in **Figure G.4-9**, shows ground track end points at very similar longitudes. The lighting conditions from one flyby to the next are also very similar. This is an artifact of the Tour trajectory needing to synchronize the timing and geometry of the flybys. Because of this, global imaging will be limited to one hemisphere and good resolution and incidence angles will be limited to about 20% of the surface.

Europa ground tracks are shown in **Figure G.4-10**. Early flybys have the lowest altitudes in the dark but have good global views of much of the surface. Later flybys have slow, low altitude, low latitude trajectories that allow good imaging and IPR observing.

Figure G.4-11 shows the Ganymede Cartesian map. The G23 flyby from the example scenario is shown in green. Ganymede flybys are widely dispersed in latitude and have views of the North and South Poles and polar regions (the Sun lit half). With some variation in approach and departure longitudes, the global imaging coverage is about 50% with

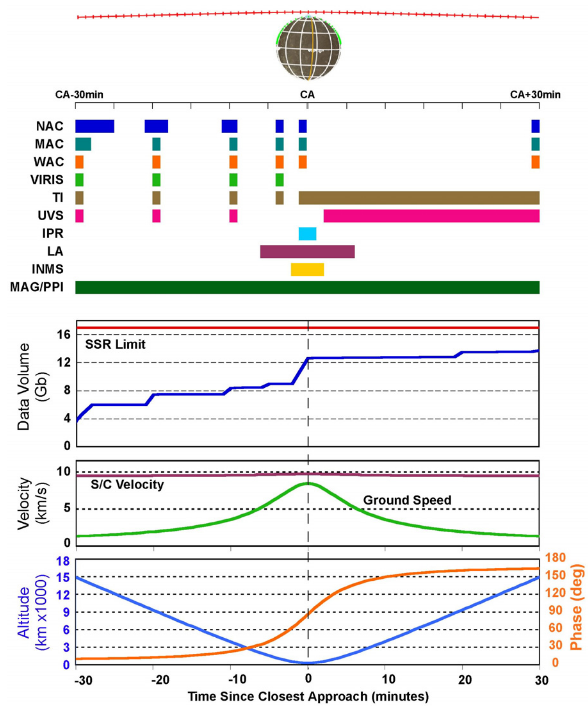


Figure G.4-8. *Callisto Example Flyby, C3, includes instrument observation schedule, data volume collection profile, S/C velocity, groundspeed, altitude, and solar phase angle*

very good sampling of altimetry and IPR over the accessible hemisphere.

With 9 flybys, Callisto has the most diversity of observing conditions. The imaging views allow roughly 85% of the surface to be imaged with 75% at better than 200 m pixel scale. **Figure G.4-12** Shows the ground track coverage. The C3 flyby has very high latitude coverage offering high resolution coverage of the Sunlit half of the northern polar region and the Pole itself.

A summary of the imaging coverage for each of the satellites is shown in **Table G.4-7**. The percentages of the surface available at ≤1000 m, ≤200 m, ≤50 m, and ≤10 m pixel resolution are rough estimates based on simulations of the flybys with NAC, MAC, and WAC FOVs shown on the surface. Estimates of time and distance below the cutoff altitudes for the altimeter and the IPR for each flyby are aggregated and shown in the table as well. The values in the table represent opportunities for imaging, altimeter, or IPR data collection. While it is likely that this performance can be achieved, complete scenarios for the Jovian Tour phase have not yet been developed.

G.4.2 Europa Science Scenarios

The Jovian Tour ends with Europa orbit insertion. Once in orbit, DSN tracking is increased to continuous tracking for 105 days to maximize science return. Focused Europa science will continue beyond the initial 105 days but with reduced tracking. The next 165 days will be targeted science and will provide key Europa science but use less tracking; one 34 m pass per day versus round the clock tracking.

In addition to the instrument based science observations, Europa gravity science will be performed in Europa orbit using the radio science capabilities of the flight system and DSN. Gravity science will use coherent, two-way Ka-band Doppler data.

The simulation tool used for scenario analysis was adapted from the tool used in the previous study. The planning payload instruments and instrument characteristics were incorporated and simulations were run for each of campaigns 1a, 1b, 2a, 2b, and 3. The planning payload instrument characteristics used in the simulation are shown in the input table in **Table G.4-8**. The table shows the instrument characteristics of raw data rate,

Table G.4-7. *Aggregate coverage extent, by satellite, for IPR and LA swath lengths and for imaging area for selected resolutions*

Sattelite	≤1000m	≤200m	≤50m	≤10m	Length IPR (km)	Length LA (km)
Io	30%	20%	5%	-	1000	7400
Europa	60%	60%	15%	0.01%	6600	19000
Ganymede	50%	50%	10%	0.02%	17000	28000
Callisto	85%	75%	5%	0.01%	15000	30000

Table G.4-8. *Scenario Instrument Inputs – Rates, Reduction Factors, Duty Cycles*

Inputs		WAC	MAC	NAC	IPR	VIRIS	UVS	TI	LA	INMS	PPI	MAG	S/C TLM
Raw data rate (Mb/s)		0.27	1.40	13.5	30	0.1	0.010	0.009	0.002	0.002	0.002	0.004	0.002
Mapping orbit duty cycle		40%	0.0%	0.00%	35%	35%	14%	100%	100%	50%	100%	100%	100%
Data reduction rate		4	4	24	107	2.5	2	3	1	1	1	1	1
Uncompressed Dvol (Mb)		907	0	0	86940	290	12	75	17	8	15.0	30.0	15.0
Compressed Rate (Mb/s)		0.068	0.35	0.563	0.280	0.040	0.0050	0.0030	0.0020	0.0020	0.0020	0.0040	0.0020
Total Dvol/Orbit #1 (Mb)	(0.17)	226.8	0.0	0.0	0.0	117.6	6.0	24.8	16.6	8.3	16.6	33.1	16.6
Total Dvol/Orbit #2 (Mb)	(0.17)	0.0	0.0	0.0	824.3	0.0	0.0	24.8	16.6	8.3	16.6	33.1	16.6
Total Dvol/2Orbit (Mb)		226.8	0.0	0.0	824.3	117.6	6.0	49.7	33.1	16.6	33.1	66.2	33.1

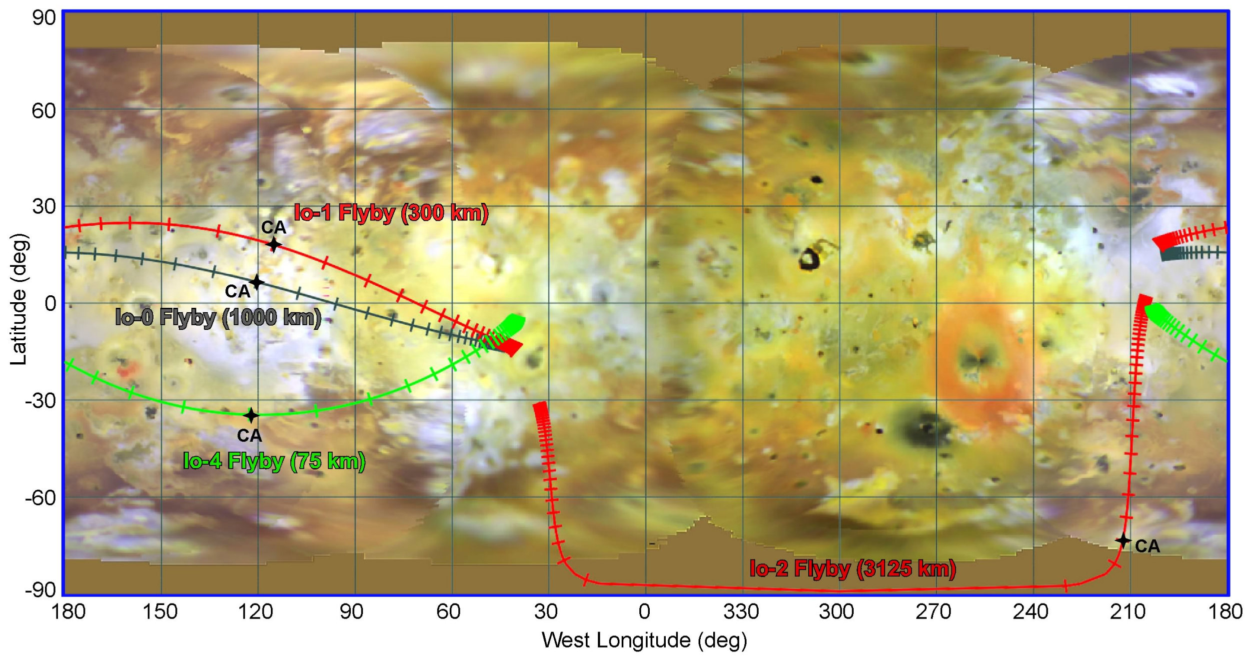


Figure G.4-9. *Io Cartesian map showing all flyby ground tracks. Ground track in green corresponds to the example scenario.*

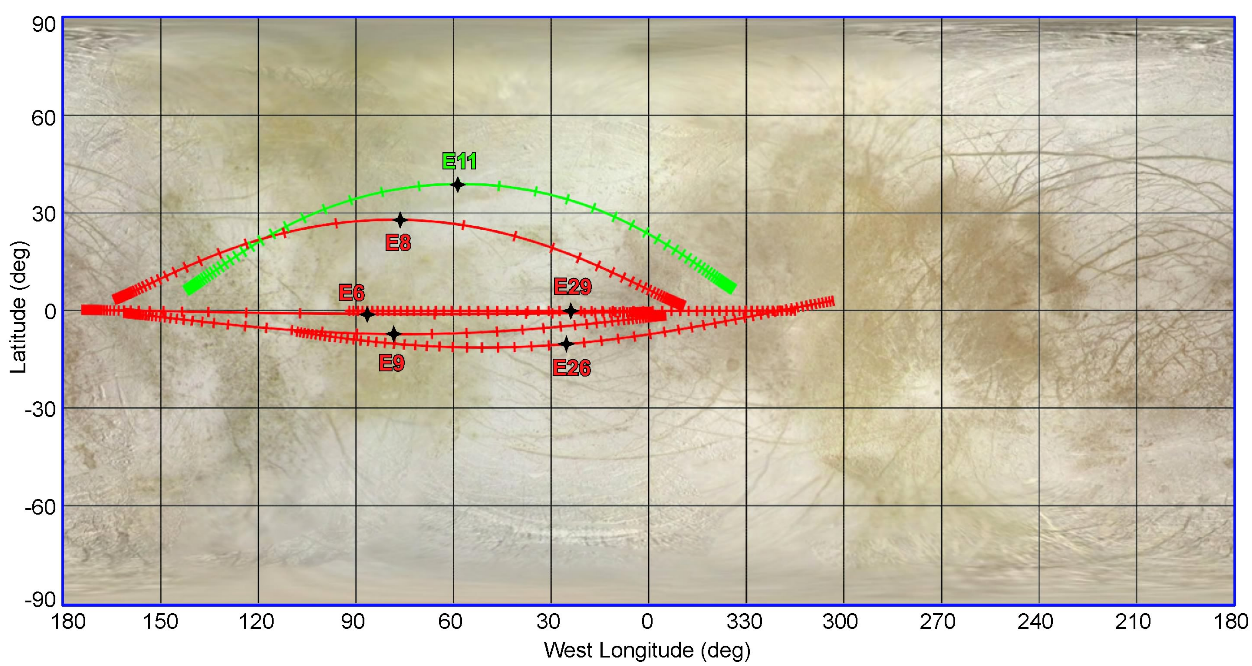


Figure G.4-10. *Europa Cartesian map showing all flyby ground tracks. Ground track in green corresponds to the example scenario.*

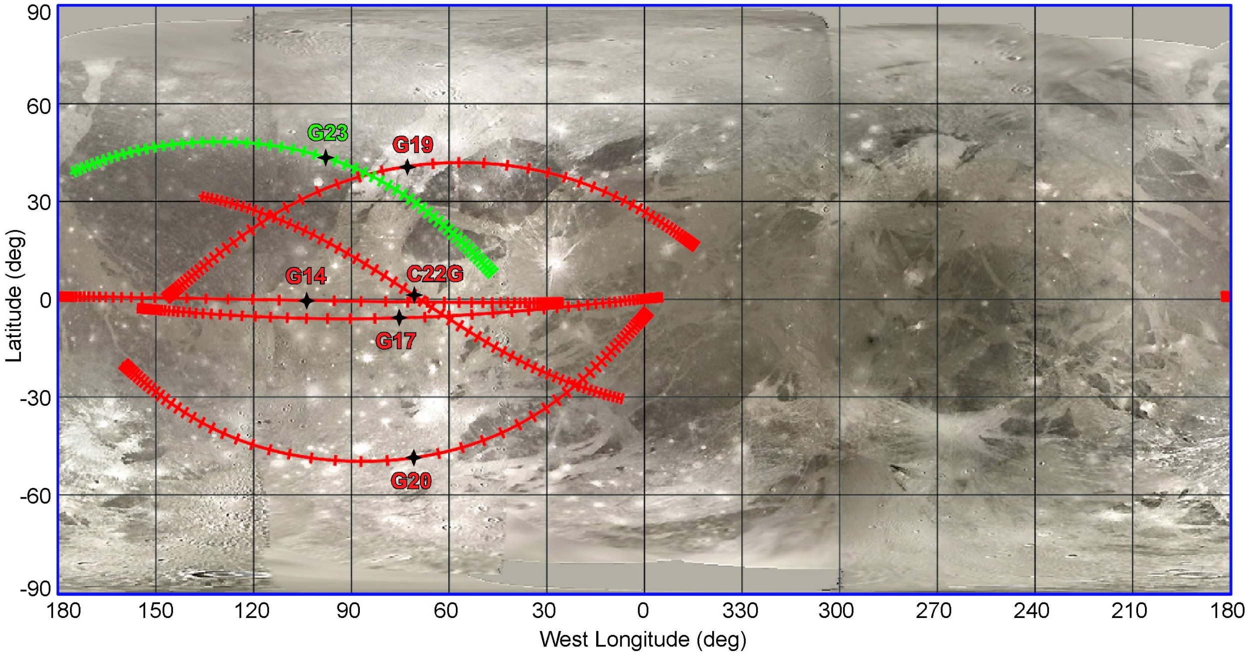


Figure G.4-11. Ganymede Cartesian map showing all flyby ground tracks. Ground track in green corresponds to the example scenario.

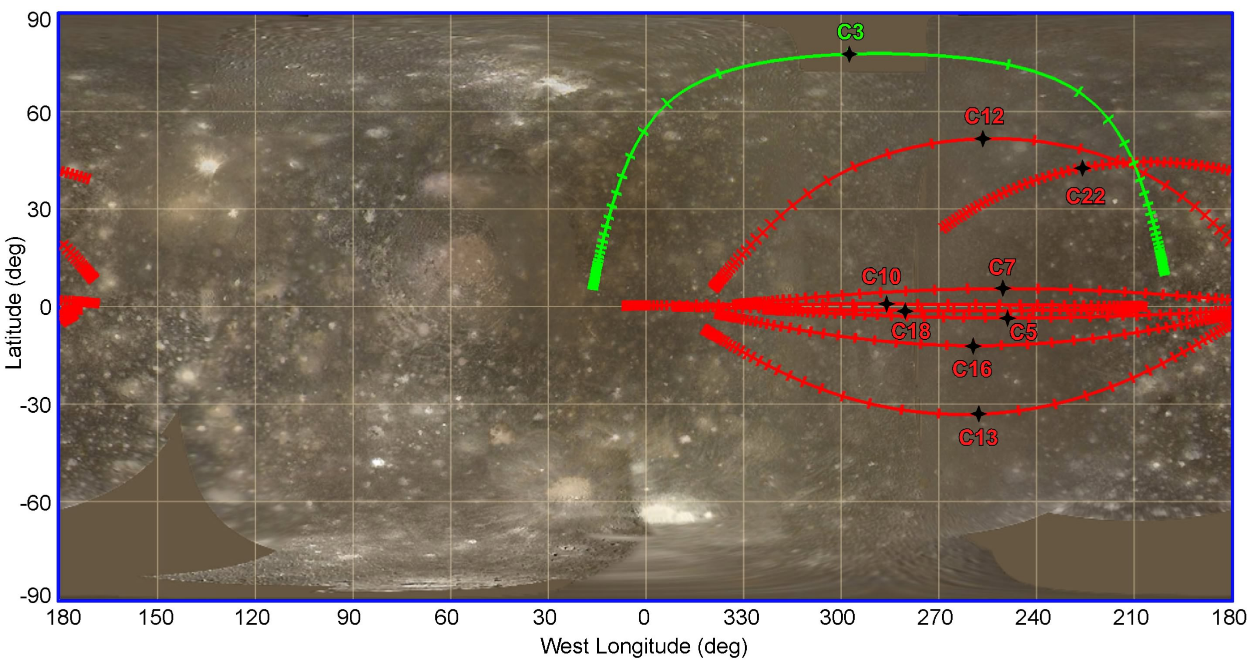


Figure G.4-12. Callisto Cartesian map showing all flyby ground tracks. Ground track in green corresponds to the example scenario.

data reduction factor, observation duty cycle and generated data volumes per orbit.

The example shown is for Campaign 1 at 200 km orbit altitude. Campaigns 2, 3, and 4 have similar characteristics but are at 100 km orbit altitude. Some instrument rates are twice as fast at the lower altitudes as the pixel rates are faster due to range and ground speed.

Figures G.4-13 through **G.4-15** show the baseline data flow simulation results for

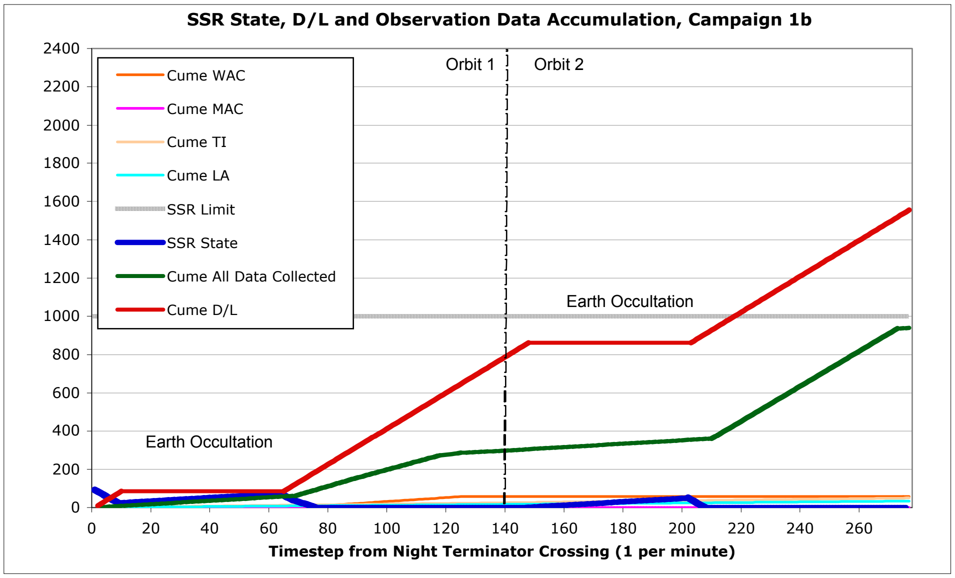


Figure G.4-13. Data Flow Simulation Results for Campaign 1

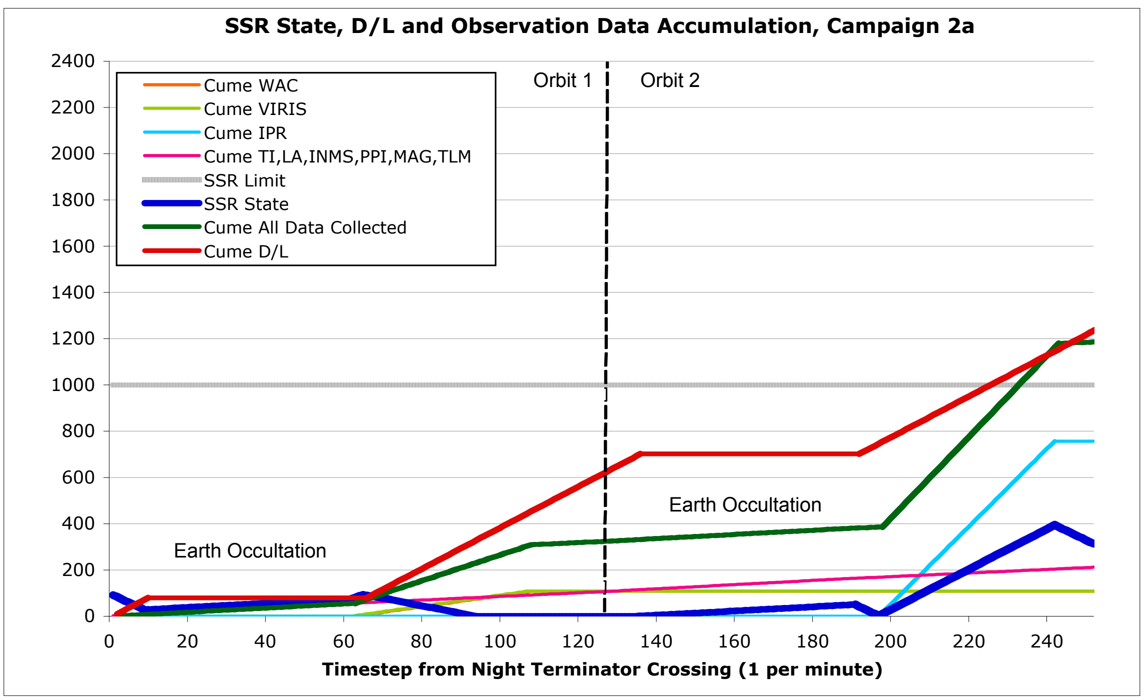


Figure G.4-14. Data Flow Simulation Results for Campaign 2

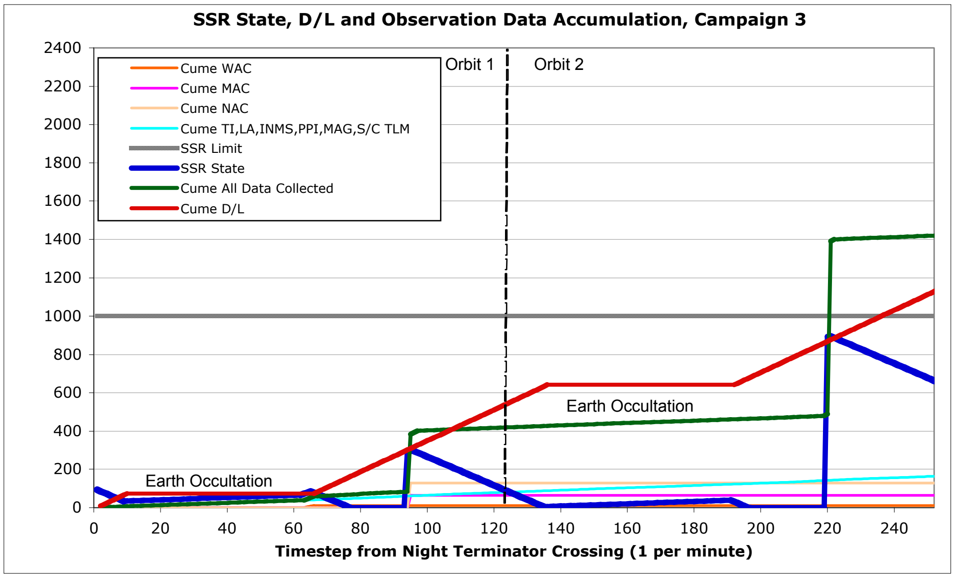


Figure G.4-15. *Data Flow Simulation Results for Campaign 3 with a coordinated target image in orbit 1 and an IPR target in orbit 2.*

Campaigns 1, 2, and 3. The red plot line shows the available accumulated downlink data volume (occultations are shown and include DSN lockup times). The green line shows the data collected as an accumulation to compare to the downlink capability. The dark blue line shows the state of the SSR at each minute. Each instruments data collection scenario is represented in the plot and the simultaneous and accumulated impacts are characterized. The examples show that accumulation in the SSR is only during occultations when a few low rate instruments are operating. These scenarios show a 10–15% use of the SSR. There is ample room for coordinated target data collection for either the ~300 Mb imaging type or the 900 Mb radar type on most orbits.

The small difference between the downlink capacity and the accumulated data collected (red and green lines) shows that at the beginning of Campaign 2 (**Figure G.4-14**), few targets can be collected. This is due to the change in orbit period (from changing altitude from 200 km to 100 km) and occultation duration (they are relatively longer due to the lower period and closer orbit geometry). By the middle of Campaign 2, completion of the shallow ocean search by the IPR allows a lower data rate, which causes the available data volume for targeting to increase. Campaign 3 shows most of its data as available for coordinated target observing. **Figure G.4-15** shows a coordinated imaging target collection in orbit 1 and an IPR target collected in orbit 2. The next orbit would be able to collect a coordinated target by not an IPR target until the SSR has been emptied. This is consistent with the acquisition frequency expectations for the IPR. Campaign 4 was not simulated. In general, it will be similar to campaign 3 but specific data collection scenarios have not been developed for Campaign 4.

Coordinated targets are collected only when analysis of upcoming data collection and downlink data volume shows there is sufficient SSR space and downlink data available to collect one. Target locations will be selected based on lists of preselected targets by type and extent and can be automatically selected to fill data volumes as they become available. This planning occurs on the ground with sequence uplink once per week, and with ephemeris updates several times per week.

The science data performance of the mission is shown in **Table G.4-9**. Performance in this context is represented by measures of daily data volume for global mapping and profiling goals and for coordinated targets and the totals of same for each campaign. The number of targets per day and per campaign are also shown as are percentage distributions for the different representative instruments. The totals column shows that the baseline

Table G.4-9. *Mission Performance – Data Volumes and Number of Targets by Instrument and Phase. Pie graphs show data volume fraction for each instrument by campaign.*

Reference S/C	Europa Campaign 1: Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	C1 Tot Vol (Gb)
Data Volume	6.1	2.3			**238**
WAC	0.74		9%		**21**
MAC		0.39	5%	13 T	**11**
NAC		0.78	9%	13 T	**22**
IPR	3.53	0.45	47%	1 T	**113**
VIRIS	0.61	0.65	15%	13 T	**36**
UVS	0.03		0%		**1**
TI	0.26		3%		**7**
LA	0.17		2%		**5**
INMS	0.09		1%		**2**
PPI	0.17		2%		**5**
MAG	0.35		4%		**10**
S/C TLM	0.17		2%		**5**

Reference S/C	Europa Campaign 2: Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	C2 Tot Vol (Gb)
Data Volume	6.0	0.9			**294**
WAC	0.62		9%		**26**
MAC	0.00	0.19	3%	6 T	**8**
NAC	0.00	0.39	6%	6 T	**17**
IPR	3.53	0.00	51%	0 T	**150**
VIRIS	0.62	0.32	14%	6 T	**40**
UVS	0.02		0%		**1**
TI	0.26		4%		**11**
LA	0.17		3%		**7**
INMS	0.09		1%		**4**
PPI	0.17		3%		**7**
MAG	0.35		5%		**15**
S/C TLM	0.17		3%		**7**

Reference S/C	Europa Campaign 3: Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	C3 Tot Vol (Gb)
Data Volume	2.0	4.5			**184**
WAC	0.04		1%		**1**
MAC		0.78	12%	13 T	**22**
NAC		1.56	24%	13 T	**44**
IPR	0.91	0.90	28%	1 T	**51**
VIRIS	0.04	1.30	21%	13 T	**38**
UVS	0.03		1%		**1**
TI	0.05		1%		**2**
LA	0.17		3%		**5**
INMS	0.02		0%		**1**
PPI	0.17		3%		**5**
MAG	0.35		5%		**10**
S/C TLM	0.17		3%		**5**

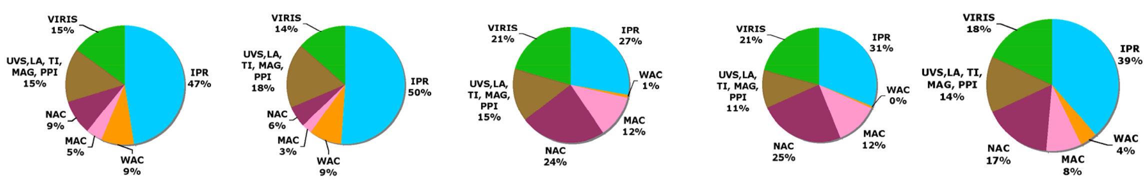
Reference S/C	Europa Campaign 4: Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	C4 Tot Vol (Gb)
Data Volume	0.4	2.6			**499**
WAC	0.01		0%		**2**
MAC		0.37	12%	6 T	**61**
NAC		0.75	25%	6 T	**122**
IPR	0.05	0.90	31%	1 T	**155**
VIRIS	0.01	0.62	21%	6 T	**104**
UVS	0.01		0%		**2**
TI	0.02		1%		**3**
LA	0.06		2%		**9**
INMS	0.01		0%		**1**
PPI	0.06		2%		**9**
MAG	0.12		4%		**19**
S/C TLM	0.06		2%		**9**

Reference S/C	All Europa Campaigns: Total Targets	% total vol	Total Vol (Gb)
Data Volume			**1215**
WAC		4%	**51**
MAC	1710 T	8%	**103**
NAC	1710 T	17%	**205**
IPR	207 T	39%	**470**
VIRIS	1710 T	18%	**218**
UVS		0%	**5**
TI		2%	**23**
LA		2%	**27**
INMS		1%	**8**
PPI		2%	**27**
MAG		4%	**53**
S/C TLM		2%	**27**

[1] MAC targets are 1 minute duration (71 km/min @200 km, 78 km/min @100 km)

[2] VIRIS targets are each 400x400 pixels, 100 Mb

[3] IPR targets are each 30 Mb/s x 30 s, 900 Mb



scenario enables collection of data nearly 800 targets in the first 3 campaigns and 1900 targets by the end of campaign 4. The values for IPR and imaging targets are different, reflecting different goals for their targets. IPR takes very large observations (900 Mb) and cannot collect at the same time as the imagers (a larger SSR would enable simultaneous targeting for a subset of the total target set).

An example of global coverage for the WAC in Campaign 1 is shown in **Figure G.4-16**. Global color coverage is complete in 3 eurosols or about 10 days. Global stereo coverage can be achieved in another 10 days, leaving 8 days in Campaign 1 for margin. A delay in mapping startup of several days can be tolerated and still achieve the Campaign 1 science goals. If not needed for typical startup delays or anomaly resolution, the extra time will be used to fill gaps, collect additional stereo images, increasing stereo resolution, and additional targets.

The WAC coverage for Campaign 2 is shown in **Figure G.4-17**. Because the WAC swaths are narrower due to lower orbit altitude, 7 eurosols are needed to achieve global coverage. Global stereo goals can be achieved in the remainder of Campaign 2. Small gaps in coverage are planned into the data allocations for Campaign 3.

Figure G.4-18 shows the ground track coverage for the 200 km orbit used in Campaign 1. This notional orbit has a 4 eurosol repeat pattern. This can be seen in the narrow spacing between adjacent ground tracks in the figure. Other repeat patterns will be considered in future studies. The ground track pattern can be used as a surrogate for LA, TI, VIRIS spectral profiles, and IPR observations. The white box in the figure represents 10 × 10 degrees on the surface. Each degree on the surface is about 27 km in distance for both latitude and longitude near the equator. The ground track separation in the first campaign will be 60–70 km at the widest points.

By the end of Campaign 3, the ground tracks will be densely scattered across Europa. Laser altimeter, thermal and spectral profiles will have grids finer than 1 degree on the surface and the radar sounder will have grids about half as fine. **Figure G.4-19** shows the ground track spacing for Campaigns 1–3. The colors show how the ground tracks build up by campaign.

