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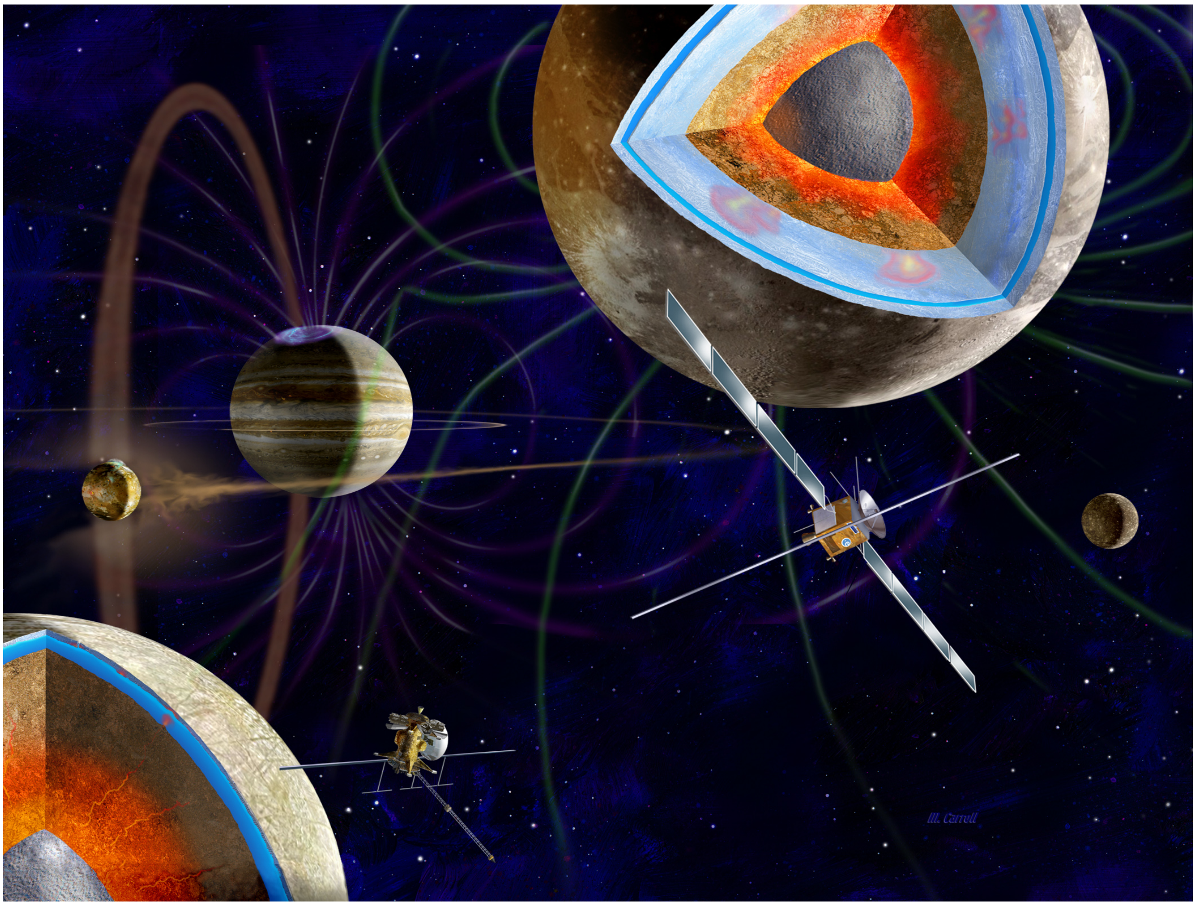
EJSM-Laplace

Exploring the emergence of habitable worlds around gas giants



Assessment Study Report

European Space Agency

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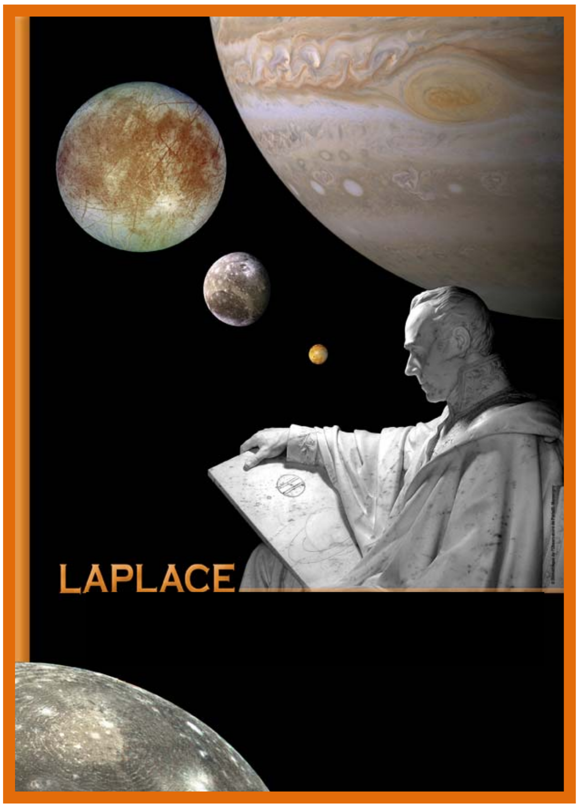
Foreword



The Europa Jupiter System Mission (EJSM-Laplace) concept results from the merging of the Large Class mission "*Laplace*" proposal in response to ESA's Cosmic Vision programme call in 2007, and of two NASA Outer Planets Flagship mission studies, "*Europa Orbiter*" and "*Jupiter System Observer*". The proposed share of responsibilities on EJSM-Laplace was achieved at the beginning of the joint ESA-NASA study that started in early 2008, when the Joint Science Definition Team (JSDT) was established. To understand the Galilean satellites as a system, Ganymede and Europa are singled out for detailed investigation by EJSM-Laplace.

EJSM-Laplace is an international mission that would be developed in collaboration between ESA and NASA. The reference mission architecture which was studied during the past 3 years consists of the following two flight elements: i) the Jupiter Ganymede Orbiter (JGO), assumed to be developed, launched and operated by ESA, ii) the Jupiter Europa Orbiter (JEO), assumed to be developed, launched and operated by NASA.

The two spacecraft, JGO and JEO, would be independently built, launched and operated in the Jovian system. The mission as studied, however, offers unique capabilities to execute an extended joint choreographed exploration of the Jupiter system before the spacecraft settle into orbit around Ganymede and Europa, respectively. JGO and JEO will be flying on two complementary trajectories and will carry complementary instruments to achieve the following science objectives: characterise Ganymede and Europa as planetary objects and potential habitats, study Ganymede, Europa, Callisto and Io in the broader context of the system of Jovian moons, and focus on Jupiter science including the planet, its atmosphere and the magnetosphere as a coupled system. EJSM-Laplace would be the first dual spacecraft mission to Jupiter. It will address several key science themes of ESA's Cosmic Vision and high priority science goals of NASA's 2003-2013 Decadal Survey. The payload of the two spacecraft would be selected in the framework of two coordinated AOs planned to be released in 2011.This report, the so-called *Yellow Book*, contains the results of ESA's Assessment Study (Phase 0/A), including a description of the mission goals, science requirements, mission scenario, a brief description of the Model Payload, a summary of the three industrial studies of JGO, and the proposed management approach. The document was written by the Joint Science Definition Team and by both the ESA Study Team and the NASA pre-Project Team.

