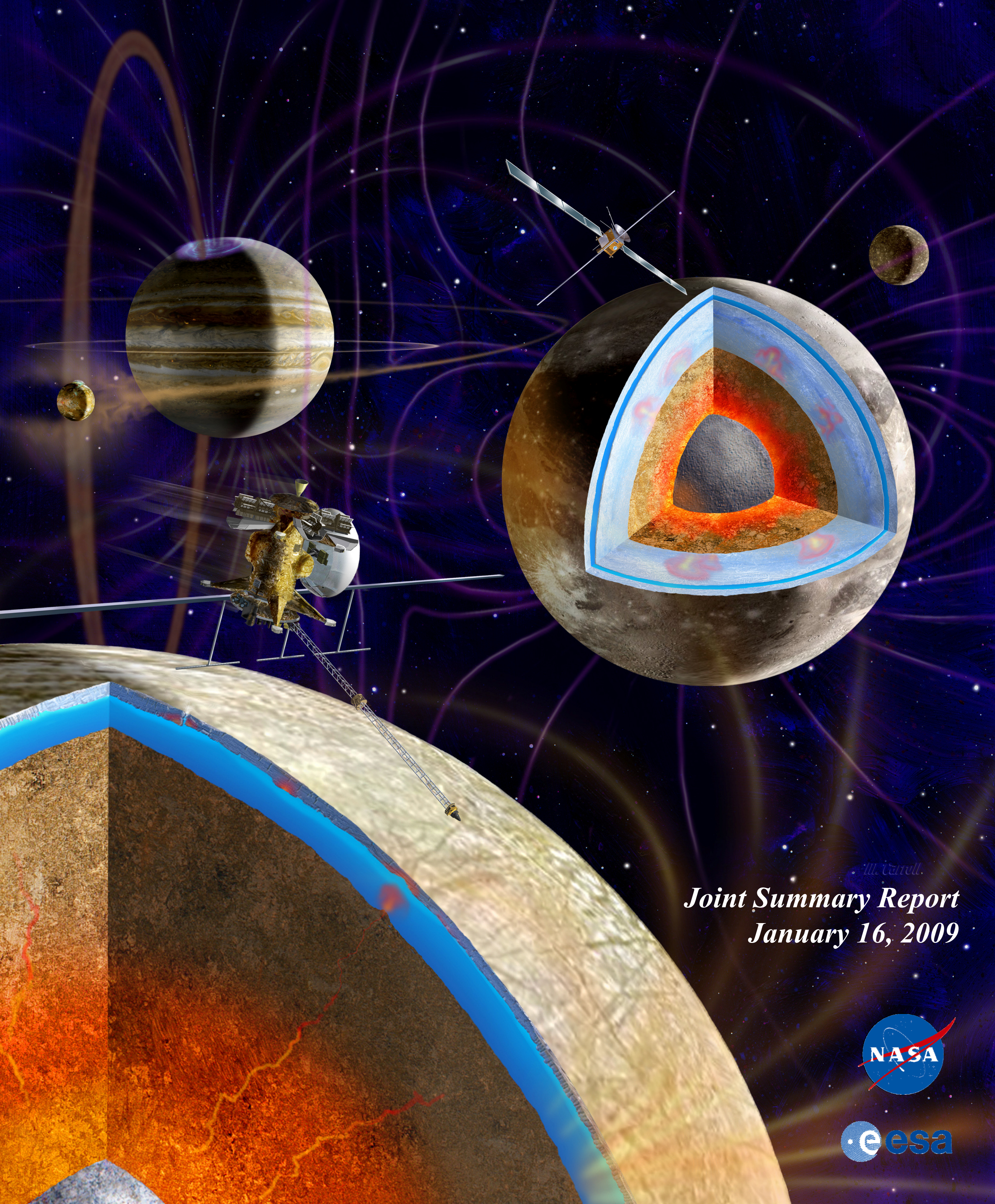
Europa Jupiter System Mission



Joint Summary Report
January 16, 2009

NASA

esa

Europa Jupiter System Mission

A Joint Endeavour by ESA and NASA

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Foreword

In February 2008, ESA and NASA initiated joint studies of two alternatives for a highly capable scientific mission to the outer planets: the Europa Jupiter System Mission (EJSM) and the Titan Saturn System Mission (TSSM). Joint Science Definition Teams (JSDTs) were formed with U.S. and European membership to guide study activities that were conducted collaboratively by engineering teams working on both sides of the Atlantic. The ESA contribution to this joint endeavor will be implemented as the Cosmic Vision Large-class (L1) mission; the NASA contribution will be implemented as the Outer Planet Flagship Mission with a launch date in 2020. An ESA Assessment Report and a NASA Final Report, which focused on the contribution of each agency to each mission, have now been completed. These will be reviewed by each agency between November 2008 and January 2009, with the agencies planning to reach a joint decision on the destination for the mission and announce that destination in February 2009. The Joint Summary Report (JSR) is intended to provide, for each of the destinations, a high-level description of the following: the science rationale and goals; the mission concept; the NASA and ESA responsibilities and interdependencies; the role of other space agencies; and the costs, schedule, and management approach. The JSR also describes the membership and roles of the JSDT and the engineering study teams that supported them and provides a guide to the extensive documentation that has been developed for each mission concept. The EJSM and TSSM study teams have worked together to develop a common format for the JSR that enables comparative evaluation of the missions while, at the same time, permitting their individual characteristics to be effectively portrayed.

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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 European Space Agency.

A Joint NASA/ESA Endeavour

Europa Jupiter System Mission

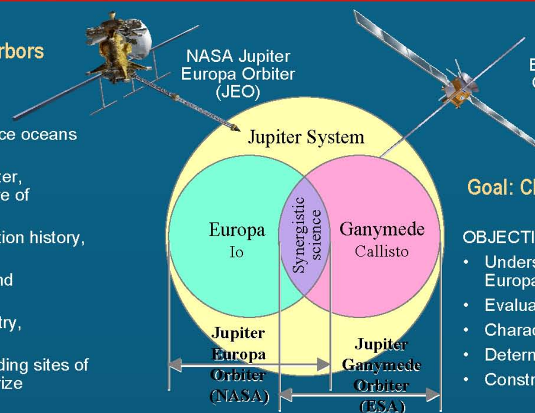
Science Theme:
The emergence of habitable worlds around gas giants

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)

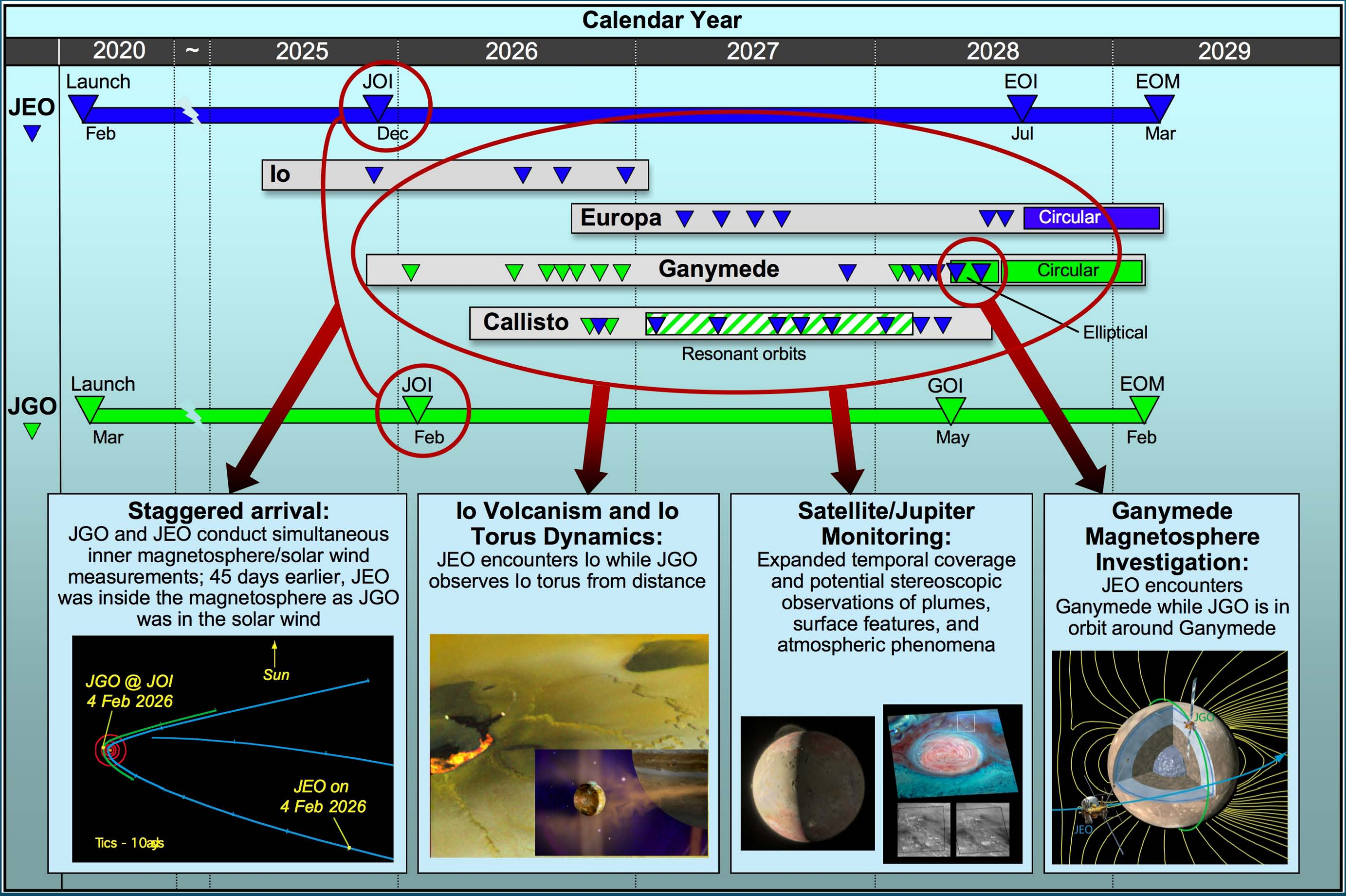
Jupiter Ganymede Orbiter (JGO)

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

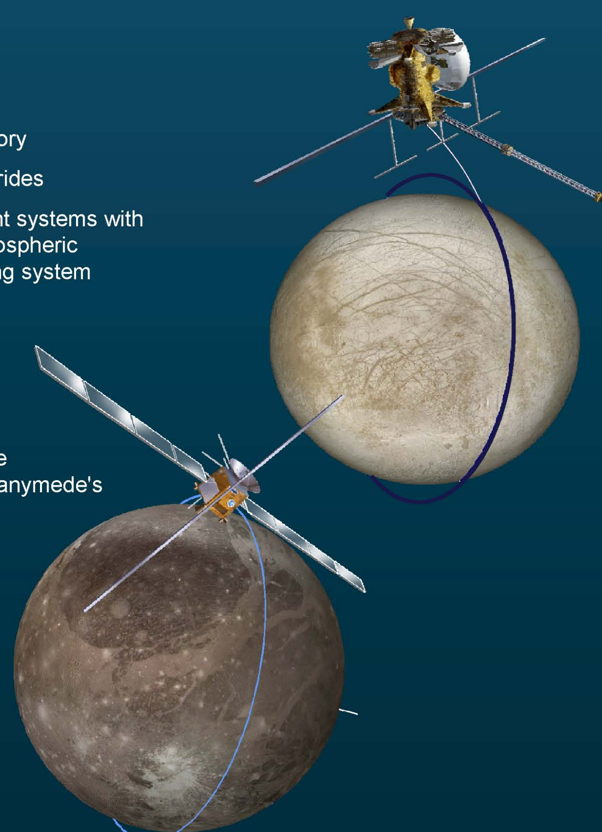
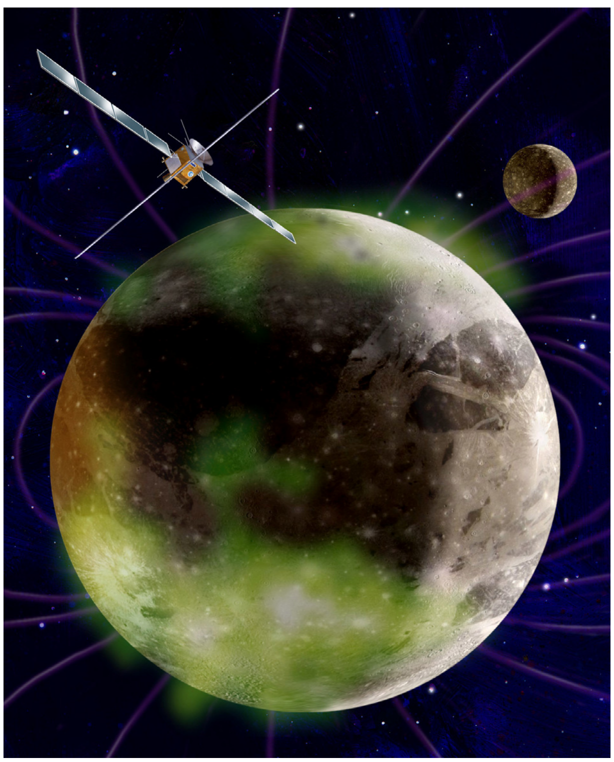


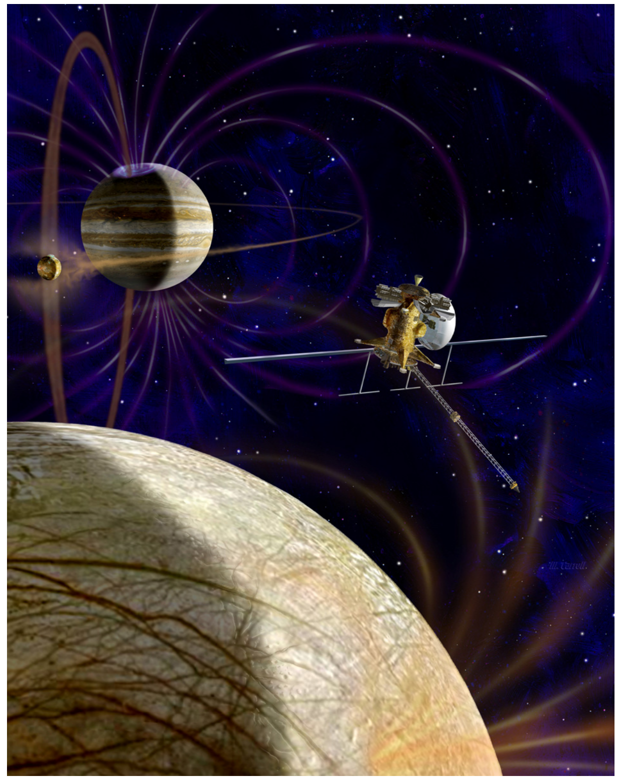
Table of Contents

1.0 OVERVIEW

Jupiter is the archetype for the giant planets of the Solar System and 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. The Galilean satellites are quite distinct with respect to their geology, internal structure, evolution, and degree of past and present activity. To place Europa and its potential habitability in the right context, as well as to fully understand the Galilean satellites as a system, the two internally active ocean-bearing bodies — Europa and Ganymede — must be understood. Thus, the Europa Jupiter System Mission (EJSM) is guided by the overarching theme: ***The emergence of habitable worlds around gas giants.***



Detailed architectural studies expanding on Europa, Ganymede, and Jupiter System science have been performed over the past decade. NASA studies have matured concepts to reach Europa. Under the ESA Cosmic Vision Programme, the *Laplace* concept has been downselected; this concept will explore the Jupiter system with a Europa orbiter, a Jupiter orbiter, and a small drop-off spacecraft in Jupiter orbit to study the magnetosphere. The NASA Europa Explorer Study and the ESA *Laplace* Study teams have now worked very closely to merge their respective concepts and align the goals through an integrated Joint Jupiter Science Definition Team (JJSDT).