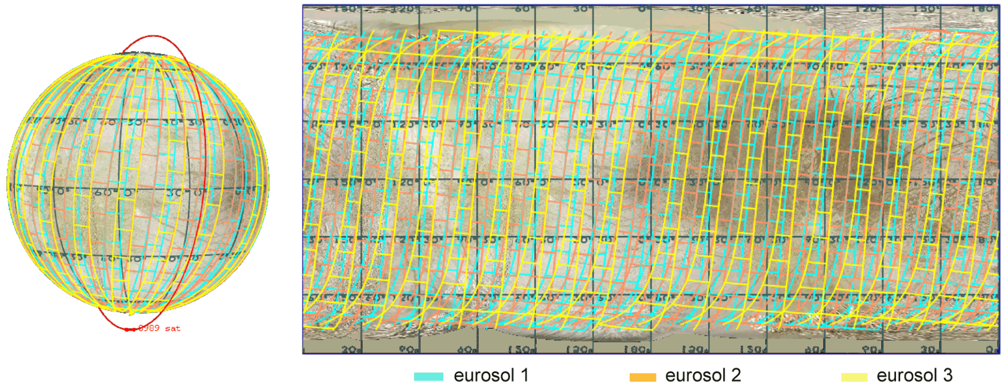


Figure G.4-16. WAC Coverage for 3 Eurosols in Campaign 1

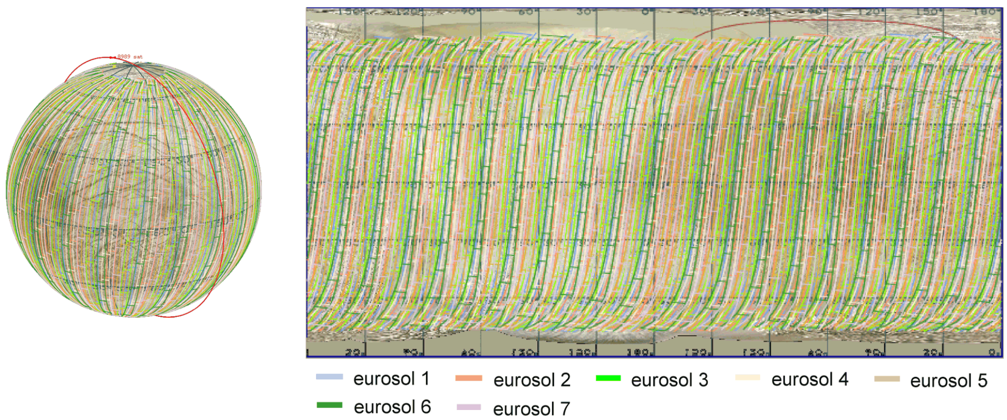


Figure G.4-17. WAC Coverage for 7 Eurosols in Campaign 2

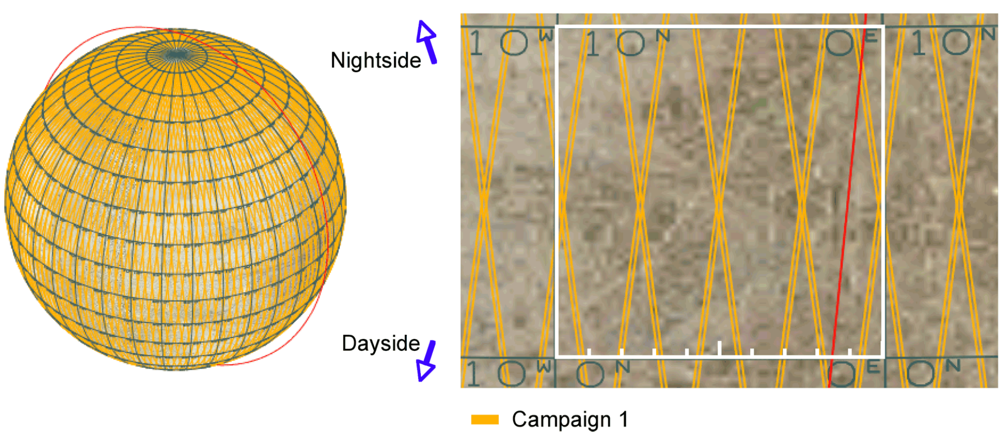


Figure G.4-18. Ground-track Coverage in Campaign 1

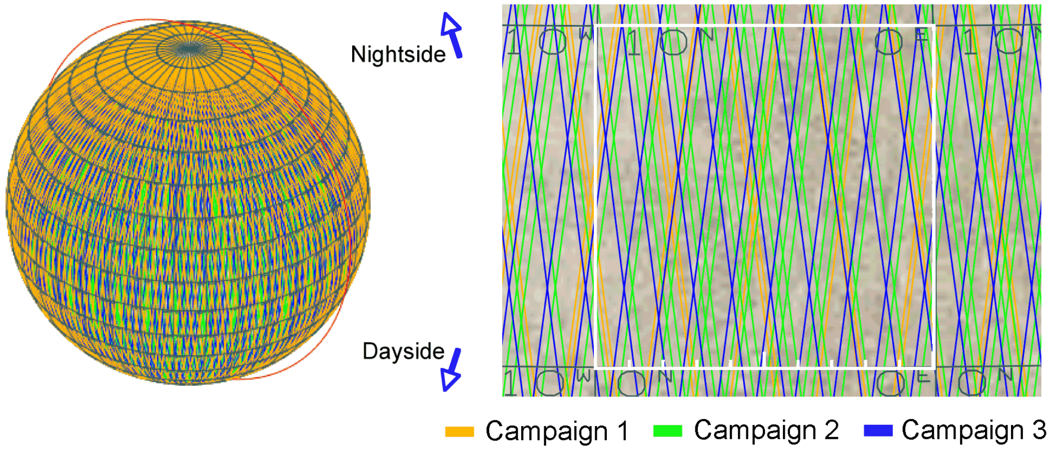


Figure G.4-19. *Ground-track Coverage in Campaigns 1–3*

Other groundtrack repeat cycles will have considerably better performance as these have very close spacing at the repeat intervals. This allows for larger gaps in the grid. Other repeat cycles can be devised to reduce the gap size with small impacts to orbit altitude and period. Other considerations for future trade studies include alternate orbit repeat patterns vs repeat geometry for swath coverage and gap fill, and idealized repeat patterns for repeat pass stereo coverage.

G.4.3 Trade Studies

G.4.3.1 Lessons Learned Study

In an effort to reduce operations costs associated with the next Outer Planet Flagship Mission (OPFM), a study was performed that examined the cost drivers of Cassini, the last Flagship mission, and several other planetary missions from both JPL and APL, specifically the Mars Reconnaissance Orbiter (MRO), MESSENGER, and New Horizons. This study was in response to the NASA request to focus on Phase E cost drivers and operations with the intent of safely lowering costs from those traditional to this class of mission.

A joint JPL, APL, and ARC study team was formed, consisting of experienced deep space mission planners, operations leads, and analysts knowledgeable of APL's and JPL's planetary operations processes. When additional information was required for the study, the respective mission teams were contacted directly.

The approach used was to develop a set of categorized space mission operations cost drivers, define measurables used to assess the degree that each driver affected each operation, characterize the operations for the specified missions to measure relative complexity and operations costs, and provide summary recommendations based upon all of the data analysis.

The study team derived a comprehensive list of space mission operations cost drivers and then evaluated each of the identified missions to characterize their relative complexity in each of these categories:

- Mission Design/Architecture
- Management and Organization
- Flight System Interfaces
- Science Operations
- Ground System Interfaces
- Testing and Validation

The determined complexity of each mission in the categories identified above was then compared against the actual (or planned, where applicable) staffing levels to evaluate relative mission costs.

As shown in the Mission Operations Lessons Learned Study (Appendix K.2), there is a direct relationship between mission complexity and operations costs. Cassini is the most complex and costly of the missions examined. However, New Horizons is the simplest of those reviewed, but not the cheapest. It was clear that the relationship between complexity and cost is not linear, and that outside factors come into play such as program cost caps. MESSENGER may be the least expensive because it had the tightest cost cap to work within. Perhaps the constraint or need to execute a mission for less money drives a certain level of efficiency; we also accept that highly complex missions such as the next OPFM will require notable funds to simply meet the technical challenges. The study concluded that the most effective means to reduce operations costs are strategic decisions during all of the mission phases to reduce operational complexity, sometimes leveraging costs upon the design (i.e., spend a little money now to save more later).

The truly valuable end product of this study is the numerous, tangible recommendations for reducing the cost and complexity for future space operations, including the next OPFM. Several of the key recommendations from this study include the following:

- Minimize non-essential activity during cruise, consider hibernation-type modes, and look to optimize training and test opportunities
- Define a clear chain of command for resolving project contention, similar to the benefits of a PI lead mission
- Streamline ITAR/TAA processes
- Incorporate flight operations expertise into the flight system design process to factor in operability
- Reduce the number of contentious flight resources (e.g., co-aligned instruments, scan platforms, and/or gimbaled antennas)
- Provide ample margins for power and data storage, and consider predefined modes to simplify planning
- Automate data playback and command uploads (e.g., CFDP and pre-allocated memory space)
- Strive for commonality in payload interfaces
- Streamline science ops planning through the use of integrated tools, model-based engineering, and state analysis
- Implement information management systems to facilitate remote planning and action item resolution
- Incorporate resource modeling and constraint checking early in planning process, and use the same models throughout the entire team.
- Consider automating downlink contacts and non-critical commanding
- Utilize common software (faster than real-time) tools throughout test and validation activities

The specific recommendations and supporting details can be found in Appendix K.1. (Operations Lessons Learned Traceability Matrix) which identifies all of the recommendations and cites where each has been applied throughout the JEO Study Report. Many of these recommendations are based on successful approaches utilized on the missions examined, including a number of ingenious features that enabled these specific programs. Application of the recommendations to the development and operations phases will foster the next OPFM to be conducted in a significantly more efficient manner.

G.4.3.2 Science Operations Concept Study

The next Outer Planet Flagship Mission (OPFM) will provide the science community with the capability to achieve a broad range of objectives with a rich set of science opportunities. The ability of the science community to take advantage of these opportunities will be dependent upon the capability to maximize ground and flight system operability in a cost conscious manner. With this goal in minds, an OPFM Science Operations Concept Study [*Paczkowski et al. 2008*] was conducted to leverage the results of the Operations Lessons Learned Study (Appendix K) into recommendations for a science operations concept that could be used for the next flagship mission. The study team consisted of highly experienced members in mission and science operations from JPL, ARC, and APL.

While many of the recommendations from the study are architectural in nature or design philosophies and have been implemented in the JEO mission concept, others are specific design recommendations and will be considered in design trades in later development phases. Recommendations will be considered in the light of cost/risk benefit trades as part of an integrated system.

A series of collaborative sessions were held focusing on a number of broad issues related to science operability, including: flight and ground system capabilities required to simplify science operations, pre-launch ground system development activities required to influence the spacecraft development to simplify science operations, post-launch/cruise development activities required to prepare for and simplify Tour and Orbital science operations, and finally, a recommendation for a possible science operations concept. In addition, to better understand operational cost, a representative workforce loading profile was developed for Tour and Orbital operations. The OPFM Science Operations Concept Study Report summarizes in greater detail these major areas.

The study team considered the differences in science operations between the Tour and Orbital Phases of this mission. The Tour Phase of the mission is characterized by multiple targeted flybys and perijove passages that provide a broad range of science investigations of the Jovian system. A considerable amount of spacecraft pointing will be required to take advantage of these science rich opportunities. Because of the large number of targets of interest and the minimal time spent close enough to do great science, the competition for key spacecraft resources will be higher than during the Orbital Phase. The nature of the Tour trajectory generally results in once-in-a-tour type of science opportunities. As such, contention for time and other shared resources will make compromise and integration between the science disciplines more difficult.

The Orbit Phase of the mission is characterized by a nadir pointed spacecraft with no off-nadir pointing and orbits that cover the same ground track over a period of time. This simplifies science operations. On the other hand, this requires rapid science integration and sequencing in order to react to new discoveries and to change the targets selected for upcoming science sequences.

The study team assumed that a distributed operations environment would be required for the OPFM, but recommends that only the instrument commanding and instrument health and safety be distributed remotely. All command generation for shared resources should be centralized, a lesson learned form Cassini where distributed shared resource commanding significantly complicated operational interfaces.

To facilitate the science operations concept developed during this study, the following key assumptions and recommendations were made regarding the flight systems:

- The flight system should be designed to maximize the science return and capabilities required for the orbital mission, and tour/flyby science shall be maximized within these design constraints.
- Optical remote sensing instruments fields of view should be co-aligned to enable collaborative observations
- Decouple fields and particles instrument pointing from optical remote sensing
- The science pointing should be decoupled from downlink pointing
- Contentious spacecraft resources shall be allocated to instruments, or science disciplines, to minimize the need for coordinated operations to the best extent possible
- Implement shared resource-policing functions
- Develop science observation software constructs for coordinated multi-instrument activities
- Data collection scheme should allow for coordinated mutli-instrument simultaneous science
- On-board blocks should enable (and facilitate) collaborative multi-instrument science collection
- Incorporate coupled thrusters into the G&C design and attitude control
- Spacecraft must have slew rate capabilities to close targeted flyby observations.
- Utilize ephemeris-based pointing, meaning that a minimal set of vectors can be updated and all of the [attitude and science] pointing will update automatically
- Incorporate time-shift capability to adjust on-board sequences relative to time-of-flight changes with a minimal set of parameters
- C&DH subsystem utilizes a file system for recording data, and ideally uses CFDP (or equivalent) to prioritize and control data playback (automatic retransmission capability)
- Consider using more integrated on-board flight system capabilities where sequencing, fault protection, and other system management functions work together seamlessly

- Minimize the number and types of instrument interfaces to make common where possible

While developing the science operations concept for the OPFM, the following key assumptions and recommendations were made regarding the ground system:

- The ground system will be designed to maximize the science return and capabilities required for the orbital mission, and tour/flyby science will be maximized within these design constraints
- Strong project science leadership is highly recommended to drive science decisions, prioritization, and conflict resolution
- Two different types of science command paths should be considered, one for internal instrument only commands and one for fully integrated science activities requiring spacecraft pointing or shared resources. Ground tools shall manage and merge these to avoid added flight system complexity
- At least one major post-launch ground system update should be budgeted for
- It is expected that the science planning/optimizer tools will be largely developed post launch. However, enough pre-launch development and testing of these tools should be done in order to influence the development of the flight system
- There will be different, separate planning processes for tour and orbital science that should utilize a common set of planning tools; use identical set of models throughout science and sequencing process
- The operations processes will need to facilitate rapid turn-around and flexibility during the orbital mission, especially for targets of opportunity
- Operability is increased with fewer parallel development tasks running concurrently, short sequence development cycles, and streamlined/automated review and validation processes
- There should be a standard interface to the sequencing/planning system for all of the instruments/science disciplines
- Preplan the initial orbital science period (30 days or so) well in advance, and then look to optimize the later orbital campaigns
- A baseline science mission should be planned and flight-tested as much as possible prior to launch so that a baseline exists that will satisfy the minimum requirements. This plan should then be updated in cruise (with increasing system knowledge) to optimize and maximize the science return
- The program should implement science opportunity planning and optimization tools that are platform independent, utilize web-services to interface between different applications, and facilitate collaboration with remote users
- Consider developing a model-based engineering and state analysis approach, or set of utilities, that would be used throughout the project lifecycle to streamline the design process, provide early validation, and facilitate planning in an agile manner

The study team strongly suggests pre-launch development include the science operations software and system requirements in order to factor operability considerations into the flight and ground systems engineering. Science operations scenarios, including both Tour and Orbital cases, and science planning tools should be developed to a sufficient level that they can be used as part of evaluating the ground and flight system requirements and capabilities, to support optimal design choices, and unified system architecture and software.

Cruise development suggestions include the use of in-flight Tour and Orbital exercises as targeted gravity assist flybys provide a unique opportunity to exercise the total system on realistic science data acquisition scenarios that simulate the operational environment. The in-flight exercises should use the processes, procedures, software, and ground system capabilities in the same manner, to the extent possible, as will be used during Tour and Orbital operations. For the Orbital phase, since no targeted gravity assist flyby can simulate this phase of the mission, in-flight exercises should be done during the ‘quiet’ cruise phase of the mission.

It is expected that the science planning tools will require multiple builds or deliveries in Phase E (prior to EOI). These software deliveries should be scheduled prior to the start of the planning process for the in-flight exercises. The subsequent builds will be delivered based on the changes required from the lessons learned during these in-flight exercises.

The study team took all of the recommendations described and developed a representative OPFM science operations process used to help develop the total mission costs for JEO. The key science operations elements include tour selection, science observation development, creation of the integrated science plan, science implementation, sequencing, and on-board execution. Key enabling tools envisioned for OPFM science planning include a science opportunity analyzer/optimizer, a web-based relational database (e.g., CIMS), sequencing utilities, and a suite of high fidelity modeling and validation tools. This was not intended to be the actual process that will be used by JEO, but a concept that demonstrates the various steps, challenges, tools, inputs, outputs, and schedule concerns associated with adequately defining and costing science operations planning. The final OPFM Science Operations Concept Study Report contains greater details on the design recommendations, science operations processes, required tools, and a list of lessons learned from Cassini

G.4.3.3 34 m Only DSN Trade Study

The purpose of the 34 m only DSN trade study was to consider the impacts to the baseline Europa Explorer study (2007 concept) of changing from the use of primarily 70 m DSN antennas during Europa orbital operations to the exclusive use of DSN 34 m antennas for that mission phase. The study was performed after the 2007 concept study was completed and prior to the start up of the 2008 study. X-band and X+Ka-band options were considered. The resulting recommendation to use moderate power on both X-band and Ka-band transmitters reflected the science requirement for dual frequency downlink. The 2008 study guidelines, in part informed by this trade study, were to use only 34 m DSN stations and to consider the use of Ka-band science data return. The 2008 study SDT reduced the Doppler requirement from dual frequency X+Ka-band to Ka-band only. The details of the trade study and the models used in the analysis were used to quickly determine a Ka-band only option that would meet the science needs and study guidelines.

G.4.3.4 Rationale for Hybrid SSR

Large volume, radiation hardened mass memory for Europa operations is massive and expensive. Trade studies conducted in the 2007 study showed the breakpoints for operations benefits of larger volume SSRs than those in the current baseline. The emphasis on Jovian Tour science in the 2008 study led to a trade study to find options for larger volume SSRs for the JEO mission. An Option to consider a large volume CRAM based SSR (from the JSO 2007 study) was considered. Another option put forward proposed a second less radiation hardened SSR for use in the Jovian Tour phase. While the CRAM based concept was large, massive, and expensive, the second SSR brought redundant functions and overhead, complicating the system design and adding mass and cost. Finally, a hybrid SSR was proposed which suggested adding radiation tolerant SDRAM to the CRAM SSR design. SDRAM components are smaller and have higher memory density and lower power than CRAM and so can be accommodated in the SSR without significant mass and power impacts. The radiation dose capability does not provide sufficient reliability to baseline for use in Europa orbit but is expected to be sufficient, with additional shielding, for use in the Tour phase prior to EOI. As the SDRAM components fail due to radiation effects, the capacity of the SSR degrades to the baseline CRAM capacity needed for operating in Europa orbit.

The question of how much data volume the hybrid SSR would need for the Tour phase was the subject of an operations scenario trade study. The key considerations for the scenario were the available downlink data volume and the minimum data desired for flyby encounters. The minimum data desired for flyby operations was defined by trade studies conducted by the Europa Explorer and Jupiter System Orbiter studies in 2007. The value of 10 Gb was derived by both mission studies. For comparison, this is 2½ times greater than the Cassini SSR volume.

The JEO telecom capability and DSN strategy provides from 14–20 Gb per week of downlink data. Due to the large memory density of SDRAM devices (1 to 2 Gb per chip), the hybrid SSR trade considered volume in units of 8 Gb and looked at volumes of 8, 16, and 24 Gbits. 16 Gb was selected as the value that is greater than the minimum needed for flyby science and is large enough to store a week's data volume.

G.5 Findings

The science objectives set by the SDT can be easily met with the flight and ground system design set in the study. With the 28 eurosol, 99-day mission for which the analysis was performed, the science goals are met with margin.

While the Jovian Tour scenarios are still preliminary, there remains great flexibility and capacity for the planning payload to conduct extensive science investigations. Not surprisingly, with a Jovian Tour mission data volume 25% greater than Cassini and the ability to collect and return 4 times more data than Cassini during satellite flybys, the JEO Tour offers a rich and complex capability for science investigations. While some science objectives could not be met with the baseline trajectory from this study, it is very likely that future analysis and optimization will provide many more geometric opportunities to meet science goals for the Jovian Tour. The science goals for the Tour were preliminary in nature. Future goals will be informed by the scenarios and capabilities of this study and will grow more detailed.

The science scenarios developed for the Europa science campaigns meet all science goals with margin. The highest priority goals are met in the first weeks of the mission. Higher resolution data sets and finer profile grids in later mission campaigns exceed the stated science goals. Future studies can trade performance for such issues as ground track repeat patterns, instrument FOV, alternate orbit strategies, and observation duty cycles to optimize performance against goals or re-work the goals for strategic needs.

The scenario studies have shown that both Jovian Tour and Europa Science orbital missions can be modeled with the developed tools and science performance can be optimized across the flight and ground system scope.

G.6 Next Steps

For future studies, anticipated changes in study goals should be factored into the operations scenarios, such as:

- Longer mission life capability
- Planning payload changes
- Refined Tour science goals
- More mature SSR concept performance
- Develop Tour scenario tools for rapid scenario analysis in more depth and breadth
- Higher fidelity scenario modeling tools to examine more options for Europa global mapping scenarios and for expanded targeting types
- Link Jovian Tour trajectory design processes with scenario analysis tools for evaluation of Tour trajectories while in process

The interaction between telecom, C&DH (throughput, compression, and mass memory), instrument characteristics (rates, compression, timing) and ground resources like DSN stations and retransmission, suggest that further optimization should be performed. The operations scenarios should inform and respond to those design iterations.

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H. TELECOMMUNICATIONS LINK ANALYSIS

H.1 Introduction

This appendix contains the performance estimates for the JEO telecommunication links. At least 3 dB of link margin is carried on all link analyses presented in this report. The telecommunications subsystem is described in §4.4. The following paragraphs detail the parameters used for the link analyses, with link performance vs. range given by charts. Link design control tables are samples of link performance at a particular range, which are presented to indicate that all parameters are accounted for and used correctly.

H.2 Requirements

The link shall provide for Command, Telemetry, and Radiometric Navigation. The following are assumed requirements based on typical performance for Deep Space Missions, and are not meant to drive the design, except for Command and Telemetry Performance.

Radiometric Navigation Performance

1. Doppler: < 0.1 mm/sec in 60 s
2. Ranging: 4 m in 10 min
3. ΔDOR (VLBI): 0.12 ns

Command Performance at BER < 1E-5

4. Minimum rate: 7.8125 bps
5. Maximum rate: 2000 bps

Engineering Telemetry Performance at FER < 1E-4

6. Minimum rate: 10 bps
7. Maximum rate: ~300 kbps (at EOI); ~500 kbps (at minimum range)

Key Functions

8. Initial Acquisition
9. Safemode Telecom & Command
10. Critical Event Data & Monitoring
11. Single fault immunity

H.3 Telecommunications Subsystem Overview

Europa-Earth range is the dominant geometric factor affecting supportable data rates. The range is 5.7 AU at the start of the Europa science phase, and reaches a maximum of 6.4 AU by the end of Campaign 3 (105 days after EOI), and the average downlink data rate decreases during this period. During the subsequent six months of Campaign 4, the range begins at the maximum value of 6.4 AU and improves to the minimum value of 4.4 AU, and the average downlink data rate increases during this period.

In order to minimize transmit circuit losses, the telecom transmit hardware is mounted on the back of the HGA which reduces the path length between the output of the high-power amplifiers and the antennas, particularly the 3 m, X-/Ka-band HGA.

Flight system communication is primarily via Ka-band during the science phase, with use of X-band for cruise, critical events, safemode, and to augment science (if power is available). Commanding is via X-band. Dual string, cross-strapped SDSTs, 25-W Ka-band TWTAs and 25-W X-band TWTAs provide X up, X/Ka down command and telemetry capability. In addition, the KaT provides a 2-way coherent, Ka carrier (Ka up/Ka down) for Doppler radio science. The power levels of the Ka-band streams are adjusted so that the output from the SDST (after the ×4 multiplier) is nine times that of the output from the KaT. The signals are combined with a magic tee allowing them to share one of the two Ka-band TWTAs, with 90% of the TWTA RF power allocated to the SDST and 10% allocated to the KaT (the redundant Ka-band TWTA can only be used by the SDST.). The Ka-band link can only be operated with the HGA, but the X-band link can be operated with the HGA, MGA, or either LGA.

The high rate Ka-band links are designed to communicate to 34 m DSN antennas. The telecom system design also accommodates even higher rate X-band links if 70 m DSN antennas are available, as well as lower rate X-band links to 34 m antennas (which can be simultaneous with Ka-band). The link performance for cruise and Jupiter system tour does not constrain the design. Also, because higher transmitter power is available on the ground, uplink margins are much higher than downlink margins, and uplink does not constrain the design. **Figure H.3-1** and **Figure H.3-2** depict downlink Pt/No (total signal power received divided by noise spectral density) and supportable data rate vs. range for the HGA, MGA and LGA. **Figure H.3-3** shows uplink Pt/No and supportable data rate vs. range for the MGA and LGA. The HGA is able to support the maximum uplink rate of 2000 bps for the entire mission.

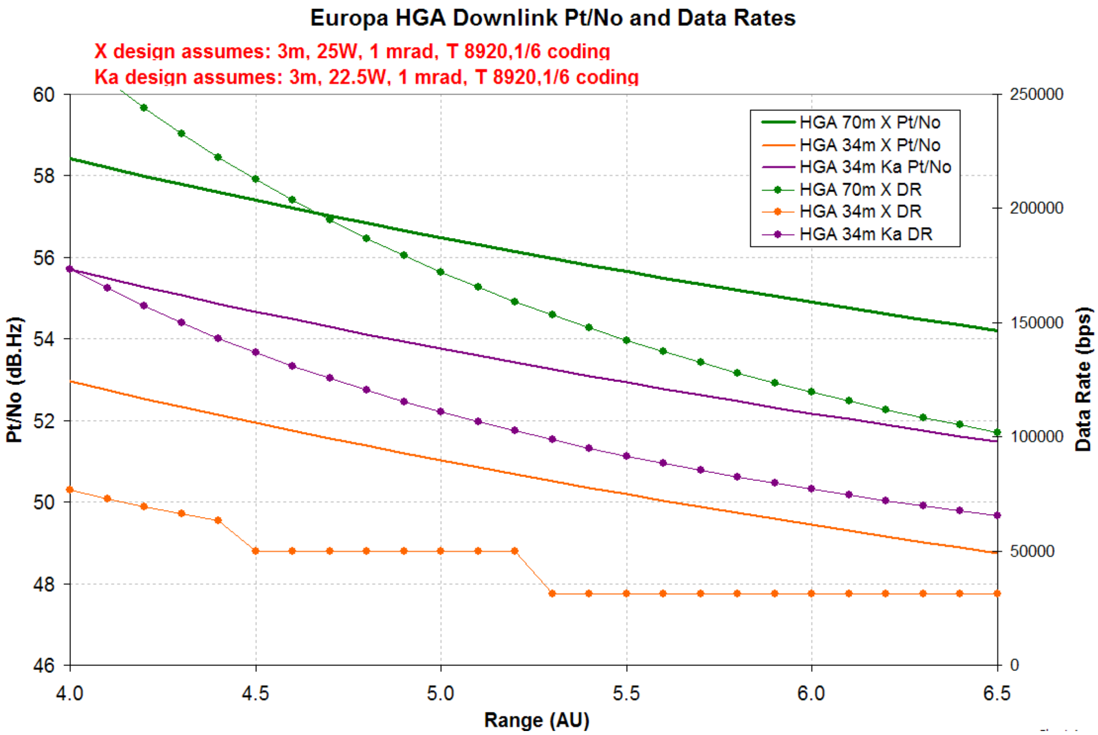

Figure H.3-1. HGA Downlink Pt/No and Data Rates vs. Range)

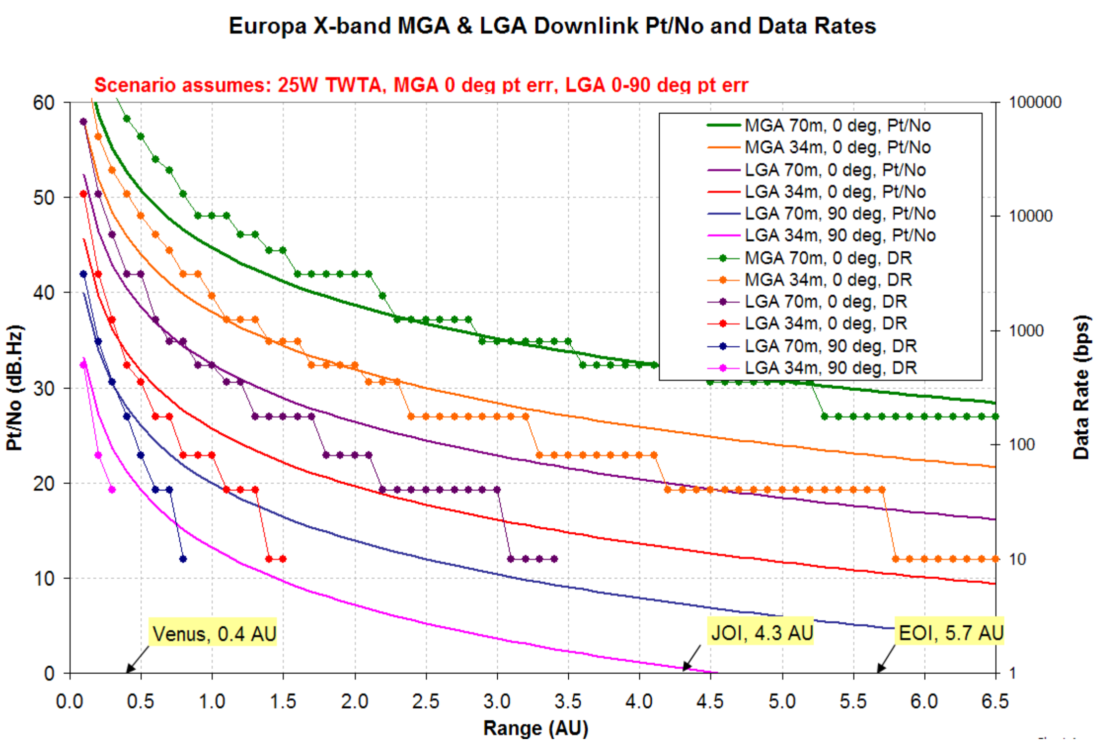

Figure H.3-2. X-band MGA and LGA Downlink Pt/No and Data Rates vs. Range

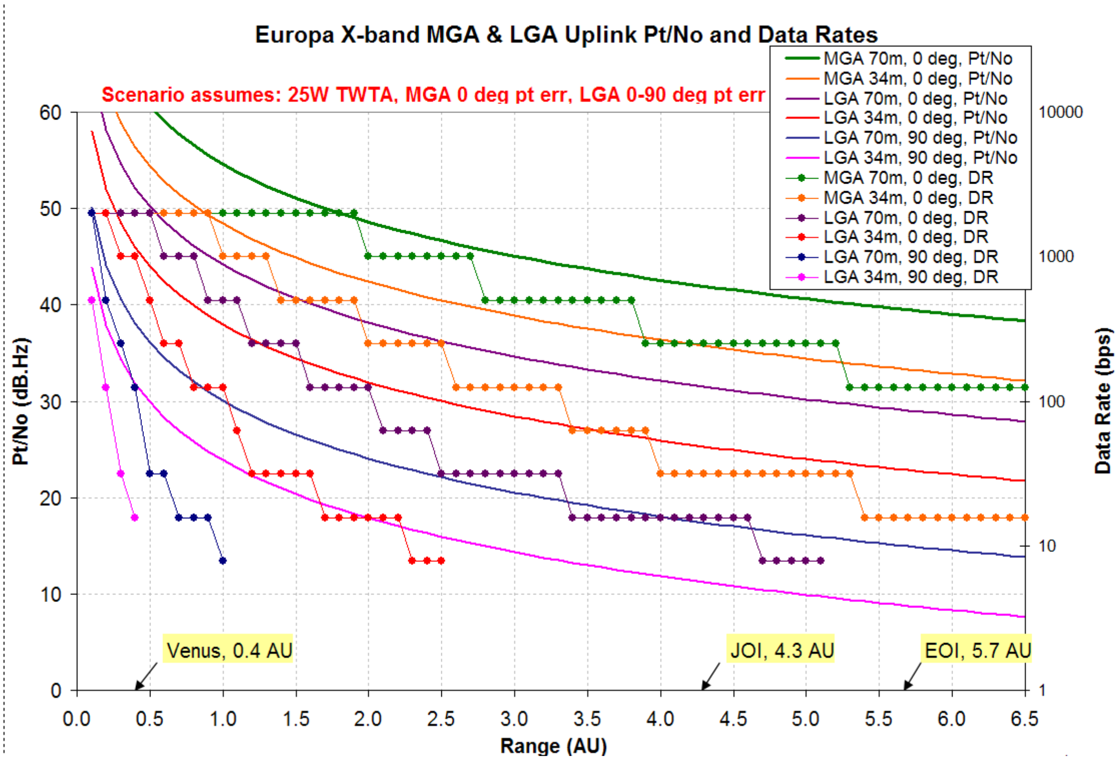

Figure H.3-3. X-band MGA and LGA Uplink Pt/No and Data Rates vs. Range

During the interplanetary cruise phase from launch until Jupiter orbit insertion (JOI), there are no requirements to use the HGA as a sunshield and no constraints on spacecraft pointing for thermal reasons. Therefore, it is reasonable to assume the spacecraft can point any of its antennas at the Earth for communications, especially since the antennas are mounted on a gimbaled HGA, which offers additional flexibility. **Figure H.3-4** and **Figure H.3-5** illustrate the supportable downlink and uplink rates during cruise, assuming concurrent "low" ranging (–3 dB uplink suppression, –0.3 dB downlink suppression). **Figure H.3-6** shows the cruise ranging SNR profile. Choice of antenna depends on various factors, including data rate and ranging requirements. For example, the plots show that a 40 bps downlink is supportable on the LGA to ~1 AU, and on the MGA to ~4.3 AU.

For critical events, such as Venus flyby, JOI, and EOI, geometry and antenna pointing constraints will determine the telecom downlink strategy. **Figure H.3-7** shows an analysis of critical event communications options. For the Venus flyby, because the range is only 0.4 AU, the LGA can be used to provide telemetry. For JOI and EOI, although the communications strategy is to earthpoint the MGA and get telemetry at up to 18 degrees off boresight for JOI and 15 degrees off boresight for EOI, the LGA can provide closed loop carrier detection (no telemetry) up to ~70 degrees off boresight. For larger LGA off boresight angles, alternative options include using a Radio Science Receiver to detect the carrier (like Cassini during Saturn Orbit Insertion), or arraying DSN antennas to improve the SNR for closed loop detection.

For the Jupiter tour and Europa science phases, baseline downlink rates assuming 90% cumulative weather distribution (average yearly statistics), 20 degree station elevation, and full Jupiter hot body noise in the beam are shown in **Figure H.3-8** and **Figure H.3-9,** respectively. The Europa science phase chart also includes a plot of the 7-day averaged Ka-band rate, which can be realized by adjusting data rates once per orbit as described in the next paragraph. The 7-day average curve is not as smooth as the other curves because the data was generated using average monthly (rather than yearly) weather statistics since Ka-band performance is sensitive to weather. As a result, there are discontinuities every month, which are smoothed by averaging.