We are extremely grateful to have taken part in this exciting journey.

The EJSM-Laplace JSDT

Mission Description

Europa Jupiter System Mission (EJSM-Laplace)		
Key Science Goals	**The emergence of habitable worlds around gas giants** • Characterize Ganymede as a planetary object including its potential habitability • Explore Europa to investigate its habitability • Explore the Jupiter system as an archetype for gas giants	
Flight elements	**Jupiter Ganymede Orbiter (JGO)**	**Jupiter Europa Orbiter (JEO)**
Model Payload	***11 instruments total mass 104 kg*** • Narrow Angle Camera • Wide Angle Camera • Visible and IR Imaging Spectrometer • Ultraviolet Imaging Spectrometer • Submillimeter Wave Instrument • Laser Altimeter • Ice penetrating radar • Magnetometer • Particle and Plasma Instrument-Ion Neutral Mass Spectrometer • Radio and Plasma Wave instrument • Radio Science Instrument	***11 instruments, total mass 106 kg*** • Narrow Angle Camera • Wide- and Medium Angle Camera • Visible-Infrared Spectrometer • Ultraviolet Spectrometer • Thermal Instrument • Laser Altimeter • Ice Penetrating Radar • Magnetometer • Ion and Neutral Mass Spectrometer • Particle and Plasma Instrument • Radio Science Instrument.
Overall mission profile	2020: Launch by Ariane-5 ECA 2020-26: VEEGA-type cruise 03/2026- Jupiter Orbit Insertion 2026-28: Jovian tour, 9 Callisto flybys 2028-29: Ganymede orbital phase (elliptical & high circular: 200-10000 km & 5000 km Low circular: 500 and 200 km)	2020: Launch by Atlas-551 2020-2026: VEEGA-type cruise 02/2026: Jupiter Orbit Insertion 2026-28: Jovian tour with flybys of Io, Europa, Ganymede and Callisto 2028-29: Europa orbital phase (200 and 100 km circular)
Spacecraft	• 3-axis stabilized • Power:solar panels:636-693W(EOM) • HGA: 3.2 m, body fixed • X- and Ka bands • Downlink >1Gbit/day • Autonomous operations • High delta-V capability (2771 m/s) • Radiation level: 85 krad /10mm Al • Dry mass: ~1700 kg	• 3-axis stabilized • Power: MMRTG 540 W (EOM) • HGA: 4 m, articulated. • X- and Ka bands • Downlink >1Gbit/day • Autonomous operations • High delta-V capability • Radiation: 2.9 Mrad/ 2.5 mm Al • Dry mass: 1714 kg
Ground TM stations	ESA Deep Space Antenna	NASA DSN
Key mission drivers and technology challenges	• Radiation • Power budget • Propulsion	• Radiation and planetary protection • Propulsion
Proposed share of responsibilities	• ESA is responsible for manufacturing, launch and operations of JGO spacecraft • NASA is responsible for manufacturing, launch and operations of JEO spacecraft • Science payload funded by ESA Member States and NASA in the framework of coordinated AOs	

Authorship and acknowledgements

The EJSM-Laplace Joint Science Definition Team

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The ESA study was led by: Jean-Pierre Lebreton, ESA Study Scientist, Dima Titov, Study Scientist Support, Christian Erd, ESA Study Manager, Arno Wielders, ESA JGO Payload Study Manager, with the Support of ESA's planning and coordination office: Fabio Favata, Marcello Coradini, Philippe Escoubet, Ana Heras.

Support to the ESA study was provided by: M. Gehler, A. Boutonnet, J. Schoenmaekers, T. Voirin, J. Sorensen, G. Santin, P. Nieminen, P. Falkner.

The three industrial studies were conducted by Consortia led by: Astrium SAS, OHB and Thales Alenia Space/France.

The front page graphics by artist Mike Carroll.

Structure of the Yellow Book and table of content

Yellow Book is structured in such a way to guide a reader through all aspects of the proposed EJSM-Laplace mission from scientific themes and objectives to concrete measurements and results of industrial studies at different levels of details. In general the science part of the Yellow Book (sections 1-6) follows the structure of the Science Requirements Matrix (Table 1-1, [14]) that provides detailed traceability of the science objectives to the measurement requirements, techniques and model instruments.

Executive Summary gives general overview of the document. Section 2 describes the high level science themes of EJSM-Laplace and their relation to ESA Cosmic Vision programme and important implications for planetary physics and astrophysics. Section 3 focuses on the EJSM-Laplace investigation strategy and pays specific attention to the synergistic science provided by the dual-spacecraft investigations. Section 4 breaks the high-level science themes into concrete science objectives that will be addressed by the mission. Section 5 summarizes measurement techniques and general requirements to the mission needed to achieve EJSM-Laplace science goals and briefly describes the science scenario, mission phases and their science priorities. Section 6 presents the model payload suite designed to achieve the science goals formulated above. This instrument complement was used as representative payload for the industrial studies. The results of these studies, including mission analysis, spacecraft design, payload accommodation, mission resources and risks are summarized in section 7. Mission operations and organization of the ground segment are briefly outlined in section 8. Section 9 describes mission management approach and schedule.

Table of Content

1 Executive Summary

The discovery of four large moons orbiting around Jupiter by Galileo Galilei four hundred years ago spurred the Copernican Revolution and forever changed our view of the Solar System and universe. Today, Jupiter is seen as the archetype for giant planets in our Solar System as well as for the numerous giant planets known to orbit other stars. In many respects, and in all their complexities, one may say that Jupiter and its diverse satellites form a mini-Solar System. By investigating this system, and thereby unravelling the history of its evolution, from initial formation of the planet to the development of its satellite system, we will gain a general understanding of how gas giant planets and their satellite systems form and evolve and of how our Solar System works.

Science background. In 1995, the *Galileo* spacecraft arrived at Jupiter to conduct a follow-up exploration in the footsteps of the *Pioneer* and *Voyager* missions. *Galileo* made new discoveries in the Jovian system, especially concerning the four Galilean satellites, which were revealed as new worlds worthy of further in depth exploration. The *Galileo* discoveries included strong evidence of sub-surface oceans hidden underneath icy crusts within Europa, Ganymede and Callisto. *Galileo* also discovered an internal magnetic field at Ganymede, a unique feature for a satellite in the Solar System. Ganymede and Europa are believed to be internally active, due to a strong tidal interaction and other energy sources. They are straddled by Io and Callisto, and thus, the study of the diversity of the planetary environment represented by the four satellites should reveal the physical and chemical mechanisms driving the evolution of the Jovian system. The discovery of sub-surface oceans on these moons led to the emergence of a new habitability paradigm which considers the icy satellites as potential habitats. The upcoming *Juno* mission, due for launch in 2011, will focus on Jupiter's deep interior and inner magnetosphere and is not designed to address key science questions for the Galilean satellites and the integrated Jupiter system. If extrasolar planetary systems are analogous to our own, then icy satellites, having a sub-surface liquid water ocean, could be the most common habitats in the universe, probably much more abundant than Earth-like environments which require highly specialised conditions which permit surface oceans. By investigating the Jupiter system, and by unravelling the history of its evolution from initial formation to the emergence of possible habitable environments, insight will be gained into how giant planets and their satellite systems form and evolve and new light will be shed on the potential for emergence and existence of life in icy satellite oceans.