Mission architecture

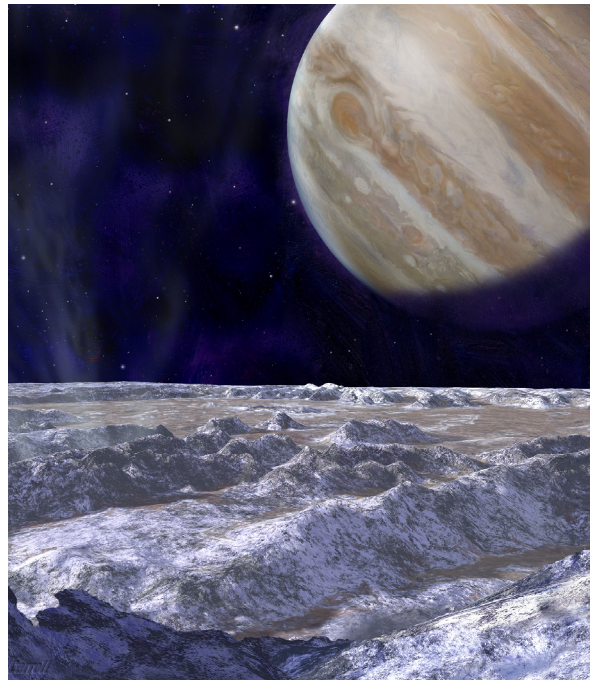
The baseline EJSM architecture consists of two primary elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). JEO and JGO will execute an intricately choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. JEO and JGO carry eleven and ten complementary instruments, respectively, to monitor dynamic phenomena (such as Io's volcanoes and Jupiter's atmosphere), map the Jovian magnetosphere and its interactions with the Galilean satellites, and characterize water oceans beneath the ice shells of Europa and Ganymede.

EJSM — An international mission that achieves Decadal Survey and Cosmic Vision goals

EJSM fully addresses the high priority science objectives identified by the National Research Council's (NRC's) Decadal Survey and ESA's Cosmic Vision for exploration of the outer solar system. The Decadal Survey recommended a Europa Orbiter as the outer planet flagship mission and also identified Ganymede as a highly desirable mission target. EJSM uniquely addresses several of the central themes of ESA's Cosmic Vision Programme, through its in-depth exploration of the Jupiter system and its evolution from origin to habitability.

Rich science of icy satellite habitability and the Jupiter system

EJSM will reveal the potential habitability of the active ocean-bearing moons Europa and Ganymede, detailing the geophysical, compositional, geological, and external processes that affect these icy worlds. EJSM will also explore Io and Callisto, Jupiter's atmosphere, and the Jovian magnetosphere. By understanding the Jupiter system and unraveling its history, the formation and evolution of gas giant planets and their satellites will be better known. Most important, EJSM will shed new light on the potential for the emergence of life in the celestial neighborhood and beyond.



Compelling scientific synergies with programmatic flexibility

The EJSM mission architecture provides opportunities for coordinated observations by JEO and JGO of the Jupiter and Ganymede magnetospheres, the volcanoes and torus of Io, the atmosphere of Jupiter, and comparative planetology of icy satellites. Each spacecraft can and will conduct "stand-alone" measurements, including the detailed investigation of Europa and Ganymede, providing significant programmatic flexibility.

Existing technologies and a low-risk approach

Although engineering advances are needed for JEO (radiation designs) and JGO, no new technologies are required to execute either EJSM mission element. The development schedule for these missions is such that a technology developed by 2012 – 2013 could easily be incorporated if it enhances the mission capability. Risk mitigation activities are under way to ensure that the radiation designs are implemented in the lowest-risk approach. The baseline mission concepts include robust mass and power margins.

2.0 SCIENCE GOALS AND OBJECTIVES

2.1 Relevance and Motivation

Some 400 years ago, discovery of the four large moons of Jupiter by Galileo Galilei changed the view of the universe forever. In the years 1995 – 2003, the Galileo spacecraft provided a wealth of information regarding the Jupiter system, despite a crippled high-gain antenna that greatly limited its data return. Today, Jupiter is the archetype for the giant planets of the 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 central to understanding the habitability of icy worlds.

By understanding the Jupiter system and unraveling its history from origin to the possible emergence of habitats, a better understanding will be gained as to how gas giant planets and their satellites form and evolve. Most importantly, new light will be shed on the potential for the emergence of life in the galactic neighborhood and beyond. Thus, the overarching theme for EJSM has been formulated as: ***The emergence of habitable worlds around gas giants***.

To address this theme, the Jupiter system will be explored, and the processes leading to the diversity of its associated components and their interactions will be studied. The focus will be to characterize the conditions that might have led to the emergence of habitable environments among its satellites, with special emphasis on the two internally active ocean-bearing worlds: Europa and Ganymede.

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 an 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, are 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.

2.2 Science Goals and Objectives

The fundamental theme for the EJSM can be further focused into science goals relating to habitability (focusing on Europa and Ganymede) and processes at work within the Jupiter System and the system's origin.

Goal: Determine whether the Jupiter System harbors habitable worlds.

Europa is believed to have a saltwater ocean beneath a relatively thin and geodynamically active icy crust (**Figure 2-1**). Europa is unique among the large icy satellites because its ocean is in direct contact with its rocky mantle beneath, where the conditions could be similar to those on Earth's biologically rich sea floor. The discovery of hydrothermal fields on Earth's sea floor suggests that such areas are excellent habitats, powered by energy and nutrients that result from reactions between the sea water and silicates. Consequently, Europa is the prime candidate in the search for habitable zones and life in the solar system. However, the details of the processes that shape Europa's ice shell, and the fundamental question of its thickness, are not well understood.

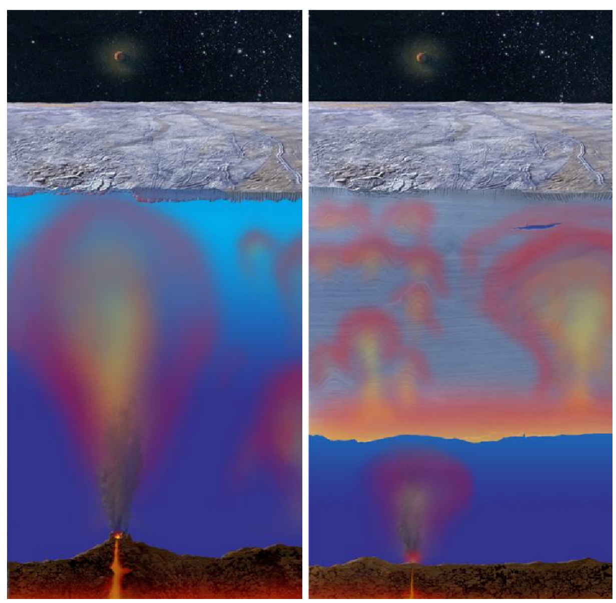


Figure 2-1: *JEO will address the fundamental issue of whether Europa's ice shell is ~ a few km (left) or > 30 km (right), with different implications for processes and habitability. In either case, the ocean is in direct contact with the rocky mantle below, which can infuse the chemical nutrients necessary 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 interaction unique in the Solar System (**Figure 2-2**).

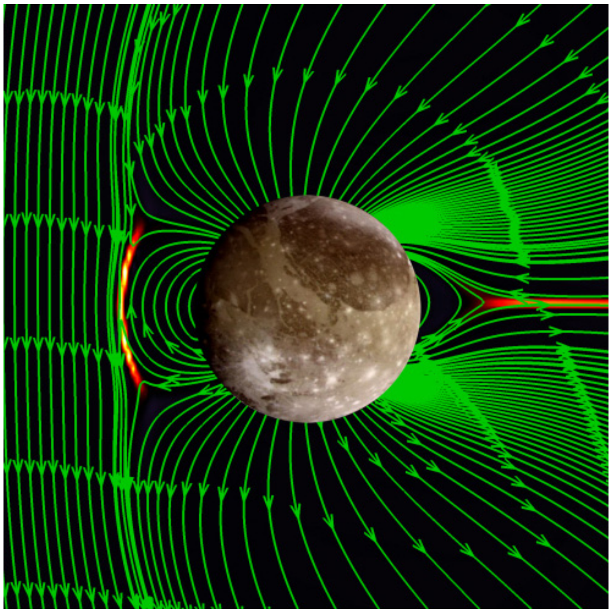


Figure 2-2: *JGO will determine how Ganymede's unique magnetic field interacts with Jupiter's, how the interactions vary with time, and the role of a convecting core and internal ocean.*

EJSM will undertake in-depth comparisons of Europa and Ganymede to establish their characteristics with respect to geophysical activity and habitability. To this end NASA's JEO spacecraft will investigate Europa in detail while ESA's JGO spacecraft will focus on Ganymede. For Europa and Ganymede, both mission elements have objectives to:

- 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.

Accomplishing these objectives will fulfill the goal of determining whether the Jupiter system harbors habitable worlds, while detailing the geophysical, compositional, geological, and external processes that affect these icy and active planet-sized worlds.

Goal: Characterize the processes within the Jupiter System.

The Jupiter system includes a broad diversity of objects, including Jupiter itself, 55 currently known outer irregular satellites, the Jovian ring system, four small inner satellites, and the four large Galilean Satellites: Io, Europa, Ganymede, and Callisto.

The Galilean satellites comprise a fascinating and diverse array of planetary bodies (**Figure 2-3**). Io is the solar system's most volcanically active world. The "ocean world" Europa is believed to have a relatively thin ice shell above a saltwater ocean in direct contact with its rocky interior. The ice-rich moons Ganymede and Callisto have similar bulk properties and both are believed to have internal oceans. However, these moons have divergent evolutionary histories: Ganymede is strongly differentiated with a hot convecting core and a history of active tectonics and icy volcanism; Callisto is weakly differentiated with no signs of internal geological activity. EJSM's strategy for understanding the Galilean satellites as a system is to conduct an in-depth comparative study of the two pairs of rockier inner Galilean satellites (Europa-Io) primarily with JEO and the icier outer satellite pair (Ganymede-Callisto) primarily with JGO, with in-depth focus on the internally active moons Europa and Ganymede and their probable subsurface oceans. The results will be placed in the broader context of the whole Jupiter system.

Io, Europa, and Ganymede are coupled in a stable resonance that maintains their orbital periods in a ratio of 1:2:4 and forces their orbital eccentricities; Callisto is not included in this resonance. Tidal interaction heats the interior of Io and is responsible for its unparalleled volcanic activity; maintains a liquid ocean within Europa and causes faulting of its surface and convection within its ice shell; and powers convection within Ganymede's metallic core to produce that satellite's magnetic field. EJSM results will enable detailed comparative studies of how the different conditions with respect to tidal heating have led to different histories and internal structures, surfaces, and dynamic activities among the four Galilean satellites.

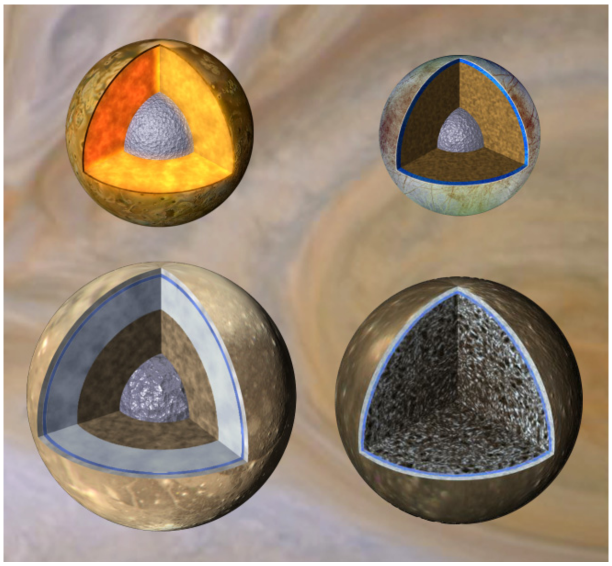


Figure 2-3: *EJSM will greatly improve upon simple models of the interior structures of the Galilean satellites based on Galileo data. The smaller, rockier pair — Io and Europa (top) — is the focus of JEO. The larger, icier pair — Ganymede and Callisto (bottom) — is the focus of JGO. All three ice-covered moons are believed to harbor oceans (blue); Europa's is the only ocean 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).*

Jupiter's internal and atmospheric structures are intimately coupled to the greater Jovian system environment. EJSM will extend Juno's investigations to the lower latitudes of Jupiter's atmosphere while focusing on complementary scientific questions through measurements of the troposphere, stratosphere, thermosphere, and ionosphere for comparisons with Jupiter's interior and magnetosphere.