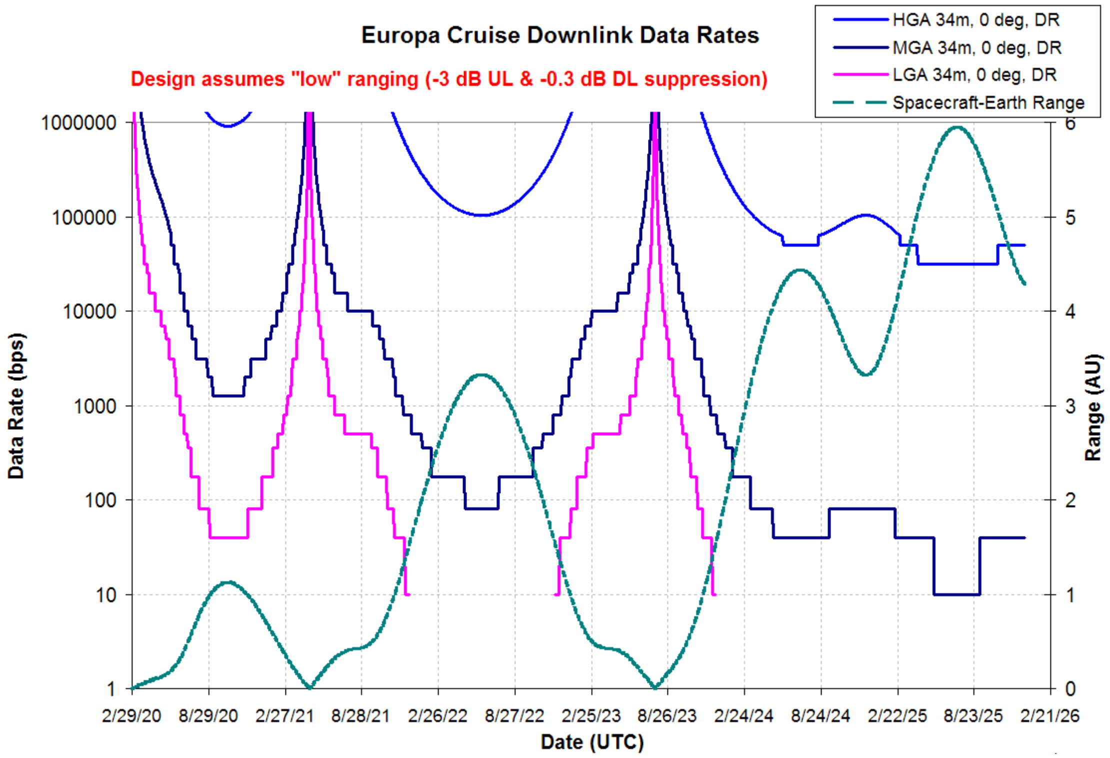

Figure H.3-4. X-band Cruise Downlink Data Rate Capability

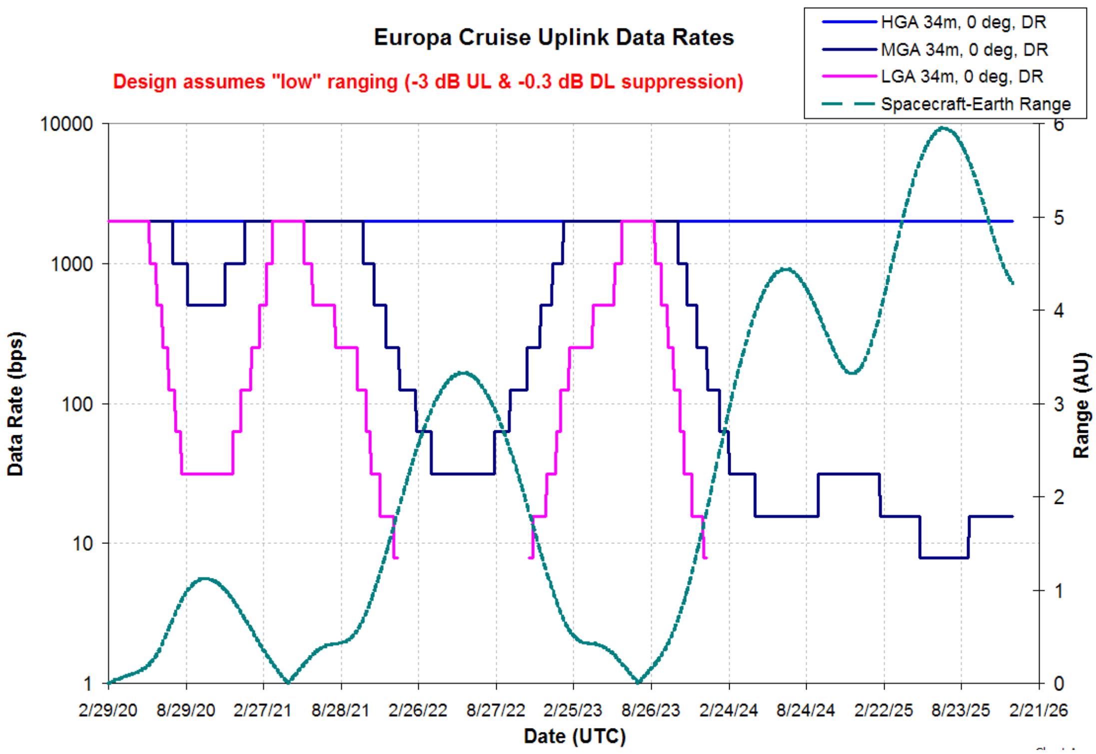

Figure H.3-5. X-band Cruise Uplink Data Rate Capability

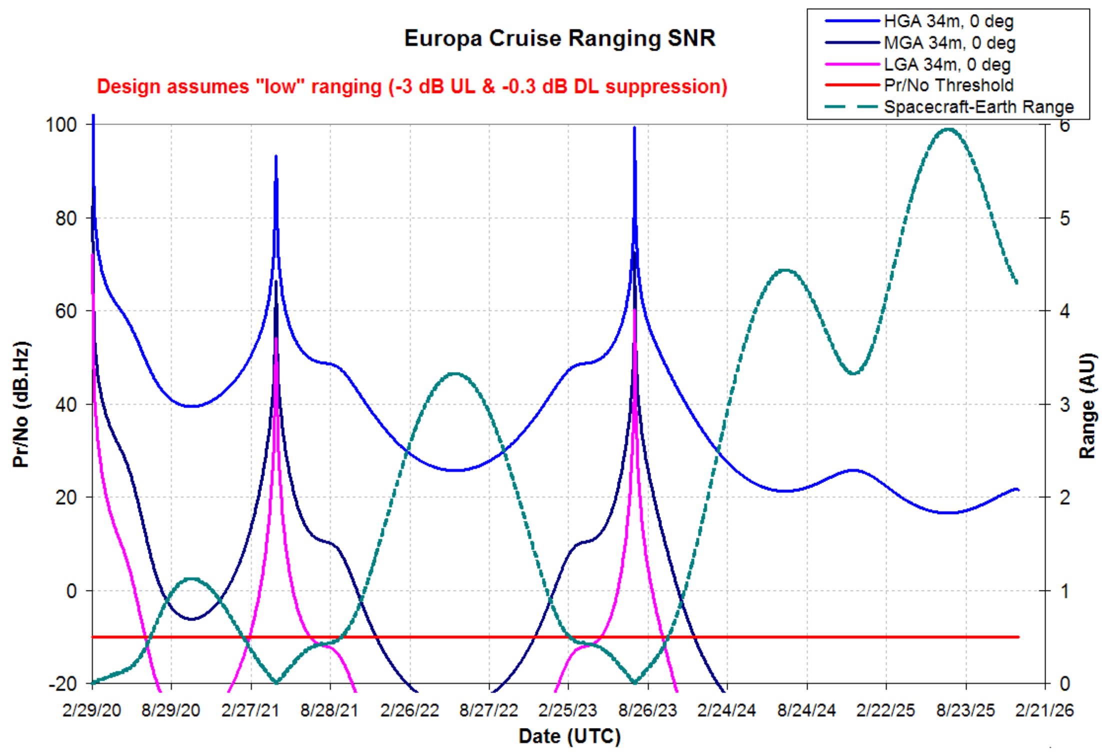

Figure H.3-6. X-band Cruise Ranging SNR

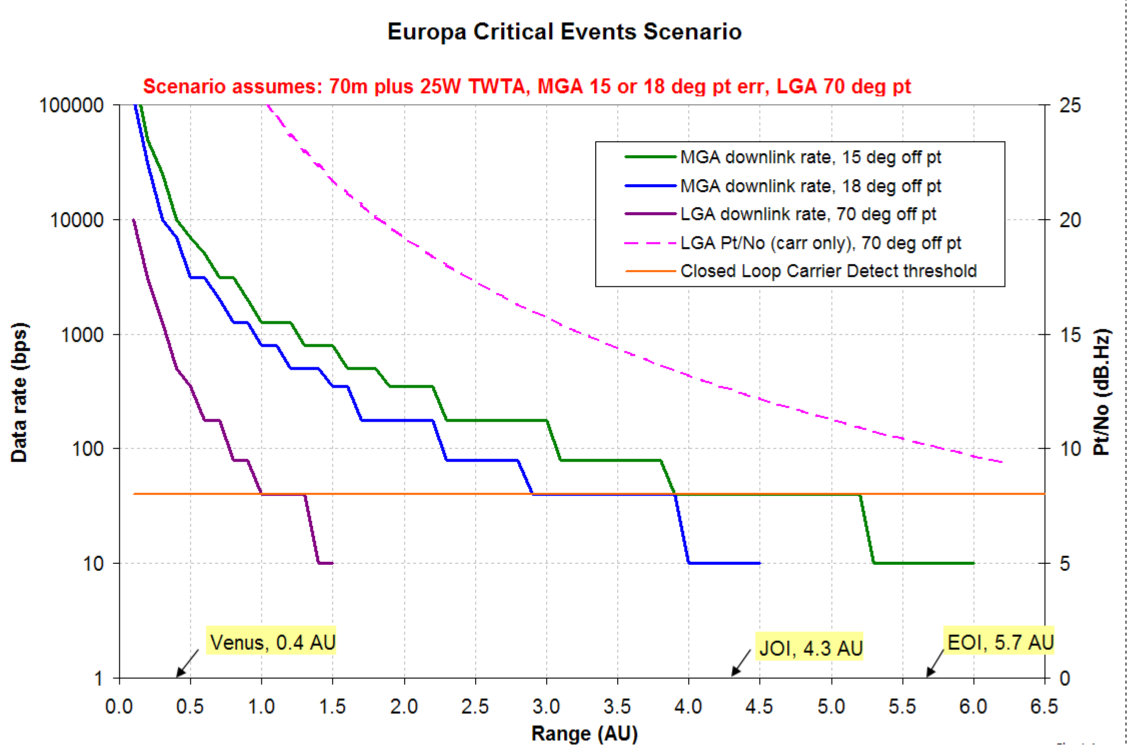

Figure H.3-7. Critical Events Communications Scenario

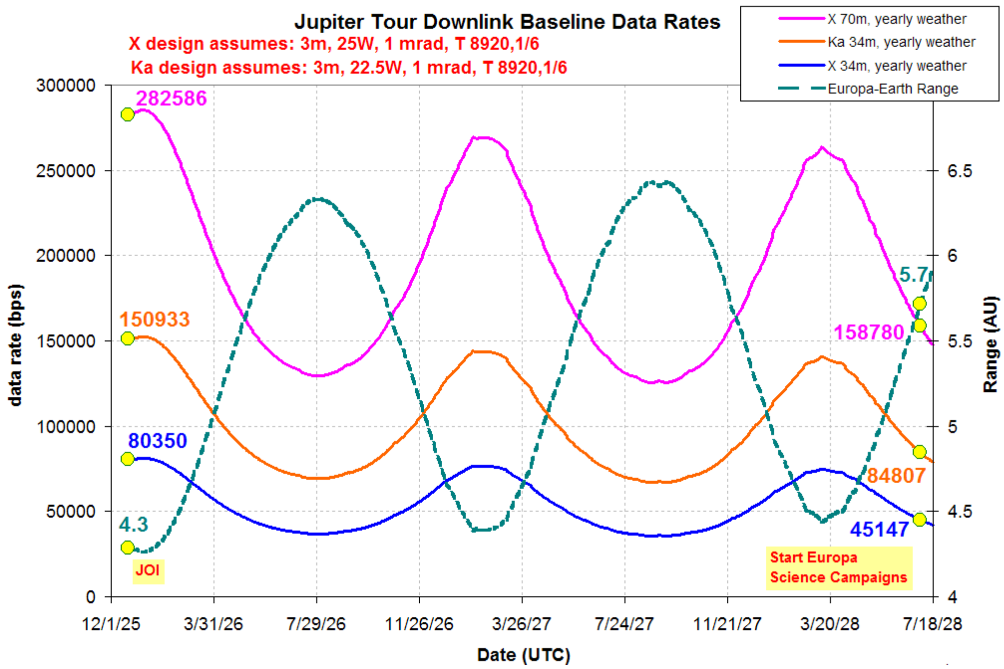

Figure H.3-8. Jupiter Tour Baseline Downlink Data Rate Capability

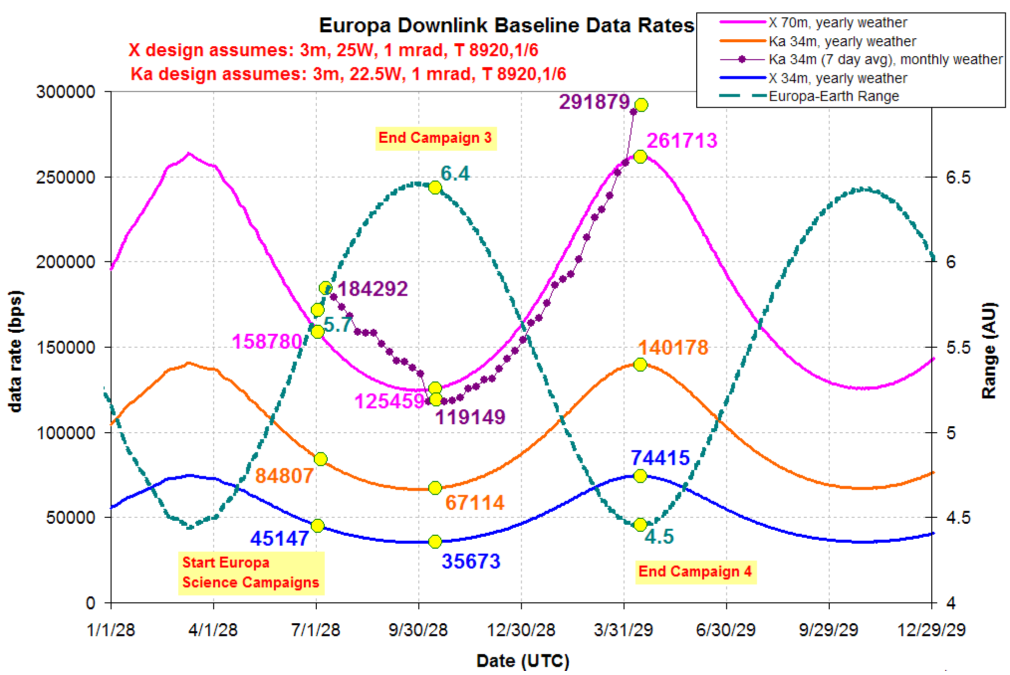

Figure H.3-9. Science Phase Baseline Downlink Data Rate Capability

For improved science data return, the Ka-band downlink rate will be increased from the reference DCT's baseline of 80 kbps to an average of ~150 kbps over the first 105 days of the science phase by varying downlink data rates throughout a tracking pass. A similar strategy could be used to increase the average X-band downlink rate if 70 m antennas are available. However, it is not as useful for 34 m tracking stations due to lower supportable data rates. For simplicity, most missions select a single downlink rate that is supportable throughout an entire DSN tracking pass, and are therefore constrained to select a rate that is supportable at the minimum elevation for the pass. For this mission, since the spacecraft is occulted by Europa for about 45 minutes once every 2.1 hours, there is a natural opportunity to change downlink rates at every occultation exit to take advantage of changing link conditions. As illustrated in **Figure H.3-10**, two temporal effects have a major impact on the supportable downlink rate: ground antenna system noise temperature (SNT) and the Jupiter hot body noise contribution. At Ka-band, the SNT fluctuates by more than a factor of two during a 34 m pass, and minimum SNT levels drop when Jupiter is not in the beam of the antenna (which is about 75% of the time). Analysis for the 105-day science phase shows that changing data rates at 0.5 dB increments once per occultation period yields an improvement of nearly 3 dB in average data rate (namely, 80 kbps to ~150 kbps). A representative 10-day period showing the data rate variation (including occultations by Jupiter, which drive the rate to zero) can be seen in **Figure H.3-11**.

Safemode communications during the science phase will be at X-band via the MGA. Since the MGA's 9 deg half-cone angle is comparable to the Sun-Probe-Earth (SPE) angle, which can be up to 12 deg at Jupiter, the simplest option is to sunpoint the MGA, and operate the MGA at SPE degrees off boresight. If desired, higher rates (or greater margin against pointing uncertainty) are achievable by earthpointing the MGA. **Figure H.3-12** and **Figure H.3-13** depict how the uplink and downlink safe mode rates vary with range and SPE if the MGA is sunpointed and earthpointed, respectively.

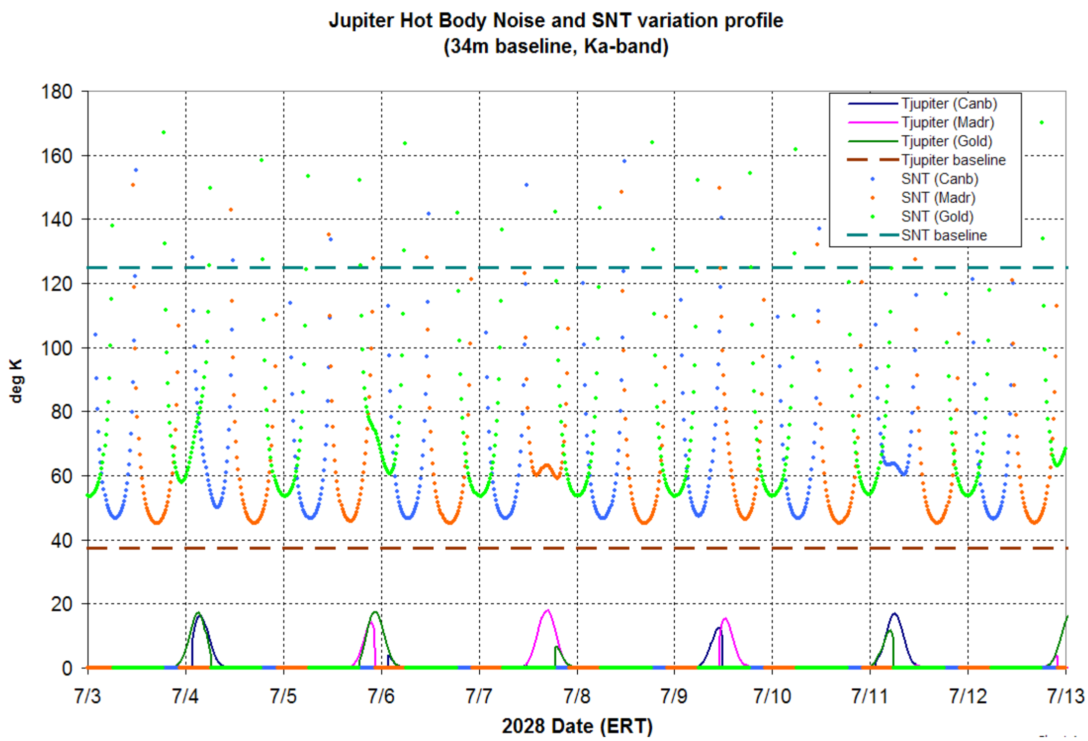

Figure H.3-10. Science Phase Ka-band Jupiter Hot Body Noise and SNT Variation Profile

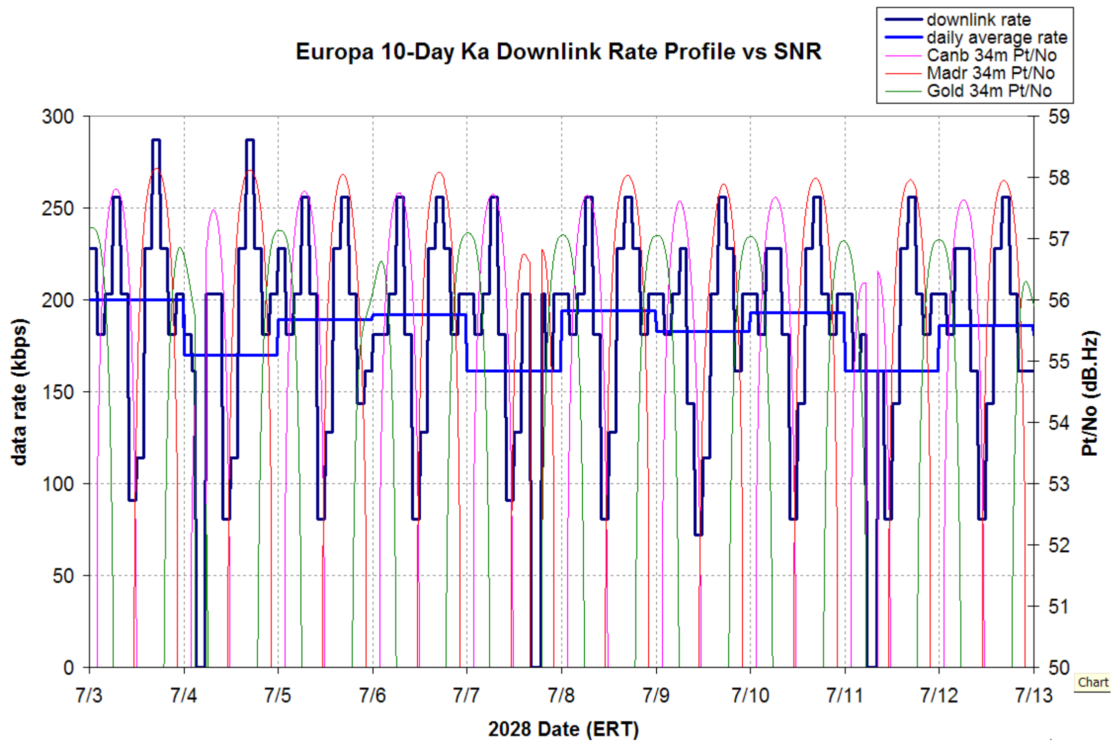

Figure H.3-11. *Science Phase Ka-Band Variable Downlink Rate Profile (10-Day Sample)*

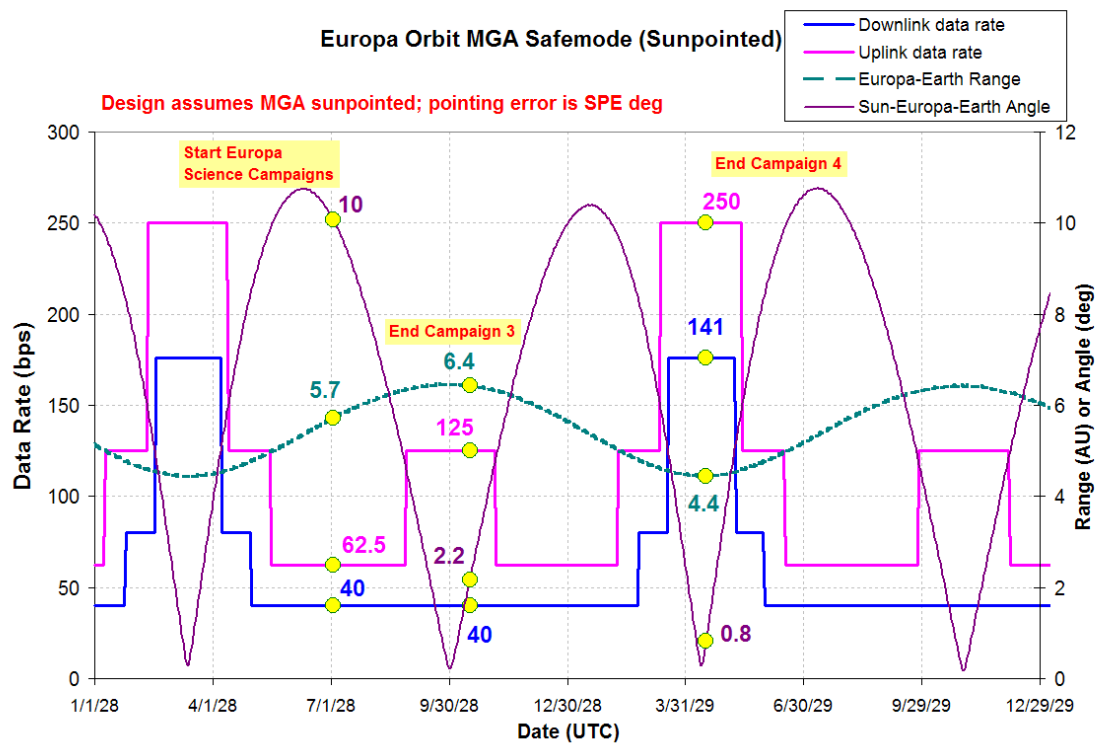

Figure H.3-12. *Science Phase Safemode with MGA Sunpointed*

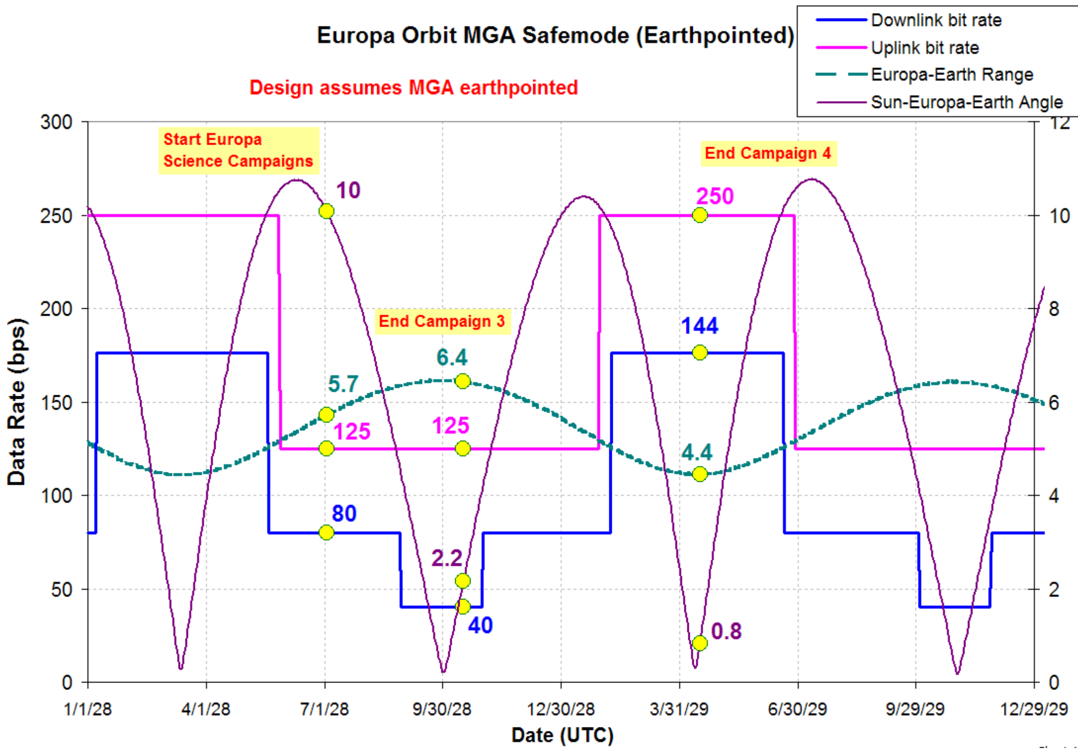

Figure H.3-13. *Science Phase Safemode with MGA Earthpointed*

H.4 Telecommunications Parameters and Assumptions

Table H.4-1 defines the Europa uplink and downlink telecommunications parameters for X-band and Ka-band. Assumptions made in the link analysis include:

- 3 dB link margin
- 90% Cumulative Weather Distribution (yearly statistics for X-band and Ka-band for DCTs and baseline rate plots; monthly statistics for Ka-band in varying data rate analysis)
- 20 deg station elevation for nominal communications; 10 deg station elevation for safe mode
- (at Europa and Jupiter) Jupiter Hot body noise in the antenna field of view (37 K for Ka-band 34 m, 13 K for X-band 70 m, 3 K for X-band 34 m)
- BPSK residual carrier modulation (QPSK, if needed for X-band high rates), 80 deg modulation index for high rates (or optimized for low rates)
- Turbo (8920, 1/3) and (8920, 1/6) encoding (for rates >40 bps); Turbo (1784, 1/2) encoding (for low rates, 10 and 40 bps)
- Ranging is off during Jupiter Tour and Europa Science Phases (and performed as needed)

H.5 Link Design Control Tables

Table H.5-1 through **Table H.5-8** contain representative link Design Control Tables (DCTs) for the JEO mission, showing link performance in the science phase, during safemode, and during cruise. For safemode, the worst case geometry (combined effect of range and off boresight angle) was considered in the DCTs. These DCTs were derived from the telecom concept and design assumptions. Because the detailed design has not yet been determined, some parameter values, such as circuit losses, were assumed based on actual designs from previous projects (with additional margin added where appropriate). In this case, parameter assumptions were derived from the MRO Telecom design which has a very similar design concept, configuration, and operations scenario. The circuit loss assumptions were compared with loss

Table H.4-1. *Europa Telecommunications Parameters*

Parameter	X-Band Value	Ka-Band Value	Parameter	X-Band Value	Ka-Band Value
Maximum S/C Range (km/AU)	9.66E+08/6.4	9.66E+08/6.4	Turnaround Ranging (Y/N)	Y (as needed)	Y (as needed)
1st Encounter Distance (km/AU), Venus	5.63E+07/0.4	-	Required Ranging Accuracy (m), at Europa	4	4
2nd Encounter Distance (km/AU), Jupiter	6.41E+08/4.3	-	S/C Transmitting Power (Watts)	25	25 (90% SDST/10% KaT)
3rd Encounter Distance (km/AU), Europa	855,203,044/5.72	855,203,044/5.72	Downlink Modulation Format Name(s)	PCM/PSK/PM	PCM/PSK/PM (SDST), Carrier Only (KaT)
Uplink Transmitter Power (W)	20,000	800	Downlink Frequency Band (GHz)	8.4-8.45	31.8-32.3
Uplink Command Mod Index (Peak Radians)	1.5	-	S/C Downlink Telemetry Mod Index (Peak Radians)	1.4/0.78	1.4/0.78
Uplink Ranging Mod Index (Peak Radians), Sinewave Ranging	1.12	-	S/C Downlink Ranging Mod Index (Peak Radians)	0.3	0.3
Uplink Frequency Band (GHz)	7.145-7.190	34.2-34.7	S/C HGA Transmit Gain (dBi) / Loss (dB)	45.8/-1.5	57.5/-1.5
Uplink Transmit Antenna Gain (dBi)	34 m, 66.9	34 m (DSS-25), 79.4	S/C MGA Transmit Gain (dBi) / Loss (dB)	19.2/-2.4	-
S/C HGA Receive Gain (dBi) / Loss (dB)	44.4/-7.0	58.1/-1.0	S/C LGA Transmit Gain (dBi) / Loss (dB)	7.2/-2.6	-
S/C MGA Receive Gain (dBi) / Loss (dB)	18.1/-7.0	-	Downlink Receive Antenna Gain (dBi)	34 m, 68.2	34 m, 78.8
S/C LGA Receive Gain (dBi) / Loss (dB)	7.7/-7.0	-	Telemetry Data Rates (b/s)	10 - 100000	32000 - 500000
Telecommand Data Rates (b/s)	7.8125 - 2000	-	Telemetry Coding (Name)	Turbo Rate 1/2 (1784), 1/3 (8920), 1/6 (8920)	Turbo Rate 1/6 (8920)
Telecommand Bit-Error-Rate	1.0E-05	-	Telemetry Frame Length	1784 and 8920	8920
S/C Receiver Noise Temperature (K)	500	500	Telemetry Frame-Error-Rate	1.0E-04	1.0E-04
S/C Receiver Bandwidth (Hz)	20	20	Implementation Loss (dB)	-0.3	-0.3
Implementation Loss (dB)	-3	-	Required Pc/No (dB-Hz), for KaT	-	27

estimates based on the telecom block diagram, and were determined to be reasonable and conservative.

The Telecom subsystem design concept in the current study is nearly identical to the 2006 Europa Explorer Study [*Europa Explorer Design Team Report, JPL D-34109, April 27, 2006*], with a few exceptions. Since there is no guarantee that 70 m antennas (or their equivalent) will be available during the Europa science phase, there was a shift from X-band to Ka-band for the high rate links. With the addition of redundant 25-W Ka-band TWTAs, the Ka-band 3.5-W SSPA was removed in favor of a magic tee combiner, which allows the KaT and SDST to share a TWTA. Due to power constraints, there was a reduction in X-band TWTA power from 50-W to 25-W.