EJSM-Laplace science goals. *EJSM-Laplace* is aimed at a thorough investigation of the Jupiter system in all its complexity with emphasis on the four Galilean satellites, and in particular the potential habitability of the two icy worlds, Ganymede and Europa. The overarching theme for *EJSM-Laplace* is: ***The emergence of habitable worlds around gas giants***. Within our Solar System, we know of one body which has experienced the emergence of life; on Earth, living organisms have developed and proliferated. Humankind wonders whether the origin of life is unique to the Earth or if it occurs elsewhere; in our Solar System or beyond. To answer this question, even though the mechanisms by which life originated on Earth are not yet clearly understood, one can assume that the necessary conditions involve the simultaneous presence of organic compounds, trace elements, water, energy sources and a relative stability of the environment over time. *EJSM-Laplace* will address the question: Are there current habitats elsewhere in the Solar System with the necessary conditions (organic matter, water, energy, stability and nutrients) to sustain life? The spatial extent and evolution of habitable zones within the Solar System are critical elements in the development and sustainment of life, as well as in addressing the question of whether life developed on Earth alone or whether it was developed in other Solar System environments and was then imported to Earth. Addressing the question of habitability in the Jupiter system is an important link to astrobiology.

The focus of *EJSM-Laplace* is to characterise the conditions that may have led to the emergence of habitable environments among the Jovian icy satellites, with special emphasis on the internally active ocean-bearing worlds, Ganymede and Europa. In order to understand the Galilean satellites as a system, Ganymede and Europa are identified for detailed investigation since they provide a natural laboratory for comparative analysis of the nature, evolution and potential habitability of icy worlds in general. Investigating their habitability includes confirming the existence and determining the characteristics of a liquid-water ocean below the icy surfaces, understanding the possible sources and cycling of chemical and thermal energy, investigating the evolution and chemical composition of the surfaces and of the sub-surface oceans, and evaluating the processes that have affected the satellites and their environments through time. The diversity of the satellite system will be studied from additional information gathered at the other two Galilean satellites, Io and Callisto. The mission will also focus on characterising the diversity of processes in the Jupiter system which may be required in order to provide a stable environment at Ganymede and Europa on geologic time scales, including gravitational coupling between the Galilean satellites and their long term tidal evolution on the system as a whole. Focused studies of Jupiter's atmosphere (its structure, dynamics and composition), and magnetosphere (three-dimensional properties of the magnetodisc and coupling processes) and their interaction with the Galilean satellites will further our understanding of the evolution and dynamics of the Jovian system. The study of the Jupiter system and its habitability has deep implications for understanding extrasolar planets and planetary systems. By performing detailed investigations of Jupiter's system in all its complexity with particular emphasis on the potential habitability of Ganymede and Europa, *EJSM-Laplace* will address in depth two key questions of ESA's Cosmic Vision programme: (1) What are the conditions for planet formation and the emergence of life? and (2) How does the Solar System work?

EJSM-Laplace mission scenario. The *EJSM-Laplace* mission would consist of two sister spacecraft: the ESA-led Jupiter Ganymede Orbiter (JGO) and the NASA-led Jupiter Europa Orbiter (JEO). They would perform a joint, choreographed dance to explore the Jupiter system and study the processes that led to the diversity of its associated components and their interactions. *EJSM-Laplace*'s ESA-led JGO and NASA-led JEO have both unique and complementary science objectives, and will constitute the first dual-spacecraft mission designed to explore the Jupiter system, working in concert to radically advance our knowledge of the system and its relationship to the emergence of habitable worlds around gas giants. Both spacecraft are designed to fly independently and would achieve spectacular science focusing on their primary goals. JGO alone would clearly achieve Cosmic Vision class science. If they fly in concert, however, they will achieve significant additional science objectives, leading to ground breaking results that would not be obtained individually.

Both spacecraft are orbital flight systems using conventional bi-propellant propulsion systems carrying two highly capable scientific payloads of up to a dozen instruments on each. X and Ka-band downlink systems will allow significant downlink capability while in the Jupiter system as well as a satellite-to-satellite communication capability that will provide unique science observations opportunities. The basic design for the orbiters is very similar to that of previous large flight systems such as *Cassini, Mars Reconnaissance-Orbiter* and *Rosetta*. New technologies are not required to execute either current mission concept, although new developments are planned focusing on lower mass instruments for JGO and on radiation designs for JEO. Planned to be launched independently in early 2020, JGO and JEO would use chemical propulsion and Venus-Earth-Earth gravity assists to arrive at Jupiter 6 years later. Launch opportunities exist nearly every year, but the mass delivered and flight times will vary. Independent developments and launches create a very flexible implementation with multiple options for obtaining significant stand alone, complementary and synergistic science to meet the *EJSM-Laplace* science objectives. JGO's trajectory will remain outside of the inner radiation belts at Jupiter and has solar arrays for its power source, whereas for JEO radioisotope power is baselined. After insertion into Jupiter orbit, both flight systems will perform tours of the Jupiter system using gravity assists of the Galilean satellites to shape their trajectories, culminating in 9-month orbital phases at Ganymede for JGO and at Europa for JEO. Since the current mission-end scenarios involve the spacecraft impacting on Ganymede and Europa respectively, necessary planetary protection requirements will be fulfilled during the mission implementation.

EJSM-Laplace model payload. Each spacecraft would carry a highly capable state-of-the-art scientific payload consisting of up to a dozen instruments for remote sensing and *in situ* studies. Model payloads for both spacecraft were assembled by the Joint Science Definition Team (JSDT) as representative instruments that address the *EJSM/Laplace* science goals. For some science goals, alternative measurement techniques have been identified and may be proposed in the framework of the planned coordinated Announcements of Opportunity. JGO and JEO model remote sensing packages would include spectro-imaging capabilities from the ultraviolet to the near-infrared, wide angle and narrow angle cameras. The model geophysical package will include laser altimetry, radar sounding and the required radio science capabilities for probing the moons' surface and interior. In addition, the JEO model payload includes a thermal mapper, while JGO includes a sub-millimeter wave instrument. Model *in situ* packages include magnetometers, radio and plasma wave instruments including electric fields sensors and Langmuir probes as well as a particle and plasma package/ion and neutral mass spectrometer. A tremendous effort has been made by the JSDT to ensure that the combination of the different instruments from the two platforms, together with the coordination of two-spacecraft observations evolving together in the system at the same time, will provide the highest science return on the numerous objectives related to the study of the emergence of habitable worlds in the Jovian system (internal structure, geology, composition, and tenuous exospheres of the icy moons; composition and dynamics of the giant atmosphere, magnetospheres and plasma environment). *EJSM-Laplace* science objectives and investigations are summarized in Table 1-1 whilst the full version of the Science Traceability Matrix which indicates how the objectives will be achieved with the model payloads is in a separate document [15].

EJSM-Laplace industrial studies. The JGO element of the *EJSM-Laplace* mission was studied by three independent industrial contractors. The JGO design has very robust heritage in previous flight systems (flown or in development) such as *Rosetta*, *BepiColombo*, *Exomars/TGO* but also telecom satellites regarding radiation. The industrial studies have proven that the specified science goals are well within current European industrial and technological capabilities and can be achieved by JGO.