Jupiter's magnetosphere is closely coupled to the upper atmosphere and interior by electrodynamic interactions. This giant magnetized environment, driven by the fast rotation of its central spinning zone and populated by ions coming from its moons, is the most accessible and intense environment for direct investigations of general astrophysical processes. EJSM will measure the dynamics of the Jovian magnetodisk (with angular momentum exchange and dissipation of rotational energy), determine the electro-dynamic coupling between the planet and the satellites, and assess the global and continuous acceleration of particles.

One of the most important aspects of solar system studies is the identification of the processes leading to the formation of gas giant planets. EJSM will provide new insight into this issue through understanding of the interior structure and properties of the Galilean satellites (especially Europa and Ganymede), derivation of the bombardment history on the Galilean satellites for application to the Jupiter system, and comparative compositional study of the satellites. Along with better understanding of Jupiter's composition, this will improve knowledge of the thermodynamics of the Jovian circumplanetary disk.

For the Jupiter system, both mission elements have objectives to:

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

Achieving these objectives will fulfill the goal of characterizing processes in the Jupiter system, and will provide for rich comparisons to Cassini results in the Saturn system.

2.3 Science Approach

Together, JEO and JGO address the science goals and objectives of EJSM (**Figure 2-4**). Each intensely investigates one internally active icy satellite and provides significant science for another, and each addresses significant aspects of Jupiter system science. The overlap provides important synergistic and complementary observations (§2.4). Nonetheless, each has the potential to be a "stand-alone" mission, providing compelling Decadal Survey and Cosmic Vision science (§2.5). This approach to EJSM provides significant programmatic flexibility.

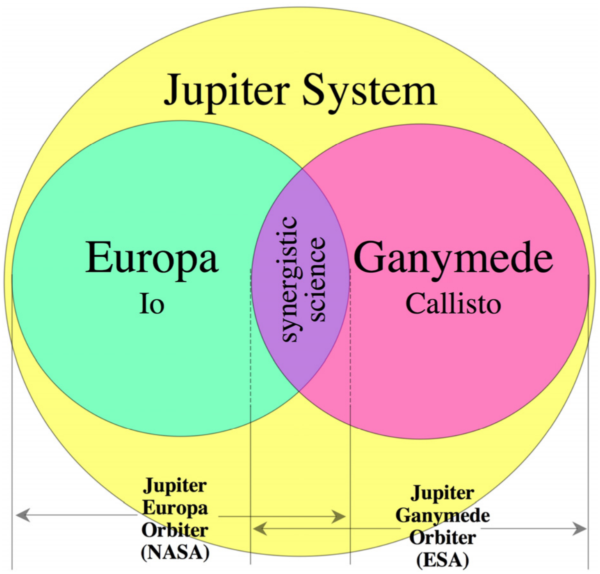


Figure 2-4: *EJSM is carried out by two flight elements, each with specific scientific targets as well as synergistic science objectives. The satellite-specific objectives of each are encompassed by Jupiter system science, as addressed in significant part by both spacecraft.*

JEO has as its sub-goal***: Explore Europa and investigate its habitability***. During its Europa orbital phase, JEO addresses the objectives of characterizing Europa's ocean and its deeper interior through geophysical methods: using gravity, altimetry, and magnetometry measurements conducted from low-altitude orbit (100 – 200 km). To characterize Europa's ice shell and any subsurface water, JEO employs ice-penetrating radar, which can map the distribution of water within and potentially beneath the ice shell. The tenuous atmosphere of Europa and its magnetospheric interactions will be investigated through magnetometry, energetic particle and plasma measurements, and UV spectroscopy, including stellar occultations. Surface composition and chemistry will be characterized by remote sensing through IR spectroscopy, and *in situ* through ion and neutral mass spectroscopy. Surface geology and potential future landing sites will be characterized through imaging at a variety of scales (100 m/pixel, 10 m/pixel, and 1 m/pixel from 100 km orbital altitude) and through thermal imaging that could locate any active "hot spots." Modest modifications of the JEO instruments ensure that they are also excellent for remote sensing and *in situ* observations of the Jupiter system, both from afar and during close satellite flybys.

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 absent, allowing for optimal spatial resolution of remote sensing instruments. The 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.

While the primary focus of JEO is to orbit Europa, the science return encompasses the entire Jovian system, especially as is relevant to Europa's potential habitability. JEO uniquely includes flybys of Io and Europa, and includes flybys of Ganymede and Callisto, along with ~ 2.5 years observing Jupiter's atmosphere, magnetosphere, and rings.

JGO has three sub-goals, expressed as: ***Determine whether the Jupiter System harbors habitable worlds; Characterize the processes within the Jupiter System; Gain new insight into the origin of the Jupiter System***. JGO addresses its sub-goal of determining whether the Jupiter System harbors habitable worlds by focusing on Ganymede. From Ganymede orbit, JGO characterizes Ganymede's ocean, deeper interior, magnetosphere, and surface using techniques analogous to those of JEO. Specifically it will exploit low-orbital altitudes to characterize the satellite's ice shell and putative ocean, understand its deeper interior and intrinsic magnetic field, and map its surface composition and geological features.

To address the JGO sub-goals pertinent to the Jupiter system, JGO will intensely investigate Callisto from a resonant orbit, and JGO will make extensive observations of the Jupiter system to complement those of JEO. Differences in techniques are that JGO uses submillimeter wave sounding (instead of an ion and neutral mass spectrometer) for compositional measurements, and JGO foregoes very high-resolution imaging. (The model payloads of JEO and JGO to accomplish the objectives are similar overall, though the characteristics of most instruments differ in detail; see §3.3 and **Table 3-4**.).

JGO results will enable detailed comparisons with the results for Europa. These results will be coupled with the data to be returned from Io, Callisto, and the Jupiter system as a whole, to provide unparalleled insight into the archetypical gas giant planetary system. In this way, JEO and JGO combine to address the overall EJSM theme of the emergence of habitable worlds around gas giants.

Should JAXA join the project, JMO will explore the Jovian magnetosphere *in situ* as a template for an astrophysical magnetised disk. Adding JMO to EJSM will afford the opportunity for "3-point" investigations of the Jupiter system via synergistic observations with JGO and JEO.

2.4 Science Synergies

The EJSM mission architecture offers unique opportunities for synergistic and complementary observations that significantly enhance the overall science return of the mission, while providing unprecedented opportunity for comparative planetology of icy satellites. An example timeline of the JEO and JGO elements (**Figure 2-5**) shows that both are planned to be in the Jupiter system simultaneously, yet with staggered arrival times at Jupiter and with different orbits. Examples of synergistic science opportunities include:

- Jupiter magnetosphere studies: In the notional example where JEO enters Jupiter orbit a few months prior to JGO (**Figure 2-5**), JGO will monitor the solar wind, while JEO observes the Jovian magnetosphere from within, to help untangle the solar-wind versus internally driven processes in magnetospheric dynamics.
- Io volcanism and torus dynamics: JEO will observe Io's volcanic activity through remote sensing and in situ observations during close flybys, while JGO will observe the global context and effects on the Io torus via remote sensing from afar.

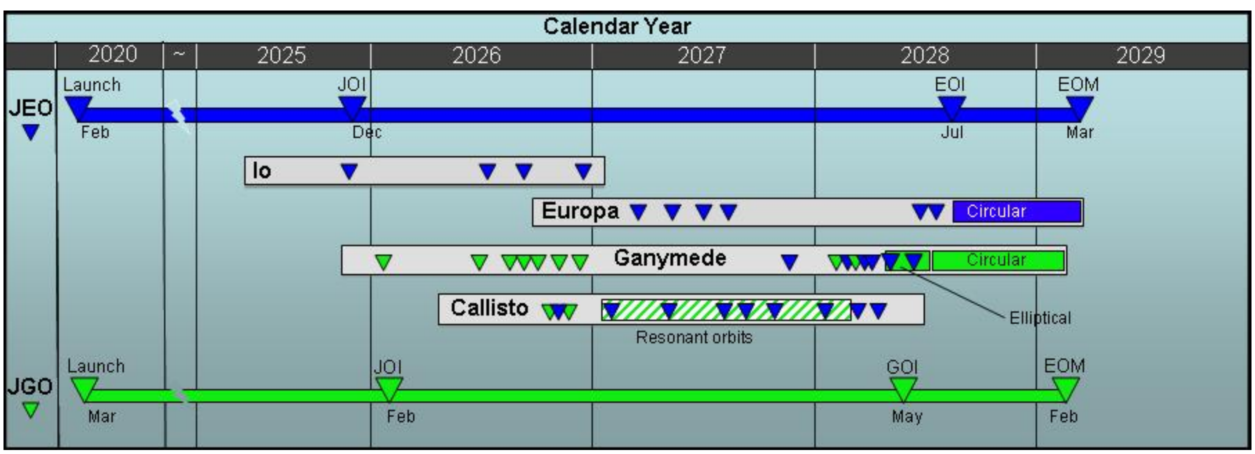


Figure 2-5: *Notional timeline for the EJSM, assuming launches one month apart in 2020. The blue bar represents the JEO mission timeline with icy moon encounters shown with triangles. Similarly, green bars and triangles represent the JGO mission timeline. The resulting synergistic observations of magnetospheric and other dynamic phenomena are unprecedented in planetary exploration and will be completed by the end of the 2020s. The relative phasing of the two spacecraft elements can be adjusted to optimize synergistic science opportunities.*

- Satellite and Jupiter monitoring: Both spacecraft will observe dynamic phenomena, such as the meteorology of Jupiter and Io's volcanic plumes, by simultaneous observations with different viewing geometries, wavelengths, and resolutions. Moreover, flybys by both spacecraft provide more complete spatial and spectral remote sensing coverage of the satellites.
- Ganymede magnetosphere studies: JGO observes the Ganymede magnetosphere in situ, while JEO monitors the external Jovian magnetosphere from Jupiter orbit and makes flybys through Ganymede's magnetosphere. Such observations allow for a better understanding of effects of Jupiter's field on the Ganymede magnetosphere and for plasma measurements by JEO that aid in interpreting JGO's measurements of the induced component of Ganymede's field.
- Comparative planetological study of icy satellites: The ultimate synergy of EJSM is that of comparative planetology that comes from the detailed understanding of the sibling icy satellites, Europa and Ganymede. The scientific benefit that is greater than the sum of the parts comes from study of both Europa, with its thin ice shell above an ocean in direct contact with its rocky mantle, and Ganymede, with its thick ice shell and ocean that is "sandwiched" between ice layers along with a hot core that generates an intrinsic magnetic field. In this way, EJSM's investigations will span the variety of potentially habitable icy worlds.

2.5 Responses to Decadal Survey and Cosmic Vision Theme

EJSM fully addresses the high-priority science objectives identified by the NRC's Decadal Survey and ESA's Cosmic Vision for exploration of the outer solar system. The Decadal Survey's Steering Group recommended a Europa Orbiter as the outer planet flagship mission and listed six science objectives, each of which will be met by JEO. The Survey also identified a Ganymede mission, such as JGO, as a highly desirable future mission. Moreover, some 20 specific questions were posed for the exploration of large satellites in the outer solar system, and EJSM, through the combined operation of JEO and JEO, will directly investigate all but one.

ESA's Cosmic Vision is structured around various themes and sub-themes, many of which will be addressed by EJSM. For example, one theme relates to understanding solar system processes. Jupiter's "mini-solar system" is ideally suited for this purpose, through study and comparison of the diverse Galilean satellites by EJSM, by investigations of the gas giant and its magnetosphere to complement anticipated Juno results, and through analyses of interactions among all the objects, such as the small satellites and the ring system. Thus, the Jupiter system is a natural laboratory for posing and testing hypotheses of planetary processes through spacecraft observations. Another Cosmic Vision theme relates to planetary formation and evolution, which EJSM will address through study of the gas giant, Jupiter. Investigations will include: a) assessing the bulk compositions of the large satellites as critical constraints on formational models, b) observing the irregular satellites and their relations to primitive objects thought to have formed the cores of the giant planets, and c) studying motions in the upper atmosphere in high resolution over long time-periods.

Astrobiology is a central theme to both the Decadal Survey and the Cosmic Vision. Determining the habitability of Europa and comparing the results with Ganymede will provide critical clues to habitability and the potential for the emergence of life in the outer solar system. While the discovery of life beyond Earth will be profound, should niches be found that are apparently habitable, yet do not contain known life forms, will be equally important.

Operation of two spacecraft in the Jupiter system provides the unparalleled opportunity to address the high-priority questions posed by the Decadal Survey and Cosmic Vision for exploration of the outer solar system. The EJSM mission concept represents a conservative and robust design approach to successfully answering these high-priority questions and making a major step forward in understanding the emergence of habitable worlds around gas giants.

3.0 MISSION CONCEPT

An international team of scientists, engineers, and managers has defined a comprehensive mission concept that is a balance between cost, risk, and science value. By using proven functionality and leveraging lessons learned from numerous flight missions, the engineering teams have designed two flight systems (JEO and JGO) that can be designed, fabricated, tested, and operated by two well-experienced organizations, NASA and ESA, using their own assets and processes. EJSM's synergy arises from having two spacecraft simultaneously operating in the Jupiter system and from acquiring simultaneous observations of certain targets where this is scientifically valuable and complementary observations of other targets for which the JEO and JGO have been separately optimized.

Building upon more than a decade of study, NASA and ESA have supplied a set of ground rules that have been used to define the more detailed assessment of EJSM. The ground rules are summarized in **Table 3-1**.