***Table H.5-1.** Science Downlink 22.5 W Ka-band, 3 m HGA, 1 mrad pointing, 34 m DSN*

	22.5 W (90% of 25 W TWTA)				
	Ka-Band HGA, 3 m antenna diameter, 0.06° off-point (1 mrad)			8.527E+08	*Range, km*
	DSN 34 station /Configuration: X/Ka RCP			5.7000	*Range, AU*
	Canberra/20 deg. elevation/90% CD Weather (Year Average)			0.79	*OWLT, hrs*
	Hot body noise = 37 K				
	2-way coherent			20	*SEP, deg*
	Tlm channel/ (Turbo 1/6, 8920 bit frame)/ FER=10^-4			20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	Ka 32000	*RF band Freq, MHz*
	TRANSMITTER PARAMETERS				
1	S/C RF Power Output	dBm	43.52	22.5	*Xmtr Pwr (W), EOL*
2	Total Circuit Loss	dB	-1.50		
3	Antenna Gain (on boresight)	dBi	57.46	0.22	*3 dB Beamwidth*
4	Ant Pointing Loss	dB	-0.82	HGA	*S/C Antenna*
5	EIRP (1+2+3+4)	dBm	98.65		
	PATH PARAMETERS				
6	Space Loss	dB	-301.17		
7	Atmospheric Attn	dB	-1.18	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	DSN Antenna Gain	dBi	78.78	Canberra: 34mBWG, DSS34	
9	Ant Pointing Loss	dB	-0.10	n/a	*LNA Selection*
10	Polarization Loss	dB	-0.03	X/Ka RCP	*DSS Config*
	TOTAL POWER SUMMARY				
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm	-125.04	2	*WAY*
12	Noise Spec Dens	dBm/Hz	-177.57		
	System Noise Temp	K	126.15		
	Vacuum, zenith	K	21.33		
	Elevation	K	1.47		
	Atmosphere	K	66.08		
	Hot Body Noise	K	37.27	from Jupiter	
13	**Received Pt/No**	**dB-Hz**	**52.53**		
	CARRIER PERFORMANCE				
14	Tlm Carrier Supp	dB	-15.21	TRUE	*TLM ON?*
15	Rng Carrier Supp	dB	0.00	0 deg	*RNG MI?*
16	DOR Carrier Supp	dB	0.00	FALSE	*DOR ON?*
17	Received Pc/No (13+14+15+16)	dB-Hz	37.32		
18	Carrier Loop Bandwidth, Bl	dB-Hz	10.00	10	*Carrier Bl, Hz*
19	Phase Noise Variance	rad^2	0.0099		
	Thermal Noise Contribution	rad^2	0.0019		
	Transmitter Noise Contribution	rad^2	0.0080		
	Solar Noise Contribution	rad^2	0.0000		
19a	Loop SNR	dB	20.06		
20	Required Carrier Loop SNR	dB	10.00		
21	**Carrier Margin**	**dB**	**10.06**		
	TELEMETRY PERFORMANCE				
22	Tlm Data Supp	dB	-0.13	80	*tlm MI, deg*
23	Rng Data Supp	dB	0.00	0	*peak rng MI, deg*
24	DOR Data Supp	dB	0.00		
25	Pd/No (13+22+23+24)	dB-Hz	52.40		
26	Data Rate	dB	49.19	82900	*data bit rate, bps*
27	Radio Loss	dB	-0.30		
28	SubCarrier Demod. Loss	dB	0.00		
29	Symbol Sync. Loss	dB	0.00		
30	Baseline Eb/No (25-26+27+28+29)	dB	2.91		
31	Output Eb/No (required to close all loop:	dB	-0.10		
31a	**Performance margin (30-31)**	**dB**	**3.01**		

Table H.5-2. *Science Downlink 25W X-band, 3 m HGA, 1 mrad pointing, 34 m DSN*

	25.0 W TWTA				
	X-Band HGA, 3 m antenna diameter, 0.06° off-point (1 mrad)			8.527E+08	*Range, km*
	DSN 34 station /Configuration: X/Ka diplexed RCP			5.7000	*Range, AU*
	Canberra/20 deg. elevation/90% CD Weather (Year Average)			0.79	*OWLT, hrs*
	Hot body noise = 3 K				
	2-way coherent			20	*SEP, deg*
	Tlm channel/ (Turbo 1/6, 8920 bit frame)/ FER=10^-4			20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 8401.419752	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	S/C RF Power Output	dBm	43.98	25	*Xmtr Pwr (W), EOL*
2	Total Circuit Loss	dB	-1.50		
3	Antenna Gain (on boresight)	dBi	45.84	0.83	*3 dB Beamwidth*
4	Ant Pointing Loss	dB	-0.06	HGA	*S/C Antenna*
5	EIRP (1+2+3+4)	dBm	88.26		
	PATH PARAMETERS				
6	Space Loss	dB	-289.55		
7	Atmospheric Attn	dB	-0.16	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	DSN Antenna Gain	dBi	68.23	Canberra: 34mBWG, DSS34	
9	Ant Pointing Loss	dB	-0.10	n/a	*LNA Selection*
10	Polarization Loss	dB	-0.02	X/Ka diplexed RCP	*DSS Config*
	TOTAL POWER SUMMARY				
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm	-133.37	2	*WAY*
12	Noise Spec Dens	dBm/Hz	-183.35		
	System Noise Temp	K	33.05		
	Vacuum, zenith	K	18.97		
	Elevation	K	0.49		
	Atmosphere	K	10.27		
	Hot Body Noise	K	3.32	from Jupiter	
13	**Received Pt/No**	**dB-Hz**	**49.97**		
	CARRIER PERFORMANCE				
14	Tlm Carrier Supp	dB	-15.21	TRUE	*TLM ON?*
15	Rng Carrier Supp	dB	0.00	0 deg	*RNG MI?*
16	DOR Carrier Supp	dB	0.00	FALSE	*DOR ON?*
17	Received Pc/No (13+14+15+16)	dB-Hz	34.77		
18	Carrier Loop Bandwidth, Bl	dB-Hz	10.00	10	*Carrier Bl, Hz*
19	Phase Noise Variance	rad^2	0.0039		
	Thermal Noise Contribution	rad^2	0.0033		
	Transmitter Noise Contribution	rad^2	0.0006		
	Solar Noise Contribution	rad^2	0.0000		
19a	Loop SNR	dB	24.10		
20	Required Carrier Loop SNR	dB	10.00		
21	**Carrier Margin**	**dB**	**14.10**		
	TELEMETRY PERFORMANCE				
22	Tlm Data Supp	dB	-0.13	80	*tlm MI, deg*
23	Rng Data Supp	dB	0.00	0	*peak rng MI, deg*
24	DOR Data Supp	dB	0.00		
25	Pd/No (13+22+23+24)	dB-Hz	49.84		
26	Data Rate	dB	46.63	46024	*data bit rate, bps*
27	Radio Loss	dB	-0.30		
28	SubCarrier Demod. Loss	dB	0.00		
29	Symbol Sync. Loss	dB	0.00		
30	Baseline Eb/No (25-26+27+28+29)	dB	2.91		
31	Output Eb/No (required to close all loops	dB	-0.10		
31a	**Performance margin (30-31)**	**dB**	**3.01**		

Table H.5-3. *Science Uplink X-band, 3 m HGA, 1 mrad pointing, 34 m DSN*

	HGA Uplink				
	DSN 20 kW/34 station /Configuration: X/Ka diplexed RCP				
	Canberra/20 deg. Elevation/90% CD Weather (Year Average)			8.527E+08	*Range, km*
	X-Band HGA, 3 m antenna diameter, 0.06° off-point			5.7000	*Range, AU*
				0.79	*OWLT, hrs*
				20	*SEP, deg*
	Command channel/uncoded, PB=1.E-5				
	2000 bps			20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 7150.75	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	Total Xmitter Pwr	dBm	72.68	20	*Xmtr Pwr (kW)*
2	Xmitter Waveguide Loss	dB	-0.60	Canberra: 34mBWG, DSS34	
3	DSN Antenna Gain	dBi	66.87	X/Ka diplexed RCP	*DSS Config*
4	Ant Pointing Loss	dB	-0.10		
5	EIRP (1+2+3+4)	dBm	138.84		
	PATH PARAMETERS				
6	Space Loss	dB	-288.15		
7	Atmospheric Attn	dB	-0.16	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	Polarization Loss	dB	-0.03		
9	Ant Pointing Loss	dB	-0.04	0.98	*3 dB Beamwidth*
10	S/C Antenna Gain	dBi	44.44	HGA	*S/C Antenna*
11	Lumped Ckt/Ant Loss	dB	-7.00		
	TOTAL POWER SUMMARY				
12	Total Rcvd Pwr (Pt) (5+6+7+8+9+10+11	dBm	-112.11		
13	Noise Spec Dens	dBm/Hz	-171.65		
	System Noise Temp	K	495.22		
14	**Received Pt/No**	**dB-Hz**	**59.78**		
	CARRIER PERFORMANCE				
15	Cmd Carrier Supp	dB	-5.82	TRUE	*CMD ON?*
16	Rng Carrier Supp	dB	0.00	0 deg (0 dB)	*RNG MI?*
17	Rcvd Carr Power (Pc) (12+15+16)	dBm	-117.92		
17a	Pc/No (17-13)	dB-Hz	53.96		
18	Carr Noise BW, BL	dB-Hz	20.38	109.1	*Carrier Bl, Hz*
19	Required Carrier Loop SNR	dB	12.00		
20	**Carrier Margin**	**dB**	**8.38**		
	COMMAND PERFORMANCE				
21	Cmd Modulation Loss	dB	-2.06	1.5	*cmd MI, rad*
22	Rng Data Supp	dB	0.00	0	*rng MI, deg*
23	Data Pwr to Rcvr (Pd) (12+21+22)	dBm	-114.16		
24	Data Rate	dB	33.01	2000	*cmd data rate, bps*
25	System Loss	dB	-3.00	*(includes radio loss)*	
26	Output Eb/No (14+21+22-24+25)	dB	21.71	*BER = 1e-5, uncoded*	
27	Threshold Eb/No	dB	9.60		
28	**Performance margin (26-27)**	**dB**	**12.11**		

Table H.5-4. *Science Downlink Ka-band Carrier (KaT), 3 m HGA, 1 mrad pointing, 34 m DSN*

	2.5 W (10% of 25 W TWTA power for KaT)				
	Ka-Band HGA, 3 m antenna diameter, 0.06° off-point (1 mrad)			9.724E+08	*Range, km*
	DSN 25 station /Configuration: Ka/Ka diplexed RCP			6.5000	*Range, AU*
	Goldstone/20 deg. elevation/90% CD Weather (Year Average)			0.90	*OWLT, hrs*
	Hot body noise = 37 K				
	2-way coherent Ka up/Ka down link			20	*SEP, deg*
				20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	Ka 32000	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	S/C RF Power Output	dBm	33.98	2.5	*Xmtr Pwr (W), EOL*
2	Total Circuit Loss	dB	-1.50		
3	Antenna Gain (on boresight)	dBi	57.46	0.22	*3 dB Beamwidth*
4	Ant Pointing Loss	dB	-0.82	HGA	*S/C Antenna*
5	EIRP (1+2+3+4)	dBm	89.11		
	PATH PARAMETERS				
6	Space Loss	dB	-302.31		
7	Atmospheric Attn	dB	-0.71	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	DSN Antenna Gain	dBi	78.66	Goldstone: 34mBWG, DSS25	
9	Ant Pointing Loss	dB	-0.10	n/a	*LNA Selection*
10	Polarization Loss	dB	-0.03	Ka/Ka diplexed RCP	*DSS Config*
	TOTAL POWER SUMMARY				
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm	-135.38	2	*WAY*
12	Noise Spec Dens	dBm/Hz	-178.13		
	System Noise Temp	K	110.79		
	Vacuum, zenith	K	29.41		
	Elevation	K	2.24		
	Atmosphere	K	41.88		
	Hot Body Noise	K	37.27	from Jupiter	
13	**Received Pt/No**	**dB-Hz**	**42.75**		

Table H.5-5. *Science Safemode Downlink X-band, MGA, Sunpointed (10 Deg Off Boresight), 70 m DSN*

25.0 W TWTA					
X-Band MGA, 10.0° off-point				8.527E+08	*Range, km*
DSN 43 station /Configuration: X/X				5.7000	*Range, AU*
Canberra/10 deg. elevation/90% CD Weather (Year Average)				0.79	*OWLT, hrs*
Hot body noise = 14 K					
2-way coherent				20	*SEP, deg*
Tlm channel/ (Turbo 1/2, 1784 bit frame)/ FER=10^-4				10	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 8401.419752	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	S/C RF Power Output	dBm	43.98	25	*Xmtr Pwr (W), EOL*
2	Total Circuit Loss	dB	-2.40		
3	Antenna Gain (on boresight)	dBi	19.24	10.00	*Boresight Angle, Deg*
4	Ant Pointing Loss	dB	-3.13	MGA	*S/C Antenna*
5	EIRP (1+2+3+4)	dBm	57.69		
	PATH PARAMETERS				
6	Space Loss	dB	-289.55		
7	Atmospheric Attn	dB	-0.32	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	DSN Antenna Gain	dBi	74.27	Canberra: 70m, DSS43	
9	Ant Pointing Loss	dB	-0.10	n/a	*LNA Selection*
10	Polarization Loss	dB	-0.05	X/X	*DSS Config*
	TOTAL POWER SUMMARY				
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm	-158.07	2	*WAY*
12	Noise Spec Dens	dBm/Hz	-181.50		
	System Noise Temp	K	51.26		
	Vacuum, zenith	K	14.69		
	Elevation	K	3.18		
	Atmosphere	K	19.86		
	Hot Body Noise	K	13.53	from Jupiter	
13	**Received Pt/No**	**dB-Hz**	**23.44**		
	CARRIER PERFORMANCE				
14	Tlm Carrier Supp	dB	-3.49	TRUE	*TLM ON?*
15	Rng Carrier Supp	dB	0.00	0 deg	*RNG MI?*
16	DOR Carrier Supp	dB	0.00	FALSE	*DOR ON?*
17	Received Pc/No (13+14+15+16)	dB-Hz	19.95		
18	Carrier Loop Bandwidth, Bl	dB-Hz	4.77	3	*Carrier Bl, Hz*
19	Phase Noise Variance	rad^2	0.0471		
	Thermal Noise Contribution	rad^2	0.0304		
	Transmitter Noise Contribution	rad^2	0.0167		
	Solar Noise Contribution	rad^2	0.0000		
19a	Loop SNR	dB	13.27		
20	Required Carrier Loop SNR	dB	10.00		
21	**Carrier Margin**	**dB**	**3.27**		
	TELEMETRY PERFORMANCE				
22	Tlm Data Supp	dB	-2.58	48	*tlm MI, deg*
23	Rng Data Supp	dB	0.00	0	*peak rng MI, deg*
24	DOR Data Supp	dB	0.00		
25	Pd/No (13+22+23+24)	dB-Hz	20.86		
26	Data Rate	dB	16.02	40	*data bit rate, bps*
27	Radio Loss	dB	-0.30		
28	SubCarrier Demod. Loss	dB	0.00		
29	Symbol Sync. Loss	dB	0.00		
30	Baseline Eb/No (25-26+27+28+29)	dB	4.54		
31	Output Eb/No (required to close all loops	dB	1.50		
31a	**Performance margin (30-31)**	**dB**	**3.04**		

Table H.5-6. *Science Safemode Uplink X-band, MGA, Sunpointed (10 Deg Off Boresight), 70 m DSN*

	MGA Uplink				
	DSN 20 kW/43 station /Configuration: X/X				
	Canberra/10 deg. Elevation/90% CD Weather (Year Average)			8.527E+08	*Range, km*
	X-Band MGA, 10.0° off-point			5.7000	*Range, AU*
				0.79	*OWLT, hrs*
				20	*SEP, deg*
	Command channel/uncoded, PB=1.E-5				
	7.8125 bps			10	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 7150.75	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	Total Xmitter Pwr	dBm	72.68	20	*Xmtr Pwr (kW)*
2	Xmitter Waveguide Loss	dB	-0.45	Canberra: 70m, DSS43	
3	DSN Antenna Gain	dBi	72.65	X/X	*DSS Config*
4	Ant Pointing Loss	dB	-0.10		
5	EIRP (1+2+3+4)	dBm	144.78		
	PATH PARAMETERS				
6	Space Loss	dB	-288.15		
7	Atmospheric Attn	dB	-0.32	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	Polarization Loss	dB	-0.05		
9	Ant Pointing Loss	dB	-2.79	10.00	*Boresight Angle, deg*
10	S/C Antenna Gain	dBi	18.11	MGA	*S/C Antenna*
11	Lumped Ckt/Ant Loss	dB	-7.00		
	TOTAL POWER SUMMARY				
12	Total Rcvd Pwr (Pt) (5+6+7+8+9+10+11	dBm	-135.42		
13	Noise Spec Dens	dBm/Hz	-171.65		
	System Noise Temp	K	495.22		
14	**Received Pt/No**	**dB-Hz**	**36.47**		
	CARRIER PERFORMANCE				
15	Cmd Carrier Supp	dB	-2.04	TRUE	*CMD ON?*
16	Rng Carrier Supp	dB	0.00	0 deg (0 dB)	*RNG MI?*
17	Rcvd Carr Power (Pc) (12+15+16)	dBm	-137.46		
17a	Pc/No (17-13)	dB-Hz	34.43		
18	Carr Noise BW, BL	dB-Hz	16.84	48.3	*Carrier Bl, Hz*
19	Required Carrier Loop SNR	dB	12.00		
20	**Carrier Margin**	**dB**	**4.84**		
	COMMAND PERFORMANCE				
21	Cmd Modulation Loss	dB	-4.53	0.94	*cmd MI, rad*
22	Rng Data Supp	dB	0.00	0.00	*rng MI, deg*
23	Data Pwr to Rcvr (Pd) (12+21+22)	dBm	-139.95		
24	Data Rate	dB	8.93	7.81	*cmd data rate, bps*
25	System Loss	dB	-3.00	*(includes radio loss)*	
26	Output Eb/No (14+21+22-24+25)	dB	20.01	*BER = 1e-5, uncoded*	
27	Threshold Eb/No	dB	9.60		
28	**Performance margin (26-27)**	**dB**	**10.41**		

Table H.5-7. *Cruise Downlink X-band, LGA, Earthpointed, 34 m DSN*

	25.0 W TWTA				
	X-Band CLGA, 0.0° off-point			1.496E+08	*Range, km*
	DSN 34 station /Configuration: X/Ka diplexed RCP			1.0000	*Range, AU*
	Canberra/20 deg. elevation/90% CD Weather (Year Average)			0.14	*OWLT, hrs*
	Hot body noise = 0 K				
	2-way coherent			20	*SEP, deg*
	Tlm channel/ (Turbo 1/3, 8920 bit frame)/ FER=10^-4			20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 8401.419752	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	S/C RF Power Output	dBm	43.98	25	*Xmtr Pwr (W), EOL*
2	Total Circuit Loss	dB	-2.70		
3	Antenna Gain (on boresight)	dBi	7.18	0.00	*Boresight Angle, Deg*
4	Ant Pointing Loss	dB	0.00	CLGA	*S/C Antenna*
5	EIRP (1+2+3+4)	dBm	48.50		
	PATH PARAMETERS				
6	Space Loss	dB	-274.43		
7	Atmospheric Attn	dB	-0.16	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	DSN Antenna Gain	dBi	68.23	Canberra: 34mBWG, DSS34	
9	Ant Pointing Loss	dB	-0.10	n/a	*LNA Selection*
10	Polarization Loss	dB	-0.02	X/Ka diplexed RCP	*DSS Config*
	TOTAL POWER SUMMARY				
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm	-158.02	2	*WAY*
12	Noise Spec Dens	dBm/Hz	-183.80		
	System Noise Temp	K	29.73		
	Vacuum, zenith	K	18.97		
	Elevation	K	0.49		
	Atmosphere	K	10.27		
	Hot Body Noise	K	0.00	from Jupiter	
13	**Received Pt/No**	**dB-Hz**	**25.78**		
	CARRIER PERFORMANCE				
14	Tlm Carrier Supp	dB	-5.52	TRUE	*TLM ON?*
15	Rng Carrier Supp	dB	-0.20	17.5 deg	*RNG MI?*
16	DOR Carrier Supp	dB	0.00	FALSE	*DOR ON?*
17	Received Pc/No (13+14+15+16)	dB-Hz	20.06		
18	Carrier Loop Bandwidth, Bl	dB-Hz	4.77	3	*Carrier Bl, Hz*
19	Phase Noise Variance	rad^2	0.0495		
	Thermal Noise Contribution	rad^2	0.0296		
	Transmitter Noise Contribution	rad^2	0.0199		
	Solar Noise Contribution	rad^2	0.0000		
19a	Loop SNR	dB	13.05		
20	Required Carrier Loop SNR	dB	10.00		
21	**Carrier Margin**	**dB**	**3.05**		
	TELEMETRY PERFORMANCE				
22	Tlm Data Supp	dB	-1.43	58	*tlm MI, deg*
23	Rng Data Supp	dB	-0.20	17.5	*peak rng MI, deg*
24	DOR Data Supp	dB	0.00		
25	Pd/No (13+22+23+24)	dB-Hz	24.14		
26	Data Rate	dB	20.37	109	*data bit rate, bps*
27	Radio Loss	dB	-0.30		
28	SubCarrier Demod. Loss	dB	0.00		
29	Symbol Sync. Loss	dB	0.00		
30	Baseline Eb/No (25-26+27+28+29)	dB	3.47		
31	Output Eb/No (required to close all loops	dB	0.40		
31a	**Performance margin (30-31)**	**dB**	**3.07**		

Table H.5-8. *Cruise Uplink X-band, LGA, Earthpointed, 34 m DSN*

	CLGA Uplink				
	DSN 20 kW/34 station /Configuration: X/Ka diplexed RCP				
	Canberra/20 deg. Elevation/90% CD Weather (Year Average)			1.496E+08	*Range, km*
	X-Band CLGA, 0.0° off-point			1.0000	*Range, AU*
				0.14	*OWLT, hrs*
				20	*SEP, deg*
	Command channel/uncoded, PB=1.E-5				
	31.25 bps			20	*Elev Angle, deg*
	Link Parameter	Unit	Design Value	X 7150.75	*RF band* *Freq, MHz*
	TRANSMITTER PARAMETERS				
1	Total Xmitter Pwr	dBm	73.01	20	*Xmtr Pwr (kW)*
2	Xmitter Waveguide Loss	dB	-0.60	Canberra: 34mBWG, DSS34	
3	DSN Antenna Gain	dBi	66.87	X/Ka diplexed RCP	*DSS Config*
4	Ant Pointing Loss	dB	-0.10		
5	EIRP (1+2+3+4)	dBm	139.18		
	PATH PARAMETERS				
6	Space Loss	dB	-273.03		
7	Atmospheric Attn	dB	-0.16	90	*Weather %*
				Year Average	*Distribution Type*
	RECEIVER PARAMETERS				
8	Polarization Loss	dB	-0.03		
9	Ant Pointing Loss	dB	0.00	0.00	*Boresight Angle, deg*
10	S/C Antenna Gain	dBi	7.68	CLGA	*S/C Antenna*
11	Lumped Ckt/Ant Loss	dB	-7.00		
	TOTAL POWER SUMMARY				
12	Total Rcvd Pwr (Pt) (5+6+7+8+9+10+11	dBm	-133.37		
13	Noise Spec Dens	dBm/Hz	-171.65		
	System Noise Temp	K	495.22		
14	**Received Pt/No**	**dB-Hz**	**38.28**		
	CARRIER PERFORMANCE				
15	Cmd Carrier Supp	dB	-4.15	TRUE	*CMD ON?*
16	Rng Carrier Supp	dB	-3.00	64.44 deg (3 dB)	*RNG MI?*
17	Rcvd Carr Power (Pc) (12+15+16)	dBm	-140.52		
17a	Pc/No (17-13)	dB-Hz	31.13		
18	Carr Noise BW, BL	dB-Hz	15.69	37.0	*Carrier Bl, Hz*
19	Required Carrier Loop SNR	dB	12.00		
20	**Carrier Margin**	**dB**	**3.69**		
	COMMAND PERFORMANCE				
21	Cmd Modulation Loss	dB	-2.64	1.3	*cmd MI, rad*
22	Rng Data Supp	dB	-3.00	64.44	*rng MI, deg*
23	Data Pwr to Rcvr (Pd) (12+21+22)	dBm	-139.01		
24	Data Rate	dB	14.95	31.25	*cmd data rate, bps*
25	System Loss	dB	-3.00	*(includes radio loss)*	
26	Output Eb/No (14+21+22-24+25)	dB	14.69	*BER = 1e-5, uncoded*	
27	Threshold Eb/No	dB	9.60		
28	**Performance margin (26-27)**	**dB**	**5.09**		

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I. LETTERS OF SUPPORT

I.1 NASA Astrobiology Institute Letter

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

October 9, 2008

Regents' Professor Ron Greeley
Co-Chair Europa-Jupiter System Mission Study
School of Earth and Space Exploration
Arizona State University
Box 871404
Tempe, AZ 85287-1404

Dear Ron:

On May 17, 2007, I sent the following e-mail message to you, Karla Clark, Bob Pappalardo, and Mitch Sogin:

> *In a Dec. 12, 2001 letter to Dr. Michael Belton (Chair of the NRC Steering Committee developing the decadal strategy for Solar System Exploration), the NASA Astrobiology Institute placed a Europa orbiter in its highest priority mission category. The envisioned orbiter featured a payload capable of confirming the presence of a subsurface ocean, characterizing the subsurface, and obtaining remote sensing observations pertinent to Europa's surface composition, geological history, and biological potential.*
>
> *The current concept for the Europa Explorer mission, as presented on May 8, 2007 to the NAI Executive Council by Mitch Sogin for the mission Science Definition Team, appears to meet these measurement objectives.*
>
> *The NAI Executive Council reaffirms that such a mission is in its highest priority mission category for advancing the astrobiological goals of Solar system exploration.*
>
> *Sincerely,*
>
> *Carl Pilcher, Director of the NAI*
> *for the NAI Executive Council*

I can confirm that this continues to be the position of the NAI Executive Council.

With best wishes,

Carl Pilcher

Carl B. Pilcher, Director
NASA Astrobiology Institute

I.2 NASA Planetary Protection Officer Letter

----- Forwarded message from Cassie.Conley@nasa.gov -----
Date: Wed, 20 Dec 2006 15:59:25 -0500
From: Cassie Conley <Cassie.Conley@nasa.gov>
Reply-To: Cassie Conley <Cassie.Conley@nasa.gov>
Subject: Re: Europa Explorer/Titan
To: James.A.Spry@jpl.nasa.gov
Cc: john.d.rummel@nasa.gov, perry.stabekis-1@nasa.gov, Karla.Clark@jpl.nasa.gov

Hi, Andy --

Here's a preliminary take before writing up a formal response: based on the specifications for Europa given in NPR 8020.12C, the requirement will be: 'Probability of contaminating the Europan ocean less than 10^-4'. An orbiter, even if it crashes, is only Cat. III, but with appropriate cleanliness required -- for Europa there's no difference in requirement between Cat. III and IV (see below).

There are no detailed specifications on how to reach a probability of contamination less than 10^-4 -- however you can convince the PPS (and me) that you're there, you're OK. In practice, as there'll be a heat source you'll likely have to be fully sterilized when you crash -- at least all surfaces, since boxes may get crushed. We don't have an approved spec. for the radiation effects, but they will likely make sterilization of exposed surfaces unnecessary, so you might only have to worry about the interior portions of the spacecraft. The Juno people have done some calculations on sterilization by Jovian radiation during their mission, as a start.

This lack of clear requirements is why I don't like the whole 'probability of contamination' approach...Here's the full spec. from 8020.12C: A.3.1 Category III/IV (Europa Orbiters and Landers). Requirements for Europa flyby, orbiter, or lander missions, including microbial reduction, shall be applied in order to reduce the probability of inadvertent contamination of an Europan ocean to less than 1x10-4 per mission. These requirements will be refined in future years, but the calculation of this probability should include a conservative estimate of poorly known parameters and address the following factors, at a minimum:

1. Microbial burden at launch.
2. Cruise survival for contaminating organisms.
3. Organism survival in the radiation environment adjacent to Europa.
4. Probability of landing on Europa.
5. The mechanisms of transport to the Europan subsurface.
6. Organism survival and proliferation before, during, and after subsurface transfer.

Preliminary calculations of the probability of contamination suggest that microbial reduction will likely be necessary for Europa orbiters as well as for landers. This will require the use of cleanroom technology, the cleanliness of all parts before assembly, and the monitoring of spacecraft assembly facilities to understand the bioload and its microbial diversity, including specific problematic species. Specific methods should be developed to eradicate problematic species. Methods of microbial reduction should reflect the type of environments found on Europa, focusing on Earth extremophiles most likely to survive on Europa, such as cold and radiation tolerant organisms.

Happy holidays to you, too!
-- Cassie
--
Dr. Catharine A. Conley
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J. JGO ELEMENT ARCHITECTURE

Details not available for public release.

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K. MISSION OPERATIONS LESSONS LEARNED STUDY

K.1 Mission Operations Lessons Learned Applied to JEO

Category	Lesson Learned	OPFM Report Section	Additional OPFM Specifics or Comments
Mission Design / Architecture	Minimizing the amount of cruise science required of the operation including that opportunistic science taken during gravity assist maneuvers. However one can not discount the benefit of using these operations to train the team and test systems for eventual prime science operations.	§4.3	The JEO tour is being designed to optimize the trajectory design and minimize radiation impacts, while achieving primary science goals; secondary or optimistic science is not a driver in the current tour implementation.
		§4.6.2.1 §G.3.2	The Cruise Phase is intended to execute minimal cruise science, but will use at least one of the gravity assist flybys to demonstrate the readiness of the flight and ground systems for Tour and Europa operations.
Management & Organization	Reduce the complexity of the contention resolution process by choosing a single PI's. Streamline the arbitration process so that it need not involve the majority of the mission planners. A strong "super PI" or Project Scientist could oversee this process.	§D.2.2	JEO is not a PI led mission, but will have a Project Scientist that heads up the project science working group (PSG) that leads the science teams in setting up the overall science observation plan used for the development and operation of the mission. The distribution of the instruments into the 5 Science Teams allows the Science Team Leads to make decisions at a lower level, resulting in a more stream-lined decision process at the PSG level. The Project Scientist should be able to facilitate a streamlined arbitration process and resolve science conflicts.
	Co-locate mission planners or have representatives with decision making capability co-located to help reduce communications delays when iterating on plans.	N/A	Sequences will be developed by multiple teams, but will be centrally integrated and tested. The large scale science operations of a Flagship mission does not lend itself to having all of the participants co-located, but proven established practices and readily available information technology facilitate the necessary interactions in an efficient manner.
	Investigate ways to streamline the ITAR/TAA processes for working with foreign instrument teams/individuals.	Future Study	Although we stand behind this recommendation, it is considered beyond the scope of the current JEO Study.
Flight System Interfaces	Evaluate operational complexity and incorporate ease-of-use features for each primary flight system with special emphasis on G&C and C&DH flight processor interfaces as they are typically the most complex.	§4.4.2	By capturing use of previously flown designs, operational lessons learned from previous use can be applied to JEO, particularly in the C&DH/avionics, AACS, propulsion, and power subsystems.
		§4.4.3.3	AACS assumes tight control of the spacecraft body attitude in order to reduce undesirable interactions between the HGA and basebody controllers.
		§4.4.3.3.1	JEO flight software will use as a basis Cassini proven algorithms to suspend star identification to protect against bright body interference, as well as AACS algorithms for false star ID due to radiation effects and thrust vector control.
		§4.4.3.4	The flight software will incorporate the following functionality: Onboard ephemeris based pointing, onboard file system, pre-allocation of SSR space by ground rules, automated file playback for downlink, CFDP for telemetry, automated retransmissions for data dropouts, and CFDP for command uplink.
		§4.4.3.5	At this time, the baseline design assumes none of the instruments require data compression services from the C&DH subsystem. The C&DH sub-system possesses sufficient processing power and data bandwidth to perform such tasks and can be a future trade study in Phase A when instruments have been selected.
		§4.4.3.5	The SSR is located in its own enclosure and connected to both C&DH strings via redundant spacewire links. This allows the mass memory data to be shared between the primary and backup computers.
	As part of the next OPF mission design effort, formalize a joint operations and flight system design process for each proposed flight system to evaluate its design in terms of operability and quantify affect on total mission costs. Note: This process was ad-hoc on past missions and subject to the availability and capability of the specific operations team involved in the early stages.	Future Study	This recommendation refers to future design efforts. The JEO Mission Study 2008 certainly considered operability throughout the flight and ground systems design, although this process was not formalized beyond the Operations Lessons Learned Study Team.

Category	Lesson Learned	OPFM Report Section	Additional OPFM Specifics or Comments
	Consider such features as: coupled thrusters, automated momentum management, scan or gimbaled platforms that can significantly reduce conflicts between instrument types (fields and particles vs. pointing) or between payload and communications system, deterministic slew paths, ephemeris based pointing.	§4.2.1.1	Adequate mounting space on the nadir pointing platform facilitates common science pointing without articulating the spacecraft.
		§4.4.1.1	An articulated HGA helps to minimize spacecraft pointing conflicts.
		§4.4.3.1	Main engine is articulated using 2-axis gimbal based upon Cassini design.
		§4.4.3.3	The RCS is comprised of 16 thrusters capable of providing 3-axis control with redundant couples and vectored translation in the spacecraft X-Y plane.
		§4.6.2.3	Science data shall mostly be collected during downlink to Earth sessions; except for low rate instruments, Europa science observations will be taken when Earth is in view, enabling rapid downlink of high volume science data. During the Tour, additional memory is available to allow on-board storage of science data, lessening the need to downlink in real-time.
		§4.6.3	Key operability features of the flight system include: Reaction wheels and coupled thrusters for greatly reduced trajectory perturbations (resulting in reduced coupling of observation pointing design and attitude control activities); On-board ephemeris based pointing for rapid observation updates; Independent sequencing for individual instruments and spacecraft activities (acq and return, health, etc); File based SSR and CCSDS protocols for file management and delivery; Autonomy for fault protection and science operations.
		§4.6.3	The flight system will allow the continuous pointing and operation of science instruments while communicating with the Earth (via 2-axis HGA gimbal).
		§4.6.6.1	Coordinated observations will be sent to the orbiter and executed via ephemeris driven on-board sequencing software.
		§4.6.5.2 §4.6.6.1	Science observations and data downlink will largely be decoupled through the use of the gimbaled high gain antenna.
	Ensure adequate power margins and consider predefined payload modes/configurations to simplify planning. Favor power over mass in use of PMD's, coupled thrusters, proper instrumentation.	§4.4.2.7.4	Current JEO design carries 33% margin on the CBE power values and includes batteries to accommodate peak power modes such as satellite flybys.
		§4.4.5.2	The Four vs. Five MMRTG trade study concluded the removal of one MMRTG from 5 to 4 would significantly reduce the science return and severely reduce the trade space flexibility in design and operational capabilities.
	Incorporate a file system and pre-allocated (by ground rules) SSR space. Sufficient margins for command and SSR memory. Use automated file playback software and CFDP minimize SSR management and to have automated retransmission for data dropouts. Consider CFDP for command uploads and potential use for telemetry.	§4.4	The data handling and processing architecture is capable of performing all science and engineering functions. Data storage space has been pre-allocated for orbital science use.
		§4.4.3.5 §4.6.1	Retransmission of downlinked data is not a JEO requirement. JEO will retransmit data to the best extent possible during the Tour Phase but not during the Europa Orbital Phase.
		§4.4.3.4	The flight software will incorporate the following functionality: Onboard file system, pre-allocation of SSR space by ground rules, automated file playback for downlink, CFDP for telemetry, automated retransmissions for data dropouts, and CFDP for command uplink.
		§4.4.1	JEO has 1 Gbit for science data storage at Europa orbit phase which will experience the total mission radiation environment, with additional science data storage capability (16 Gbits) for the Jupiter tour phase which is roughly the first half of the radiation dose. Since the larger science data storage needs are during Jupiter tour only, softer components will be used for cost and resource efficiency. Larger memory capacity in orbital phase is limited in usefulness because this phase is downlink bandwidth limited.
		§4.6.6.1	The SSR holds coordinated target observation data until it can be downlinked (along with the other data collected). On average, less than one target per orbit will fit in the data stream. Two coordinated targets can be collected at a time for delayed downlink. The IPR full resolution targets are 900 Mb and only one of these can be collected at a time.