International co-operation. *EJSM-Laplace* is based on a strong ESA-NASA collaboration building on the *Laplace* proposal in response to ESA's Cosmic Vision call merged with two NASA Outer Planets Flagship mission studies, "*Europa Orbiter*" and "*Jupiter System Observer*". The mission will further develop the cooperative spirit within the Outer Planet science community forged by the successful *Cassini-Huygens* mission to the Saturn system and will consolidate scientific and engineering efforts across Europe, the US and beyond. The *EJSM-Laplace* mission concept is an open one which could be further enhanced by additional elements that would be developed by other international partners, such as Jupiter

Magnetospheric Orbiter (JAXA), a Europa Lander (RSA) and a Europa penetrator (ESA-UK study).

In summary. Following the successful implementation of the *Mars Express* and *Venus Express* missions to our neighbouring planets, the *Cassini-Huygens* tour of the Saturn-Titan system and the upcoming *BepiColombo* mission to Mercury and the *Rosetta* cometary rendezvous, a mission to the Jupiter system, which addresses a broad spectrum of fundamental questions in planetary science, is a natural and important step in European exploration of our Solar System. Addition of *EJSM-Laplace* to the ESA science programme would offer numerous opportunities for public outreach activities. *EJSM-Laplace* would build on scientific, technological and international collaboration heritage from previous similar ambitious space missions and will potentially pave the way for future extensive *in situ* endeavours to be conducted, targeting giant planets like Saturn, Uranus, Neptune and their moons, or even more distant objects, as in the Kuiper belt. More importantly, the *EJSM-Laplace* science return will expand our comprehension of the whole Solar System and point to profitable directions for future investigations of objects outside our neighbourhood.

Table 1-1 *Short version of the EJSM-Laplace Traceability Matrix.*

		Science objective	Science Investigation
Europa and Ganymede: investigating habitability	Ocean	Characterize the extent of the ocean and its relation to the deeper interior.	Determine the amplitude and phase of the gravitational tides.
			Ganymede: Characterize the space plasma environment to determine the magnetic induction response from the ocean. *Europa*: Determine the magnetic induction response from the ocean and characterize the influence of the space plasma environment on this response.
			Characterize surface motion over the tidal cycle.
			Determine the satellite's dynamical rotation state (forced libration, obliquity and nutation).
			Ganymede: Investigate the core and rocky mantle. *Europa*: Investigate the core, rocky mantle, rock-ocean interface, and compensation of the ice shell.
	Ice	Characterize the ice shell and - for Europa only - *any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.*	*Ganymede*: Characterize the structure of the icy shell including its properties and the distribution of any shallow subsurface water. *Europa:* Characterize the distribution of any shallow subsurface water and the structure of the icy shell including its subsurface properties.
			Search for an ice-ocean interface.
			Ganymede: Correlate surface features and subsurface structure to investigate near-surface and interior processes. *Europa*: Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.
			Europa only: Characterize regional and global heat flow variations.
	Composition	Determine global composition, distribution and evolution of surface materials, *especially as related to habitability* (for Europa only).	Characterize surface organic and inorganic chemistry, including abundances and distributions of materials with - for Europa only - *emphasis on indicators of habitability and potential biosignatures*.
			Ganymede: Relate compositions and properties and their distributions to geology. *Europa*: Relate material composition and distribution to geological processes, especially material exchange with the interior.
			Investigate surface composition and structure on open vs. closed field line regions.
			Determine volatile content to constrain satellite origin and evolution.
			Europa only: Characterize the nature of exogenic (e.g. Io) materials
	Geology	*Ganymede*: Understand the formation of surface features and search for past and present activity. *Europa*: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for potential future in situ exploration.	Determine the formation mechanisms and characteristics of magmatic, tectonic, and impact landforms.
			Europa only: Determine sites of most recent geological activity, and evaluate future potential landing sites.
			Constrain global and regional surface ages.
			Investigate processes of erosion and deposition and their effects on the physical properties of the surface.
	Local environment	Characterize the local environment and its interaction with the jovian magnetosphere.	*Ganymede only*: Globally characterize Ganymede's intrinsic and induced magnetic fields, with implications for the deep interior.
			Ganymede only: Characterize particle population within Ganymede's magnetosphere and its interaction with Jupiter's magnetosphere.
			Ganymede only: Investigate the generation of Ganymede's aurorae.
			Ganymede only: Determine the sources and sinks of the ionosphere and exosphere.
			Europa only: Characterize the composition, structure, dynamics and variability of the bound and escaping neutral atmosphere.
			Europa only: Characterize the composition, structure, dynamics and variability of the ionosphere and local (within the Hill sphere) charged particle population.

Goal	Theme	Science objective	Science Investigation
Explore the Jupiter system as an archetype for gas giants	Jovian atmosphere	Characterize the atmospheric dynamics and circulation.	Investigate the dynamics of Jupiter's weather layer.
			Determine the thermodynamics of atmospheric phenomena.
			Quantify the roles of wave propagation and atmospheric coupling.
			Investigate auroral structure and energy transport.
			Understand the interrelationships of the ionosphere and thermosphere.
		Characterize the atmospheric composition and chemistry.	Determine Jupiter's bulk elemental abundances.
			Measure the composition from the stratosphere to low thermosphere in three dimensions.
			Study localized and non-equilibrium composition.
			Determine the importance of moist convection in meteorology, cloud formation, and chemistry.
		Characterize the atmospheric vertical structure.	Determine the three-dimensional structure from Jupiter's upper troposphere to lower thermosphere.
			Explore Jupiter's interior density structure and dynamics below the upper troposphere.
			Study coupling across atmospheric layers.
	Jovian magnetosphere	Characterize the magnetosphere as a fast magnetic rotator.	Understand the structure and stress balance of Jupiter's magnetosphere.
			Investigate the plasma processes, sources, sinks, composition and transport (including transport of magnetic flux) in the magnetosphere and characterize their variability in space
			Characterize the large-scale coupling processes between the magnetosphere, ionosphere and thermosphere, including moons footprints.
			Characterize the magnetospheric response to solar wind variability and planetary rotation effects.
		Characterize the magnetosphere as a giant accelerator.	Detail the particle acceleration processes.
			Study the loss processes of charged energetic particles.
			Measure the time evolving electron synchrotron emissions.
		Understand the moons as sources and sinks of magnetospheric plasma.	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.
			Study the interactions between Jupiter's magnetosphere and Io, Europa, Ganymede, and Callisto.
			Study the interactions between Jupiter's magnetosphere and small satellites.
	Study the Jovian satellite and ring system	Study Io's active dynamic processes.	Investigate the nature, distribution and magnitude of tidal dissipation and heat loss on Io.
			Investigate Io's composition and active volcanism for insight into its origin, evolution and geological history (particularly of its silicate crust).
			Determine Io's dynamical rotation state (forced libration, obliquity and nutation).
			Investigate the interior of Io.
			Understand satellite origin and evolution by assessing sources and sinks of Io's crustal volatiles and atmosphere.
		Study Callisto as a witness of the early jovian system.	Investigate the interior of Callisto.
			Characterize the space plasma environment to determine the magnetic induction response from Callisto's ocean.
			Characterize the structure and properties of Callisto's icy shell.
			Constrain the tidally varying potential and shape of Callisto.
			Determine the Callisto's dynamical rotation state (forced libration, obliquity and nutation).
			Characterize surface organic and inorganic chemistry, including abundances and distributions of materials and volatile outgassing.
			Characterize the ionosphere and exosphere of Callisto.
			Relate material composition and distribution to geological and magnetospheric processes.
			Constrain global and regional surface ages.
			Determine the formation and characteristics of magmatic, tectonic, and impact landforms.
		Characterize the rings and small satellites.	Conduct a comprehensive survey of all the components of the Jovian ring-moon system.
			Identify the processes that define the origin and dynamics of the ring dust, source bodies, and small moons.
			Characterize the physical properties of the inner small moons, ring source bodies and dust.
			Remotely characterize the composition, properties and dynamical groupings of the outer, irregular moons.
			Perform disk-resolved and local characterization of one or more outer, irregular moons.