Table 3-1: *NASA/ESA-provided ground rules lay the framework for study of EJSM.*

Power Source Options	RPS Options - MMRTG or ASRG – to be provided by NASA, Solar
Planetary Protection	Europa Category III: ≤10^{-4} probability of contaminating the Europa's ocean, Ganymede Category II
Launch Vehicle (LV)	NASA: Delta IV-H, Ares and Atlas family—costs given including launch services and nuclear processing, ESA: Soyuz or Ariane 5
Technology Philosophy	NASA: Conservative approach ESA: TRL>5 by the start of B2 (~2012)
Launch Dates	Nominally 2020 but investigate 2018–2022
Ground Stations	NASA DSN Capability: Ka band downlink available, current 70 m equivalent capability available (emergency use only), current 34 m available, DSN ground system throughput of up to 100 Mb/s ESA: ESA ground stations
Architecture	NASA: Europa Orbiter as documented in 2007 study ESA: new design, no restrictions; some heritage from previous ESA Technology Reference Studies
Radiation Design	NASA: Further refine and begin executing 2007 plan ESA: Design goal <100 krad for the whole mission (no additional margins)

3.1 Mission Architecture Overview and Design

The expansive Jupiter system is scientifically rich and is best studied using multiple elements. To explore the system in detail, two flight systems, performing an intricately choreographed dance to explore the system from every perspective, are envisioned. Though both will examine the whole system, one will focus on the inner two Galilean satellites and the other will focus on the outer two Galilean satellites. Both flight elements perform multi-year studies of the Jupiter system, including the giant planet's magnetosphere, rings and atmosphere, and the Galilean moons. JGO will focus on Ganymede and Callisto, while JEO will focus on Io and Europa (but also studying Callisto and Ganymede up close). This architecture allows JGO to stay outside the most intense radiation belts and, thus, be designed for a lesser radiation environment. JEO and JGO carry 11 and 10 instruments, respectively (§3.3). Complementary instrumentation allows for each flight system to study the whole system from different perspectives and provide data for synergistic science.

Launched independently in early 2020, each spacecraft will use chemical propulsion and Venus and Earth gravity assists to arrive at Jupiter approximately 6 years later. Opportunities were studied between 2018 and 2022 to launch these flight systems. For each opportunity, the mass delivered varies, but flight time to Jupiter can be traded to deliver adequate mass.

It is important to note that the launches of JEO and JGO are NOT dependent on each other. The mission trajectories while in the Jupiter system are very flexible and can be easily altered to accommodate changes in programmatic or scientific priorities. Numerous parameters in the trajectory designs provide flexibility to alter flight times, tour lengths, and orbital insertion timing to adjust the coincidence of the two flight systems in orbit at Jupiter. Each flight element is launched and operated independently to meet its primary science goals.

After insertion into Jupiter orbit, both flight systems will perform tours of the Jupiter system using gravity assists of the Galilean moons to shape the trajectory and to perform science measurements. JGO uses a gravity assist maneuver at Ganymede to shape its initial 13×245 R_j highly elliptical Jupiter orbit, thereby avoiding the main radiation belts of Jupiter. After a nearly 10-month tour through the Jupiter system — performing measurements in the magnetosphere, observing Jupiter and performing a series of Ganymede flybys — JGO moves to a Callisto resonant orbit. JGO performs remote sensing observations during 19 flyby opportunities, with closest approach at 200 km. After more than a year in this resonant orbit with Callisto, JGO moves to Ganymede into an elliptical polar orbit (200 km × 6000 km) for up to 80 days, acquiring, among other observations, measurements in the magnetosphere of Ganymede. Thereafter, JGO enters into a 200 km near-polar circular orbit for close observations of Ganymede with durations of 140 to 180 days (depending on the accumulated radiation total dose and orbital stability). The mission will end when the flight system impacts Ganymede's surface.

JEO enters the Jupiter system by using Io for gravity assist. This lowers the required propellant load but increases the radiation exposure of the flight system. The technical trade between propellant mass and shield mass still leaves more delivered mass capability (a dry mass increase of ~ 160 kg). JEO has a 30-month Jupiter system tour that includes 4 Io flybys (including one at 75 km), 9 Callisto flybys (including one near-polar), 6 Ganymede flybys (including 4 at < 1000 km), and 6 Europa flybys (including 3 early flybys at low altitude). JEO enters orbit at Europa and spends the first month in a 200-km circular orbit and then descends to a 100 km-circular for another 8 months. The mission will end when the flight system impacts Europa's surface.

The JEO floor mission is defined by taking the baseline mission concept (same as the NASA-only mission concept) and descoping elements of mission capability. The prioritized list of descopes is presented in **Table 3-2**. This list was worked between the JJSDT and study team. The resulting floor mission concept includes 7 instruments (some with less capability than their baseline versions), a 24-month tour phase, and only 3.5 months in Europa orbit.

3.2 Mission Elements

3.2.1 Flight System

The two flight systems are very similar to other large orbital spacecraft (e.g., Cassini, Mars Reconnaissance Orbiter). The similarity of the science objectives and instrumentation necessitates that flight systems with very comparable functionality are required. Conceptual designs for JGO and JEO are shown in **Figures 3-1** and **3-2**, respectively.

Table 3-2: *JEO's prioritized descopes can be exercised to mitigate future problems. The actual order will depend on nature of problem to be mitigated.*

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.

Propellant accounts for 50 - 60% of the total mass of both these systems. Dominated by the significant amount of propellant required to enter orbit at their respective destinations, the flight systems use the large propulsion tanks as the primary structure around which the system is built.

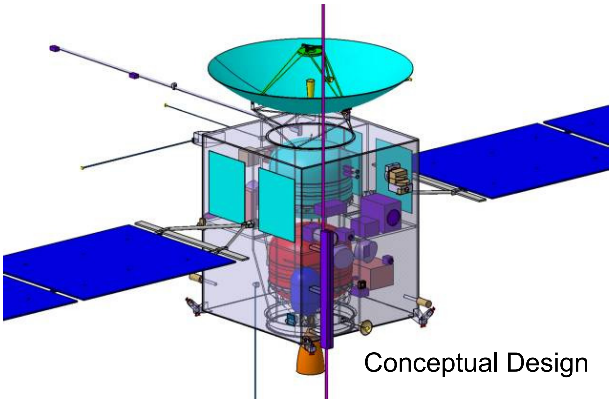


Figure 3-1: *The JGO baseline Flight System utilizes solar power to operate 10 instruments while in the Jupiter System, including the time spent in resonant orbit at Callisto and in tight orbit at Ganymede.*

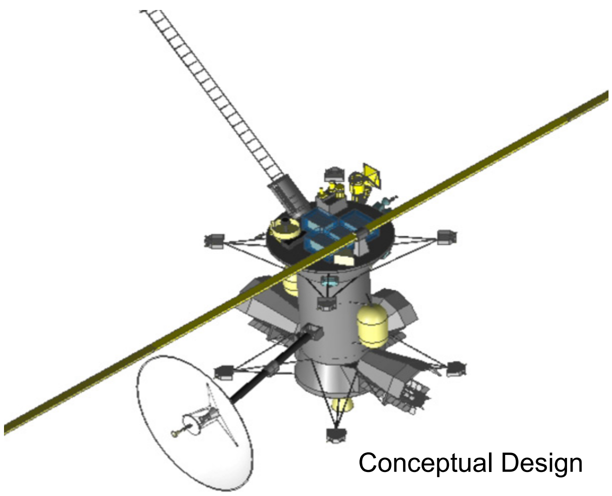


Figure 3-2: *The JEO baseline Flight System uses radioisotope power to operate 11 instruments while in the Jupiter system and makes many flybys of all four Galilean satellites before entering a tight circular orbit at Europa.*

Typical mass and power margins held in Pre-Phase A are 30 - 50% (margin/CBE). Both JEO and JGO are designed conservatively with significant mass margins, as shown in **Table 3-3**. Power margins (margin/CBE) are 50% for JEO and 20% for JGO and are consistent with organizational guidelines. There is additional flexibility on both spacecraft for available power that can be overcome by strategically operating the instruments at varying duty cycles. However, even with current assumptions, the resources available for instrument operations far exceed those needed to meet the minimal science requirements as defined by the JJSDT.

Design characteristics that are similar:

- Full redundancy for engineering functions.
- Three-axis-stabilized structure using both thrusters and reaction wheels for control.
- Bi-propellant chemical propulsion systems with single main engine.
- Lithium ion battery energy storage.
- Multi-Layer Insulation and radiators for thermal control.
- X/X-band for telecommunications, commanding, tracking, and emergency communications.
- A Ka-band transponder for dual-band radio science (X and Ka).

Table 3-3: *Significant mass margin is available given current launch vehicle capability and launch opportunities with both systems carrying enough propellant for the full dry mass capability.*

Dry Mass (excluding Adapter)	JEO	JGO
Current Best Estimate (CBE) without contingency or margin	1371 kg	957 kg
Subsystem Contingency	338 kg	106 kg
Required System Margin	224 kg	213 kg
Extra Margin	336 kg	333 kg
Total Dry Mass Available	2271 kg	1610 kg
Total Margin (Total Margin/CBE)	66%	68%
Total Margin (Total Margin/Total)	40%	41%%

The radiation environment of the Jupiter system is highly complex and, unlike the Earth's radiation belts, is dominated by electrons. The radiation dose rate near the orbit of Europa is roughly a factor of 30 higher than near the orbit of Ganymede. However, the actual ratio is a function of the amount of shielding because more energetic electrons predominate at Europa. For electronic design purposes, it is the integrated mission dose that is important and, in this respect, the differences between JEO and JGO are not as pronounced. For instruments, it is often the instantaneous fluence that drives the shielding requirements.

Radiation design points have been established for both flight elements of EJSM. These points give guidance to mission and component designers for performing trades within the mission concepts without having to adjust designs when the actual estimates based on trajectories fluctuate. Actual estimated radiation exposures based on baseline trajectories are currently within the design points are shown in **Table 3-4**.

Table 3-4: *The radiation environment experienced by JEO contains more penetrating spectral components than JGO. As a result, even with shielding equivalent to 8 mm of aluminum, components experience almost 1 Mrad on JEO but less than 100 krad on JGO.*

	JEO	JGO
Design Point behind 100 mils (2.5 mm) of Al	2.9 Mrad	1.1 Mrad
Current estimated exposure behind 100 mils (2.5 mm) of Al	2.8 Mrad	900 krad
Design Point behind 8 mm of Al	820 krad	100 krad
Current estimated exposure behind 8 mm of Al	810 krad	82 krad
Current Best Estimate for shielding mass	190 kg	80 kg

Since JGO focuses on Callisto and Ganymede, it can stay outside Jupiter's main radiation belts. JGO uses shielding as the primary protection for standard electronics, resulting in approximately 80 kg of shielding for instruments and avionics. This shield mass estimate corresponds to the 82-krad current estimate environment.

For JEO, exploring the inner Galilean satellites exposes the system to a greater radiation dose. The JEO design levels are much higher than is practical for standard parts and shielding. Therefore, JEO takes a more aggressive approach and assumes all electronics will be designed with radiation-hardened electronics to minimize shielding required. Some electronics and detectors will utilize spot shielding to lower radiation exposure. Approximately 190 kg of shielding is estimated for the JEO mission. Other significant flight system differences between JEO and JGO are:

- JGO is able to use solar arrays, due to the lower radiation exposure, and carries a total 51-m^2 solar array, with GaAs solar cells optimized for Low Intensity Low Temperature and one degree of freedom. JEO uses Radioisotope Power Sources (note that the baseline design for JEO can be implemented with 5 MMRTGs or 5 ASRGs).
- JGO uses a heritage 2.8-m fixed High Gain Antenna while JEO uses a heritage 3.0-m 2-degree-of-freedom High Gain Antenna.
- JEO augments the telecom system with Ka-Band downlink for telemetry.
- JEO augments its electrical heater thermal system with Radioisotope Heater Units.
- The Command and Data Handling system for JEO consists of RAD750 computer and has 20 Gbits of memory (4 Gbits are megarad hard). JGO uses a LEON2 Fault Tolerant processor and 256 Gbits of flash memory. JEO's smaller on-board data storage is driven by the higher radiation environment and mitigated by the near-real-time downlink approach adopted by JEO (data is only buffered on-board) and mitigated with the articulated High Gain Antenna.

As a result of both the higher power and higher capability telecommunications systems on JEO, its downlink data rate is roughly 10 times that for JGO (300 - 600 kbps vs. 40 - 66 kbps).

3.2.2 Launch Vehicle

The launches of the JGO and JEO flight systems are not dependent on each other. ESA will launch the JGO flight system and NASA will launch the JEO flight system. The parameters for the two 2020 launches are shown in **Table 3-5**.

Table 3-5: *By using Venus and Earth gravity assists, very capable flight systems can be delivered to Jupiter within 6 years to begin multi-year investigations of the Jupiter system.*

	JEO	JGO
Launch Vehicle	Atlas V 551	Ariane 5 ECA
Launch Date	2/29/20	3/11/20
Trajectory	VEEGA	VEEGA
Flight Time to Jupiter	5.8 years	5.9 years
Delta V	2260 m/s	~3000 m/s
Launch Mass Capability	5040 kg	4362 kg
Launch Vehicle Adapter	123 kg	190 kg
Propellant	2646 kg	2562 kg
Current Best Estimate Dry Launch Mass	1367 kg	957 kg
Total Dry Mass Margin	973 kg	653 kg

3.2.3 Ground System

EJSM does not require any new capability within the ground stations currently envisioned in the near term for NASA's DSN or ESA's ESTRACK. The baseline MOS for JGO is to be provided by ESA/ESOC and supported by the ESA ground station network (ESTRACK).

The Cebreros 35-m station (see **Figure 3-3**) will be used during the cruise phase and the observation phase at Jupiter. Additional support will be provided by New Norcia for critical phases, such as flybys and insertion.