Category	Lesson Learned	OPFM Report Section	Additional OPFM Specifics or Comments
		§4.6.5.2	Data volume will be allocated and factored into science sequences. Margins and flexible sequencing strategies will allow DSN track times to change without disrupting science observations. With time to process and space in the SSR to work with, data reduction techniques such as windowing or selective downlink become possible.
	Strive for commonality in payload instrument telemetry and command interfaces.	§4.8.4	Future trade studies on the payload on-board data processing architecture will consider this recommendation within the specific context of JEO and its selected payload.
		§4.4.3.5	The 1553 bus carries both commands to and data from the low-speed instruments. The high-speed instruments and the mass memory are connected to the C&DH subsystem via spacewire links (point-to-point connections) provided by the system flight computer. These spacewire links carry both the commands to the instruments and the data from the instruments.
		§4.6.4	JEO provides a standard instrument GDS interface and tools to all instrument providers.
Science/ Mission Operations	Incorporate a planning process that is efficient enough for JEO/Titan orbital operations, and modify as necessary for tour operations. Consider cost constraining planning tools (i.e., market based and priority based systems).	§G.4.3.1	The Outer Planets Flagship Mission Science Operations Concept Study Report (Paczkowski, et al. June 2008, JPL D-46870) was conducted to leverage the results of the Operations Lessons Learned Study into recommendations for a science operations concept that could be used for the next flagship mission.
		§4.4.2.7.1	JEO will employ a market-based system approach for allocating resources (e.g., mass, power, data rate, budget, etc.) for instrument development, as was successfully done on both Cassini and the Terra (EOS AM-1) Platform. This approach will be explored for use in operations as well.
		§4.6.4	Operate the spacecraft as a system and not a collection of subsystems
		§4.6.4	Use early gravity assists to test and demonstrate science and instrument interfaces and operations
		§4.6.4	Develop planning process that is efficient for orbital operations, but plan to update as required for tour.
	Develop process that minimizes the number of planning iterations, bounds time allocated to planning each significant event, and incorporates the principle of "good enough".	§4.10	JEO science and operations planning shall be flexible and streamlined to not only facilitate the mission objectives, but foster contingency response and recovery with minimal impacts.
		§4.6.4	Science and mission planning tools to enable short (1 week) planning cycles.
		§4.6.4	The Mission Operations System design incorporates the ideas to constrain planning time, model flight constraints, allocate contentious resources, develop science observation constructs for coordinated multi-instrument activities, and implement iteration limitations in the science planning process.
		§4.6.6.1	The short planning duration accommodates large ephemeris errors based on poor gravity field knowledge early in the orbiting mission. As mapping progresses, the short planning cycle enables the adjustment of data collection profiles to avoid redundant coverage or recover observation opportunities lost due to telecom link outages, spacecraft engineering events (e.g., OTMs), or safing events. Routine engineering activities such as OTMs, reaction wheel momentum desaturation, and health and safety activities will be planned and uplinked to the orbiter on a weekly basis, coinciding with mapping sequence uploads.
		§4.6.6.1	Coordinated target observations will be selected, by ground software, for one to two day planning cycles. Only targets predicted to pass under the nadir track of the orbiter will be considered for selection.
	Develop an integrated planning and sequencing tool based on model-based engineering and state analysis that would be used throughout the project lifecycle.	§4.10	Integrated sequencing tools enable fault recovery while maintaining optimal science collection.
		§4.6.4	Model based engineering and state analysis tools to be used from concept development through operations

Category	Lesson Learned	OPFM Report Section	Additional OPFM Specifics or Comments
		§4.6.4	Integrated spacecraft state analysis tool that enables fewer people to safely operate the spacecraft; Planning tools shall support early design and operations development
Ground System Interfaces	Incorporate information management systems (i.e., CIMS) for entire team's remote access to planning products, telemetry, command sequences, and action item tracking.	§4.6.4	The Mission Operations System design and implementation includes a rich online collaboration system to support remote planning and operations support
	Have a PI set priorities. Have ground system and planners implement those priorities and optimize supporting processes as needed.	§4.6.4	Treat all trades (spacecraft, operations, science, etc.) as mission trades to work toward best cost/risk for the overall mission (rather than optimizing an element and adding significant cost/risk to another without making the conscious trade).
		§D.2.1	Project System Engineer will continue into Phase E to ensure that a strong trade process is in place and executed.
	Incorporate resource modeling and flight constraints models in early in planning process for early identification of problems. Permit science planners access to models of similar fidelity as what MOC uses for end validation. Make accessible to distributed team.	§4.4.4.1	JEO will have 3 primary system testbeds: 1 single-string and 2 dual-string. The Mission System Testbed (MSTB) is a dual-string high-fidelity testbed that is dedicated to mission system tests, operations, and science planning in Phase E.
		§4.6.4	Spacecraft analysis tools used by mission planners and system analysts made available to science teams (early) to ensure all players are using the same tools when planning
	Incorporation of flight system faster than real-time software models for resource and constraints checking (i.e., SoftSim or Statesim).	§4.4.4.1	A high fidelity model-based flight software simulation capability (S-Sim) is baselined.
	Adoption of unattended pass operations for non command passes. Limit number of command passes. Rely on automated limits and alarms checking versus manual, by FC or ACE.	Future Study	The current JEO Study is too early in the development process to define this level of detail of ground system operations. The technology required to implement this recommendation is readily available, but will likely improve by the time the JEO ground system will be designed and implemented.
	Unattended (automatic) radiation of non critical commands	Future Study	JEO will implement the best proven operational practices available at the time, working within the project's accepted risk posture.
	Streamlined process for late knowledge updates including ephemeris and time shifts.	§4.6.4.3 §4.6.7	Recent experience from MRO and MER has shown that rapid data delivery and quick look processing as well as rapid decision making and activity planning are possible for the planning schedules needed by JEO.
		§4.6.4.3 §4.6.7	MER has shown that one day turn around of science products to next day activity plans is possible over mission lifetimes as long as or longer than JEO's.
	Consider incorporating real-time automated assessment tools and post event trending tools (i.e., MRO).	Future Study	JEO will implement the best proven operational tools available at the time, leveraging those previously used on past missions in a cost effective manner.
Testing and Evaluation	Adopt logical testing steps with software tools catching problems upstream (with faster than real-time software) of more sophisticated (real-time hardware) simulations downstream.	§4.4.4	JEO will verify and validate the mission system to ensure it meets specifications and is capable of accomplishing the science objectives. A combination of system analysis, modeling and simulation tools, engineering development unit hardware and testbeds, flight software testbeds utilizing simulations and engineering model (EM) hardware, flight system functional/environmental testing ATLO and readiness tests will be used.
	Incorporate software tools, scripts, to aid in H/W simulator setup and configuration control using planning system inputs for starting conditions. Use checkpoint and restart process for H/W simulations.	§4.4.4.1	Simulators will be built to allow for interchangeability between software models and hardware EMs in the "hardware-in-the-loop" testbeds in such a way that is transparent to the flight software. This will enable the ability to use the same test scripts whenever the testbed models are interchanged with EMs.
		§4.4.4.1	The simulation environment interfaces and procedures will be compatible with those of the hardware testbeds.
	Automate syncing of S/W sim (and H/W sim tools) with flight for proper configuration control. Perform periodic audits.	Future Study	The current JEO Study is too early in the development process to define this level of detail.

Category	Lesson Learned	OPFM Report Section	Additional OPFM Specifics or Comments
	Incorporate tools for post simulation data processing and distribution - reduce labor and time requirements.	Future Study	The current JEO Study is too early in the development process to define this level of detail.
	For geographically distributed team members, provide easy access to data for each reviewer. (i.e., MRO has web based results outside flight ops network)	Future Study	JEO will implement the best proven practices available at the time, leveraging those previously used on past missions (e.g., Cassini, MSGR, and MRO) in a cost effective manner.
	Have good validation of software simulators so they can be used in place of hardware simulators. Incorporate fidelity into software models match hardware simulations as closely (and quickly) as possible.	§4.4.4.1	There will be a simulation environment that can off-load the hardware-in-the-loop testbeds as well as using the EM integration effort to help enhance evaluation of model fidelity.
	Use real-time simulators by exception (only as needed), faster than real-time software for all nominal operations. Ensure adequate numbers and fidelity of real-time hardware simulators during each phase of the mission.	§4.4.4.1	Only the MSTB will have hardware versions of the engineering subsystems; they will be simulated on the other testbeds. The MSTB can utilize either software or hardware versions of the engineering subsystems.

K.2 Mission Operations Lessons Learned Study for The Next Outer Planets Flagship Mission (OPFM)

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K.2.1 Executive Summary

As an effort to reduce operations costs associated with the next Outer Planets Flagship Mission (OPFM), Jet Propulsion Laboratory (JPL) tasked the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to lead a study of the Cassini mission operation cost drivers and those of other planetary space missions, including two missions currently operated at APL, MESSENGER and New Horizons, and JPL's Mars Reconnaissance Orbiter.

The study team derived a comprehensive list of space mission operations costs drivers and through the evaluation of each mission and found the following to be the top cost drivers:

a. Mission architecture: Includes mission trajectory, type, duration, number of flybys or gravity assist maneuvers.
b. Management and project organization: Considers organization structure, geographical boundaries, and organization conduct.
c. Flight system interfaces:

   Systems: Includes number of flight vehicles, system redundancy, complexity of fault protection systems, number of engineering calibrations.

   Guidance and control system design: sensors, actuators, control modes, pointing constraints and accuracy, momentum management scheme, number of tunable parameters, articulating mechanisms.

   Command and data handling: Number of fight software applications, stored command management or scripting capabilities, type of data recorder, data storage margin, memory margin for commands, number of tunable parameters, data identification and tracking.

   Payload: Number and type of instruments, degree to which instrument processor interfaces and capability, number of instrument mechanisms.

d. Science operations: Includes science mission duration, science team structure, number of interfaces between instrument teams, number and density of science observations, type of observations, level of post launch science operations development, instrument data volume, data latency requirements, number of instrument and calibration and maintenance operations, data quality requirements.

Each of the missions studied were characterized for their relative complexity in each of the above major categories and other minor ones, and compared against the actual (or planned, where applicable) staffing levels of each mission at key mission phases. The results of this analysis are charted in Figure K.2-1.

This plot shows New Horizons, MRO, and

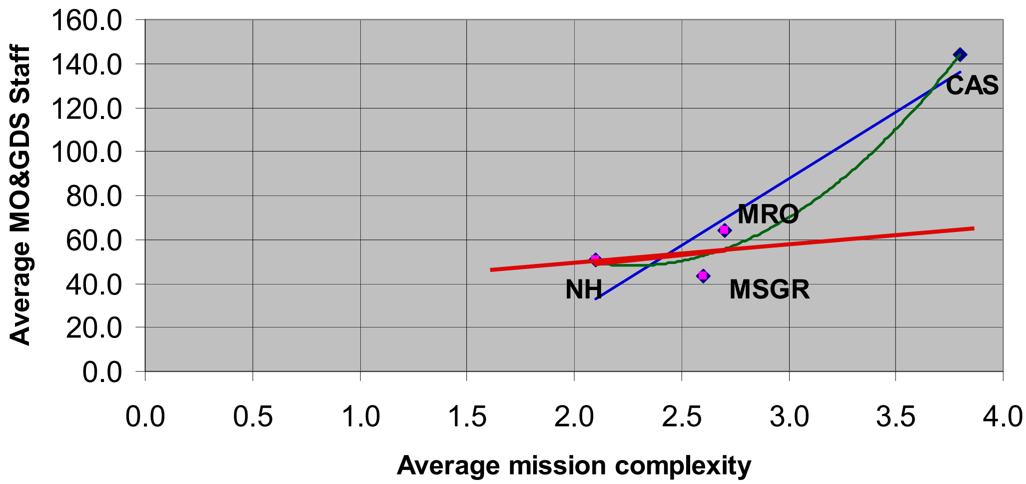

Figure K.2-1. Mission ops team size vs. average mission complexity.

MESSENGER are relatively near each other on the complexity vs. cost grid, while Cassini is in a region on its own in terms of both complexity and cost. A least squares fit of the four data points is shown as a blue line, the green line an exponential fit. Both CAS and NH are above the linear fit while MSGR and MRO are both below it indicating they may be the most efficient of the four operations. MESSENGER falls the furthest below.

A least squares fit of the MRO, MESSENGER, and New Horizons data points is shown as the red line. While one would not expect a simple linear increase in cost as complexity rises significantly (complexity across systems can have a compounding affect) it can serve as a guide for the lower bound of the expected cost increase. Conversely, the exponential fit to actual costs, including Cassini (green line) can serve as an upper bound for expected operations cost.

The study's most valuable end product is the numerous, tangible recommendations for reducing the cost and complexity for future space operations, including the next OPF. Recommendations are described in detail in §K.5 and organized by cost driver categories:

- Mission Design/Architecture
- Management and Organization
- Flight Systems Interfaces
- Science Operations
- Ground System Interfaces
- Testing and Validation

Many are based on successful approaches utilized on the missions under study. Application of those recommendations to the development and operations phases will permit future operations to be conducted in a significantly more efficient manner.

K.2.2 Introduction

In December 2007, NASA's Planetary Science Division announced its intent to conduct Phase-2 studies for the next OPFM. JPL held the overall responsibility to conduct the associated OPF Phase-2 studies for Titan and Europa destined missions. One of the several tasks identified in the Statement of Work from NASA was to perform a Mission Operations Lessons Learned Study (referred to here on as the LL Study) with special focus on Phase E cost drivers and operations. The intent of the LL Study was to safely lower Phase E operations costs from those traditional to this class of mission. Mark Holdridge (APL) led the study with a team formed from several institutions, including APL, JPL, and ARC. Consequently, a LL Study was kicked-off in late February 2008 and given the following task:

> *"Capture relevant lessons learned from the past and present operational missions, including Cassini, in the area of Phase E cost drivers and operations. Document the collective experience base of both APL and JPL from a variety of missions conducted by the two Centers that covers a spectrum of mission complexity and implementation modes such as Cassini, MESSENGER, STEREO, New Horizon and MRO . Examine the implementation approach of relevant missions in the areas of GDS, MOS, Science Operations Systems, and flight/ground functionality and performance allocation. Identify the cost drivers and assess related risk postures. Provide briefing to the MOS/GDS/Science Center task of the EJSM and TSSM OPF teams in those areas addressing cost, performance and risk and recommendations for approaches to minimizing cost. Document results in a written report. Provide write-up to the final Mission Concept Report."*

The joint JPL/APL/ARC study team consisted of experienced deep space mission planners, operations leads, and analysts knowledgeable of APL's planetary mission operations and of JPL's Cassini and Mars Reconnaissance Orbiter (MRO) operations processes; where additional information was needed, the LL study team sought it from the mission team. The study proceeded with the following subtasks identified to reach the goals of the study:

Study Plan

1. Develop a set of space mission operations cost drivers and organize into major categories and subcategories
2. For each cost driver category, define measurables that can be used to assess the degree to which each driver affects each operation. Define any supplemental information also needed to characterize each mission.

3. Interview each operation under study (Cassini, MRO, New Horizons, and MESSENGER) and obtain metrics and supporting information that characterize each operation and measure its complexity or difficulty level related to each cost driver and to each other.
4. Compile MO&GDS staffing levels for each mission, pre- and post-launch, by similar WBS elements.
5. Data Analysis and recommendations.
   5.1. Review all mission characteristics and compare and contrast each operation in terms of relative complexity and associated cost (staffing)
   5.2. Identify those cost drivers that had the most affect on each operation.
   5.3. Develop a set of recommendations designed to lower total mission operations (and total mission) costs for next OPF mission.

Despite being included in the task statement, time and resource limitations precluded the team assessing relative risk postures and comparisons of each missions risk stance. While this alone did not affect identification of efficient operations techniques, it prohibited qualifying actual mission costs in terms of its risk stance.

It should be noted that many of the individuals supporting the LL Study have also worked on the missions under study (expediting the data collection process) and some were serving in systems engineering related capacities on the either or both the Titan or Europa OPF study teams, thereby facilitating the transfer of lessons learned to the respective design efforts.

K.2.3 Mission Operations and Ground Data System Cost Drivers

The LL Study Team formulated a list of major categories of space mission cost drivers and expanded each to formulate a complete criteria by which operations can be evaluated and relative complexities assessed.

A summary of the major cost drivers identified and associated measurables are included below. Each operation was assessed individually using these criteria.

a. Mission architecture: Includes mission trajectory, type, duration, number of flybys or gravity assist maneuvers.
b. Management and project organization: Considers organization structure, geographical boundaries, organization conduct.
c. Flight system interfaces:
   - *Systems*: Includes number of flight vehicles, system redundancy, complexity of fault protection systems, number of engineering calibrations. Also includes operations complexity of each spacecraft subsystem.
   - *Guidance and Control System Design*: sensors, actuators, control modes, pointing constraints and accuracy, momentum management scheme, number of tunable parameters, articulating mechanisms.
   - *Power System Design*: power system margin, energy management complexity, power generation (solar vs. nuclear).
   - *Propulsion System Design*: propellant margins, operations constraints limitations, propulsion type (mono, bi-prop, hybrid, Ion), couple vs. decoupled thrusters.
   - *Thermal System Design*: number of thermal constraints to be managed by operations team, level of onboard thermal control automation, special data analysis or planning tools required.
   - *Command and data handling:* Number of flight software applications, stored command management or scripting capabilities, type of data recorder (volatile vs. non-volatile, use of file system or other onboard data management techniques, including CFDP), data storage margin, memory margin for commands, number of tunable parameters, data identification and tracking.
   - *Communications:* Downlink bandwidth requirements and overall margins, number of supported data rates,

ability to add new data rates in phase E, relay or multi-vehicle communications, fixed or gamble antennas, radiometric tracking requirements.

- *Payload:* Number and type of instruments, degree to which instrument processor interfaces and capability vary, number of instrument mechanisms.

d. Science operations: Includes science mission duration, science team structure, number of interfaces between instrument teams, number and density of science observations, type of observations, level of post launch science operations development, instrument data volume, data latency requirements, number of instrument and calibration and maintenance operations, data quality requirements.

e. Ground systems interfaces: Sizing of S/W maintenance and enhancement effort, centralized or distributed data processing and distribution centers, standard vs. specialized data products, heritage of ground system, hardware simulator number and fidelity, number and type of workstations,

- *Mission planning:* Level of automation and special S/W tools, number and type of flight constraints, resource constraints and margin availability, level of command block reuse, onboard sequencing capabilities (use of onboard macros, event driven commanding …), command sequence planning process and number of iterations.
- *Mission control:* Level of automation of real-time flight control operations for both assessment and commanding functions, density of DSN supports required, number of contingencies to plan for.
- *Mission assessment:* Level of automation of trending and assessment tools, data trending and review requirements.

f. Testing and validation: Includes ease of systems to validate command sequences early in sequence development process, level of scripting or automation in configuring and operating test environment and assessing test results. Extent to which real-time (hardware) simulators used vs. faster than real-time (software) simulators.

Separate evaluations of each mission's complexity relative to the above cost drivers can be found in the upcoming sections.

K.2.3.1 MRO Mission Summary and Primary Cost Drivers

K.2.3.1.1 Mission Summary

The Mars Reconnaissance Orbiter (MRO) was launched on August 12, 2005 on an Atlas V401 launch vehicle from Cape Canaveral Air Force Station and arrived at Mars on March 10, 2006. MRO carries a rich set of science instruments to Mars to survey the global and regional aspects of mars in addition to special targeted observations. There is also a set of engineering instruments providing optical navigation, Ka-band telecommunication and ultra-high frequency (UHF) relay services.

After a seven-month interplanetary cruise, MRO was captured into a 35.5-hour orbit around Mars. On March 23, 2006 MRO began its aerobraking phase and reduced its orbital time to less than two hours to reach the desired ascending node time of 3:00 pm Mars Local Time. Due to its orbit geometry and science requirements, the MRO aerobraking period involved 5 months of highly intensive operations period.

In August 2006 after successfully completing the aerobraking phase, a set of maneuvers were conducted to finalize the Primary Science Orbit (PSO). A set of transition activities were carried out, including engineering and science instrument calibrations and a weeks worth of "science practice" just prior to solar conjunction. During the 2-year primary science phase MRO will return at least 34 Tb of science data and a maximum of over 200 Mb per day. MRO will collect most of its science data in a constant nadir pointing mode, however, high resolution targeted data at angles of up to 30 deg off-nadir will be collected up to twice per orbit.

K.2.3.1.2 MRO Primary Cost Drivers

Management and Project Organization

The MRO team is comprised of six organizations: JPL (which manages MRO), Lockheed Martin Space Systems, Applied Physics Lab, University of Arizona, Malin Space Science System, and the Italian Space Agency (ASI). Together this comprises a total of twelve teams during the post-launch phase. The majority of mission operations teams are co-located at JPL and at LMSS in Denver, Colorado. Science operations teams are located throughout the country and with the cooperation of ASI.

Some orbiter mission operations team members, tools and services are shared across projects in a multi-mission organization located at both JPL and LMSS. This sharing of infrastructure and workforce offsets potential cost increases due to distributed operations.

Orbital operations requirements translated into two parallel teams where one worked on the three-shift a day aerobraking operations and the other worked on the planning, development and testing activities.

Flight System Interfaces

The MRO spacecraft is single fault tolerant with most orbiter subsystems block redundant and cross-strapped. Attitude control is 3-axis stabilized with high precision pointing and fully gimbaled solar arrays and high gain antenna. The flight computer is a RAD 750 flight processor with ample memory resources and high throughput components for a throughput margin of ~70%. A series of on-board software constraints and compression and formatting processes assure high throughput rates and isolation of instrument command and flight software errors to single instrument data streams. The science data collected is stored in the 160 Gb on-board solid state recorder (SSR). The SSR is formatted as a high speed raw data input buffer and a large storage location for formatted data awaiting downlink.

MRO communicates with Earth via the DSN at a large variety of rates up to 6 Mbps and utilizes either Reed-Solomon or Turbo encoding schemes. MRO downlink also utilizes the CCSDS File Delivery Protocol (CFDP) to help identify data gaps and facilitate retransmission if needed. With the current Deep Space Network (DSN) contact schedule of 19 eight-hour tracks per week, the Baseline mission plan is for MRO to return 34 Tb of raw science data during the two-year primary science phase.

Eight scientific and two engineering investigations were selected by NASA. Four science investigations are led by Principal Investigators (PI) with PI provided instruments, two use facility instruments and have appointed team leads, and two are investigations led by PIs that make use of engineering systems on the orbiter. In addition, two engineering demonstrations, led by PIs and a UHF relay radio system are included as payloads.

The payloads are:

- Mars Color Imager (MARCI)—PI provided
- Mars Climate Sounder (MCS)—PI provided
- High Resolution Imaging Science Experiment (HiRISE)—PI provided
- Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)—PI provided
- Context Imager, (CTX)—facility instrument with appointed team lead
- Shallow (Subsurface) Radar, (SHARAD)—The Italian Space Agency (ASI) provided this facility instrument. The SHARAD investigation team includes members from both ASI and NASA.
- Gravity Science Investigation—PI led, uses orbiter telecom system
- Atmospheric Structure Facility Investigation—PI led using accelerometers and other orbiter telemetry during aerobraking.
- Optical Navigation (Camera)—PI led, operated during cruise phase only
- Ka-band Telecommunication demonstration—PI led, demonstrated in cruise phase, partial failure prevents prime mission operations
- Electra, UHF communications and navigation package—operated by orbiter operations teams in support of Mars surface missions.

Ground Systems Interfaces

The MRO ground system functions are provided by the following organizations:

- Deep Space Network—DSN provides the data capture and command delivery functions. Data capture functions include not only the traditional telemetry processing such as frame sync and packet extraction but also the CFDP processing.
- Multi-mission Ground System Services—MGSS provides telemetry display and channel processing, sequence generation

and science data server for raw data distribution, and navigation software.

- MRO project—MRO provides facilities at JPL and LMSS. These include unique science target planning software, spacecraft performance and analysis software; and multi-mission software adapted to support MRO ATLO activities. In addition, MRO provides hardware procurement and installation, and integration of the software and hardware into an operable system.
- Science teams—Each science team provides facilities, software, and hardware for their own command generation and standard and special data processing.

Mission Operations

The MRO mission operations system (including the ground data system) is developed and managed by JPL across the distributed organizations. During the development phase the Mission Operations System provides: system engineering, including both MOS and GDS system engineering functions and coordination of the flight teams and data system development activities; MOS team development for all the flight and science teams during phase E; and data system development functions in support of flight and science team needs

During the operations phase the organization is structured into teams which cover all aspects of a flight project. Teams include the Flight Engineering Team (at both JPL and LMSS), Mission Planning and Sequencing Team, Navigation team, Science Operations Teams (at JPL and remote sites), and the Ground Data System team. Additionally, a Chief Engineer is appointed to coordinate all system engineering operations as well as lead anomaly responses.

Science Operations

During the Primary Science Phase (PSP), the MRO operations teams were presented with two major challenges—unprecedented high data rate and data volumes, and complex science planning and resource sharing. Each of the science instruments had its unique requirements for global mapping, regional survey, and targeted observations. Some instruments preferred nadir-only observations, while others required off-nadir observations (especially for stereo viewing). The requirements from these instruments presented a significant challenge for the design of a complex science planning and resource allocation process. In addition, because of the high resolution instruments, the process for maintaining required navigation accuracy was challenging.

MRO science operations are conducted in two parts. The teams, either individually or in cooperation with other teams, select their off nadir and coordinated target observations. The Payload Operations Support Team at JPL, following predefined procedures, integrates the science team observation requests to produce a combined and conflict free list of targets. The target list is uplinked to the orbiter for ephemeris based timing and pointing execution. Each instrument team provides all of its own command sequences and routes them to the orbiter via automated uplink processes. The teams use their remaining observation time and data resources to build non-targeted, nadir based observation sequences that are sent to the orbiter as needed.

Cost Driver/Mitigators Summary

- Complex resource allocation for pointing and data volume is a significant driver mitigated by on-board ephemeris based timing and pointing, and by centralized coordination and allocation of pointing and data resources.
- Extremely large data volumes drive cost by allowing large numbers of observations by a large and complex payload and by the need for high volume data processing and distribution systems.
- The large numbers of observations are mitigated by the allocation and coordination processes.
- The data processing and distribution costs remain high but are mitigated in part by common raw data distribution methods and legacy systems for some instruments.

K.2.3.2 Cassini Mission Summary and Primary Cost Drivers

K.2.3.2.1 Mission Summary

The Cassini mission to Saturn, a joint endeavor of NASA, the European Space Agency and the Italian Space Agency is a flagship mission to orbit the Saturnian system carrying a diverse set of 12 science investigations. Also onboard Cassini is a scientific probe called Huygens that was released from the main spacecraft to parachute through the atmosphere to the surface of Saturn's largest and most interesting moon, Titan, which is shrouded by an opaque atmosphere. Titan's atmosphere includes organic compounds leading scientists to believe that the moon may be like a frozen vault of conditions similar to those on Earth before life began. The Cassini orbiter also uses imaging radar to map Titan's surface.

Launched in 1997, Cassini's interplanetary trajectory took 7 years to reach Saturn, including two gravity assists from Venus and one from Earth. The prime mission of 4 years included 45 encounters with Titan, 9 with icy satellites, 74 Saturn periapses as well ring crossings. The extended mission, which will be starting in 2009, will provide additional flybys of Titan (26), icy satellites (9), and Saturn periapsis and ring crossings (59).

K.2.3.2.2 Cassini Primary Cost Drivers

It should be recognized that Cassini, as a flagship mission, is the most complex mission architecture out of the four studied. The in-situ ESA Probe accommodation, multiple of flybys and ring crossings and duration of the science mission is significantly more operationally demanding than the other missions being analyzed in this study.

Management and Project Organization

The Cassini management is co-located at JPL, with eight remote science team participating, including one international one. Details of the various remote operations sites are listed in the *Science Operations* section below. Since Cassini is a directed flagship mission, the science investigations were selected via NASA AO. There are 12 instrument PIs and interdisciplinary science investigations. They each have specific mission objectives to meet but need to work closely together given the interactive nature of the operations. This requires extensive meetings to agree on negotiated activities and priorities for each event.

The operations teams include Spacecraft Operations (SCO), Navigation, Science & Uplink (SP and ULO) and Mission Support & Services (MSS). There is no mission manager; the team chiefs carry those responsibilities.

Finally, having a large budget encouraged doing many new things to improve the GDS and project development process that usually translated into greater costs. The larger budget also drove a need to have greater oversight that has its own increased cost.

Flight System Interfaces

Cassini is a three-axis stabilized spacecraft outfitted with 12 diverse science investigations. The instruments often have multiple functions, equipped to thoroughly investigate all the important elements of the Saturnian system. Cassini's remote sensing instruments provide data for global studies of Saturn's atmospheric temperatures, clouds, and composition, as well as studies of Saturn's rings and its many natural satellites.

The spacecraft communicates through body-fixed antennas: one high-gain and two low-gain, and is powered by three Radioisotope Thermoelectric Generators (RTGs) providing ~700 W at the end of prime mission. The Attitude Control Subsystem (ACS) uses three Inertial Reference Units (IRUs) and a Stellar Reference Unit (SRU), or star tracker, to determine both the spacecraft's position and orientation. Reaction Wheel Assemblies (RWAs) are one of the two systems used to provide pointing control of the spacecraft in flight (with the thrusters of the Propulsion Module Subsystem as the other). The thrusters, along with a main engine, also perform orbit trim maneuvers (OTMs) to keep Cassini following the chosen trajectory around Saturn.

The science instruments are all body-mounted; a scan platform was deleted as a cost-saving measure during spacecraft design and integration. Thus the entire spacecraft must be rotated for any one instrument to achieve a desired pointing attitude, and also to point the high gain antenna at Earth for communications. Data taken by the instruments is stored on two solid-state recorders (SSR), with a total capacity of 4.6 gigabits. The spacecraft utilizes the Deep Space Network to downlink, on average, over one gigabit of data daily.

Several significant design features drive Cassini's operations cost. Some of these are unique to the mission and the circumstance of the mission, but some are lessons that are applicable to future missions, such as the Outer Planets Flagship mission. This summary will highlight both.

The spacecraft was not designed for maximum operability. One of the key design cost drivers on Cassini is the fact that all 12 of the instruments and high gain antenna are body fixed. While some of the collaborating instruments are mounted to observe simultaneously (for example, the optical remote sensing [ORS] instruments are co-boresighted, along with the Radar), there are still the fields and particle instruments that require different look directions and the HGA that needs to point toward Earth during daily downlink DSN passes. In addition, the ORS observations also require scan modes and mosaics by spacecraft pointing that conflict with each other.

Further complicating the already involved planning for spacecraft pointing, the reaction wheel usage for each science observation activity must be analyzed by special tools for potential RWA degradation, and steps in the planning process have been added for the turn profiling evaluation. That analysis feeds back into the observation design, which is then reworked with the science planning teams as necessary in order to maintain a sustainable science and engineering performance.

Another design impact on operations has been the uncoupled thrusters. Every time thrusters are fired, including the routine RWA unloadings, the Navigation team has to model and measure the resulting ΔV in its orbit determination. Again, special analysis tools and steps in operations have been developed to accommodate this design implementation. Unplanned ΔV increases the Navigation Team's workload.

The 2.3 Gb mass memory storage element, a solid-state recorder, does not have a file system. Science data accounting was labor intensive due to the memory architecture (which was typical of the architectures of the time for spacecraft). While this design feature has not significantly increased the size of the team, the data management on Cassini complicates the operations and adds to the process of planning and integrating a sequence.

Science Operations

On a typical day in the Cassini tour, the spacecraft collects science data for 15 hours by orienting the spacecraft at a variety of targets. One instrument at a time dictates the pointing of the spacecraft, and other instruments may "ride along" and collect data at the same time. Collaborative data collection is often negotiated between the science teams. The remaining 9 hours is spent in one block on Earth-point, downlinking the data. Control of the spacecraft is done, for the most part, from autonomous sequences stored onboard the spacecraft. Spacecraft sequencing uses a combination of centralized commands (for control of the system level resources) and instrument commands to conduct activities and maintain the health and safety of the spacecraft. The spacecraft is flown with sufficient margins to allow the instruments to operate fairly independently from each other, and with a minimum of real-time ground intervention.