2 EJSM-Laplace Science Themes

The discovery of the Galilean moons has changed our understanding of the Jupiter system, our local Solar System, and beyond. Crucially, it has highlighted Jupiter as an archetype for gas giant planets. The detailed exploration of Jupiter's four diverse Galilean satellites (three of which are believed to harbour subsurface oceans), is therefore central to elucidating the habitability of icy worlds in general. By understanding the Jupiter system and unravelling its history from origin to the possible emergence of habitats, we augment our knowledge as to how gas giant planets and their satellites form and evolve.

The proposed EJSM-Laplace mission will perform synergistic and detailed two spacecraft investigations of Jupiter and its system in all their interrelations and complexity with particular emphasis on Ganymede and Europa, and their potential habitability. EJSM-Laplace will address in depth two of the four themes of ESA's Cosmic Vision programme:

- *Theme 1: What are the conditions for planet formation and the emergence of life?*
- *Theme 2: How does the Solar System work?*

The mission has been conceived to observe all main components of the Jupiter system and decode their complex interactions. Central to this system, the four Galilean satellites represent a diverse range of internal structures and varying local environments. EJSM-Laplace will consist of two spacecraft – the ESA-provided Jupiter-Ganymede Orbiter (JGO) and NASA's Jupiter-Europa Orbiter (JEO). They will investigate in detail two categories of Galilean satellites:

- *Ganymede and Callisto - dominantly icy bodies (JGO)*
- *Europa and Io - dominantly rocky bodies (JEO).*

In addition EJSM-Laplace will study Jupiter itself and its rapidly rotating magnetosphere, as well as investigating the coupling processes within the Jupiter system.

The main science objectives of JGO and JEO are described in detail in the following section but may be briefly summarized as follows. At Ganymede EJSM-Laplace would characterize the ocean layer and detect subsurface water reservoirs; study Ganymede's intrinsic magnetic field and magnetosphere; provide detailed topographical, geological and compositional mapping of Ganymede; study the physical properties of the icy crust; characterize the internal mass distribution, dynamics and evolution of Ganymede's interior; and investigate the generation and dynamics of both moons' exospheres.

For Europa, the focus will be to characterize the extent of the ocean and its relation to the deep interior; characterise the ice shell and any subsurface water, including heterogeneity; understand the nature of the surface-ice-ocean exchange; determine the global surface composition and chemistry; understand the formation of surface features leading to identification and characterisation of candidate sites for future *in situ* exploration.

For Jupiter's satellite system, temporal variations in Io's activity will be studied, and investigations of Callisto as a witness of the early Jovian system will be performed. The complex interactions between the Galilean moons and the Jovian magnetosphere will be investigated, as will gravitational coupling and long-term tidal evolution. Observations of the small satellites will include improved mass determination, ephemerides, surface composition definition, and potentially provide new detections.

At Jupiter, the study of the atmosphere will include an investigation of the 3-D properties of the thermal structure, dynamics and composition of the different layers, along with coupling processes within the atmosphere. The focus in Jupiter's magnetosphere will include an investigation of the 3-D properties of the magnetodisc, and in depth study of the coupling processes between the magnetosphere, ionosphere and thermosphere. Planetary auroral and radio emissions, and their response to the solar wind conditions, will be elucidated. An understanding of the various coupling processes between the different components which make up the Jupiter system will allow its evolution and development to be studied. Environmental investigations by EJSM-Laplace will shed new light on the potential for habitability in our galactic neighbourhood and beyond. Thus, the overarching theme for EJSM-Laplace is ***the emergence of habitable worlds around gas giants***.

2.1 Emergence of Habitable Worlds Around Gas Giants

2.1.1 Habitability in the Universe

Habitability is commonly understood as "the potential of an environment (past or present) to support life of any kind." (Steele et al., 2005) The concept does not relate to whether life actually exists or has existed, but to whether environmental conditions are available that could support life. Although habitability is thus decoupled to some extent from the existence of life, to be meaningful it still needs an understanding of what life is. An entirely satisfying definition of life does not yet exist and may be difficult to derive (Cleland and Chyba, 2007). It includes properties such as consuming nutrients and producing waste, the ability to reproduce and grow, pass on genetic information, evolve via Darwinian evolution, and adapt to the varying conditions on a planet (Sagan, 1970). In recent years it has been suggested that life increases the entropy production rate of a planet (e.g., Kleidon and Lorenz, 2005).

Terrestrial life as we know it requires liquid water. In its simplest form, habitability (e.g., Kasting et al., 1993) thus requires the stability of liquid water on a planet or moon. Water is an abundant compound in our galaxy, and is found in many places, from cold dense molecular clouds to the innermost layers of hot circumstellar envelopes (e.g., Cernicharo and Crovisier 2005). However, life will probably never spontaneously originate and evolve in bodies of pure water because life also requires the supply of biogenic elements (C, H, O, N, P, S) to drive biochemical reactions. Habitability therefore rests on the fulfillment of four conditions (Figure 2-1): water, elements, energy, and time. Depending on the spectral type of the star, planetary orbital distance, and the related efficiency of atmospheric loss processes, liquid water bodies can be rapidly frozen. The essential question is then if the liquid water can exist for sufficient periods of time to be biologically useful.