For JEO, a standard MOS will be developed by JPL, and NASA's Deep Space Network will be used for tracking support (see **Figure 3-3**). During the interplanetary and tour phases of the mission, daily tracking coverage (one track per day) will be shared among 34-m stations at Goldstone, Madrid, and Canberra. During the first 105 days in orbit at Europa, 24-hour coverage is assumed; this will require coverage from all three stations. After the first 105 days in Europa orbit, tracking will resume at 1 track per day, as in the tour portion of the mission.

JGO and JEO can be supported by the opposite networks (DSN and ESTRACK, respectively) using standard services for emergencies and critical events. If needed, provisions for mutually supportive backup command, telemetry, and navigation services can be included in the MOS designs for both missions using current capabilities.

3.3 Model Payloads

The EJSM model payload instruments were identified by the JJSDT to respond directly to the science objectives as outlined in §2.0, along with traceability back to the science measurement requirements. This planning payload, while notional, is used to bound the engineering aspects of the mission design, spacecraft, and operational scenarios associated with obtaining the data to meet the science objectives.

One common challenge for the instruments is the performance and availability of sensors that can meet the Jovian radiation and planetary protection requirements. The challenge for JEO is greater than for JGO as the radiation flux and total dose is higher for JEO.

For the model payload, instruments were evaluated on the basis of their ability to meet the measurement objectives, perform in the radiation environment, and meet planetary protection requirements. Special attention was given to the JEO instruments due to the higher radiation flux and total dose. Only publicly available information is used in the concept designs. Other techniques are available that would lower resource requirements; however, information on those techniques is not publicly available and, therefore, not included in this report.

The model payload instruments were used to show proof of concept only, and should not be taken to be final selections nor final implementations. Alternative instrument concepts and techniques may be selected via the NASA/ESA coordinated Announcement of Opportunity process to meet the mission objectives. **Table 3-6** presents the model payloads, their primary science contribution and key characteristics. The mass of the JEO payload is 106 kg without shielding and the JGO payload is 73 kg without shielding. These mass estimates account for projected modifications necessary to perform in the radiation environment. Mass for shielding is estimated separately.

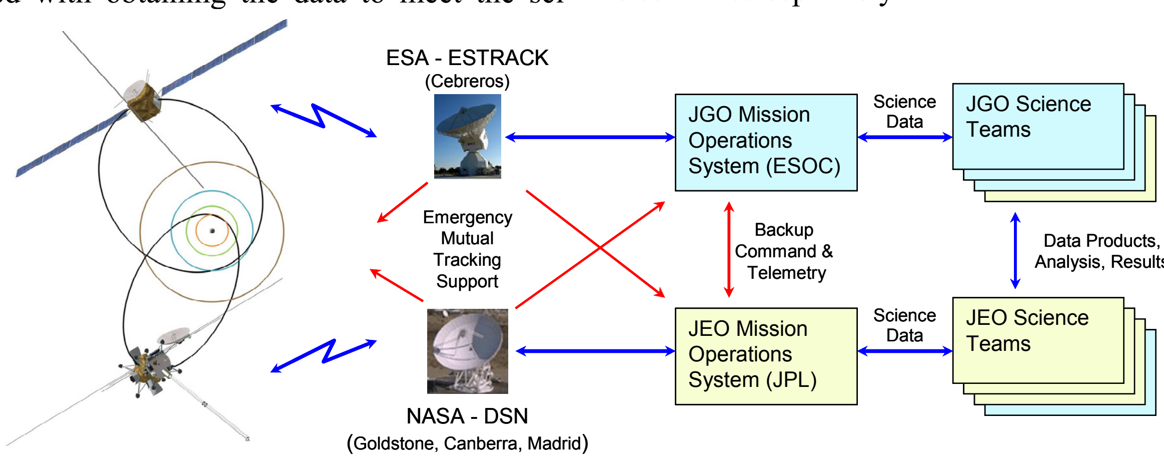


Figure 3-3: *Both missions will be independently operated using mature Mission Operations Systems and tracking systems as shown in Blue paths. NASA-ESA tracking system interoperations capabilities are currently in place, shown in Red and could be used to further enhance the capabilities or robustness of EJSM.*

Table 3-6: *The complementary model payloads on the two flight systems provide unprecedented opportunities to obtain simultaneous observations of a single phenomenon.*

Model Payload	JEO		JGO	
	Science Contribution	Characteristics	Science Contribution	Characteristics
Laser Altimeter	Amplitude and phase of gravitation tides on Europa; Quantitative morphology of Europa surface features	Single-beam @1064 nm 50 m spot @ 100 km 26 Hz pulse rate	Amplitude and phase of gravitation tides on Ganymede; Quantitative morphology of Ganymede surface features	Single Beam @ 1064 nm 10 m spot @ 200 km 175 Hz pulse rate
Radio Science	Tidal state of Europa to determine the extent of the ocean and its relation to the deeper interior; Interior state of Ganymede & Callisto	2-way Doppler with Ka-band transponder Ultra-stable Oscillator	Interior state of Ganymede, presence of a deep ocean and other gravity anomalies	2-way Doppler with Ka-Band transponder Ultra-stable Oscillator
Ice Penetrating Radar	Europa ice/water interface and identify warm ice and/or water pockets within the ice shell	Dual frequency: 50 and 500 MHz, Vertical depths: 3 and 30 km Dipole antenna: 30 m	Structure of the Ganymede subsurface & identify warm ice and/or anomalies within the ice shell	Single frequency: 20-50 MHz Dipole antenna: 10 m
Visible-IR Spectrometer	Composition of non-ice components on Europa, Ganymede & Callisto; State & crystalinity of ices; Io volcano monitoring; Jupiter atmosphere composition	Pushbroom imaging spectrometer with two channels and along-track scan system Spec. range: 400-5200 nm Spec. res: 5 nm @< 2.6 μm Spec. res: 10 nm @> 2.6 μm IFOV: 0.25 mrad @< 2.6 μm IFOV: 0.50 mrad @> 2.6 μm FOV: 9.2°	Composition of non-ice components on Ganymede & Callisto; State & crystality of surface ices	Pushbroom imaging spectrometer with two channels with scan system Spec. range: 400-5200 nm Spec. res: 2.8 nm @<2.2μm Spec. res: 5 nm @ >2.2 μm IFOV: 0.125 mrad IFOV: 0.250 mrad FOV: 3.4°
UltraViolet Spectrometer	Composition & dynamics of the atmospheres of the Galilean satellites	EUV grating spectrometer with scan system for stellar occultations Spectral range: 70-200 nm IFOV: 1.0 mrad FOV: 3.7°	Composition & dynamics of the atmospheres of Ganymede & Callisto	EUV and FUV+MUV grating spectrometers Spectral range: 50-320 nm IFOV: 0.01 mrad FOV: 2°
Ion and Neutral Mass Spectrometer	Composition of sputtered products from Europa	Reflectron Time-of-Flight Mass range: 1-300 Daltons Mass res: >500	N/A	N/A
Thermal Instrument	Map temperature anomalies and thermal inertia of surface materials on Europa; Jupiter atmosphere composition & dynamics	Pushbroom imaging thermopile line arrays Thermal band: 8-20 μm Thermal band: 20-100 μm 4 narrow filter bands IFOV: 2.5 mrad FOV: 3.0°	Map temperature anomalies and thermal inertia of surface materials on Ganymede	Imaging microbolometer array Thermal band: 7.4 – 21.7 μm 4 narrow filter bands, IFOV: 0.5 mrad FOV: 6.9°
Narrow Angle Camera	Local-scale geologic processes on Europa, Ganymede & Callisto; Io volcano monitoring; Jupiter cloud dynamics & structure	Orbital Mode: Panchromatic pushbroom imager OpNav Mode: Panchromatic framing imager Jovian Science Mode: 9 color framing imager (filter wheel) IFOV: 0.01 mrad FOV: 1.2°	N/A	N/A
Wide and Medium Angle Camera	Regional-scale Europa Morphology & topography from stereo; Global to regional-scale morphology of Io, Ganymede & Callisto; Jupiter atmosphere dynamics	Wide: 3-color + panchromatic Pushbroom IFOV: 1 mrad FOV: 58 deg Med: panchromatic Pushbroom IFOV: 0.1 mrad FOV: 11 deg	Global morphology of Ganymede; Global to regional scale morphology of Callisto	Wide: 12 filters Framing IFOV: 2 mrad FOV: 117 deg Med: 4-color + panchromatic Pushbroom IFOV: 0.25 mrad FOV: 14.7 deg

Model Payload	JEO		JGO	
	Science Contribution	Characteristics	Science Contribution	Characteristics
Magnetometer	Induction response from the Europa Ocean; Presence and location of water within Ganymede & Callisto	Dual tri-axial fluxgate sensors 10 meter boom	Ganymede's intrinsic magnetic field and its interaction with the Jovian field	Dual tri-axial fluxgate sensors 3 meter boom
Plasma and Particles	Interaction between icy satellites and the space environment to constrain induction responses; Composition and transport in Io's plasma torus	Plasma Analyzer Electrons : 10 eV – 30 keV Ions: 10 eV – 30 keV Particle Analyzer Electrons : 30 keV to 1 MeV Ions: 30 keV to 10's of MeV High-energy Electrons >2, >4, >8 and >16 MeV	Interaction between Ganymede & Callisto and the space environment to constrain induction responses	Plasma Analyzer Electrons: 1 ev – 20 keV Ions: 1- eV – 10 keV Particle Analyzer Electrons: 15 keV -1 MeV; Ions: 3 keV - 5 MeV, ENA: 10 eV – 100 eV
Submillimeter Wave Sounder	N/A	N/A	Dynamics of Jupiter's' stratosphere; Vertical profiles of wind speed and temperature	2 channels Spec. range: 550-230 μm FoV: 0.15° – 0.065°

Synergistic and complementary instruments carried by the separate mission elements enhance the science while maintaining a strong science return value for each independent element. With the goal to explore the Jupiter system as a whole in addition to focused investigations of individual satellites, the payloads provide instrumentation for remote sensing (during flybys, as a distant observer and while in orbit around Europa and Ganymede) and to characterize the Jovian environment.

Remote sensing instruments provide overlapping spectral coverage to readily facilitate data cross-correlation and analysis. Comparable field and particle payloads will provide new information on the three-dimensional and temporal variability of the Jupiter radiation environment. The combined capability of the two mission elements will provide science return that exceeds that of each standing alone.

3.4 Operational Scenarios

There are 2 major sciences phases of science for EJSM: Jupiter System Science and Icy Moon Orbital Science. Jupiter System Science will be the principal focus of the Jovian Tour phase of the JGO and JEO flight systems. There are 3 sub-phases: 1) Jupiter System Science for JEO and JGO, 2) Callisto Science for JGO, and 3) Io Science for JEO. Icy Moon Orbital Science is comprised of Ganymede Orbital Science for JGO and Europa Orbital Science for JEO. At the end of Prime Mission, the project will either be allowed to extend the mission or will enter the decommissioning and disposal phase.

The five mission operational scenarios are summarized in **Table 3-7**. The interplanetary phase is typical of outer planets missions and is not discussed further.

3.4.1 Jupiter System Science

The Jupiter System Science investigations fall into five categories: satellite surfaces and interiors, satellite atmospheres, plasma and magnetosphere, rings and small bodies, and Jupiter atmosphere. 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 trajectories are optimized for meeting the science requirements along with duration, delta-v and radiation dose. In addition to the encounter observations, periodic distant monitoring observations of Io, its plasma torus, Jupiter, and its ring system, dust and gas, and small bodies are planned. Monitoring and measurement of the system plasma environment and magnetosphere and the Jupiter atmosphere will be accomplished through routine periodic measurements each week. During the Jupiter System Science sub-phase the instruments focusing on Jupiter science will be operating with higher priority with respect to the other instruments.

During the Callisto Science sub-phase, JGO will focus on understanding its water-rock distribution, and its evolution. JGO will be able to collect and downlink 12 - 20 Gb for each Callisto flyby. JEO will make several close flybys of Callisto while JGO is in the resonant orbit, allowing synergistic science observations.

***Table 3-7.** Pre-planned mission phases and campaign allow for early decisions on the highest priority science and more efficient operations.*

Mission Phase	Jupiter Europa Orbiter	Jupiter Ganymede Orbiter
Jupiter System Science	Jupiter System Science Campaign: 18 months • 8 Callisto flybys, including North Pole observing • 6 Europa Flybys, IPR ocean search, 60% global imaging • 6 Ganymede flybys, 50% global imaging • Transfer to Europa circular orbit Io Campaign: 12 months • 1st Io flyby (pre-JOI) is primarily for engineering purposes • 3 Io flybys, 30% global imaging • 1 Callisto flyby	Jupiter System Science Campaign: 12 months • 4 Ganymede flybys • Move to resonant Callisto orbit Callisto Science Campaign: 15 months • Resonant Callisto orbits, 19 flybys • Global imaging • Move to Ganymede elliptical orbit
Icy Moon Orbital Science	Europa Orbital Science • Engineering Assessment: prepare for orbital ops (5 days) • Europa Campaign 1: Global Framework 200 km (28 days) • Europa Campaign 2: Regional Processes 100 km (43 days) • Europa Campaign 3: Targeted Processes 100 km (28 days) • Europa Campaign 4: Focused Science 100 km (165 days)	Ganymede Orbital Science • Ganymede Campaign 1: 200x6000 km orbit (up to 80 days) • Ganymede Campaign 2: 200 km circular orbit (up to 180 days)

Specifically during the Io Science sub-phase, JEO will be making close flybys of Io (as close as 75 km) and imaging 20% of Io's surface at 200 m/pixel resolution. At the same time, JGO will be monitoring Io from a distance to add context to JEO observations.

Each orbiter will be able to collect 10 - 20 Gb of science data during closest approach for each flyby. JEO and JGO can store and return all of the collected data from flyby and observing opportunities within scheduled downlink times. Both orbiters have similar payloads and data acquisition capabilities with minor variations in data rates and compression schemes. One difference is that during observations, JGO will not be able to maintain Earthpoint for communications, whereas JEO will be able to use its HGA to maintain pointing for navigation tracking and telemetry downlink.