The operation of the Cassini spacecraft is centered at the JPL in Pasadena, California. The Huygens Titan Probe was operated from the Huygens Probe Operations Centre in Darmstadt, Germany. The Cassini mission planning, real-time operations, science planning/sequence integration, navigation, and spacecraft operations teams, as well as the program management, are co-located at JPL. The science teams are led using a distributed operations structure to allow scientists to operate their instruments from their home institutions, which are spread across different states and even different countries. Cassini instruments that serve multiple investigations are called facility instruments. Facility instruments were provided by JPL, NASA Goddard Space Flight Center or by ASI. A JPL team called the instrument operations (IO) team operates the facility instruments, except for INMS. Instruments that serve individual investigations are provided and operated by a Principal Investigator (the INMS is operated like a Principal Investigator instrument). For teams not resident at JPL, an Investigation Scientist or dedicated member of the Instrument Operations team assists in timely production and review of sequence products. A list of the remote ops team sites:

- JPL: RSS, RADAR, Science Planning, Mission Planning, Uplink Ops, S/C ops, Navigation, IO, Management
- Boulder, CO: ISS, UVIS
- Tuscon, AZ: VIMS
- San Antonio, TX: CAPS
- Iowa City, IA: RPWS
- Ann Arbor, MI: INMS
- Maryland: CIRS, MIMI
- London, UK: MAG
- Germany: CDA, Huygens

Distributed operations places observing decisions, including generation of instrument internal subsequences, in the hands of the science teams. The implementation of distributed operations for the Cassini mission is achieved through computers, computer-resident software and communication lines provided by JPL to the remote sites, as well as science participation in the uplink (mission planning, sequence development) and downlink (Principal Investigator instrument health monitoring) processes. Cassini uses virtual teams for mission planning and sequence development. These teams bring together people for the development of a given product. The product generation for a particular sequence block (covering 4 weeks of activity, typically) takes ~20 weeks to generate, requiring multiple virtual teams to be working at any one given time. Also, science data accounting was labor intensive due to the memory architecture (which was typical of the architectures of the time for spacecraft).

Instrument development for operability plays a key role in cost of science operations. Some areas that Cassini instruments could have improved for better ease of operations: 1) more complete development of instrument flight rules before launch so that the operations team can more realistically plan activities beforehand, 2) better instrument accommodation to minimize impacts on the operations of the other instruments, e.g., radiator placement. Areas that Cassini instruments did provide for operability include: 1) data compression internal to instrument for a cleaner interface between the spacecraft team and the instrument team, 2) some of the instruments have internal sequencing memory for storing instrument commands for the upcoming sequence to further decouple themselves from spacecraft resource management, and 3) for real-time non-interactive instrument commands, some of the instrument can also bypass the sequencing process by using the ASP tool.

Ground System Interfaces

Cassini is the earliest of the 4 missions studied in this report, with Phase B starting in 1989, with capabilities and technologies of that time. Many of the capabilities now used in more recent missions such as MRO, MER, MESSENGER and New Horizons were not available when Cassini was being designed and implemented. Although some features, such as web-based tools have been incorporated, the Cassini design largely reflects decade-old systems and architectures.

Many of the ground software planning tools were immature or unavailable at the start of the science planning for the prime mission. This resulted in homegrown tool development at the instrument sites and across the ops teams. System engineering of these types of ground software tools were lacking without sufficient resources need to be applied to Phase C development, so that the tools are not integrated and require the responsible teams to run them. Streamlining the tools, teams, and processes then becomes difficult. This led to accommodating remote operations with some attempt to standardize the interfaces but still enabling the science teams to work with their own tools. Allowing the science teams to use their own tools turned out to create additional problems; during science planning the teams using different tools produced differing results for the same spacecraft activities these conflicts then required additional analysis and reconciliation by the spacecraft and planning teams.

All of these issues (Spacecraft operability, ground system, and science operations) are a key part of the reasons why the uplink process takes 22 weeks prime mission (26 weeks in extended mission when new mission plans are in place) to develop a 4-week sequence of activities. This process requires that at any one time there are at least 5 sequence blocks being developed at various stages of definition each with a dedicated team. Improvements in spacecraft operability, more updated and integrated ground system planning and analysis tools, and a more cost-restrained science team will significantly reduce a future outer planets mission as compared to Cassini.

K.2.3.3 New Horizons Mission Summary and Primary Cost Drivers

K.2.3.3.1 Mission Summary

New Horizons will be the first mission to perform a close-up flyby of Pluto, its moons including Charon, and potentially a Kuiper belt object. Launched on January 19, 2006, the New Horizons spacecraft will have a 9.5-year journey before reaching its closest approach (~12,500 km) to Pluto on July 14, 2015. During the 9.5-year cruise to Pluto, a single gravity assist was performed as the spacecraft encountered its closest approach of Jupiter (~32 Jupiter radii) on February 28 2007, a little more than one year after launch. This is the only gravity assist required during the entire mission. Leading up to the Jupiter Gravity Assist (JGA) there were only three trajectory correction maneuvers (TCM) required to target the Jupiter flyby aimpoint. There is not another TCM expected until the final months leading up to the Pluto/Charon encounter. Nine months out of the year the spacecraft is in hibernation mode with only a single beacon contact per week and a single telemetry contact per month. A single gravity assist coupled with a low number of TCMs and relatively large flyby distances has helped simplify the overall operation and reduce mission risk. The ability to place the spacecraft in hibernation mode greatly reduces operational costs.

Aspects of the mission architecture that most affected mission operations costs include:

- Simple mission design profile minimizes number of gravity assists and TCMs, reducing operational complexity and risk
- Spacecraft can be placed into hibernation mode during long cruise periods minimizing operational staffing levels and DSN costs
- Single opportunity for Pluto encounter leaves zero tolerance for errors. Requires extensive planning and testing effort to ensure encounter sequence accuracy and robustness.

K.2.3.3.2 New Horizons Primary Cost Drivers

Management and Project Organization

The New Horizons team is comprised of three organizations (APL, SWRI, and Kinetix) with a total of eight teams during the post-launch phase. A majority of the teams are co-located at APL in Laurel, MD, except for the payload and SOC teams which are located at SWRI in Boulder, CO and the navigation team which is located in Arizona. The New Horizons mission is managed by a single Principal Investigator (PI), Alan Stern. Having only one PI has facilitated the management of the science operation by providing clear guidance to the science teams on science observation priorities and science related operational issues. The high level of co-location has facilitated the operation by making it easier to access key staff when needed, and minimizing travel requirements needed to support reviews and meetings.

- Single PI lead mission. Facilitates management of the science operation, provides clear guidance on science priorities and conflict resolution.
- Majority of teams are collocated. Allows quick access to key staff when needed. Provides strong, cohesive relationships amongst team members. Minimizes travel requirements.

Flight System Interfaces

The New Horizons spacecraft is of a small, agile design with both 3-axis and spin stabilized control modes. 3-axis control is required for science operations and the spin-stabilized mode is used during the cruise and hibernation phases. The spacecraft employs redundancy for most components, including G&C sensors and actuators, major electronics, flight processors and data recorders. There are no reaction wheels and all spacecraft trajectory and attitude control is done via thrusters. The power system utilizes a radioisotope thermoelectric generator (RTG). The thermal system is based on a "thermos bottle" design to maintain safe operating temperatures with minimal operations intervention. The science payload consists of seven instruments, including Ralph (visible and infrared imager), Alice (UV spectrometer), PEPSSI (energetic particle spectrometer), SDC (dust counter), LORRI (long-range imager), SWAP (solar winds and plasma spectrometer) and REX (radio science experiment). The spacecraft uses a fixed high-gain and medium-gain antenna for communications with Earth via the DSN.

- Small, agile design with no moving parts reduces operational complexity.
- A wide range of system redundancy coupled with extensive, well-designed fault protection simplifies operations and reduces mission risk.
- Power system RTG and thermos bottle design simplifies operations.
- Passive-spin stabilized design allows operation of the spacecraft in open-loop control mode. Allows for long-term hibernation mode and reduces risks for many operational activities.
- Limited resources need to be tightly managed to execute Pluto encounter (i.e., power margin, thruster counts, memory space, and

bandwidth). Significantly complicates encounter sequence development and execution.

Mission Operations

Mission operations for New Horizons is managed by the APL mission operations (MOPS) team in Laurel, MD. MOPS is responsible for all spacecraft realtime command, control and assessment functions. MOPS interfaces with the DSN to schedule and coordinate realtime contacts with the spacecraft. MOPS is also responsible for supporting the mission planning process and translating activities from the master schedule into spacecraft command sequences. As part of this process MOPS is responsible for building and maintaining all models, constraints and documentation associated with the operation. MOPS also performs all software and hardware simulation activities required to validate command sequences. MOPS interfaces with the spacecraft and instrument engineering teams, the navigation team and program management to coordinate long term planning and day to day operations. The mission operations staff was at its highest levels through launch, commissioning and the Jupiter flyby campaign. During the nine month hibernation period each year, MOPS staffing is at a minimum level.

Science Operations

The SWRI team in Boulder, CO lead by PI Alan Stern manages Science operations for New Horizons. The SWRI team defines science observation details and priorities, provides instrument commanding details, and manages instrument engineering issues. For the Pluto/Charon encounter the science campaign will span one year centered ±6 months around closest approach. Since there is only one opportunity to execute the encounter, extensive measures are taken to ensure sequence accuracy and robustness. Due to the long duration of the cruise phase, Pluto encounter planning and testing is being done early while the most knowledgeable staff is still available. There is a plan to perform at least two Pluto encounter rehearsals prior to the actual encounter in 2015. Following the encounter it is estimated that it will take six months to play back all of the science data. There is also an extended mission following the retrieval of the Pluto/Charon science data. During this extended mission one or more Kuiper belt objects may be targeted for flyby or distant observation.

Ground System Interfaces

The New Horizons ground system is based on extensive heritage from the NEAR, CONTOUR and MESSENGER programs. The core realtime command and telemetry system is the EPOCH 2000 system provided by Integral Systems Inc. (ISI). The APL software group also develops and maintains software to provide functionality not provided by the core EPOCH system. The New Horizons planning and scheduling system is based on the JPL suite of planning tools, SEQADAPT and SEQGEN. In addition, MOPS uses a contractor developed software simulator tool (STATESIM) to process and validate command sequences. Assessment functions are supported by APL developed software tools, engineering dump (telemetry decom) and Plotter (data plotting). The MOPS team also utilizes a high-fidelity hardware in the loop simulator (NHOPS) for testing. APL provides a secure network allowing team members to remotely use the ground system. The Science Operations Center (SOC) is located at SWRI and has a direct interface to the APL MOC.

K.2.3.4 MESSENGER Mission Summary and Primary Cost Drivers

K.2.3.4.1 Mission Summary

The MErcury, Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is a Discovery Class mission that will become the first spacecraft to orbit Mercury, the inner-most planet in our solar system. MESSENGER was launched on August 3, 2004 and will cruise through the solar system until March 2011, gradually altering its path about the Sun to more closely match that of Mercury until Mercury Orbit Insertion (MOI). Once in Mercury orbit, MESSENGER's prime science mission begins and will continue for one Earth year (two Mercury solar days). The primary science goal of the first Mercury solar day is to obtain global mapping measurements from various instruments, while the second Mercury day will focus on targeted science investigations.

Aspects of the mission architecture that most affected mission operations costs include:

- Multiple-gravity-assist trajectory with one Earth, two Venus, and three Mercury flybys; science activities are conducted during each of these flybys except for Venus-1.
- Five deterministic deep space maneuvers and an orbit insertion burn are required.
- Once in Mercury orbit, a correction maneuver will be required approximately every 88 days to maintain the spacecraft's orbital position. The timing of these maneuvers is critical and constrained due to the need to orient the sunshade to protect the main body of the spacecraft from direct sunlight.
- Spacecraft momentum is controlled passively so that propulsive momentum dumps can be minimized and are not routinely planned.

K.2.3.4.2 MESSENGER Primary Cost Drivers

Management and Project Organization

The Johns Hopkins University Applied Physics Laboratory (JHU/APL or APL) designed, built, and manages MESSENGER. APL continues to manage spacecraft operations and the science team under the guidance of the Principle Investigator (PI), Sean Solomon of the Carnegie Institute of Washington. KinetX, Inc. is part of the project team, and provides the mission navigation services and products. Applied Coherent Technology Corporation (ACT) has been contracted for help with SOC implementation and development of the Planetary Data System (PDS) archive products. The Deep Space Network (DSN) provides the required ground antennas and communication network interfaces. MESSENGER averages three 8-hour tracks per week during cruise, with additional time for critical activities, and expects to have one 8-hour track per day during orbital operations for two years. The MESSENGER program supports the typical set of NASA mission reviews, including formal external reviews for critical Phase E events, such as flybys and orbit insertion. Development of the orbital concept of operations (ConOps) and detailed planning were deliberately deferred until Phase E, including maturation of a key science optimization, planning and sequencing utility called SciBox. The spacecraft and ground system did have full functionality to execute the mission at launch, although two flight software loads were planned during the Cruise period to correct any code deficiencies or add desired enhancements.

Associated cost drivers summary:

- Single PI lead mission. Facilitates management of the science operation, provides clear guidance on science priorities and conflict resolution.
- Majority of teams are collocated. Allows quick access to key staff when needed. Provides strong, cohesive relationships amongst team members. Minimizes travel requirements.
- SOC co-located at APL along with Mission Operations.
- Development of the orbital concept of operations (ConOps) and detailed planning were deliberately deferred until Phase E, including maturation of a key science optimization, planning and sequencing utility called SciBox.

Flight System Architecture

MESSENGER is a single spacecraft mission whose critical components are block redundant, non-critical components are functionally redundant, and has nearly-full box-level cross-strapping. The spacecraft has three basic modes: Operational, Safe Hold, and Earth Acquisition. Additionally, the Autonomy subsystem has its own set of modes (test, cruise, MOI, and orbit) to control which protective measures are active for a given point in the mission. The Autonomy subsystem provides fault protection for the spacecraft through the implementation of a rule-based engine and response macros. The Guidance and Control (G&C) subsystem has internal modes that match those of the spacecraft, in addition to containing further subdivisions such as the solar arrays having three unique control modes. Both the Autonomy and G&C subsystems are managed by manipulating onboard parameters and user-controlled options.

The MESSENGER flight system is three-axis controlled through the use of reaction wheels, two co-aligned star trackers, Sun sensors, IMUs, and decoupled 4.4 N and 22 N hydrazine thrusters. It also contains a 660 N engine and bi-propellant subsystem.

The Power and Thermal subsystems were specially designed for the inner solar system (<0.7 AU), including an 8′ × 6′ ceramic-fabric sunshade and gallium arsenide solar panels that are 2/3 OSR materials. The power generated by the solar arrays is inversely related to the Sun distance. Since the spacecraft was specifically designed for operations near or at Mercury, periods outside of 0.7 AU required special handling such as "flip-flopping" the spacecraft at farther Sun distances to allow direct sunlight to heat the body, conserving power. Throughout the mission, power/thermal management is required for all eclipse periods to maintain battery discharge current constraints, and during all orbital "hot-planet" periherm periods when thermal radiation from the planet can damage spacecraft components.

MESSENGER has two main processors with a total of four code images (one is the active RAM executable) that house both the Command and Data Handling (C&DH) and G&C flight software. The autonomy software resides in two fault protection processors that have a total of four code images. The payload consists of nine instruments with seven individual processors and flight code (two images per processor) with common prime and redundant Data Processing Units (DPUs). The C&DH subsystem contains a total of 1024 macros for command sequence execution, ephemeris loading, and user-defined on-board blocks (OBBs); autonomy contains its own separate macro space.

The Communication subsystem (Comm) uses X-band to provide a maximum data rate of 104 kbps and an emergency rate of 10 bps through a phased array antenna high-rate antenna, a fanbeam antenna, and low-gain hemi antennas to the DSN. The Comm subsystem also supports ranging and DDOR activities with the DSN, as well as Radio Science (RS) measurements at Mercury. Data return can be maximized by optimizing the downlink rate through a series of "stepping" functions tailored for each DSN ground station and sequenced based on the DSN allocation schedule.

Associated cost drivers summary:

- There are multiple spacecraft modes, with several subsystem (G&C and Autonomy) having their own internal sub-modes that control the overall configuration and behavior.
- MESSENGER has over 2500 user-defined and maintained parameters. For any given activity, approximately 100–150 of these must be modified. Maintaining knowledge of, and the precise values of each of these places a heavy burden on the operations team.
- There are some impingement issues with the thrusters, as they can interact with the solar arrays at certain panel positions, causing the team to develop an array management scheme dependent on the type of burn and the solar distance at which it is being performed.
- MESSENGER has multiple articulating mechanisms, including two single-axis gimbaled solar arrays, the MDIS pivot, and electronically steered phased array antennas.
- Extra care is required to control where the spacecraft center of mass (Cm) is relative to the body, and necessitates performing a propellant centering burn after large thruster firings to relocate the fuel thus shifting the Cm. Alternate techniques are being implemented as well, including attitude alternations during non-contact periods to help minimize the total propellant used during cruise.
- Since the spacecraft was specifically designed for operations near or at Mercury, periods outside of 0.7 AU required special handling such as "flip-flopping" the spacecraft at farther Sun distances to allow direct sunlight to heat the body, conserving power.
- Throughout the mission, power/thermal management is required for all eclipse periods to maintain battery discharge current constraints, and during all orbital "hot-planet" periherm periods when thermal radiation from the planet can damage spacecraft components.
- The payload consists of nine instruments with seven individual processors and flight code (two images per processor) with common prime and redundant Data Processing Units (DPUs).
- Science and housekeeping data is stored on a 1 GB standard Solid State Recorder (SSR) that utilizes an on-board file system and the CCSDS File Delivery Protocol (CFDP) for data playback and management.

Mission Operations

Mission operations for MESSENGER is managed by the APL mission operations (MOPS) team in Laurel, MD. MOPS is responsible for all spacecraft realtime command, control and assessment functions. MOPS interfaces with the DSN to schedule and coordinate realtime contacts with the spacecraft. MOPS is also responsible for supporting the mission planning process and translating activities from the master schedule into spacecraft command sequences. As part of this process MOPS is responsible for building and maintaining all models, constraints and documentation associated with the operation. MOPS also performs all software and hardware simulation activities required to validate command sequences. MOPS interfaces with the spacecraft and instrument engineering teams, the navigation team and program management to coordinate long term planning and day-to-day operations.

Associated cost drivers summary:

- Team has extensive operations heritage (planning, sequencing and testing processes) from NEAR and CONTOUR missions. Strong familiarity with APL built spacecraft and ground systems.
- All new and critical activities and products are tested on a hardware-in-the-loop simulator, with a faster-than-realtime software simulator used for all routine command sequences.
- Many team members support multiple functional areas, reducing staff size.

Science Operations

The payload consists of a wide-angle and narrow-angle imager, an atmospheric and surface composition spectrometer, a magnetometer, a gamma-ray and neutron spectrometer, an energetic particle and plasma spectrometer, an X-ray spectrometer, a laser altimeter, and RS. A primarily co-located science team manages the instruments with science goals and observations coordinated through a single PI, discipline groups, a weekly coordination meeting, the Payload Operations Manager (POM), and a unified Science Operations Center (SOC) located at APL. A typical cruise sequence period is two weeks long and requires six planning weeks, with one week long sequences planned for orbit. All science operations are coupled to the spacecraft sequencing, and must balance shared power, pointing, and data resources. A typical two-week cruise period produces ~2 Gb of data, a core flyby period of five hours produces ~7 Gb of data, and the total mission is expected to generate between 20 and 90 GB depending on total duration and DSN coverage.

Associated cost drivers summary:

- Science teams work cooperatively and are managed by a single PI to prioritize science observations.
- For large coordinated events, such as flybys or MOI, a Critical Event Planner (CEP) oversees a phased production of the integrated command sequence.
- A typical cruise sequence period is two weeks long and requires six planning weeks, with one week long sequences planned for orbit.
- All science operations are coupled to the spacecraft sequencing, and must balance shared power, pointing, and data resources.

Ground System

The MESSENGER ground system is based on extensive heritage from the NEAR and CONTOUR programs. The core realtime command and telemetry system is the EPOCH 2000 system provided by Integral Systems Inc. (ISI). The APL software group also develops and maintains software to provide functionality not provided by the core EPOCH system. The MESSENGER planning and scheduling system is based on the JPL suite of planning tools, SEQADAPT and SEQGEN. In addition, MOPS uses a contractor developed software simulator tool (STATESIM) to process and validate command sequences. The APL developed software tools engineering dump (telemetry decom) and Plotter (data plotting) provide semi-autonomous (requires human oversight) assessment functions. The MOPS team also utilizes a high fidelity hardware-in-the-loop simulator for testing. APL provides a secure network allowing team members to remotely use the ground system.

A combination of manual and software verification tools are used to verify all of the command inputs, including those from the science teams. All new and critical activities and products are tested on the hardware-in-the-loop simulator, with the faster-than-realtime software simulator used for all routine command sequences. For large coordinated events, such as flybys or MOI, a Critical Event Planner (CEP) oversees a phased production of the integrated command sequence. Two phases (A and B) represent full builds and testing of this sequence with Phase-A culminating with a successful hardware simulation, and Phase-B with execution on the spacecraft. Oversight of this crucial sequence transitions from the CEP to the MOPS Lead at the start of Phase-B. The final tool set for orbital science operations was deliberately deferred into Phase E and is currently under development. All spacecraft telemetry is archived at APL, and all science data is pushed over to the MESSENGER SOC located at APL for processing and PDS population.

Associated cost drivers summary:

- The MESSENGER ground system is a combination of COTS and GOTS products, such as the SeqAdapt and SeqGen AMOS tools and the EOPCH T&C system, wrapped with APL in-house generated glue-ware and utilities.
- Extensive ground system heritage from previous mission for both realtime operations and mission planning and sequencing. Reduces costs and risks associated with new development and teams needing to learn and test a new system.

K.2.3.5 Relative Cost Driver Comparisons

The study team numerically scored each of the four mission's complexity by evaluating those attributes that most affected operational complexity. The results for each mission are listed in **Table K.3-1**. As can be seen by "total weighted average score", the Cassini mission ranked the most complex overall. The Cassini mission ranks highest in complexity in every category. MESSENGER and MRO are nearly tied for second (well within the error bounds of the estimates) with New Horizons operations rated the least complex overall. The drivers for obtaining the relative scoring for each mission are included in each mission's costs drivers as described in the preceding report sections.

As each cost driver category can not be treated equally (i.e., thermal control operations are not as difficult in general as G&C). To help correct for this in computing the average scores, a weighting was applied as shown in **Table K.2-1**. Individual flight system interfaces were scored and the weighted scores shown in the roll up line. This line was then weighted relative to the other major categories and then averaged. The Flight System Interfaces were given a weight of 4, followed by a 3 for science operations, 2s for mission architecture and organization, and finally a 1 for ground system interfaces. While one can argue about the individual weights, the important point is the application of the weights tended to amplify the average score separations rather than alter the relative complexity order. These same scores are plotting in **Figure K.2-1**.

Table K.2-1. *Relative mission complexity.*

Level of Difficulty 4 = Highest; 1 = Lowest	Weighting Factor	MSGR		NH		Cassini		MRO	
Mission Architecture	2		3.5		1		4		3
Mgmt and Org	2		1		2		4		3
Flight Sys Architecture (roll up)	4		2.8		2.0		3.3		2.0
System	1	**3**	3	**1**	1	**3**	3	**3**	3
G&C	1	**3**	3	**1**	1	**4**	4	**2**	2
Power	0.5	**2**	1	**3**	1.5	**3**	1.5	**1**	0.5
Prop	0.5	**4**	2	**1**	0.5	**2**	1	**1**	0.5
Thermal	0.25	**2**	0.5	**1**	0.25	**2**	0.5	**1**	0.25
C&DH/SSR	1	**2**	2	**3**	3	**4**	4	**2**	2
Comm	0.5	**3**	1.5	**2**	1	**2**	1	**3**	1.5
Payload	1	**3**	3	**3**	3	**4**	4	**2**	2
Science Operations	3		3		3		4		3
Ground System Interfaces	1		2		2		4		3
Total Average Score			**2.6**		**2.1**		**3.8**		**2.7**

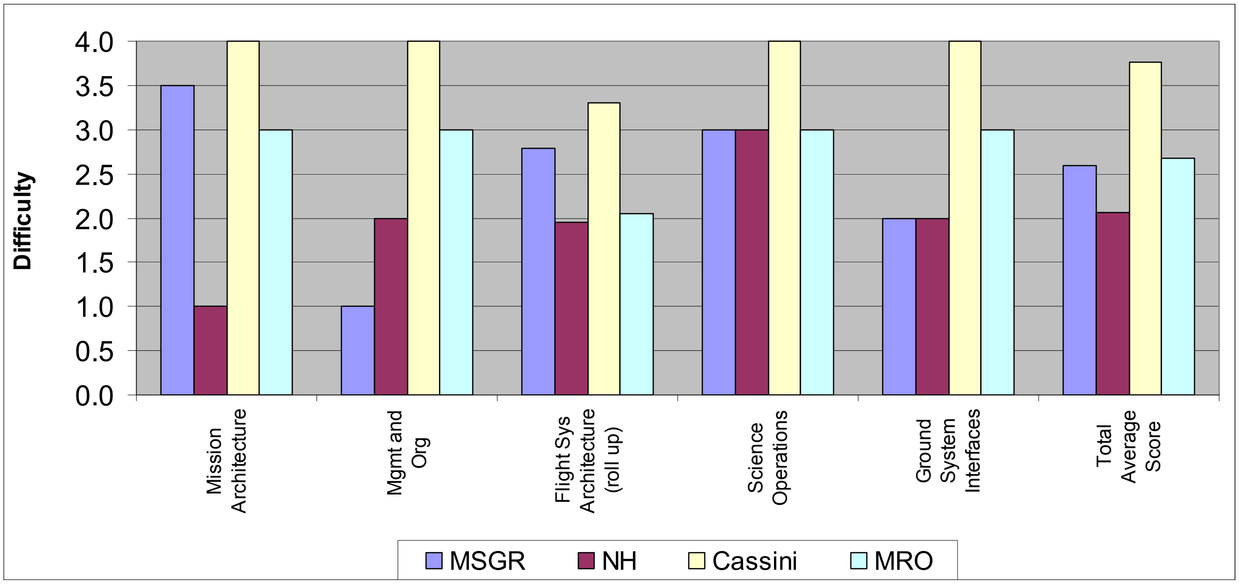

Figure K.2-1. *Relative mission complexity.*

It should be noted that while this study focused on what made the missions complex and hence costly to operate, all missions studied included a number of ingenious operations features that enabled the operations or made them more efficient. The studies recommendations and conclusions (reference §K.5) are largely drawn from comparing what worked and what did not work for these for missions.

K.2.4 MO & GDS Staffing and Comparisons

The cost of Phase E operations were assessed in terms of total FTE at 3 points in each mission: 1) launch operations which typically represent a peak in operations staffing levels, 2) launch plus one year which typically represent cruise operations, and 3) prime science phases which are representative of the final mission staffing. It should be noted science operations costs data proved to be problematic to collect for each mission due to programmatic and contractual barriers in reporting costs to APL and JPL. This made is impossible to compare “apples to apples” for science operations staffing levels at this time.

The cost of Phase B and C/D preparations are reported and compared as a sum for each phase so that the relative cost for each mission to reach the same level of maturity could be compared. What follows are descriptions and data for each missions staffing levels in the four primary operations areas, including mission operations, ground data systems, navigation (post launch only), and engineering support.

Side-by-side comparisons of the four missions for pre and post launch staffing levels are shown in §K.3.4.

K.2.4.1 MRO Mission Operations and GDS Staffing

The MRO development started while the transition from the faster-better-cheaper philosophy to more of a traditional development had just begun. Mission success is number one priority. During the development phase many development activities sprung forth due to the new philosophy to achieve success in the mission as a top priority.

K.2.4.1.1 MRO Development Phase Staffing

In Phase A/B, MRO spent 99 work-months (WM) in the area of MOS development and six WM in the GDS development. In Phase C/D, MRO spent 580 WM in the area of MOS development and 372 WM in the area of GDS development.

MOS development is defined to include mission management, mission operations system engineering, flight team development, flight operations process and interface development, science operations process and interface development, flight system scenario testing, training, and flight operations readiness tests. The GDS development is defined to include project unique software development, multi-mission software adaptation, integration and test, and hardware procurements.

Table K.2-2. *MRO Phase E, MO&GDS staffing.*

Categories	12/1/2005 (Cruise)	3/1/2006 (MOI)	7/1/2006 (Aerobraking)	7/1/2007 (PSP)
Management Staff	2.0	2.0	2.0	2.0
MOS/GDS System Eng.	6.0	7.1	7.2	4.4
MOS Development & Ops				
Flight Engineering Team (at LMSS)	24.4	26.6	26.6	16.0
Navigation Team	8.9	10.2	10.9	6.3
Mission Planning and Sequencing Team	3.0	3.0	4.3	3.0
Payload Operations Support Team	3.0	3.0	3.0	3.0
End-to-end Data Accountability Team	3.0	3.0	3.0	3.0
Others	8.0	8.0	8.0	5.0
GDS Development & Ops	3.1	4.0	2.8	2.5
Multi-mission Development & Ops	10.3	9.1	6.4	10.4
Total Staff Months	**71.7**	**76.0**	**74.2**	**55.6**

K.2.4.1.2 MRO Phase E Staffing

Table K.2-2 shows the FTE associated with a few unique project milestones during MRO's operations phase.

The Flight Engineering Team number in the above table represents the total staffing at LMSS. This number includes LMSS management and administrative personnel, system coordinator, subsystem engineers, orbiter testbed operators, and real time operators. JPL provides supports for this team, including in the areas of system coordinators, ACS engineers and realtime operators. The number labeled with "others" represents the additional supports to the FET as described above in addition to the phase leads support. Phase lead is the lead engineer for a MRO phase as the MRO goes through launch, cruise, MOI, aerobraking, and primary science and relay phases. A comparison of MRO staffing levels to other missions for similar functions is included in §K.3.4.

K.2.4.2 Cassini Mission Operations and GDS Staffing

By any measure Cassini is a large and complex mission, and also predates all of the other missions studied in this report by many years. At the time it was on the leading edge of new operating and development paradigms, and using the then new technologies such as shared file systems like AFS, and the WWW. As such, the level of effort consumed during development was very significant. This large effort was fueled by several factors that are described earlier in §K3.2.2.

K.2.4.2.1 Cassini Development Phase Staffing

The labor shown in Table K.2-3 is broken into development phase (B and C/D) staffing. The development phase shows the total Ground system labor during development phases. The Phase E staffing presents 3 representative snapshots of the staffing to support cross mission comparison. This is done to minimize the potentially overwhelming impact of mission duration and provide a duration independent means to compare Cassini operations staffing to other missions. The development staffing for Cassini breaks out as follows:

This MOS development staffing includes the following mission operations and ground system related activities:

a) MOS Mgt and MOS Engineering.
b) Distributed operations interface engineering
c) Operations planning, engineering, training, and execution
d) Software development and testing in support of operations. This includes the small amount adaptation to the existing ground system software. This also includes new development in support of entirely new flight software, new planning and sequencing tools, new distrib-

Table K.2-3. *Cassini development phase staffing.*

	Phase B	Phase C/D	Total
MOS Development	72	4651	4723
System I&T and ATLO	48	1789	1837
Total Staff Months			**6560**

uted file system and data distribution system, and distributed science operations centers.

MOS development does not include most of the science processing and instrument accommodation related development, which is book kept separately as part of the science costs.

The System Integration and Test development efforts include system I&T and ATLO related staff. This includes all of the spacecraft and ground system support utilized in the course of planning and performing ATLO.

K.2.4.2.2 Cassini Phase E Staffing

Cassini Phase E efforts included a significant amount of post launch development to accommodate the evolving planning tools needed to support the tour activities and to address the improved understanding of the spacecraft and better ways of operating the mission that came with experience.

Table K.2-4 presents the average monthly staffing FTEs at three points in the mission, shortly after launch, one year into the cruise, and during primary science operations.

The labor categories above include the following efforts:

- *Project Management:* Project management and related support staff.
- *Engineering Support:* This includes all of the spacecraft subsystem engineers and planning engineers required to fly the mission. In addition this would include the engineers involved in some of the tool development that didn't fall under the GDS tool development umbrella.
- *Mission Operations:* Includes the flight control team, the sequence team, data management team, DSN schedulers, science planners, and other people directly supporting mission operations but not tied to the spacecraft engineering team or ground system engineering team.
- *Ground Systems:* Primarily this is the set of people involved in maintaining the infrastructure for all project members, both hardware and software, including the communications infrastructure and the distributed science operations interfaces.
- *Navigation:* This includes the navigation operations and tool development performed during cruise to prepare for the tour. Once in the tour phase this staffing is used primarily to accommodate the constant maneuvering required (at least twice monthly maneuvers) to safely make all of the planned flybys and science observations. A factor that impacts navigation labor is the use of uncoupled thrusters on the spacecraft that complicate Orbit Determination and Trajectory analysis and requires additional labor to accommodate. Navigation also includes the mission design and planning work used in support of the flyby selection and design.

Table K.2-4. *Cassini Phase E staffing at launch, cruise and primary science.*

	Launch + 2 months	Launch + 12 months	Primary Science Ops
Project Management	13	13	9
Engineering Support	100	75	49
Mission Operations	42	28	15
Ground Systems	23	17	13
Navigation	22	18	30
Subtotal	**200**	**151**	**116**
SOC + Science Ops + Science Support	55	55	60

K.2.4.3 New Horizons and MESSENGER Mission Operations and GDS Staffing

MESSENGER and New Horizons missions followed the same basic approach to staffing their respective operations as both are operated from the same MOC at APL. **Figure K.2-2** shows the integrated total staff months for Phases B and CD separately for the two missions. Below is a description of what work is performed in each of the work categories represented.