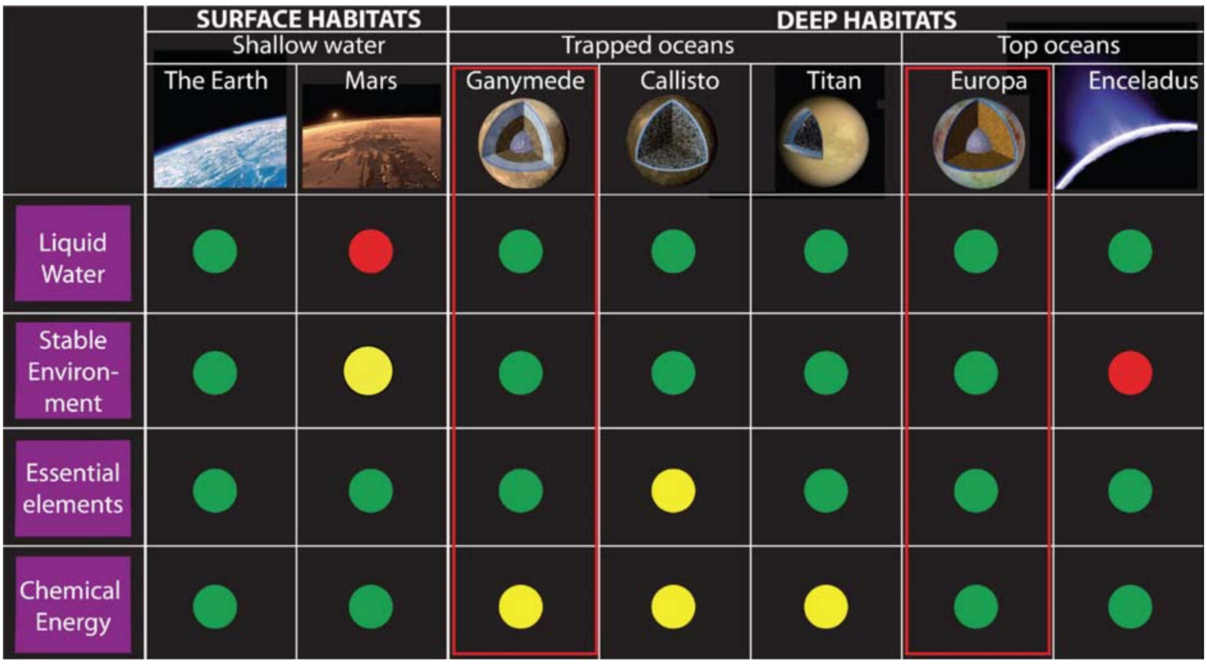


__Figure 2-1.__ Present state of the existing and past habitable worlds in the solar system. For each planet or moon, the status of the four pre-requisites for life to be sustained is ranked from red (not possible), to yellow (likely but not yet demonstrated) and to green (demonstrated or very likely).

2.1.2 Emergence of Habitable Worlds Around Gas Giants

The Galilean satellites provide a conceptual basis within which new theories for understanding habitability can be constructed. Measurements from the *Voyager* and *Galileo* spacecraft revealed the potential of these satellites in this context, and EJSM-Laplace will greatly enhance our knowledge of habitability, particularly through the synergistic science made possible by JGO and JEO. The EJSM-Laplace strategy of studying the Jovian system as a whole therefore provides a framework within which conditions for habitability in the Universe will be constrained. The discovery of liquid water on Europa would also have large implications not only on our understanding of the habitability in the Solar System but also on the astrobiological potential of small icy worlds since we will be able to set constraints on the possibility for the emergence of life on such bodies.

Large satellites of gas giants at orbits beyond the ice-line, such as Jupiter or Saturn, contain a large amount of water. In fact, given that the average density of the icy satellites is ~1.8 g cm^{-3}, the larger moons can be assumed to be composed of almost 45% of water. Thus, icy layers are very thick, ~600 km for Ganymede, Callisto, and Titan. For Callisto, *Galileo* data indicate that it is probably not fully differentiated, implying a thicker ice layer but one which is mixed with silicates.

It is known, even at Earth where life mostly depends on solar energy that habitats exist deep in the oceans in eternal darkness feeding on geothermal energy. If liquid layers exist below ice layers and these water-reservoirs are in contact with heat sources from the interior of the planet, life may have originated within such subsurface habitats despite the hostile surface conditions. Indeed, it is likely that Europa represents the only example of such a habitat in the solar system, besides Earth.

Liquid water reservoirs have been proposed on Europa, Ganymede and Callisto from geophysical models, based on Galileo observations. Where oceans are covered by ice shells, as is probably the case for the icy satellites of Jupiter (Schubert et al., 2004) which are located well outside the conventional habitable zone of the Sun, liquid water may exist almost independent of the input of stellar energy. Here, tidal dissipation and radiogenic energy keep the water liquid (e.g., Spohn and Schubert, 2003; Hussmann et al., 2006). Considering the pressure range encountered within the icy moons, four different scenarios can be defined. These result from varying thicknesses of the water ice layers and the liquid ocean with respect to the silicate floor (*Figure 2-2*). Case 2 in *Figure 2-2* is highly probable for the largest moons (Ganymede and Callisto), while case 3 is more probable for Europa and smaller icy moons if they host liquid reservoirs such as Enceladus (Blanc et al. 2009). This is because Europa possesses a thinner icy layer (80-180 km) (Anderson et al., 1998), since the amount of water present is estimated to be ~10%. Europa's ocean is especially interesting for habitability because it may be in contact with the rock layer. This substrate may be geologically active and affected by hydrothermal processes, similar to the terrestrial sea floor, which is a biologically rich environment (Kargel et al. 2000). This could enhance habitability conditions because the rock layer could release elements and energy sources to the surrounding water ocean. Differentiation of the rock could be responsible for the presence of salts and other essential elements in the ocean, and produce the low albedo terrains seen on the surface.

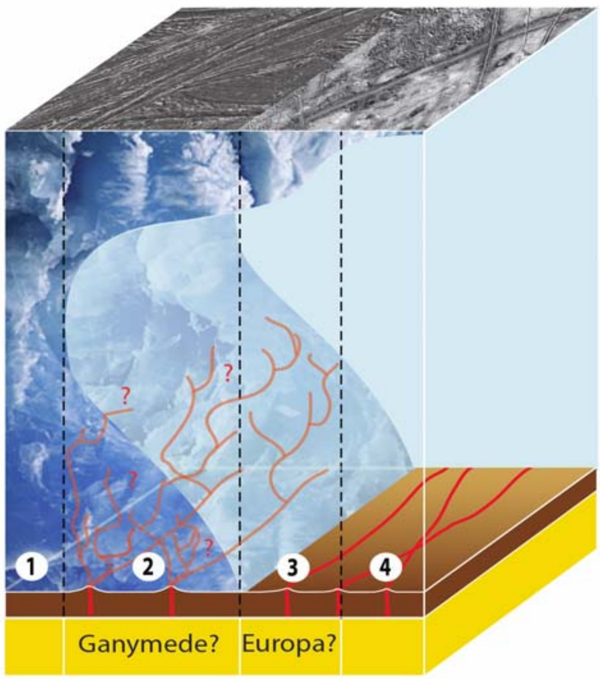


Figure 2-2. *Possible locations of liquid layers in the icy moons of Jupiter are shown here as a function of depth: 1) completely frozen; 2) three-layered structures impeding any contact between the liquid layer and the silicate floor; 3) thick upper icy layer (>10 km) and a deep ocean; 4) very thin upper icy layer (3-4 km). Cases 3 and 4 are the most probable for Europa, and cases 1 and 2 for Ganymede and Callisto.*

On the larger icy moons Ganymede and Callisto, where internal pressures are sufficient to allow for the formation of high pressure ice phases, the existence of an ocean suggests that it could be enclosed between thick ice layers. Chemical and energy exchanges between the rocky layer and the ocean, which are so important for habitability, cannot be ruled out but would imply efficient transport processes through the thick high pressure icy layer. Such processes are indeed possible (Sohl et al, 2010) but not as straightforward as the exchanges which can be envisaged for Europa. This provides an interesting difference compared to the Europan example, the implications of which must be understood.

On Ganymede and Europa, endogenous materials may rise to the surface through fractures and cryomagmatic processes, thereby revealing properties of the deep aqueous environment for remote observation. Volatiles, organics and minerals solidified from the aqueous cryomagmas, could be detected remotely from an orbiting spacecraft. Analysis of these materials will give great insight to the physico-chemistry and composition of the deep environments.