3.4.2 Icy Moon Orbital Science

Due to power and data downlink restrictions not all instruments can operate simultaneously during orbital operations. Prioritized observations and time-sharing of observational time are used lower the average power required during any orbit. To ensure that all scientific goals can be achieved a combination of onboard data processing, data compression, and sequential operation of instruments will be used to reduce the data volume required for downlink. With the anticipated onboard processing capability, both JEO and JGO will be able to optimize the amount of data to be returned to Earth.

The highest data return for JGO (~300 Gb) will occur during the Ganymede circular orbit campaign. The main drivers for data volume will be the cameras, the V/NIR Imaging spectrometer (VIRHIS), and the radar, which all have high data rates (up to 5 Mb/s). Both the cameras and the spectrometer have compression factors ranging from 2 to 10 using new compression algorithms. Operating the instruments in a sequence such as every other orbit will be necessary to fit into the ~ 1.7 Gb average daily downlink data volume. In the circular orbit campaign, JGO will collect observations for 16 hours per day and downlink data for 8 hours.

For the JEO Europa Science phase, the data acquisition strategy is designed to obtain the highest-priority observations first and quickly. Following a brief engineering assessment period, data taking proceeds through 4 campaigns, beginning with the Global Framework campaign, then focusing on Regional Processes, then concentrating on Targeted Processes to address local-scale science questions and then performing Focused Science for follow-up on discoveries made during the earlier campaigns. Throughout the Europa Science phase, several instruments collect data continuously, both on the day and night sides of Europa: Radio Science (RS) — 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 UltraViolet Spectrometer (UVS) is operated for a few minutes each orbit to collect stellar occultation observations of selected UV source stars.

For the other remote sensing instruments, a 2-orbit repeating scenario is planned, which permits power and data rate balancing. Even orbits emphasize optical remote sensing by the Wide Angle Camera (WAC), and the VIRIS spectrometer, 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.

JEO targeted observations are of two types; coordinated imaging targets and IPR full rate targets. The coordinated imaging targets collect nested observations among the optical remote sensing instruments (MAC, NAC and VIRIS), along with the profiling IPR mode, and the continuously operating TI and LA (**Figure 3-4**). IPR full rate targets (30 seconds, 30 Mb/s, with MAC context) will also be collected. Over 1900 targeted observations, of both types, are obtained during the Europa Science Phase. While targets are collected in all campaigns, they support focused science goals including identification of candidate sites for future landers.

3.4.3 Extended Mission

Both orbiters have the additional capacity to support an extended icy moon orbiting mission if approved. It is expected that the functionality of the flight systems will decay as the radiation exposure increases and the performance will degrade until, if left operational, a fatal failure occurs.

3.4.4 Decommissioning and Disposal Phase

The Decommissioning and Disposal Phase will put the orbiters on a trajectory spiraling toward their respective moons' surface. This phase can be planned or left to happen naturally. The decaying orbits will provide extraordinary opportunities for atmospheric, deep interior and surface measurements.

3.4.5 Data Return

Detailed operational scenarios, based on achieving the highest priority data first, ensure that the instruments perform the required measurements for the science goals to be fulfilled. A total of ~ 1.5 Tbits of data is returned from JGO and ~ 4.5 Tbits from JEO through their prime missions. The potential cumulative data return is double that of the Cassini prime mission (2.8 Tbit) and is 3 orders of magnitude more than Galileo was able to return. Though Galileo was able to contribute extraordinary scientific value, this increased data volume will be able to answer the questions raised by Galileo.

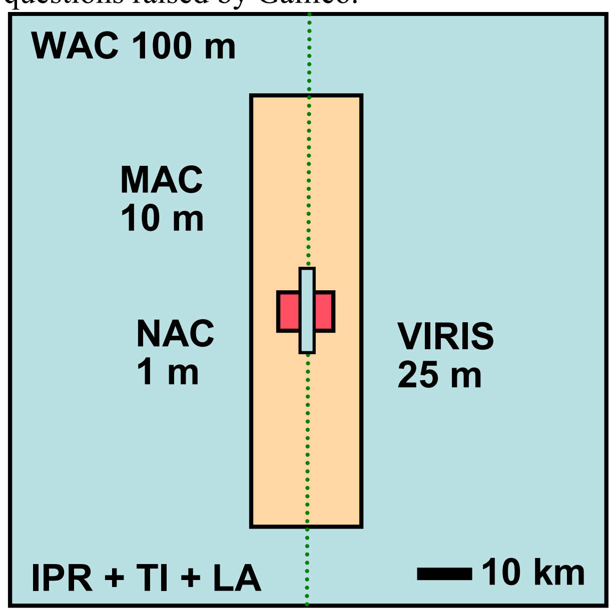


Figure 3-4: *Nested JEO FOVs provide for coordinated targeted observations (resolution/pixel indicated).*

3.5 Planetary Protection

The JEO and JGO missions present very different planetary protection challenges. Specifically, due to the hypothesized resurfaceing methods, the likelihood of a spacecraft fragment being transported to the liquid ocean is very different between Europa and Ganymede.

Current Planetary Protection 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 1×10^{-4} per mission." Since the resurfacing rate of the surface of Europa is believed to be high, the probability that contamination of the ocean will occur if the spacecraft hits the surface is deemed to be unity. It has been determined that it is infeasible to leave Europan orbit at the end of the mission. This led to the conclusion that surface impact at the end of the mission is the appropriate technical and scientific approach. Accordingly, it is necessary to eliminate viable microorganisms from the spacecraft before it impacts the surface.

Planetary protection requirements for the JEO mission will be met through:

- Prelaunch sterilization to control bioburden for those areas not sterilized in flight, and
- In flight sterilization via radiation prior to Europa orbit insertion.

The NASA Planetary Protection Officer has indicated approval of this approach given that the specific requirements for Europa can be met [*Conley 2006*]. The JEO mission will be classified as category III under current COSPAR and NASA policy [*COSPAR 2002*].

Ganymede is believed to be much less active geologically than Europa, greatly reducing the probability that surface contamination will find its way to the sub-surface ocean. This moon is currently classified as category II under COSPAR and ESA policy. Accordingly, even though JGO will impact that moon at mission end, standard processes for cleaning are acceptable and no sterilization is required.

A Joint NESA-ESA Planetary Protection Working Group has been established for the Outer Planet missions and plans for meeting currently envisioned requirements have been vetted by and have been agreed to by this Working Group.

3.6 Technology Needs

There are no new technologies required to implement the EJSM 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. The Departments of Defense and Energy as well as industry have invested in technologies and developments that directly benefit the current JEO concept. Industrial entities in Europe have been developing electronic components to withstand high radiation environments as well. Though JGO's lower expected radiation dose allows many standard parts to be used, if desired, more radiation-hardened parts have been developed by CERN, for use in the European market. Though new technology developments are not required, it will be necessary to adapt current designs to perform within the radiation environment and to meet the planetary protection requirements. This is especially true for JEO where the predicted radiation exposure over the life of the mission is about 3.5 times that expected for JGO.

Although current technologies are sufficient to perform a scientifically engaging mission to Jupiter, Ganymede and 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: Advanced Stirling Radioisotope Generators (ASRGs), solar arrays, memory, advanced sensors, and DSN upgrades.

JEO is compatible with use of either type of Radioisotope Power Source (RPS) (MMRTG, ASRG, or a combination of both); however, a timely decision is needed as the design of the flight system progresses to avoid costly changes and delays. The timing of the RPS decision is not under the control of the JEO project. To mitigate this risk, the project will work closely with the Program Executive at NASA Headquarters during the RPS Development Program to ensure that requirements are known and a final decision on RPS is made prior to the completion of Phase A.

3.7 Other Risk Areas and Their Mitigation

Radiation poses a unique technical challenge for EJSM due to the flight system spending a significant time in the 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.

Exposure to these large dose rates will present challenges for the science instruments even with localized shielding. High radiation fluences create radiation noise that degrades the performance of detectors in science instruments and star trackers. Extensive work was performed at JPL and APL in 2008 to characterize the potential impact on the types of detectors that would be needed for the model payload; this work produced very encouraging results. It was determined that a combination of radiation-hardened components and shielding would be effective in ensuring that instrument and engineering subsystems function correctly within this environment.

In 2008, NASA started executing a risk mitigation plan focused specifically on identifying the highest impact areas and beginning to mitigate risks in those areas. The extensive work performed in 2008 by NASA provided further confidence that parts, materials and sensors/detectors are available to perform the JEO mission as conceived. Most of the 27 documents and presentations are intended for public release via the http://opfm.jpl.nasa.gov website. The primary audience for this information is potential instrument providers to help mitigate design and operational risk associated with instruments proposed to the Announcement of Opportunity.

For JGO, the radiation exposure is much lower and the approach is to keep the levels low enough to use standard parts and materials. Most of the information produced in the NASA 2008 effort is applicable to designs for JGO as well.

The **Planetary Protection** sterilization requirement for the JEO mission element is also a risk area. As discussed earlier, all components, electronics and materials must be sterilized prior to entering Europa orbit. Early identification of parts and materials which can withstand the sterilization and radiation requirements is essential to risk mitigation.

Both Radiation and Planetary Protection risks might directly impact the cost and schedule for both the spacecraft and instrument development. Early risk mitigation is crucial to decreasing the cost risk associated with fixing issues found late in the design cycle. The Risk Mitigation Plan for radiation and planetary protection was developed and is currently being executed. Specifics of the Risk Mitigation Plan and the assessment of sensors, detectors and other instrument components of the model payload can be found in the documents as listed in §8.

Inherent in broad-science mission development is cost risk associated with the **maturation and stability of the science objectives and mission concepts**. Rigorous analysis over the course of the study has resulted in a JEO implementation design that balances science, cost and technical considerations. The cost risk associated with the JEO science and mission concept has been offset by the extensive mission studies performed by NASA over the past 12 years and these studies have increased the confidence in the validity of the cost estimate. Mature and stable science objectives have fed high-fidelity mission conceptual technical and operational designs culminating in the studies performed in the past 3 years at JPL and APL with only minor changes to the mission, spacecraft and operational designs. By exploring scientific and implementation aspects early and thoroughly, the mission concept has become stable and less vulnerable to costly changes without considerable analysis by the science and project team and so is no longer a significant risk item.

4.0 NASA AND ESA IMPLEMENTATION RESPONSIBILITIES

4.1 Mission Elements

ESA will be responsible for the design, development and test of the JGO flight and ground elements. ESA will also procure the launch vehicle and launch services for JGO. NASA will be responsible for the design, development and test of the JEO flight and ground elements. NASA will also be responsible for procuring the launch vehicle and all launch services including launch approval for the JEO Flight System.

4.2 Science Instruments

The science instruments aboard JGO and JEO will be solicited via a coordinated Announcement of Opportunity (AO) by NASA and ESA for PI-led investigations and for interdisciplinary scientist (IDS) investigations. European instruments will be provided by national agencies and institutes, while US instruments will be from NASA Centers, universities, industry, or other science organizations. No pre-determined assignment for instrument delivery is anticipated (e.g, facility instrument). U.S. instruments on JGO or European instruments on the JEO could be selected either from the natural selection process or at the discretion of the decision makers for the best interests of the mission (e.g., to have the same instrument on both spacecraft or to have access to a key technology on both spacecraft).

4.3 Science Teams

All selected investigation leads will form the Project Science Group (PSG) that will be co-chaired by the NASA and the ESA Project Scientist. European scientists will be funded through their national agencies. Given the long mission duration, it is anticipated that a second (or more) solicitation will be prudent as the flight systems approach Jupiter to engage scientists who will not be available when the initial AO is released (not yet established in their field).

4.4 Flight Operations

ESA will be responsible for operating JGO while NASA will be responsible for operating JEO. The international PSG will work directly with NASA and ESA to coordinate the science operations performed by the two flight elements to optimize the science return.

4.5 Management Approach

Management of EJSM will draw from experience in the coordination of orbital missions at Mars (the ESA Mars Express and the NASA Mars Reconnaissance Orbiter). Since JEO and JGO will be developed separately and launched separately on NASA and ESA LVs, the ESA and NASA management structures do not need to be tightly coupled. However, there will be coordination in the areas of spacecraft communications, science data product production and archiving, and science operation planning.

The management effort will build upon the relationships developed during the current study phase and following the selection of the destination in February 2009 and involve close coordination between NASA and ESA and partners and contractors. Technical Assistance Agreements authorizing Caltech/JPL and Johns Hopkins University/APL to undertake cooperatives studies and implementation activities with ESA and other entities and individual European scientists have now been approved by the U.S. State Department and will facilitate close working relationship on the studies and the project when it begins.

5.0 NASA-ESA INTERDEPENDENCIES

5.1 Launch Capabilities

There are no launch interdependencies between the ESA JGO mission element and the NASA JEO mission element. The launch date of these two mission elements is currently scheduled so that the time that the two flight elements are operating together in the Jupiter system is maximized. Neither mission element is dependent on deliveries from the other in order to launch. Also, many launch windows for both mission elements exist with excellent synergistic science. If JEO and JGO are launched in separate opportunities 1 to 3 years apart, none of the Europa- and Ganymede-specific science is impacted and science complementarities will be retained; however, science synergies dependent on simultaneous observations in the Jupiter system will be impacted due to the reduced time that JGO and JEO spend in Jupiter orbit together. The potential impact could be mitigated by lengthening the tour portion of the first element to reach Jupiter.

5.2 Telecommunications

There are no telecommunications interdependencies between the ESA JGO mission element and the NASA JEO mission element.

5.3 Radioisotope Power Systems

There are no dependencies between NASA and ESA for radioisotope power systems. The JEO flight system will use radioisotope power and radioisotope heating units (RHUs): the JGO uses solar power and does not use RHUs.

6.0 COST AND SCHEDULE

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.