K.2.4.3.1 New Horizons and MESSENGER Phase-B Staffing

Mission Operations Team

During this phase, a majority of the mission operations work is the responsibility of the Mission Operations Manager (MOM). Primary responsibilities of the MOM during this time period include:

- Refine Mission Operations Plan and derive operations related requirements
- Support development of the MOC-SOC and MOC-Ground Station ICDs
- Participate in spacecraft and ground system design trades
- Develop preliminary ground station plan and update MOC requirements

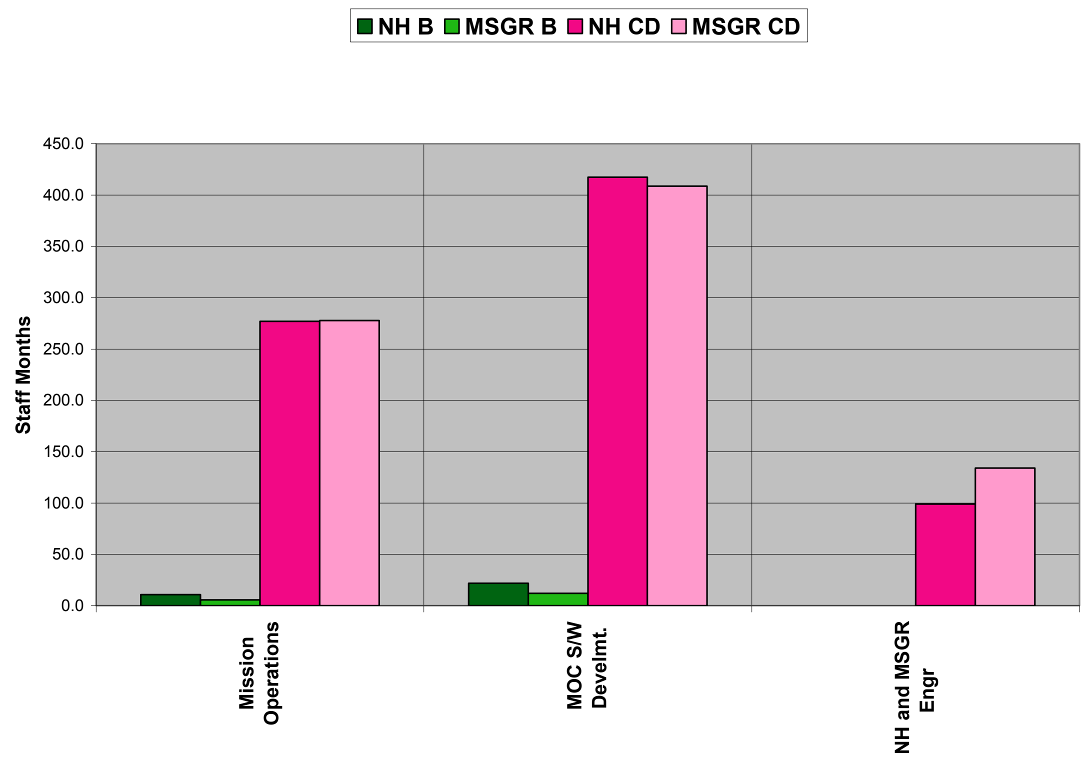

Figure K.2-2. *New Horizons and MESSENGER Phase B&CD, MO&GDS staffing.*

- Configure the Mission Operations Development Plan
- Develop Mission Operations PDR Presentation (request help as needed)
- Specify requirements for ground software tools

MOC Software Development Effort

During this phase, the ground software lead is overseeing ground system planning efforts. Tasks required during this phase include:

- Development of a Ground System Software Requirements document
- Development of a Ground System Concept of Operations document
- Leading the Software Requirements Review
- Provision of inputs to hardware procurement planning
- Documentation of the system level Software Development plan
- Identification of required ICDs, review hardware procurements, perform trade studies
- Development of integration test plans to support MOC and flight to MOC system testing
- Development of and presentation of the preliminary ground software design at the ground system PDR and mission level PDR

K.2.4.3.2 New Horizons and MESSENGER Phase-C/D Staffing Summary

Phase-C/D Mission Operations Effort

Primary responsibilities of the MOM and operations team during this time period include:

<u>Detailed Design Phase</u>

- Continue to refine MOPS plan, schedule, staffing and devise test plan
- Develop and document MOPS interfaces with SOC, Ground Station, Navigation & Mission Design
- Continue coordination efforts with ground system and ground station representatives
- Begin spacecraft and instrument knowledge capture to support User's Guide, command sequence and test plan development
- Review and support C&T database and display page development and maintenance

- Develop MOPS test plan and test verification matrix
- Develop MOPS CDR presentation and support Critical Design Review
- Continue to refine all program required MOPS documentation as needed
- Complete subsystem and instrument knowledge capture
- Complete MOPS inputs/reviews to C&T database
- Monitor and help test ground system deliveries
- Develop Mission Operations Review presentation and support review
- Complete documentation of MOPS interfaces
- Continue development of real-time procedures, command sequences, flight constraints and MOPS tools
- Complete MOPS test development, execution & requirements verification
- Train and certify flight controllers and mission analysts
- Support Launch & Early Operations and Flight Readiness reviews

Phase-C/D Ground Software Development Effort

- Ground software team finalizes detailed design of the ground system for each computer software component (CSC) based on earlier defined system requirements
- Software build review schedule is refined, identifying contents for each build
- Develop and present the ground software design at the ground system CDR and mission level CDR
- Software build reviews are held for each scheduled build delivery
- Implementation and unit testing is performed for each software build
- Source code is configured, unit tests are executed and reviewed for each build
- Formal acceptance testing is performed for each software build delivery
- Configuration management process initiated for requested changes
- Software executable deployment and release notes documentation
- Implementation and comprehensive testing is performed for each software build

K.2.4.3.3 New Horizons and MESSENGER Phase-E Staffing Summary

Figures K.2-3 and K.2-4 show the relative FTEs for New Horizons and MESSENGER Phase E flight operations for each major category of work at launch, launch plus 1 year, and prime science operations. Both mission operations were on the same staffing scale and both started off with more than what they presently have or intend to have during prime science phases. It should also be noted that while the operations staffing is generally organized into two physically separate teams, some sharing of team members during peak periods of operations has begun. This has served to help level the number of total staff numbers. Below is a description of what tasks are included in each category plotted.

Engineering Support

Once control authority of the spacecraft transitions to the operations team at launch, varying levels of support is required from the spacecraft and subsystem engineers that designed and are the experts in their respective subsystems. Typical subsystem engineers include mission design, G&C, power, thermal, autonomy, C&DH/FSW, propulsion, and RF. These people are responsible for detailed training of the operations personnel and oversight of their subsystems, including assessment, anomaly resolution, and technical jurisdiction over all flight activities involving their subsystem or related components.

Mission Operations

This work category captures those staff associated with the mission operations (MOPS) team. Typically this team is led by the Mission Operations Manager (MOM) and Deputy Mission Operations Manager (DMOM). There are mission analysts, or off-line staff responsible for the planning and day-to-day execution of specific spacecraft operations that act as the liaisons to the subsystem and instrument technical leads and other operational support elements, including navigation, DSN, and the ground system interfaces. Planning and execution of spacecraft events includes designing how an activity is to be performed, interacting as necessary with the appropriate technical leads, conducting reviews, testing, overseeing the eventual flight execution, and documenting the results as necessary. Mission analysts perform mission planning and sequencing

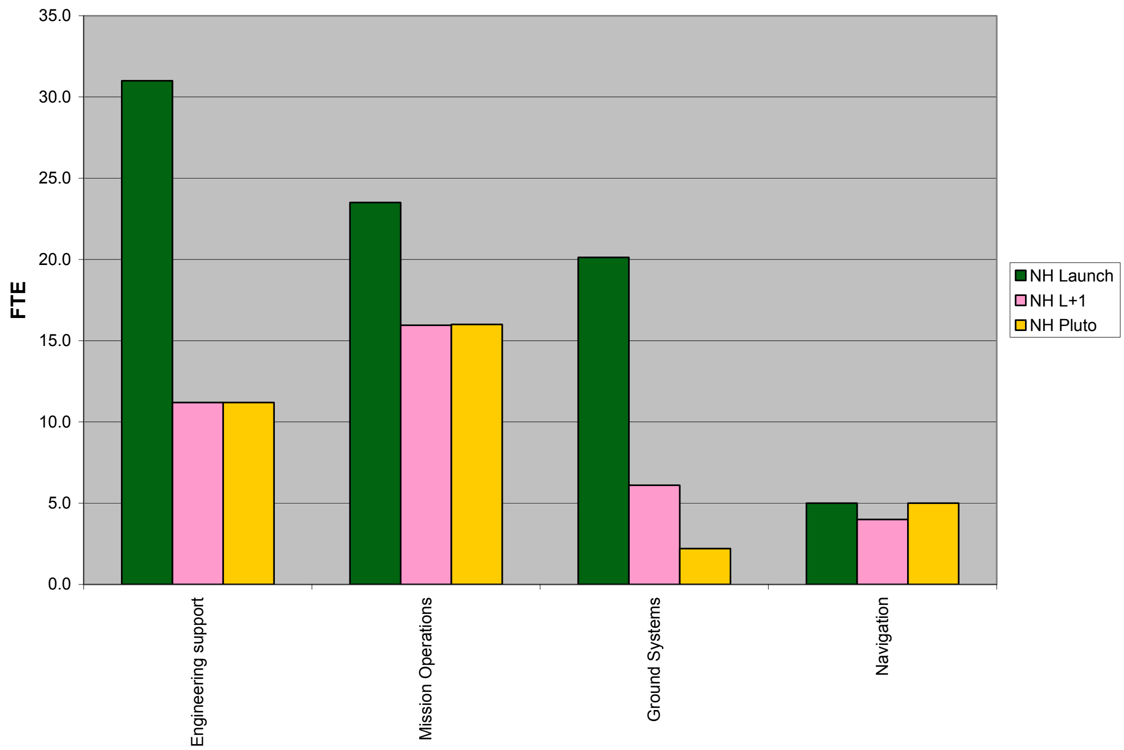

Figure K.2-3. *New Horizons Phase E, MO&GDS staffing.*

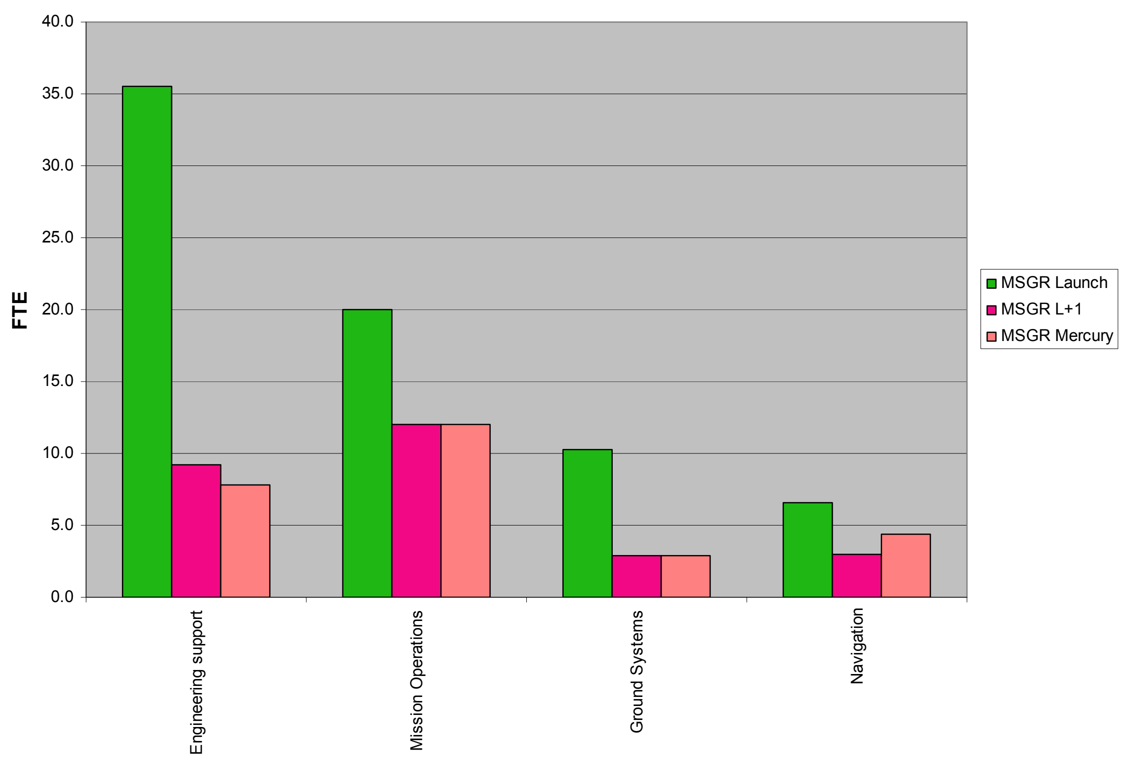

Figure K.2-4. *MESSENGER Phase E, MO&GDS staffing.*

tasks, DSN schedule coordination, spacecraft assessment, data distribution, science interfacing, and initial anomaly detection/resolution and recovery activities. This category further includes realtime flight controllers (FCs), or those staff that directly interface with the spacecraft through the telemetry and command system and with the DSN via network and voice interfaces, as well as the flight controller lead that is responsible for the management and scheduling of the FCs.

Ground System

The ground system work category for Phase E covers all of the staff associated with providing software fixes, and re-test as needed, to the baselined system in place at launch. These people ensure software fixes are documented and closed out in a controlled problem reporting system. Ground personnel provide the IT security plan as required by NASA IONET, and maintain monitoring applications and logs as required. This work element addresses all of the workstation system administration that includes setting up new equipment, maintaining the ground system to APL Space Department standards, managing user accounts, and establishing automated data back-ups. People within this element also provide communications system administration post-launch, including voice box and network setup and maintenance. Note, much of this support is shared across multiple missions, and the numbers shown are representative of only the mission specific services provided.

Navigation

The commercial organization KinetX, Inc. provides navigation support to the New Horizons mission. They are responsible for orbit determination, maneuver design, and trajectory reconstruction throughout the mission. They also provide launch support, pointing predicts, ephemeris files, and other navigational products to various project elements. The people under this work category work closely with mission design and G&C staff captured in other elements as described above.

K.2.4.4 Staffing Level Comparisons and Relative Complexity

K.2.4.4.1 Development Phase (Phases B and C/D) Staffing Comparison

Mission Operations and Ground Data System staffing levels were collected for each of the 4 mission studies. Pre-launch Phase B and CD staffing was summed over each project's phase boundaries. The resulting integrated staff-months are shown in **Table K.2-5**. For Phase B, MESSENGER expended the least amount of staff, and MRO the most. For Phase C/D, MESSENGER, MRO, and New Horizons were "in family" and Cassini was significantly greater, than the others missions and clearly "out of family" for the development phases.

Science operations costs were not compared due to the difficulty of passing the required data through the programmatic and contractual barriers and due to differences in reporting costs to APL and JPL. This made is impossible to compare "apples to apples" for his category at this time. As noted earlier, science operations by the science teams is not accounted here. To compare science operations costs, coordination at the PI or NASA HQ level would be required.

K.2.4.4.2 Mission Operation Post-Launch (Phase E) Staffing Comparison

Staffing levels for post launch operations were gathered at 3 key points in each mission, including launch, launch plus one year, and prime science operations. The staffing levels are plotted in **Figure K.2-5**. These include Mission Operations, Engineering, Ground Data Systems, and Navigation efforts combined. For the same reasons as discussed for the pre-launch staffing, these numbers do not include instrument support, science planning, or SOC development and operations.

Staffing during prime science operations for both MESSENGER and New Horizons are obviously at planned levels (yet to begin) whereas for MRO and Cassini they are actuals.

***Table K.2-5.** Integrated MO&GDS staff months for pre-launch preparations.*

	Phase B				Phase C/D			
	MSGR	NH	MRO	Cassini	MSGR	NH	MRO	Cassini
Mission Operations	5.5	10.8	99.0	60.0	277.7	277.1	580.0	2963.0
MOC S/W Devel.	12.2	21.8	6.0	12.0	408.8	417.4	372.0	1688.0
NH and MSGR Engr					134.1	98.9		
Staff Totals	**17.7**	**32.6**	**105.0**	**72.0**	**820.6**	**793.3**	**952.0**	**4651.0**

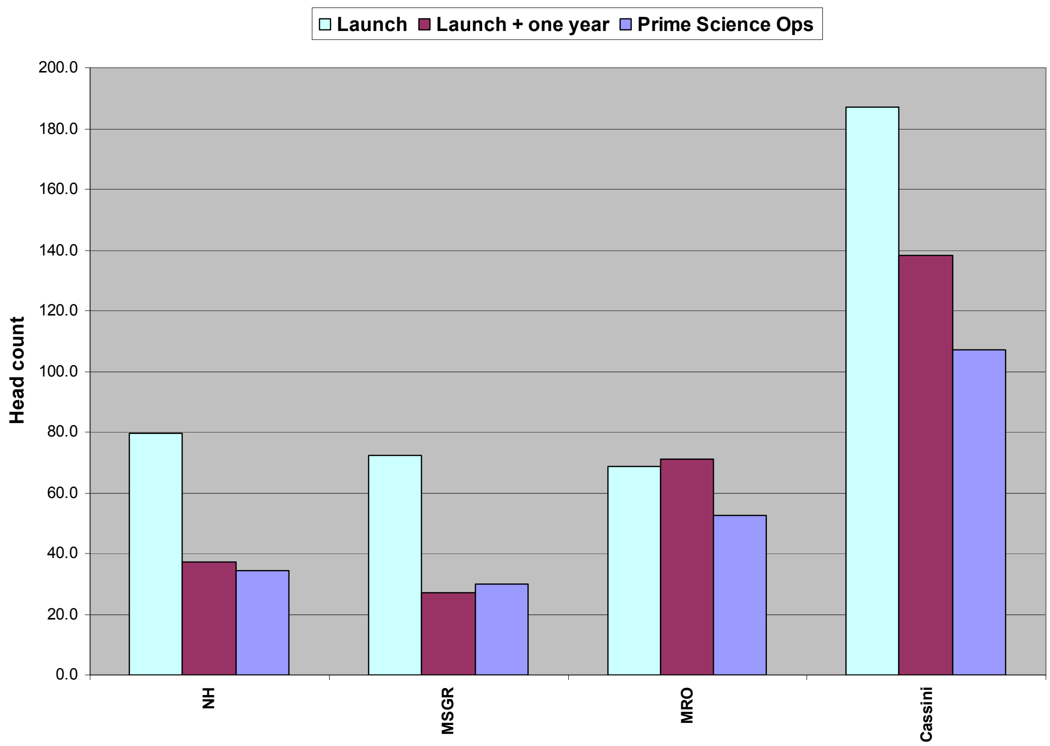

Figure K.2-5. *Phase E operations staffing snapshots.*

Each mission except MRO had its greatest effort at launch. It was problematic to separate out the MRO engineering staff that supported ATLO versus that which supported the flight operation. Hence it is safe to assume MRO also had a larger team at launch than the rest of its mission phases yet it is not evident in **Figure K.2-5**. While Cassini's staffing levels are higher than the other 3 missions, they could be explained by the Cassini's overall mission complexity being a 3.8 vs. 2.6/2.7 for the next most complex missions MESSENGER and MRO (Reference **Table K.2-1**).

K.2.4.4.3 Mission Operation Post Launch (Phase E) Staffing vs. Complexity Comparison

To better compare and contrast each operation's complexity and associated staffing, an average staff was computed using the staffing levels shown in **Figure K.2-5**. That average staff was then plotted for each mission against its respective complexity as determined by the study team (see §K.4.4.1). The results are shown in **Figure K.2-6**.

This plot shows New Horizons, MRO, and MESSENGER are relatively near each other on the grid and Cassini is in its own in terms of both complexity and cost. A least squares fit of the 4 data points is shown as a blue line. The green line is an exponential fit of the same data. Both CAS and NH are above the linear fit while MSGR and MRO are both below it indicating they may be the most efficient of the four operations. MESSENGER falls the furthest below, also falling below the exponential line indicating it *may* be the most efficient of the set. This would not be too surprising given it is the only Discovery mission in the set and hence cost capped. It was regularly stated by those that worked this mission when explaining the pressures experienced that MESSENGER is a "Flagship mission on a Discovery budget."

A least squares fit of the MRO, MESSENGER, and New Horizons points is shown with the red line. Extending this line at its slope to Cassini complexity levels does suggest Cassini and other missions of similar complexity would be expected to cost more, but less than current Cassini levels. Recommendations for reducing mission complexity and operations cost are summarized next in

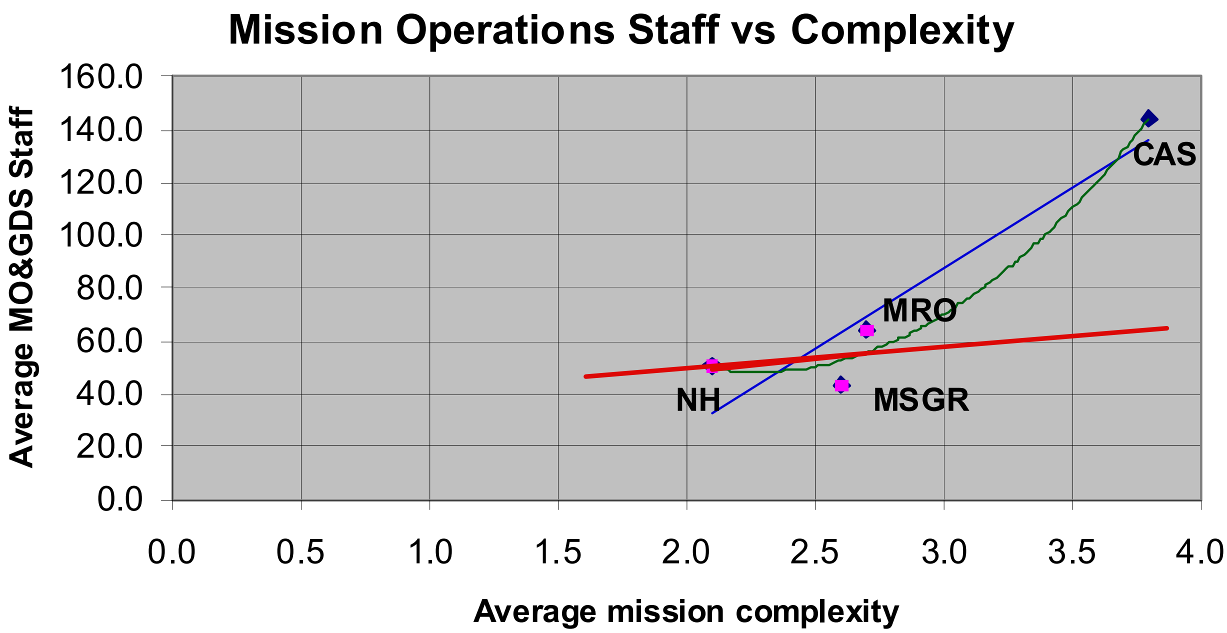

Figure K.2-6. *Phase E operations staff vs. mission complexity.*

§K.2.5, *Recommendations for Reducing Flagship Phase E Costs*. These recommendations, if incorporated into the next OPF mission should result in significant cost savings for that overall mission operation.

K.2.5 Recommendations for Reducing Flagship Phase E Costs

This section captures the primary recommendations for reducing mission operating costs and total mission costs for future deep space missions based on the experiences of Cassini, MRO, MESSENGER, and New Horizons mission operations. While not all recommendations are within the control of the Project, they are included to inspire future mission implementation of lower cost mission operations. Also, some of the recommendations could also help to reduce development costs and cost risk as well.

Mission Design/Architecture

While there are a number of primary cost drivers stemming from mission architecture decisions (mission duration, complexity of the trajectory, complexity of the science mission), these are typically not negotiable unless science requirements can somehow be reduced or less demanding trajectories found. Hence the most practical way to save cost is to minimize the amount of activity during cruise, including use of hibernation-type modes and foregoing opportunistic science taken during gravity assist maneuvers and otherwise along the way to the primary destination. However, one should not discount the benefit of using these opportunities to train the operations team and test systems for eventual prime science operations.

Management and Organization

- Reduce the complexity of the contention resolution process by choosing a single PI. Streamline the arbitration process so that it need not involve the majority of the mission planners. A strong "super PI" or Project Scientist could oversee this process.
- Co-locate mission planners or have representatives with decision making capability co-located to help reduce communications delays when iterating on plans.
- Investigate ways to streamline the ITAR/ TAA processes for working with foreign instrument teams/individuals.
- Improve the process for communication within the project by providing a central document repository that is readily accessed by all project members, subject to ITAR restrictions

Flight Systems Interfaces

Evaluate operational complexity and incorporate ease-of-use features for each primary flight system with special emphasis on G&C

and C&DH flight processor interfaces (as they are typically the most complex). While enhancing the operability of these interfaces may add to development and test scope, there are many features that can be incorporated that save considerably more money over the course of the mission than the upfront costs.

- As part of the next OPF mission design effort, formalize a joint operations and flight system design process for each proposed flight system to evaluate its design in terms of operability and quantify affect on total mission costs. Senior flight operations personnel could be temporarily assigned to augment the OPF operations team to assist in the assessment function. Note: This process was ad-hoc on past missions and subject to the availability and capability of the specific operations team involved in the early stages.
- Consider such features as: coupled thrusters, automated momentum management, scan or gimbaled platforms that can significantly reduce conflicts between instrument types (fields and particles vs. pointing) or between payload and communications system, deterministic slew paths, ephemeris based pointing.
- Ensure adequate power margins and consider predefined payload modes/configurations to simplify planning. Favor power over mass in use of PMDs, coupled thrusters, proper instrumentation.
- Incorporate a file system and pre-allocated (by ground rules) SSR space. Sufficient margins for command and SSR memory. Use automated file playback software and CFDP to minimize SSR management and to have automated retransmission for data dropouts. Consider CFDP for command uploads and potential use for telemetry.
- Strive for commonality in payload instrument telemetry and command interfaces.

Science Operations

- Incorporate a planning process that is efficient enough for Europa/Titan orbital operations, and modify as necessary for tour operations. Consider cost constraining planning tools (i.e., market based and priority based systems).
- Develop process that minimizes the number of planning iterations, bounds time allocated to planning each significant event, and incorporates the principle of "good enough."
- Develop an integrated planning and sequencing tool based on model-based engineering and state analysis that would be used throughout the project lifecycle.

Ground System Interfaces

- Incorporate information management systems (i.e., CIMS) for entire team's remote access to planning products, telemetry, command sequences, and action item tracking.
- Have a PI set priorities. Have ground system and planners implement those priorities and optimize supporting processes as needed.
- Incorporate resource modeling and flight constraints models in early in planning process for early identification of problems. Permit science planners access to models of similar fidelity as what MOC uses for end validation. Make accessible to distributed team.
- Incorporation of flight system faster than real-time software models for resource and constraints checking (i.e., SoftSim or Statesim).
- Adoption of unattended pass operations for non-command passes. Limit number of command passes. Rely on automated limits and alarms checking versus manual, by FC or ACE.
- Unattended (automatic) radiation of non critical commands (i.e., SOHO or ACE)
- Streamlined/automated real-time process for late knowledge updates, including ephemeris and time shifts.
- Consider incorporating real-time automated assessment tools and post event trending tools (i.e., MRO).

Testing and Validation

- Adopt logical testing steps with software tools catching problems upstream (with faster than real-time software) of more sophisticated (real-time hardware) simulations.
- Incorporate software tools, scripts, to aid in H/W simulator setup and configuration control using planning system inputs for starting conditions. Use checkpoint and restart process for H/W simulations.

- Automate syncing of S/W sim (and H/W sim tools) with flight for proper configuration control. Perform periodic audits.
- Incorporate tools for post simulation data processing and distribution—reduce labor and time requirements.
- For geographically distributed team members, provide easy access to data for each reviewer. (i.e., MRO has web based results outside flight ops network)
- Have good validation of software simulators so they can be used in place of hardware simulators. Incorporate fidelity into software models match hardware simulations as closely (and quickly) as possible.
- Use real-time simulators by exception (only as needed), faster than real-time software for all nominal operations. Ensure adequate numbers and fidelity of real-time hardware simulators during each phase of the mission.

K.2.6 Acknowledgements

The study team would like to thank the following representatives of JPL's Cassini mission operations, most notably, Brian Paczkowski, for taking the time away from their ongoing operations duties to help describe Cassini operations processes:

- Laura Burke
- Dave Mohr
- Brian Paczkowski

In addition, the study team would like to acknowledge the participation of individuals from NASA ARC that participated in team discussions sharing with us relevant experience in automation approaches used on MER, Phoenix, and MSL.

- Mike McCurdy
- Jim Kurien
- Alonso Vera

Finally, the following members of JPL's OPF study teams also contributed to the working discussions and/or editing of the final report:

- Matt Bennett
- Robert Rasmussen
- Jan Ludwinski
- Thomas Magner

L. SUPPLEMENTAL MATRICES

L.1 How JEO and EJSM Respond to the Decadal Survey

As described in Section 2.7, the JJSDT evaluated both the JEO alone and the EJSM against the Decadal Survey (1) Steering Group Recommendations for a Europa Geophysical Observer, (2) Large Satellites panel recommendations, and (3) Giant Planets panel recommendations. These ratings are shown in **Table L.1**.

Science Value Scoring			
5	Definitely addresses full	2	May address partial science
4	May address full science	1	Touches on science
3	Definitely addresses partial	0	Does not address science

	JEO	JEO + JGO	Comments	JEO Science Objective
DECADAL SURVEY STEERING GROUP RECOMMENDATIONS:				
"EUROPA GEOPHYSICAL EXPLORER" SCIENCE OBJECTIVES				
Group 1:				
Determine the presence or absence of an ocean.	5	5		A. Ocean
Characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layer.	5	5		B. Ice
Understand the formation of surface features, including sites of recent or current activity, and identify candidate landing sites for future lander missions.	5	5		D. Geology
Group 2:				
Characterize the surface composition, especially compounds of interest to prebiotic chemistry.	4	4	An *in situ* surface element would be required to achieve full science.	C. Chemistry
Map the distribution of important constituents on the surface.	5	5		C. Chemistry
Characterize the radiation environment in order to reduce the uncertainty for future missions, especially landers.	5	5		C. Chemistry D. Geology
LARGE SATELLITES PANEL THEMES AND KEY QUESTIONS:				
Theme 1. Origin and Evolution of Satellite Systems				
1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO	C. Chemistry E. Jupiter System
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)	4	5	Scoring does not reflect the emphasis on Titan. Detailed investigations of Ganymede and Callisto are facilitated by JGO	E. Jupiter System
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?	5	5		A. Ocean B. Ice C. Chemistry D. Geology E. Jupiter System
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?	5	5		D. Geology E. Jupiter System

	JEO	JEO + JGO	Comments	JEO Science Objective
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and is Ganymede unique?	3	5	Detailed investigation of Ganymede's magnetic field is accomplished by JGO, and synergies with JEO.	E. Jupiter System
Theme 2. Origin and Evolution of Water-Rich Environments in Icy Satellites				
1. What is the chemical composition of the water-rich phase?	4	4		C. Chemistry E. Jupiter System
2. What is the distribution of internal water, in space and in time?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO.	A. Ocean B. Ice E. Jupiter System
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?	5	5	Emphasis on investigations in orbit around Europa. The JEO and JGO satellite tours places Europa in context with the other satellites. JGO orbital science increases the rating beyond that anticipated by the Decadal Survey.	A. Ocean C. Chemistry D. Geology E. Jupiter System
4. Can and does life exist in the internal ocean of an icy satellite?	3	3	Scoring emphasizes focus on assessing potential for habitability rather than direct search for life.	A. Ocean C. Chemistry E. Jupiter System
Theme 3. Exploring Organic-Rich Environments				
1. What is the nature of organics on large satellites?	4	5	Inclusion INMS as part of the payload facilitates direct sampling of materials, especially at Ganymede & Callisto.	C. Chemistry E. Jupiter System
2. What are the processes currently affecting organic-rich surfaces?	4	5	Direct monitoring of the radiation environment provides insight into processes at Europa (JEO); JGO will examine the impact of the radiation environment on organic materials at Ganymede.	C. Chemistry E. Jupiter System
3. How does organic chemistry evolve in a hydrocarbon solvent?	0	0		N/A
4. How do atmospheric processes affect organic chemistry?	3	3	JEO investigates sputtering processes and the effects on chemistry.	C. Chemistry E. Jupiter System
Theme 4. Understanding Dynamic Planetary Processes				
1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?	4	4	Scoring reflects that JEO is not optimized for Io science.	A. Ocean E. Jupiter System
2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?	5	5	Scoring reflects emphasis on Europa science by JEO.	C. Chemistry D. Geology E. Jupiter System
3. What are the complex processes and interactions on the surfaces and in volcanic or geyser-like plumes, atmospheres, exospheres, and magnetospheres?	4	5		C. Chemistry D. Geology E. Jupiter System
Large Satellites Panel overall high-priority questions:				
1. Is there extant life in the outer solar system?	3	3	Scoring emphasizes focus on assessing potential for habitability rather than direct search for life.	A. Ocean C. Chemistry E. Jupiter System
2. How far toward life does organic chemistry proceed in extreme environments?	3	3		C. Chemistry E. Jupiter System

	JEO	JEO + JGO	Comments	JEO Science Objective
3. How common are liquid-water layers within icy satellites?	4	5	Detailed investigations of Ganymede and Callisto are facilitated by JGO.	A. Ocean B. Ice E. Jupiter System
4. How does tidal heating affect the evolution of worlds?	4	5	Scoring reflects that JEO is not optimized for Io science. Detailed investigations of Ganymede and Callisto are facilitated by JGO	A. Ocean E. Jupiter System
DECADAL SURVEY GIANT PLANETS PANEL				
Theme 1. Origins and Evolution				
Giant Planets: general				
1. How did the giant planets form?	1	3		E. Jupiter System
2. What are the orbital evolutionary paths of the giant planets?	1	1		E. Jupiter System
3. Does Jupiter have a rock-ice core?	0	0		N/A
4. What are the elemental compositions of the giant planets?	2	3		E. Jupiter System
5. What are the internal structures and dynamics of the giant planets?	0	0		N/A
Theme 2. Interiors and Atmospheres				
Interiors				
1. What is the nature of phase transitions within the giant planets?	0	0		N/A
2. How is energy transported through the deep atmosphere? Do radiative layers exist?	0	0		N/A
3. How and where are planetary magnetic fields generated?	0	0		N/A
4. What is the nature of convection in giant planet interiors?	0	0		N/A
5. How does the composition vary with depth?	0	1		N/A
Atmospheres				
6. What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?	4	5		E. Jupiter System
7. What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?	4	5		E. Jupiter System
8. How and why does atmospheric temperature vary with depth, latitude, and longitude?	2	4	JGO provides addition opportunities for radio science investigations	E. Jupiter System
9. How does the aurora affect the global composition, temperature, and haze formation?	3	4		E. Jupiter System
10. What produces the intricate vertical structure of giant planet ionospheres?	3	4		E. Jupiter System
11. At what rate does external material enter giant planet atmospheres, and where does this material come from?	0	2		N/A

	JEO	JEO + JGO	Comments	JEO Science Objective
12. What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?	0	0		N/A
Theme 3. Rings and Plasmas.				
Rings				
1. What are the most important mechanisms for ring evolution on long and short time scales? How do self-gravity, viscosity, ballistic transport, and collisions interact?	2	2		E. Jupiter System
2. What do planetary rings teach us about nebulas around other stars?	2	2		E. Jupiter System
3. What are the present physical properties (composition, size distribution, shapes) of particles in the various rings and of distinct regions within the various rings?	2	2		E. Jupiter System
4. What is the present mass flux into the various ring systems? What are the present size, mass, velocity, and composition distributions of the influx population?	2	2		E. Jupiter System
5. What is the relationship between local ring properties and those properties observable by remote sensing?	2	2		E. Jupiter System
6. How fast are angular momentum and energy being transferred among rings and moons?	2	2		E. Jupiter System
7. What is the influence of magnetospheric plasma on the rings?	1	1		E. Jupiter System
Plasmas				
1. What is the nature of the electrodynamic coupling between major satellites and the ionospheres of their planets?	4	5	Scoring reflects JGO emphasis on observations in orbit at Ganymede.	E. Jupiter System
2. What is the spatial and temporal structure of centrifugally driven plasma transport in a rotation-dominated magnetosphere?	4	4		E. Jupiter System
3. What role does electromagnetic angular momentum transfer, as observed in giant planet magnetospheres, have in solar system formation?	2	2		E. Jupiter System
4. How do the Io plasma torus and analogous structures at other planets convert planetary rotational energy into electromagnetic radiation over a wide range of frequencies?	4	4		E. Jupiter System
5. How are angular-momentum transfer and other global magnetospheric processes revealed through auroral emission features?	3	3		E. Jupiter System
6. How and where is the jovian planetary wind generated? Does Saturn have a planetary wind?	1	1		E. Jupiter System
7. How does the jovian pulsar work? Do other giant planets exhibit pulsar behavior?	1	1		E. Jupiter System

L.2 JGO Traceability Matrix

The JGO Science Traceability matrix is shown in Table L.2. The color coding for the investigations and measurements is identical to that of the JEO Science Traceability Matrix and described in Table 2.4-3. The JGO element was evaluated and the degree to which the JGO's model payload addresses each investigation was rated in an identical methodology as for the JEO Traceability Matrix. This Science Value score is shown in the last column of Table L.2. This structured approach to the derivation of investigations and measurements clearly demonstrates the breadth of the science available within the Jupiter System. For more information on the JGO mission concept, see Appendix J.