Icy and liquid layers are probably not solely constituted of pure H_2O. It is likely that salty materials such as salt hydrates are trapped within Europa (Kargel et al., 2000). Many other compounds such as CO_2 (Europa, Ganymede and Callisto), or CH_4 (Titan) have been observed on surfaces and may emerge from the deep interiors of the moons. NH_3 is also suspected to exist on Titan (Nelson et al., 2009). The role of organic material is vital to the potential habitability of the body. The fundamental biochemistry required is based on carbon compounds: amino acids, nucleotide bases, sugars, alcohols, and fatty acids. C, H, O, N, P, S are the chemical building blocks of life, but other elements such as Na, Mg, K, Ca, Fe are also major components (Wackett et al., 2004).

Such organic matter and other surface compounds will experience a different radiation environment at Europa than at Ganymede (due to the difference in radial distance from Jupiter) and thus may suffer different alteration processes, influencing their detection on the surface. Deep aqueous environments are protected by the icy crusts from the strong radiation that dominates the surfaces of icy satellites. Because radiation is more intense closer to Jupiter, at Europa's surface, radiation is a handicap for habitability, and it produces alteration of the materials once they are exposed (Delitsky and Lane, 2007, 2008). The effect of radiation on the stability of surface organics and minerals at Europa is poorly understood. Therefore, EJSM-Laplace instrumentation should target the environmental properties of the younger terrains where materials could have preserved their original characteristics. Measurements from terrains on both Europa and Ganymede will allow a comparison of different radiation doses and terrain ages from similar materials. The positive side of radiation is the generation of oxidants that may raise the potential for habitability and exobiology. Surface oxidants could be diffused into the interior, and provide another type of chemical energy (Hand et al., 2007).

EJSM-Laplace will therefore address key areas that emerge in the study of habitable worlds around gas giants including the ***determination of the volume of liquid water*** in the Jovian system. The mission will also establish the inventory of biologically-essential elements on the surfaces of the Galilean moons, and determine the magnitude of transport of biologically essential elements among the moons which exchange material as a result of volcanism, sputtering, and impacts. The mission may help to infer important properties such as the pH, salinity, and water activity of the oceans and investigate the effects of radiation on the detectability of surface organics.

2.2 The Jupiter System as an Archetype for Gas Giants

EJSM-Laplace will perform a comprehensive study of how the Jupiter system works, including in depth studies of the Galilean moons with particular focus on Ganymede and Europa, the planet itself, and its vast rotating magnetosphere. Understanding the complex interplay of the individual elements will allow a more complete picture to emerge of the Jupiter system acting as an exemplar for gas giant planets in the wider Universe.

2.2.1 Jupiter System Components

The Jupiter system is the largest coupled planetary system within our solar system, and has been previously referred to as a "mini solar system" in its own right. Within this huge system exists a multitude of diverse objects, which can be divided into multiple "sub-systems":

- Jupiter the planet, with its diverse range of atmospheric phenomena from the deep interior, through the dynamic weather layer (and its giant storms, belt/zone contrasts and temporal variability) to the stratosphere, upper atmosphere and its coupling to the immediate planetary environment.
- A huge satellite system including 55 outer irregular small satellites (1 to 100 km class objects), the four large Galilean satellites, Io, Europa, Ganymede, and Callisto (1000 km class objects), the four inner satellites Metis, Adrastea, Amalthea and Thebe (10-100 km class objects), and by extension the Jovian ring system located in the inner regions.
- The tenuous atmospheres of the Galilean satellites, generation mechanisms, variations, and interactions with the surrounding local environment.
- Jupiter's giant magnetosphere, the largest in the solar system, within which all other objects are imbedded including two unique components, Io which is the main source of material and Ganymede with its mini-magnetosphere embedded within Jupiter's.

To understand this complex system in its entirety, we first need to understand the physical characteristics of each of the individual aspects, then how they are coupled and continuously interact, and finally how the system as a whole works under the effect of multiple interconnected processes.

2.2.2 Jupiter System Coupling Processes.

The entire system is intricately linked through gravitational and electromagnetic interactions, and atmospheric and interior coupling processes. Jupiter itself interacts in a variety of important ways with the other system components. Tidal interactions between Jupiter and the three satellites trapped in the Laplace resonance, Io, Europa and Ganymede, redistribute momentum and energy among the four objects. Not only are they responsible for Io's spectacular volcanic activity, but they also likely play a key role in maintaining a subsurface ocean close to the surface of Europa on geological timescales.

The strong intrinsic magnetic field of Jupiter, generated by internal dynamo action, extends to considerable distances beyond the planet's "surface", forming the largest magnetosphere in the Solar System whose fields and particles continuously interact with all the satellites. Jupiter's conducting upper atmosphere is strongly coupled to the rapidly rotating planetary magnetic field lines which extend from their anchor points in the upper atmosphere into the magnetosphere. Due to satellite related mass-loading in the equatorial magnetosphere and subsequent sub-corotation of the magnetospheric field and plasma, a drag force is created in the upper atmosphere, at the feet of the field lines in the ionosphere, due to ion-neutral collisions. Subsequently, an electromagnetic torque is communicated back along magnetic field lines to the magnetosphere attempting to keep it in corotation with the planet. This current system, together with the associated intense particle precipitation, is an important source of momentum and heat for the upper atmosphere.

A diversity of processes then couple Jupiter's field and plasma environment to its satellites: driven by planetary rotation, the fast rotating magnetic field lines sweep by all satellites, forming individual interactions in each case. The electrically conducting sub-surface oceans at the Galilean satellites interact with the rotating magnetic field of Jupiter to produce induced field signatures, providing vital information on their characteristics. Active volcanoes on the moon Io interact with the surrounding magnetosphere producing the Io plasma torus, which follows the orbit of Io, providing the dominant plasma source for the entire magnetospheric system. The electromagnetic effect of the comet-like addition of plasma mass into the system is felt both locally and globally throughout the system. Through a series of poorly understood acceleration, heating and transport processes, this Iogenic plasma generates the diversity of populations of the Jovian particle environment. This field and particle environment in turn interacts with the surfaces of the Galilean moons in a variety of ways depending on the shielding (or otherwise) of particles from the surfaces through the differing electromagnetic interactions. As mentioned previously, the intrinsic magnetic field of Ganymede couples with the surrounding Jovian magnetosphere to form a magnetosphere in miniature within the

Jovian system. Finally, several processes directly couple Jupiter's upper atmosphere to its satellites and magnetosphere: unipolar induction of the satellites moving through magnetic field lines generate localized electric current loops extending from the satellites and closing through Jupiter's upper atmosphere (Figure 2-3).