JAXA is still evaluating whether a contribution to the EJSM mission will be a piggy-back spacecraft on JGO or its own independently launched mission (part of a Trojan asteroid mission). No cost estimate is provided here.

6.1 NASA Costs

The JEO Phase A through F lifecycle cost estimate for the baseline mission concept is \$3.8 B RY (\$2.7 B (FY07)) including 37% reserves. The floor mission concept is estimated at \$3.0 B RY (\$2.1 B ((FY07)). NASA-only versions are identical to the baseline and floor and thus have the same cost. These estimates include costs for the JEO spacecraft, science and instruments, Atlas V 551 launch vehicle, power source, ground system and operations. The Project cost assumes it will 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. The cost estimate is shown in detail in the NASA Jupiter Europa Orbiter Mission Final Report [*JPL D-48279*].

6.2 ESA Costs

The preliminary cost evaluation performed during the CDF study suggests that the cost of the current configuration of the JGO will stay below the Cosmic Vision L-Class mission cost envelope of 650M€. This estimate includes costs for the JGO spacecraft, the Ariane 5 launch, mission operations and science operations. It excludes the cost for the scientific instruments that are provided by science institutes in ESA member states and funded nationally.

6.3 High-Level Schedule

The development schedules for JEO and JGO for the baseline 2020 launch 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 6-1**. There are no technical obstacles to supporting launch dates as early as 2018.

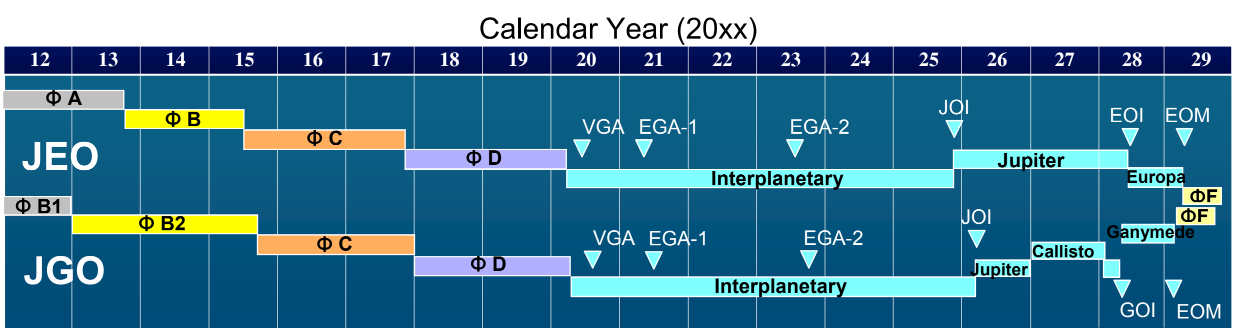


Figure 6-1: *The concurrent but independent development of the JGO and JEO flight elements allow simultaneous Jupiter System science, enabling unprecedented observations of a single phenomenon from two different vantage points.*

7.0 STUDY TEAM MEMBERS AND ROLES

An international science and technical team was formed by NASA and ESA with the goal to develop a focused cost-effective Europa Jupiter System Mission. The JJSDT and technical team worked as a seamless integrated unit to define a mission that fully responds to the Statement of Work and Ground Rules for this study while at the same time assuring that the optimal balance between science cost and risk was achieved.

7.1 Joint Jupiter SDT Function and Membership

The international JJSDT, representing over half-a-dozen countries, focused on the science aspects while the study team focused on the technical and programmatic aspects of the mission concept. The JJSDT membership is shown in **Table A-1** in Appendix A. There was extensive interaction between the science and study members throughout the study ensuring that the science goal and objectives were feasible and realistic given the technical and programmatic constraints and approaches. Seven JJSDT meetings were held which included interactions with the study team.

7.2 NASA Study Team

NASA chartered JPL to lead a US study to further define the 2007 Europa Explorer (EE) mission concept while incorporating Jupiter System science, as defined in the 2007 Jupiter System Observer study. JPL was also chartered to refine the radiation risk reduction plan developed in 2007 and to begin executing the plan. JPL enlisted APL to add additional expertise to this study.

The NASA study team included personnel from JPL, Johns Hopkins University/Applied Physics Lab (JHU/APL), NASA and Ames Research Center (NASA ARC). The NASA Study Team membership is shown in **Table A-2** in Appendix A. JPL provided study leadership, task management, requirements definition, system engineering, and mission system design (flight and ground). APL participated in mission system engineering, requirements analysis, project risk assessment, payload system engineering, project system integration and test and Phase E lessons learned.

7.3 ESA Study Team

The ESA effort was led by the study leadership with the detailed technical aspects of the study largely being performed in the ESA Concurrent Design Facility (CDF) format. The ESA Study Team membership is shown in **Table A-3** in Appendix A. The CDF Team took the science, mission and payload requirements documents provided by the JJSDT and Engineering Team and developed the JGO concept in a rapid, concurrent methodology utilized on numerous ESA studies in the past. A total of seven CDF Team sessions were used over the course of two months.

7.4 Other Study Support

Two other potential contributions to EJSM were reviewed by the JJSDT. Neither concept was accepted as a part of the baseline due to their lack of definition. Both could be reconsidered in the future if desired.

JAXA continues to study potential ways to complement the NASA and ESA spacecraft by providing a third platform, the JMO. The enhanced mission will offer a unique capability to perform 3-dimensional observations in the energetic center of the solar system. JMO will be launched as an additional payload with JGO or as a stand-alone launch.

Interest was shown by the Russian Space Agency to provide a Europa Lander. Also, a United Kingdom Consortium expressed interest in supplying a small penetrator.

8.0 GUIDE TO STUDY DOCUMENTATION

The international team from NASA and ESA has been building upon previous studies to configure a single mission concept which balances cost, risk and scientific value while responding to the science objectives of the Decadal Survey and Cosmic Vision Programme. The resulting Europa Jupiter System Mission is the culmination of over a decade of detailed conceptual studies resulting in two flight elements, JEO and JGO. The decoupling of the design and delivery elements of the flight elements allows flexibility in all aspects of mission development including study documentation. An overview of the 2008 study documentation and its immediate predecessors is shown in **Figure 8-1**.

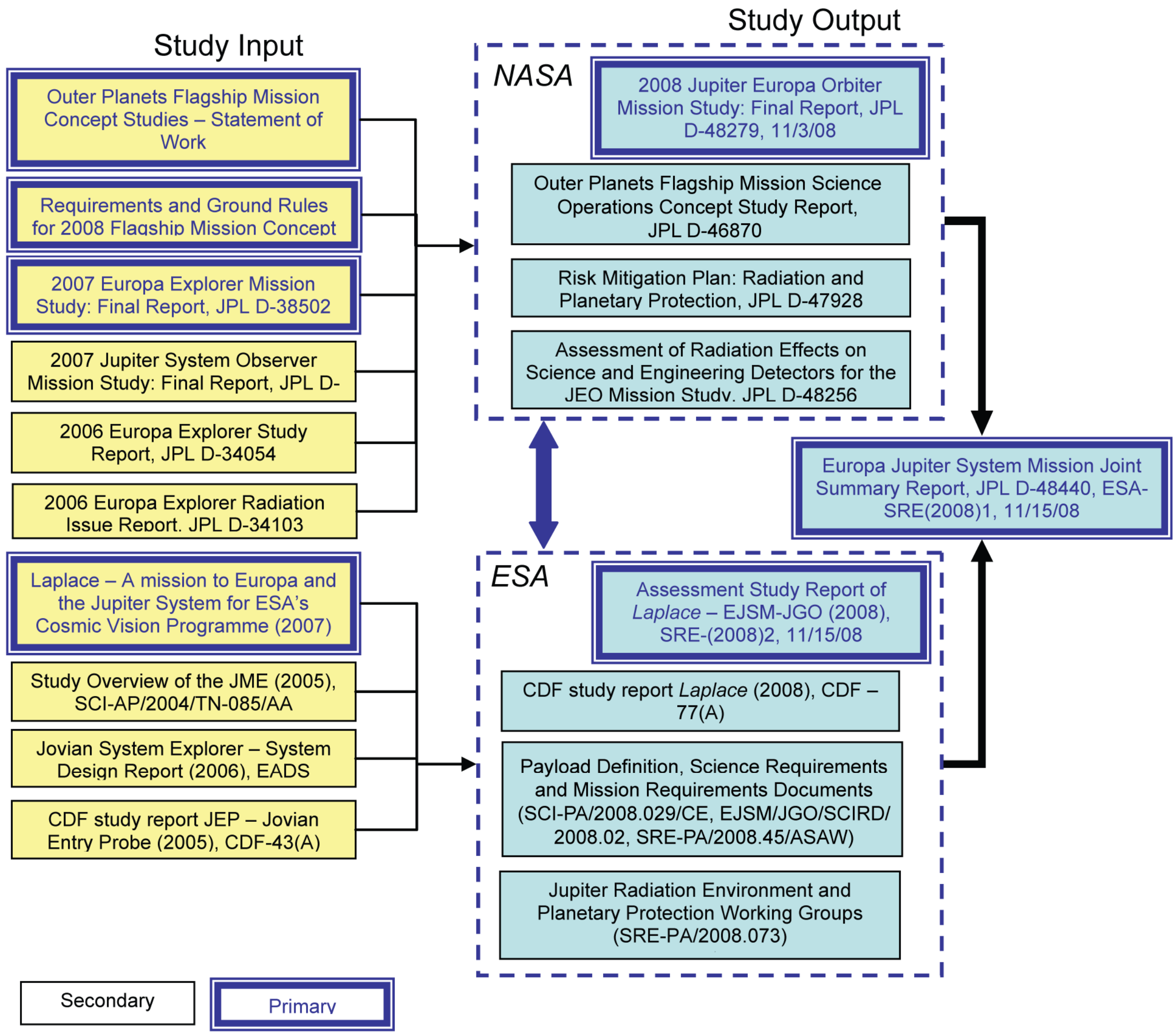


Figure 8-1: *The 2008 NASA and ESA and studies are founded on extensive previous work and have produced detailed documentation to show the how the risk of designing for the challenging environment has been mitigated both by architecture and action, to ensure an executable mission concept which is scientifically engaging while maintaining significant cost and risk margins.*

8.1 NASA Study Documentation

8.1.1 2007 OPFM Studies

The study of an orbital mission to Europa started at NASA right after the arrival of Galileo in the Jupiter system. A synopsis of the NASA studies through 2007 is found in Assessment of Alternative Europa Mission Architectures [*JPL 08-1*]. In 2007, NASA initiated Phase I studies of potential Outer Planet Flagship missions to four icy satellite targets including missions to Europa, the Jupiter system and Ganymede. This breadth of study culminated last year in two reports: the 2007 Europa Explorer Mission Concept [*JPL D-34054*] and the 2007 Jupiter System Observer [*JPL D-38503*].

Neither of these studies included international participation and in fact both were conducted in parallel to ESA's 2007 Cosmic Vision proposal cycle.

The Europa Explorer concept was a very capable orbiter that conducted extensive Europa science while in orbit at Europa. Jupiter system science was not a Level 1 science objective. The Jupiter System Observer concept focused on Jupiter system science and ultimately obtained orbit at Ganymede. Science, technical, and cost results from these studies were used as a stepping off point and resource for the NASA portion of the 2008 EJSM Study.

8.1.2 2008 Study Ground Rules and Statement of Work

Upon completion of NASA's 2007 OPFM studies and their independent review, NASA Headquarters elected to continue studying missions to two of those targets; Europa and the Jupiter System (hence EJSM) and Titan and the Saturn System (hence TSSM). In the same time frame, NASA and ESA agreed that the 2008 studies will be done as a collaborative effort thereby integrating results from the 2007 NASA studies and ESA Cosmic Vision Programme selection. As a result, Ground Rules and statement of work documents were developed and provided (as highlighted in **Table 3-1**) to further focus the Europa Jupiter System Mission. The Ground Rules describe parameters and tasks constraining the OPFM studies; the Statement of Work provides additional guidance on tasks and constraints unique to the mission.

8.1.3 2008 Mission Concept Study Report

NASA Headquarters requirements to JPL for execution of the 2008 JEO study are documented in the form of a Statement of Work and Ground Rules. The overarching approach was to integrate the results of the two studies from 2007 (JSO and EE). The result of the mission concept development for the 2008 Jupiter Europa Orbiter Mission Concept can be found described in: K. Clark, R. Greeley, and R. Pappalardo [*2008*], *2008 Jupiter Europa Orbiter Mission Study: Final Report, JPL D-48279*. As a part of the 2008 NASA activity, several documents related to risk mitigation for the radiation and planetary protection requirements were released. A complete listing can be found in the 2008 JEO Final Report.

8.2 ESA Study Documentation

In 2003, ESA's Science Payload & Advanced Concepts Office started a combination of activities to identify and to start the development of critical technologies that will be required for future scientific missions. This was done through studying several challenging and scientifically relevant missions, which were not part of ESA's science program at the time, and focusing on the medium term enabling technology requirements. Several of these studies were focused on the Jupiter system.

The main effort concentrated on the Jovian Minisat Explorer, to understand the challenges of a remote sensing mission to Europa. The study included two industrial studies, based on a solar powered and on radioisotope powered spacecraft options as well as internal reviews using the Agency's CDF that resulted in further evolution of the design.

The Jupiter Entry Probe study, performed by a dedicated CDF team, was initiated to investigate the critical technologies and issues related to the design of a ballistic Jovian entry probe, with the aim of performing atmospheric measurements during descent and to survive to an ambient atmospheric pressure up to 100 bar.

In the third study, the Jovian System Explorer focuses on a cost-efficient and technologically feasible mission architecture for a multi-spacecraft exploration of the Jovian magnetosphere and atmosphere, while providing a preliminary assessment of the logistics and enabling technology development.

8.2.1 *Laplace* Proposal for Cosmic Vision 2015 – 2025

In response to ESA's call for mission proposals for the Cosmic Vision 2015 – 2025 Programme, which was issued in March 2007, the *Laplace* proposal was put forward by the scientific team. Following that submission, the *Laplace* mission was selected for further study, in collaboration with NASA, and the share of responsibilities was agreed upon as presented in this report.