JGO Focus Areas:	Origins	Evolution	Processes	Habitability

Science Value Scoring			
5	Definitely addresses full	2	May address partial science
4	May address full science	1	Touches on science
3	Definitely addresses partial	0	Does not address science

JGO Traceability Matrix

Science Objective		Science Investigation	Measurements	Science Value
Ganymede	Characterize Ganymede as a planetary object including its potential habitability	Ice shell and ocean	Constrain the tidally varying potential and shape - Time dependent altimetry and gravity to determine Love numbers h2 (tidal amplitudes) and k2 (tidal potential). Requires determination of the surface motion that correlates with the eccentricity tidal potential to 1-meter accuracy, and a determination of the time dependent degree-2 gravitational acceleration to 0.1 mgal at Ganymede. Alternatively, the eccentricity tidal k2 and h2 at accuracy 0.01. It will determine whether an ocean exists.	4
			Study the induced magnetic field at multiple frequencies; a) global determination of induction response at multiple frequencies (orbital as well as Jupiter rotation time scales) at Ganymede to an accuracy of 0.1 nT; b) looking for secular variation of the 'steady' field or variation in the induction signal since Galileo; c) magneto-telluric effects from ocean currents. Sensitivity to 0.1 nT.	3
			Subsurface characterization - Determine the presence and location of shallow liquid water (including brines).	5
			Constrain the amplitude of forced libration and obliquity and non-synchronous rotation; a) determination of the libration amplitude to 10m accuracy; b) measure the pole position to determine the obliquity of the spin axis; c) search for changes in pole position (obliquity) over periods of years (total temporal baseline >1 year and > 3 years strongly desired).	3
		Ganymede's magnetosphere	Globally characterize Ganymede's intrinsic magnetic field (to accuracy of 0.1nT). Perform near-surface (100-200 km altitude) global magnetic sounding at spatial resolutions of ~300 km (repeat several times to detect variability and to separate intrinsic and induced field).	3

JGO Traceability Matrix				Science Value
Science Objective		Science Investigation	Measurements	
			Characterize particle population within Ganymede's magnetosphere and its interaction with Jupiter's magnetosphere; a) measure the velocity space distribution of thermal plasma with 10 s resolution; b) measure differential directional fluxes of energetic ions and electrons at keV to MeV energies with a 10 s resolution; c) measure the intensity of local radio and plasma waves vs. frequency; d) measure the energetic neutral atom distributions at different energies.	2
			Investigate the generation of Ganymede's aurora. Measure UV emission of Ganymede's aurora.	3
			Study of the ionosphere and exosphere of Ganymede; a) measure the dust population in the vicinity of Ganymede and its interaction with the Jovian magnetosphere; b) measure the sputtered neutral and charged particle population; c) measure the magnetic field vector; d) measure the energetic neutral atom distribution; e) composition of the exosphere: Multi-wavelength (UV-VIS-NIR) characterization and mapping of the abundance at different heights over the surface through limb scans.	2
			Investigate surface composition and structure on open vs. closed field line regions; a) image Ganymede at FUV-NIR wavelengths at 1km resolution; b) measure the magnetic field vector at 1 s resolution.	4
		Geology and search for past and present activity	Improve global and regional mapping; a) image with a resolution of 200 m/pxl for at least 50 % of the surface area (One filter / panchromatic filter); b) mid-res global surface coverage (~ 500 m/pxl) - (One filter / panchromatic filter); c) global surface coverage (~1-2 km/pxl) using four spectral filters from about 350 nm to 1000 nm; d) coherent image mosaics (camera data) at given spatial resolution and viewing angle (not too oblique plus suitable sun elevation - e.g. mid-morning/mid-afternoon); e) acquire new high res (<10 m/pix) images of selected areas.	4
			Topographic mapping of large fractions of the surface; a) obtain profiles using laser altimetry; b) derive digital terrain models from stereo imaging (requires imaging of surface area under slightly different angle, but similar sun elevation); c) correlate tectonism on Ganymede with dynamics in the ice shell (obtained by ice penetrating radar).	4
			Subsurface characterization; a) characterizing the near-surface tectonic and volcanic processes and their relation to interior processes; b) identify the dynamical processes that cause internal evolution and near-surface tectonics; c) determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.	4
			Determine global and regional surface ages; a) measure crater distributions by complete image coverage at 200-500 m/pxl resolutions plus sufficient high-resolution target areas (10-50 m/pxl); b) monitor over several years Ganymede's surface in order to identify newly-formed craters (from comparison with Galileo data); c) study of the impactors characteristics (craters catenae formed by disgregated comets).	3

JGO Traceability Matrix				Science Value
Science Objective		Science Investigation	Measurements	
		Surface composition and physical properties of near-surface layers	Nature and location of non-ice and organic compounds; a) Mapping spectrometer data with sufficient spectral and spatial (at least 500 m/pxl) resolution in the NIR and UV; b) correlate surface composition and physical characteristics (e.g., grain size) with geologic features; c) search for spectral signatures of organic compounds in the NIR (3-5 microns) and UV; d) ion and neutral surface measurements; e) sampling of dust from low orbit and close flyby (< 200 km altitude); f) determine abundances of major elements at surface by X-ray spectroscopy.	**3**
			Characterization of hemispheric differences to constrain the existence and rate of mass transfer processes. Determination of the surface regolith properties (particle size, composition, distribution, crystallinity) between; a) leading vs trailing hemispheres (role of impactors and dust); b) north vs south hemispheres (role of sputtering and amorphization induced by magnetospheric particles).	**3**
		Deep interior	Precise determination of low-degree static gravity field and shape; a) determination of static J2 and C22 coefficients; b) test of hydrostaticity: determination of J2 and C22 from independent (polar and equatorial) flybys; c) determination of degree 2 static topography to at least ten-meter accuracy by laser altimetry and imaging.	**5**
			Detailed study of the intrinsic magnetic field - (see "Magnetosphere of Ganymede" subsection).	**4**
			Search for deviations from hydrostatic equilibrium and for mass anomalies; a) Constraints on non-hydrostatic components from higher harmonics at 10-7 accuracy for the non-dimensional gravitational harmonics; b) High-order gravity sounding to ~300 km horizontal resolution from an altitude of < 200 km.	**4**

Satellite system	Study the Jovian satellite system	**Callisto: Study its surface composition, physical properties, putative ocean, and internal structure**	Constrain the tidally varying potential and shape - Time dependent altimetry and gravity to determine Love numbers h2 (tidal amplitudes) and k2 (tidal potential). Requires determination of the surface motion that correlates with the eccentricity tidal potential to 1-meter accuracy, and a determination of the time dependent degree-2 gravitational acceleration to 0.1 mgal at Callisto. Alternatively, the eccentricity tidal k2 and h2 at accuracy 0.01. It will determine whether an ocean exists.	3
			Study the induced magnetic field at multiple frequencies; a) global determination of induction response at multiple frequencies (orbital as well as Jupiter rotation time scales) at Ganymede to an accuracy of 0.1 nT; b) looking for secular variation of the 'steady' field or variation in the induction signal since Galileo; c) magneto-telluric effects from ocean currents. Sensitivity to 0.1 nT.	3
			Subsurface characterization - Determine the presence and location of shallow liquid water (including brines).	4
			Composition of the surface - Nature and location of non-ice and organic compounds; a) mapping spectrometer data with sufficient spectral and spatial (at least 500 m/pxl) resolution in the NIR and UV; b) correlate surface composition and physical characteristics (e.g., grain size) with geologic features; c) search for spectral signatures of organic compounds in the NIR (3-5 microns) and UV; d) ion and neutral surface measurements e) Sampling of dust from low orbit and close flyby (< 200 km altitude); e) determine abundances of major elements at surface by X-ray spectroscopy.	4
			Constrain the amplitude of forced libration and obliquity and non-synchronous rotation; a) determination of the libration amplitude to 10m accuracy; b) measure the pole position to determine the obliquity of the spin axis; c) search for changes in pole position (obliquity) over periods of years (total temporal baseline >1 year and > 3 years strongly desired).	3
			Precise determination of low-degree static gravity field and shape of Callisto; a) determination of static J2 and C22 coefficients; b) test of hydrostaticity: determination of J2 and C22 from independent (polar and equatorial) flybys.	4
			Topographic mapping of large fractions of the surface; a) obtain profiles using laser altimetry; b) derive digital terrain models from stereo imaging (requires imaging of surface area under slightly different angle, but similar sun elevation); c) study dynamics in the ice shell (obtained by ice penetrating radar).	4
			Characterization of Callisto exosphere - Determine the composition of the Callisto' exospheres. Multiwavelength (UV-VIS-NIR) characterization and mapping of the abundance at different heights over the surface through limb scans. Determine temperature of surface volatiles that support the exospheres.	3
			Characterization of hemispheric differences to constrain the existence and rate of mass transfer processes. Determination of the surface regolith properties (particle size, composition, distribution, crystallinity) between; a) leading vs trailing hemispheres (role of impactors and dust); b) north vs south hemispheres (role of sputtering and amorphization induced by magnetospheric particles).	3

			Determine global and regional surface ages; a) measure crater distributions by complete image coverage at 200-500 m/pxl resolutions plus sufficient high-resolution target areas (10-50 m/pxl); b) monitor over several years satellite's surfaces in order to identify newly-formed craters (from comparison with Galileo data); c) study of the impactors characteristics (craters catenae formed by disagregated comets).	**4**
			Improve imaging coverage of Callisto's surface; a) mapping of at least 50 % of the surface (~ 200 m/pxl); b) global coverage (~ 1-2 km/pxl) with four spectral filters from about 350 nm to about 1000 nm; c) HR images with a resolution of 200 m/pxl for at least 30 % of the surface area; d) acquire new high res (<10 m/pix) images of selected areas.	**4**
		Io and Europa	Study of pick-up & charge-exchange processes in plasma/neutral tori; a) remote-sense the radio, UV to VIS/IR emissions from the Io and Europa tori as well as in (high energy) energetic neutral atoms; b) remote-sense the radio, UV to VIS/IR auroral footprints of Io and Europa.	**2**
			Monitor Io's activity at a wide range of longitudes and local times; a) study Io's hemispheric volcanic activity; b) photometry to determine bolometric albedo.	**2**
			Characterization of satellites' exospheres - Determine the composition of the satellites' exospheres. Multi-wavelength (UV-VIS-NIR) characterization and mapping of the abundance at different heights over the surface through limb scans. Determine temperature of surface volatiles that support the exospheres.	**3**
		Improve our understanding of the irregular satellites	Physical characterization & chemical composition of outer irregular satellites (only if a close flyby turns out to be feasible); a) satisfactory global (for determining size, shape and possible companion bodies) and regional imaging resolution (200-500 m/pxl); b) study of the surface photometric parameters through phase and light curves (looking at zero phase angle desirable) and weathering processes; c) multi-wavelength (UV -VIS/NIR - Thermal) characterization and mapping of the surface composition; d) determination of the satellite's mass from radio science tracking; e) measure the neutral and charged particles sputtered off the surface.	**3**
			Astrometric observations of irregular satellites - Evaluation of the orbital motion of the satellites with respect to stars (long exposure MAC - NAC images).	**2**
			Search for new outer irregular satellites - Search for new satellites by using long exposure MAC images.	**2**
		Investigate the inner region of the Jupiter system including the ring system	Physical characterization & chemical composition of the ring system & search for new associated satellites; a) determine the structure and particle properties of the Jovian ring system in 3D: global imaging of the entire ring system over a range of time-scales and in a wide range of phase angles; b) multi- wavelength (UV-VIS-NIR) characterization and mapping of the ring particles composition and photometric behavior over a wide range of phase angles; c) search for new associated satellites (with radius < 8 km); d) sampling of dust particles: 3D distribution, and dynamics; investigate dust grain composition and size; e) dynamical interactions between rings and satellites; f) Map the energetic neutral atoms distribution.	**3**

			Physical characterization & chemical composition of Thebe, Amalthea and other small inner satellites; a) global imaging to improve the determination of satellites' size, shape and cratering history; b) study of the surface photometric and thermophysical parameters through phase and light curves (looking at low phase angles desirable); c) (at least for Thebe and Amalthea): multi-wavelength (UV- VIS-NIR) disk-integrated characterization of the surface composition to confirm them as sources of the ring particles.	**3**
			Determine improved ephemerides for small inner satellites - Evaluation of the orbital motion of the satellites with respect to stars (long exposure MAC - NAC images).	**1**
Jupiter	**Study the Jovian atmosphere**	**The upper atmosphere**	Determination of general circulation & composition in the upper atmosphere from UV and H^{3+} measurements; characterization of auroral activity from H^{3+} (IR) and H_2 (UV) observations.	**4**
			Characterization of the vertical coupling in the atmosphere & of its drivers (EUV heating, ion drag or wave activity).	**4**
			Temperature structure retrieval from upper atmosphere to the troposphere through radio occultations technique, line profiles in submm range UV and thermal infrared measurements.	**4**
			Characterization of ionospheric total electron densities & variations.	**3**
			Characterization of the wave activity at low- to mid-latitudes and eddy activity and eddy meridional transport.	**3**
		The stratosphere	Determination of the composition: H_2O (characterization of latitudinal variations, dynamics, role in atmospheric chemistry); HCN (dispersion following the SL9 impact), hydrocarbons (stratospheric chemistry) and haze; characterization of the strength of vertical mixing.	**5**
			Determination of temperature structure from stellar and solar occultations over a wide range of latitudes in the upper stratosphere (1-km at 20°K per measurement).	**4**
			Determination of the general circulation in the stratosphere.	**4**
		The troposphere	Determination of chemical composition: condensable species (NH_3, H_2O) and disequilibrium species (PH_3, CO) at high spectral resolution (R>1000).	**4**
			Characterization of the strength of the vertical coupling in the atmosphere up to the troposphere.	**4**
			Determination of the composition & vertical structure of clouds and cloud size distribution.	**3**
			Study of the relation between the upper troposphere circulation & the deep circulation below the clouds & processes driving the jets circulation. Potential vorticity retrieval from combined dynamics and thermal measurements.	**3**
		The internal structure of Jupiter	Constrain the existence and size of a core, and the nature of the H-H_2 phase transition - Monitoring of global oscillation modes of the planet (up to degree l=25 floor, up to degree l=50 desired goal).	**1**

Magnetosphere	**Study the Jovian magnetodisk/magnetosphere**	**The magnetosphere as a fast magnetic rotator**	Characterize the 3D properties of the magnetodisk with the help of in-situ measurements of the magnetic field vector, plasma and energetic ions and electrons from eV to MeV at 1 min resolution or better to resolve the acting processes, with nearly 3D coverage in order to obtain good and reliable plasma moments (density, pressure, bulk flow velocity).	**3**
			Improve our understanding of the plasma processes acting in the magnetodisk by measuring high frequency fluctuations of electric and magnetic fields from Hz to MHz.	**2**
			Investigate the plasma sources, mass loading variability, composition, transport modes, and loss processes in the magnetosphere with the help; a) of in-situ measurements of the magnetic field vector and of charged plasma and neutral energetic particles from eV to MeV with good angular and temporal resolution, with nearly 3D angular coverage; b) of in-situ measurements of plasma and energetic major and minor ion species, including composition capabilities and elemental mass ionic charges at 1 min resolution or better; c) remote radio, UV to VIS/IR measurements of Io and Europa tori emissions as well as in (high-energy) energetic neutral atoms.	**2**
			Measure dust composition and charge states (including Io dust streams) to better understand the coupling between dust and magnetospheric plasma at Jupiter.	**3**
			Characterize the large-scale coupling processes between the magnetosphere, ionosphere and thermosphere; a) by remote-sensing continuously the jovian radio and auroral emissions in the IR, UV and X-ray wavelengths with high resolution, including the footprints of the moons and their variability; b) improving our understanding of the morphology and modulation of radio auroral emissions by measuring plasma waves and radio emissions vs. frequency with high spectral resolution in frequency from the key regions in the magnetosphere; c) determining the magnetospheric mapping of auroral/radio features by measuring in-situ at 1 min resolution the properties of the plasma and energetic ions and electrons in the medium-energy range (100s eV-100s keV) and magnetic field vectors in the region where the corotation breaks-down, in combination with the remote-sensing of the radio and auroral emissions.	**3**
			Magnetospheric response to solar wind variability; a) Measure solar wind parameters (magnetic field components, density, bulk velocity, dynamic pressure); b) measure the jovian radio and auroral emissions in the IR, UV, X wavelengths, in combination with in-situ solar wind measurements; c) mapping on a global scale the (high-energy) energetic neutral atoms resulting from charge exchange processes; in combination with in-situ solar wind measurements.	**2**
			Look for direct evidence of the effects of the solar wind and planetary rotation on driving magnetospheric dynamics, by searching for large-scale changes in the in-situ properties of the plasma, energetic particles, and magnetic field, and by characterizing the spin-periodic modulation of magnetospheric parameters.	**2**
		The magnetosphere as a giant accelerator	Characterize the time evolving Jovian radiation environment by measuring in-situ the properties (fluxes, pitch angle distribution) of the charged energetic particle populations (ions and electrons) in the keV to MeV energy range in various regions of the magnetosphere.	**3**

			Improve our understanding of the particle bombardment of the surfaces of the moons by determining the composition and charge state of the charged energetic particle populations (ions and electrons) in the keV to MeV range in the inner and middle magnetosphere.	**2**
			Detail the particle acceleration processes by measuring the plasma waves and radio emissions vs. frequency in the Hz to MHz range, in combination with in-situ charged energetic particle measurements.	**3**
			Study the loss processes of charged energetic particles by measuring at different energies the time evolving (high-energy) energetic neutral atoms resulting from charge exchange reactions.	**2**
			Measure the time evolving electron synchrotron emissions using ground-based observations in the Ghz range, in combination with in-situ measurements of energetic electrons.	**3**
Jupiter system	**Study the interactions occurring in the Jovian system**	**Satellite / magnetosphere interactions: the magnetosphere as a magnetized binary system**	Observations of the moon auroral magnetic footprints. Observe the magnetic footprints in the visible, IR and UV wavelengths.	**3**
			Study of pick-up & charge-exchange processes in plasma/neutral tori; a) measure the low-energy pick-up ion distribution; b) remote sense the Europa and Io Torus in VIS/IR, UV and using their radio and ENA emissions; c) measure the energetic particle distributions for ions and electrons; d) measure the plasma properties of ions and electrons; e) measure the energetic neutral atom distribution at low energy; f) measure the magnetic field vector; g) measure the plasma/radio emissions vs. frequency.	**2**
			Analysis of plasma/surface sputtering processes; a) measure the neutral and charged particles sputtered off the surface; b) measure the dust particles (impacting the surface and ejected from the surface).	**2**
			Analysis of moon micro-signatures to quantify fundamental processes; a) measure the energetic charged particle absorption signatures; b) measure the local plasma properties; c) measure the magnetic field vector.	**3**
		Tidal coupling among Jupiter and the Galilean satellites	Determine long-term changes of the orbits of the Galilean satellites; a) accurate positions of the satellites (on the order of a meter (desired)) from spacecraft in combination with ground-based observations; b) Imaging of satellites with background starfield. Desired: constrain the secular acceleration of all the moons to $5 m/yr^2$ (corresponds to ~a few meters in orbit location).	**4**
			Study the coupled evolution of Io Europa and Ganymede by determining internal structures, heat flows, and tidal responses of the moons.	**5**
		Physico-chemistry of the small bodies	Study the composition of the dust particles; a) sampling of dust particles 3D distribution and dynamics; b) investigate dust grain composition and size.	**0**

M. ADDITIONAL REPORTS ON CD

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N. COMPLIANCE MATRIX

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O. INTERNATIONAL CONTEXT

There are ample indications that the EJSM, like Cassini/Huygens, could be an international collaboration in flight hardware and engineering as well as scientific involvement. With its sizeable Solar System Exploration budget NASA is expected to be the primary source of funding for a flagship outer planets mission. But despite their smaller overall budgets, space-faring organizations outside the US could make significant contributions to the flight systems, operations, and science of such a mission. For this reason, NASA included as one of its guidelines for this study the option of international collaboration with ESA, further described in the Requirements and Ground Rules (NASA 2008).

O.1 Space-Faring Organizations Outside the United States

There are multiple non-US space-faring organizations that could participate at various levels, ranging from large, well-financed efforts such as the European Space Agency (ESA) to fledgling programs that have not yet ventured on their own beyond Earth orbit. The following subsections describe first the agencies considered “prime candidates,” and then other agencies that might make smaller contributions.

ESA

ESA is the primary agency for space flight and research of the European Union (EU), with financial support from the EU and its Member States. It has a significant yearly budget for exploration and scientific research. With its demonstrated capabilities for flight system development and fabrication, launch, and deep space operations, ESA is fully capable of conducting robotic interplanetary science missions on its own, as demonstrated by such missions as Rosetta, Mars Express, and Venus Express. ESA’s launch capability does not include launch vehicles as large as the largest in NASA’s stable, but its largest, the Ariane V, has sufficient launch capacity to deliver a scientifically viable spacecraft to the Jupiter system via gravity assists in the inner solar system and possibly Jupiter. However, ESA currently cannot fabricate a radioisotope power source (RPS) sufficient to power a spacecraft for a long-lived mission beyond Jupiter, and French law currently prohibits launch of RPSs from ESA’s primary launch facility in Kourou, French Guiana. If ESA contributes a long-lived flight element requiring an RPS of more than a few Watts electrical output, under current schedules the US would have to supply it, and under current laws and policies it would have to launch on a US launch vehicle. But the French laws that prohibit launches of nuclear materials from Kourou are being reviewed, and ESA is actively studying the resources needed to enable such launches.

ESA Member States

ESA is not the only space agency within the EU: multiple EU Member States also have their own national space agencies, such as Germany’s DLR and Italy’s ASI. They have their own budgets and their own histories of flight experience. Germany’s DLR has developed space propulsion system components and scientific instruments designed to operate in the outer solar system, both certified for flight on flagship US missions (Galileo and Cassini) with demonstrated success. ASI has significant experience with advanced spacecraft radio systems, providing major components of the Cassini telecommunications and radio science systems. They also built and flew, with Dutch collaboration and US launch, the successful BeppoSax X-ray observatory. Member states can also provide scientific expertise, as they have for Cassini/Huygens.

JAXA

The Japanese Aerospace Exploration Agency (JAXA), like ESA, has demonstrated flight system development and fabrication, launch, and deep space operations capabilities on their own (though with a lesser degree of success so far). JAXA has expressed a strong desire to collaborate with ESA in magnetospheric research, specifically proposing to provide a Jupiter-orbiting magnetospheric research flight element that might ride on an ESA (possibly with NASA involvement) Jupiter mission, as mentioned in §G.2.

Other National Space Agencies

There are four other national space agencies with credible capability to provide contributions such as flight elements to an international outer planet mission, though others are rapidly developing their capabilities. The four are the Canadian Space Agency (CSA), the Russian

Space Research Institute (IKI), the Indian Space Research Organization (ISRO) under India's Inter-Ministerial Space Commission, and the China National Space Administration (CNSA). Canada, though lacking its own launch capability, has a long history of building its own Earth-orbiting robotic spacecraft and other flight hardware such as the robotic arms on the US Space Shuttle and International Space Station. Its government agency CSA (ASC in French) was established in 1989. CSA has had the Microvariability and Oscillation of Stars (MOST) observatory satellite in operation since 2005, and plans to launch in 2009 the Near Earth Object Surveillance Satellite (NEOSSat), confirming CSA's ability to build scientific instruments and conduct scientific investigations in space. Canada also has a well-established program of space science research and could contribute scientists to a TSSM science team.

Born in the days of the Soviet Union, the Russian agency formerly had significant capabilities commensurate with a large budget: a well-established research program, demonstrated flight system development, fabrication, launch, and deep space operations capability, and fabrication and launch of RPSs. But there were severe budgetary cutbacks after the collapse of the USSR, reducing Russian scientific space activity to a small fraction of its former level. IKI personnel have suggested the intent to recapture some of the pre-USSR-collapse scope. ISRO currently has limited launch and deep space operations capability limited to cislunar space, but has long-range plans that include the lead role in an orbiter mission to Mars. Their next planned planetary mission, Chandrayaan, is a lunar mission, their first foray beyond geostationary orbit. CNSA has significant launch capability, but its deep space operations capabilities appear driven by a strong effort toward a manned exploration program in cislunar space. There is no apparent effort in science extending beyond cislunar space.

O.2 ESA's Cosmic Vision 2015–2025 Program

ESA usually performs its long-term planning in approximately 10-year segments. They are nearly three years into the current planning activity, the *Cosmic Vision 2015–2025* (CV) Program, whose goal is to plan ESA's space science program for the 2015–2025 period. CV began with a call to the European space science community to propose high-priority science themes to be addressed in the CV time frame. ESA considered those proposed themes and produced a document, *Cosmic Vision: Space Science for Europe 2015–2025*, to list and describe the themes selected for subsequent steps of the process. For the science community the next step was to prepare proposals for studies of mission concepts to address the science themes. The proposals were for *studies* of mission concepts to provide ESA with sufficient information to make selections for implementation later in the process. Acceptance of the study proposal was by no means a confirmation that the proposed concept would actually fly. Note that this was not just for planetary science: all branches of space science, such as astronomy and astrophysics, and heliospheric studies, were included, so a wide range of mission types were involved.

ESA classifies its major science missions into Small-, Medium-, and Large-class missions, denoted S, M, and L respectively. The mission-related goal of CV is to plan ESA's M and L missions for the 2015–2025 time frame. Cost caps are associated with the classes, with M limited to 350M Euros and L to 650M Euros. These are costs to ESA, which in general are not total mission costs. For ESA missions, ESA usually provides (i.e., finances) the spacecraft, the launch vehicle, and other "standard" mission items and services, but not the science instruments and some other items that are contributed by European Union Member States at no cost to ESA. There are no well-defined rules for which components, systems, or services the Member States contribute. Each mission is negotiated with a unique agreement.

Science community teams proposing science objectives and mission concepts in response to the call for proposals were required to declare the mission size class for their concept. Outer solar system (OSS) missions are difficult, so credible OSS mission concepts are all L-class missions. Even then, there are few scientifically viable missions to outer solar system destinations that can be flown within a cost of 650M Euros plus Member State contributions.

ESA received three such proposals and accepted two for studies: *Laplace*, a mission to Europa and the Jupiter System, and TandEM, a Titan and Enceladus mission. The decision was not made without regard to NASA. ESA was aware of NASA's interest in an outer solar system flagship mission, and the *Laplace*/ TandEM selections mirror NASA's stated interests at the time. With new Cassini/Huygens successes being announced on an almost daily basis, there is strong motivation among the planetary science community and many space agency administrators to make the next outer solar system flagship mission another international collaboration, in the spirit of Cassini/Huygens.

Negotiations among the US, NASA, the EU, and ESA led to the structure of NASA's and ESA's current outer planet flagship studies. For the Jupiter system, the *Laplace* concept's Europa-orbiting element is replaced by a US Jupiter Europa Orbiter currently under study, and the US Jupiter System Observer (JSO) concept is subsumed into *Laplace's* ESA Jupiter Ganymede Orbiter under study by ESA. JAXA might also provide a Jupiter-orbiting element for conducting Jovian magnetospheric investigations. This establishes the foundation and structure for the EJSM study and associated studies by ESA. For the Saturn system, a recasting of NASA's Titan Explorer and Enceladus Explorer concepts, along with ESA's TandEM concept, as a single mission, assigns a Titan orbiter to NASA and one or more *in situ* elements to ESA. This establishes the foundation and structure for the TSSM study and associated studies by ESA.

Although at the initiation of this study there was a schedule misalignment between NASA's and ESA's development schedules. This has been resolved via the regular NASA/ESA bilateral discussions. New guidelines originating in those discussions target a 2020 launch date with options for 2018–2022 launches. The flexibility inherent in the EJSM architecture provides robustness against potential future schedule problems arising from programmatic, technical or cost issues. Examples of this flexibility include:

- Lack of physical interface allows separate development cycles, so changes in schedule do not impact the flight elements
- Separate launches of Europa orbiter and Ganymede orbiter elements allow decoupling of NASA and ESA schedule
- Trajectories are numerous and can be easily adjusted to better accommodate overlap of the systems in Jupiter orbit

O.3 NASA-ESA Collaboration Potential

Both NASA and ESA have expressed interest in a collaborative flagship mission to the Jupiter System. There are multiple different avenues for implementing such collaboration, involving science team members, flight hardware including RPSs, launch vehicles and services, operations, deep space communications, and other aspects of a deep space mission. NASA-ESA collaborations are done on a no-funds-exchange basis, so implementation plans that involve either agency buying equipment or services from the other side of the Atlantic are not workable. Instead, any exchanges must be done on the basis of offsetting contributions, much like a barter system, and must be negotiated uniquely for each mission.

A brief summary of each agency's capabilities sets the framework for building a collaboration. NASA is technically capable of conducting every aspect of a Europa or Ganymede orbiter on its own, but the funding level needed outstrips what is expected for SMD in the anticipated time frame. For the anticipated funding level available, \$2–3B (FY07), NASA can probably fly a very capable Europa orbiter (the objective of this study), but without the capability to orbit another moon such as Ganymede. ESA's capabilities closely mirror those of NASA in many important respects, with a few notable exceptions. Currently ESA cannot provide RPSs or launch vehicles larger than their Ariane 5, and cannot launch any RPS from their prime launch site at Kourou, French Guiana. With the L-class limit of \$650M Euros cost to ESA, it is unlikely ESA could afford a capable orbiter mission to Europa, even with contributed RPSs, but they could probably design and fabricate, with assistance from Member States, an orbiter to Ganymede with European-built solar arrays.

The simplest collaboration option with current capabilities and policies is to have a capable NASA-led Europa orbiter launch separately from a ESA-led Ganymede orbiter.

This arrangement eliminates the physical NASA/ESA interfaces and therefore does not suffer from the potential schedule conflict mentioned in §G.2.

The Cassini/Huygens mission is an example of a more elaborate collaboration arrangement. ESA and its Member States provided not only the Huygens *in situ* probe and support hardware, but also provided science instruments and other flight hardware for the Cassini orbiter. Science team members were traded across NASA/ESA boundaries as well. If NASA and ESA deem it worth the more complex interfaces, there is a variety of arrangements possible that could resolve schedule conflicts and yield a more scientifically rich mission, though probably at a somewhat increased total mission cost. Items potentially available for trading include science instruments and other flight hardware, operations and tracking services, science expertise, and even launch vehicles and services.