8.2.2 ESA CDF Report

The ESA internal assessment of the Jupiter Ganymede Orbiter feasibility was carried out in May and June 2008 with the assistance of ESA/ESTEC Concurrent Design Facility and ESA/ESOC for mission analysis and mission operations. The CDF consists of a temporary team of about 25 engineers of all involved disciplines and studied possible design options, including high level trade-offs being able to converge on a preliminary optimized design. This process allows identification of critical elements, and also highlighting of technology needs. A preliminary budget of the studied elements was provided.

The CDF team performed a bottom up design of the orbiter. A final report from that effort was delivered.

8.2.3 ESA Assessment Report

The conclusions of the CDF Report were taken as input to this assessment report. The main elements that were studied in the CDF activity were used for this report. However the baseline choice of final mission parameters and instruments has changed slightly since the completion of the CDF study and the description of the new baseline is included in this report.

8.3 Study Review Process

Elements of the JEO study report have been reviewed extensively by independent sets of discipline specialists and by APL/JPL management as follows:

1. The team has gained the support of the NASA PPO for the PP approach concept [*Conley 2006*] which was re-iterated in 2008.
2. The Science Goals and Objectives were subjected to a review at various science meetings by independent planetary scientists.
3. The Science Goals and Objectives and the mission concept were presented at the Outer Planets Assessment Group (OPAG) meeting in April and November 2008.
4. The mission concept and approach was subjected to two NASA HQ interim reviews in April and June of 2008.
5. 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.
6. 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.
7. The mission implementation has been reviewed by technical, management, and cost review boards and line management organizations internal to JPL and APL.
8. The Risk Mitigation Plan: Radiation and Planetary Protection has been reviewed by technical experts at APL and JPL.
9. Finally, the overall concept study report was reviewed by both JPL and APL management prior to submission to NASA for independent review.

9.0 SUMMARY AND CONCLUSIONS

The Europa Jupiter System Mission (EJSM) concept represents the culmination of recent NASA and ESA efforts to define a mission to the Jupiter system that will represent a major scientific step beyond the Galileo mission. In 2007, NASA performed mission concept studies focused on four icy moon targets including two in the Jupiter system - Europa and Ganymede. Also in 2007, ESA put forth its Cosmic Vision 2015 – 2025 call for mission concepts which resulted in selection of the *Laplace* concept for a mission to the Jupiter system. In February 2008, NASA and ESA Study teams began working very closely to integrate NASA's Europa Explorer and ESA's *Laplace* concept as EJSM under the guidance of a Joint Jupiter Science Definition Team. This Joint Summary Report describes the principal features of EJSM. More detailed documentation for in-depth study of EJSM is described and referenced in Section 8.

EJSM will conduct a comprehensive exploration of the Jupiter system while also performing focused science related to formulated hypotheses.

- Investigates the emergence of habitable worlds around gas giants by intensively exploring two icy worlds with global oceans - Europa and Ganymede.
- Leverages synergistic NASA/ESA resources, reduces risk, and ensures technical readiness.
- Ensures programmatic flexibility with independent and frequent launch opportunities.
- Enables dramatic increases in scientific knowledge by using the latest technology, focused instruments and tailored trajectories.
- Engages scientists from the full range of planetary science disciplines – Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, and Magnetospheres.

The baseline architecture for EJSM consists of two primary elements operating in the Jovian system at or close to the same time: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). JEO and JGO are two free-flying flight elements with unique yet synergistic science objectives. JEO and JGO execute intricately choreographed and coordinated exploration of the Jupiter System with numerous flybys of Io, Europa, Ganymede and Callisto before they are inserted into orbit of Europa and Ganymede. The scientific return is resilient to changes in the launch date of either JEO or JGO. Each flight system carries specifically selected and complementary instruments to monitor time-varying phenomena such as Io's volcanoes and Jupiter's Red Spot, map the intricate interrelationship of Jupiter's magnetosphere with that of Ganymede and to probe beneath the ice shells of Europa and Ganymede.

Both JEO and JGO flight system designs are based on already proven functionality of deep space orbiters. No new technologies are needed for JEO or JGO although significant engineering developments are required for JEO (radiation designs) and JGO. Current risk mitigation activities are under way to ensure that the radiation designs are implemented with the lowest risk approach. The robust baseline mission concepts include generous mass and power margins.

In addition to the JEO baseline mission concept described herein, NASA requested that a NASA only mission and floor mission concepts (with the prioritized descopes from the baseline) be developed. For JEO, due to the independence of the launches, the NASA-only mission is identical to the JEO baseline concept.

EJSM is a robust mission concept which will revolutionize scientific knowledge of Europa, Ganymede and the Jupiter system. Both scientifically and technically mature, it is ready to be initiated now.

APPENDIX A. STUDY TEAM MEMBERS

Table A-1: *The Joint Jupiter Science Definition Team draws from over half-a-dozen different countries and 3 continents. The international team worked in an integrated fashion to form the theme, goals, and objectives for EJSM. In addition, the JJSDT gathered input from two dedicated community science forums and 18 invited talks.*

Name	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

Name	Affiliation	Expertise
Japan JJSDT Membership		
Masaki Fujimoto	Institute of Space and Astronautical Science / Japan Space Exploration Agency	Fields & Particles
Takeshi Takashima	Institute of Space and Astronautical Science / Japan Space Exploration Agency	Fields & Particles
Sho Sasaki	National Astronomical Observatory of Japan	Satellites
Yasumasa Kasaba	Tohoku University	Fields & Particles
Yukihiro Takahashi	Tohoku University	Jupiter

Table A-2: *The integrated NASA technical team draws from organizations with deep-space mission experience as well as a wealth of experience in radiation design to define the NASA-led element of EJSM: JEO. The focus of this year's NASA effort was the JEO conceptual designs and risk reduction related to radiation and planetary protection.*

Member	Affiliation	Expertise
Ronald Greeley – Co-Chair	Arizona State University	Europa
Bob Pappalardo – Study Scientist	Jet Propulsion Laboratory	Europa and Jupiter System
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
Marc Foote	Jet Propulsion Laboratory	Thermal Instrumentation
Henry Garrett	Jet Propulsion Laboratory	Jupiter Environments
Dan Goods	Jet Propulsion Laboratory	Artist
Paula Grunthaner	Jet Propulsion Laboratory	Instrument Workshop, Sensors and Detectors
Dave Hansen	Jet Propulsion Laboratory	Telecommunications
Ted Hartka	John Hopkins University — Applied Physics Lab	Mechanical, Structure, and Mechanisms
Ken Hibbard	John Hopkins University — Applied Physics Lab	Systems Engineering
Mark Holdridge	John Hopkins University — Applied Physics Lab	Operations
Denise Hollert	Jet Propulsion Laboratory	Structures and Mechanisms
Kevin Hussey	Jet Propulsion Laboratory	Visualization
Steve Jaskulek	John Hopkins University — Applied Physics Lab	Particle and Plasma Instrumentation
Allan Johnston	Jet Propulsion Laboratory	Electronic Parts
Ed Jorgenson	Jet Propulsion Laboratory	Cost
Insoo Jun	Jet Propulsion Laboratory	Radiation Environments and Shielding
Richard Key	Jet Propulsion Laboratory	Systems Engineering

Member	Affiliation	Expertise
James Kinnison	John Hopkins University — Applied Physics Lab	Systems Engineering — Risk Assessment
Ken Klaasen	Jet Propulsion Laboratory	Instruments
Kevin Kloster – Student	Jet Propulsion Laboratory — Purdue University	Trajectory Design
Kevin Lane	Jet Propulsion Laboratory	Visualization
Sima Lisman	Jet Propulsion Laboratory	Attitude and Articulation Control Subsystem
Rob Lock	Jet Propulsion Laboratory	Mission Planning and Operational Scenarios
Jan Ludwinski	Jet Propulsion Laboratory	Mission Design
Carolina Maldonado	Jet Propulsion Laboratory	Command and Data Handling
Bill McClintock	Laboratory for Atmospheric and Space Physics	UV Spectrometer Instrumentation
Steve McClure	Jet Propulsion Laboratory	Electronic Parts
Peter Meakin	Jet Propulsion Laboratory	Attitude, Articulation and Control
Joe Means	University of California Los Angeles	Magnetometer Instrumentation
Anthony Mittskus	Jet Propulsion Laboratory	Telecommunications
Robert Miyaki	Jet Propulsion Laboratory	Thermal Control
Ricardo Mondoza	Jet Propulsion Laboratory	Telecommunications
Ted Moshir	Jet Propulsion Laboratory	System Modeling
Dave Muliere	Jet Propulsion Laboratory	VIS-IR Spectrometer Instrumentation
Barry Nakazono	Jet Propulsion Laboratory	Propulsion
Pablo Narvaez	Jet Propulsion Laboratory	EMI/EMc/Magnetics
Joe Neelon	Jet Propulsion Laboratory	Operational Scenarios
Bill Nesmith	Jet Propulsion Laboratory	ASRG/RPS
Matt Noble	John Hopkins University — Applied Physics Lab	Camera Package Instrumentation
Brian Okerlund	Jet Propulsion Laboratory	Configuration
Joon Park	Jet Propulsion Laboratory	Artist
Anastassios Petropoulos	Jet Propulsion Laboratory	Trajectory Design
Nick Pinkine	John Hopkins University — Applied Physics Lab	Operations Lessons Learned
Bob Rasmussen	Jet Propulsion Laboratory	Systems Engineering
Ed Reynolds	John Hopkins University — Applied Physics Lab	Project Management
David Roth	John Hopkins University — Applied Physics Lab	Radiation Effects
Ian Ruiz	Jet Propulsion Laboratory	Command and Data Handling
Ali Safaeinili	Jet Propulsion Laboratory	Ice Penetrating Radar Instrumentation
Karen Sampley	Jet Propulsion Laboratory	Enterprise Support, Secretarial
Paul Schmitz	Glenn Research Center	ASRG/RPS
Calina Seybold	Jet Propulsion Laboratory	Command and Data Handling
Mike Shafto	Ames Research Center	Operations
Eddy Shalom	Jet Propulsion Laboratory	Avionics
Richard Shaltens	Glenn Research Center	ASRG/RPS
Doug Sheldon	Jet Propulsion Laboratory	ASICs and FPGAs
Jon Sims	Jet Propulsion Laboratory	Trajectory Design
Dave Smith	NASA Goddard Space Flight Center	Laser Altimeter Instrumentation
Andy Spry	Jet Propulsion Laboratory	Planetary Protection
Karl Strauss	Jet Propulsion Laboratory	Solid State Memory
Erick Sturm	Jet Propulsion Laboratory	Systems Engineering
Grace Tan-Wang	Jet Propulsion Laboratory	Systems Engineering
Steve Thibault	John Hopkins University — Applied Physics Lab	Integration and Test
Valerie Thomas	Jet Propulsion Laboratory	Mission Assurance
Paul Timmerman	Jet Propulsion Laboratory	Power
Dogan Timucin	Ames Research Center	Radiation Circuit Modeling
Violet Tissot	Jet Propulsion Laboratory	Schedules
Ramona Tung	Jet Propulsion Laboratory	Telecommunications
Steve Vance	Jet Propulsion Laboratory	Science

Member	Affiliation	Expertise
Tracy Van Houten	Jet Propulsion Laboratory	Systems Engineering
Corby Waste	Jet Propulsion Laboratory	Artist
Kevin Weaver	Ames Research Center	Radiation Circuit Modeling
Greg Welz	Jet Propulsion Laboratory	Operations
Lawrence Wilfarth	John Hopkins University — Applied Physics Lab	Cost
Ed Wong	Jet Propulsion Laboratory	Attitude and Articulation Control Subsystem
Peter Wurz	University of Bern	Ion & Neutral Mass Spectrometer Instrumentation
Tsun-Yee Yan	Jet Propulsion Laboratory	Radiation Effort Management and System Model
Chen-Wan Yen	Jet Propulsion Laboratory	Trajectory Design
Mary Young	Jet Propulsion Laboratory	Documentation

Table A-3: *The ESA technical team utilized the broad experience base of the Concurrent Design Facility to rapidly digest the science, payload and mission requirements to arrive at a conceptual design for JGO which met the needs of the JJSDT.*

Member	Affiliation	Expertise
Anamarija Stankov — ESA Study Manager	European Space Agency	Project Management and Systems Engineering
Peter Falkner	European Space Agency	Project Management and Systems Engineering
Arno Wielders — Study Payload Manager	European Space Agency	Payload Management
Robin Biesbroek — Concurrent Design Facility Study Lead	European Space Agency	System Engineering and Mission Analysis
Massimo Bertinelli	European Space Agency	Communications
Torsten Bieler	European Space Agency	Cost
Arnaud Boutonnet	European Space Agency	Mission Analysis
Andrew Caldwell	European Space Agency	Systems Engineering
Marco Chiappone	European Space Agency	Risk
Giovanni Chirulli	European Space Agency	Thermal Systems
Antonio G. De Luca	European Space Agency	Power
Paolo De Pascale	European Space Agency	Mission Analysis
Don De Wilde	European Space Agency	Configuration/Structure
Jean-Francois Dufour	European Space Agency	Data Handling
Domenico Giunta	European Space Agency	Communications
Borja Gutierrez	European Space Agency	Simulation
Naomi A. Murdoch	European Space Agency	Instruments
Sandra Oberhollenzer	European Space Agency	Propulsion
Massimo Palladino	European Space Agency	Mechanisms
Ulrike Ragnit	European Space Agency	Programmatics
Ilaria Roma	European Space Agency	Systems Engineering
Jens Romstedt	European Space Agency	Planetary Protection
Giovanni Santin	European Space Agency	Radiation
John Sorenson	European Space Agency	Radiation
Keith Stephenson	European Space Agency	Power
Rainer Timm	European Space Agency	Ground System and Operations
Thomas Voirin	European Space Agency	Guidance, Navigation and Control

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