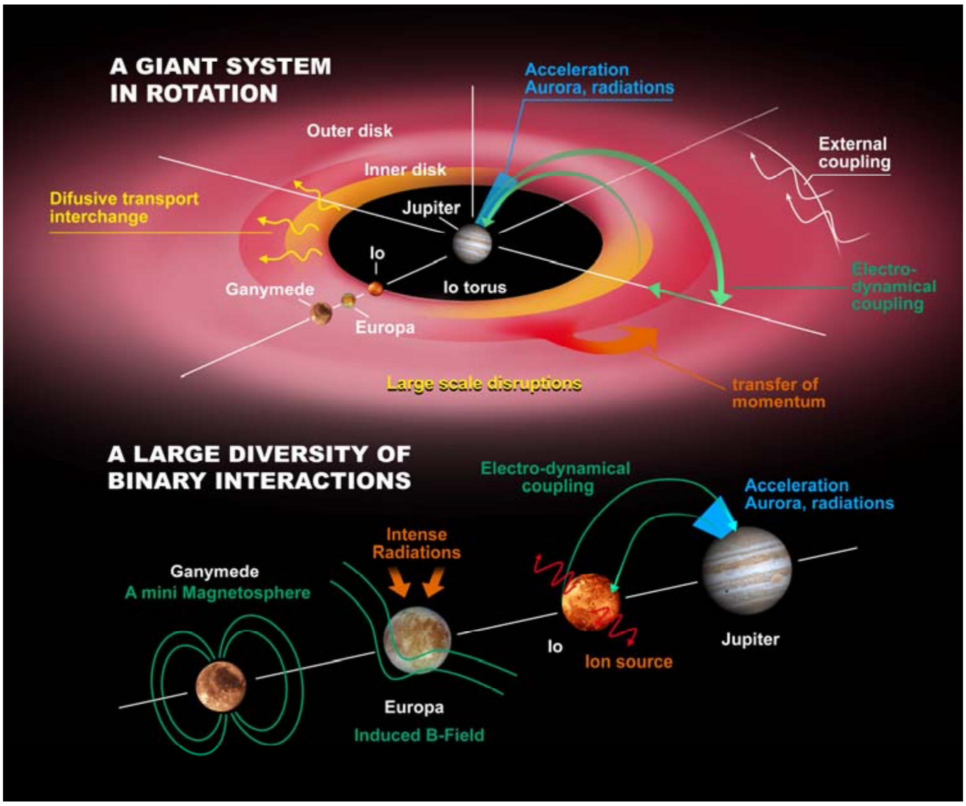


Figure 2-3. *Electrodynamic interactions play a variety of roles in the Jupiter system: generation of plasma at the Io torus, magnetosphere / satellite interactions, dynamics of a giant plasma disc coupled to Jupiter's rotation by the auroral current system, generation of Jupiter's intense radiation belts.*

2.2.3 Origin and Formation

The limited information available on the formation of giant planets argues in favour of the nucleated instability scenario (Lunine et al., 2004). In such a scenario, giant planets should form a solid core of the order of 10 Earth masses, through accretion of the primordial icy planetesimals of the outer solar system that would act as the accretion centre for the gas of the Solar Nebula. The limited lifetime of the Solar Nebula, which has been constrained to about 10 Ma through astronomical observations of circumstellar disks around near-by stars (Meyer et al., 2006), poses a strict constraint to the formation time of the planetary core and the accumulation of the gas. Accretion of gas and solid material into Jupiter's envelope actually works through the formation of a sub-nebular disk, and it is within this sub-nebular disk that formation of regular satellites by accretion of solids is believed to take place. Their further differentiation, should then be completed before the complete decay of ^{26}Al, which is the energy source for this differentiation, namely in a time between 2.5-5 Ma. As for the origin of the irregular satellites, they are presently believed to be captured objects from the population of primordial icy planetesimals. If that is so, they are key witnesses of the population of objects present at the orbit of Jupiter in the late phases of its formation, and may have a direct connection to the Trojan asteroids.

EJSM-Laplace will develop a combination of observation techniques to untangle the mystery of the formation of the Jupiter system.

The relationship between the formation of the Galilean satellites and that of Jupiter would be investigated via measurements of the abundances of the stable isotopes of C, H, O and N and of noble gases in the ices of these satellites, and via the determination of their internal structure. Complementary analysis of the cratering record on the surfaces of regular satellites would provide information on the ages of these surfaces and on the reality and characteristics of the Late Heavy Bombardment (Gomes et al. 2005; Tsiganis et al. 2005), one of the landmark events in the evolution of the early Solar System. Finally, by investigating the composition of the small regular satellites and, should the possibility presents, the irregular satellites, EJSM-Laplace will improve our knowledge of their formation processes and of the planetesimals which contributed to the formation of the Jovian system (see e.g. Coradini et al. 2010).

2.3 ESA's Cosmic Vision Connections

The study of the Jupiter system and its habitability has deep implications for improving our understanding of extrasolar planets and planetary systems. Jupiter is a template, accessible in the Solar System, for the many gas giants now discovered around other stars. The question of their formation, dynamics, and evolution, and of the habitability of their satellites can presently only be addressed through the example of Jupiter, hence determining the habitability there holds universal consequences.

For these reasons, EJSM-Laplace will address in depth two of the four themes of ESA's Cosmic Vision programme:

Theme 1: What are the conditions for planet formation and the emergence of life?

Within this theme EJSM-Laplace will address Cosmic Vision sub-theme ***1.3 Life and habitability in the Solar System*** by exploring the surface and sub-surface of Europa, Ganymede and Callisto including their subsurface water oceans and their environment in the Jupiter system. Comparisons of three very different objects will provide new light on conditions for habitability in the outer solar system, and around gas giants in the Universe.

EJSM-Laplace will address sub-theme ***1.1 From gas and dust to stars and planets*** by studying the composition of Jupiter and its satellites, which are essential to understand the origin of the system and its relation to other regions of planet formation in our galaxy. From the analysis of the cratering record on the satellites' surfaces, it will provide constraints on the surface ages, and the period of the "late heavy bombardment"of the early solar system (Gomes et al., 2005). It will contribute also to sub-theme ***1.2 From exoplanets to biomarkers*** by studying Jupiter and its potentially habitable satellite system as an analogue to Jupiter-like planets and their as yet undetected satellite systems around other stars.

Theme 2: How does the Solar System work?

EJSM-Laplace will perform a detailed and comprehensive study of the Jupiter system. In doing so, it will greatly contribute to a much improved understanding of how the Solar System works from two perspectives: 1) the Jupiter system may be regarded as "mini solar system" with a comparable degree of complexity, and 2) Jupiter itself is a key element in the solar system with a major impact on the dynamics and evolution of the Solar System and its different planets.

Within this theme EJSM-Laplace will address the Cosmic Vision sub-theme ***2.1 From the Sun to the edge of the Solar System*** by studying the plasma and magnetic field environment in the Jovian system (as a mini solar system) as well as the magnetosphere of Ganymede. The radiation environment and its implications for habitability in particular will be investigated at Europa and Ganymede. It will also address sub-theme ***2.2 The Giant planets and their environments*** by studying 1) the atmosphere of Jupiter, 2) the interiors, oceans and icy crusts of Europa, Ganymede and Callisto, and 3) the diversity of the other satellites, and how all these objects interact with the Jovian magnetosphere. EJSM-Laplace will study the complex coupling processes in the Jovian environment that are key to understanding the evolution of the satellites.

2.4 *Implications for Astrophysics and Planetary Physics*

2.4.1 Extrasolar Planetary Systems

Over the coming two decades, transit experiments, both space-based (e.g. CoRoT, Kepler) and ground-based (e.g. M-Earth, SuperWasp), combined with radial velocity follow-up observations, will allow us to detect planets of terrestrial sizes and masses around all kinds of cool stars, and provide measurements of their radii and masses. Detailed analysis of the transit shapes, or transit timing techniques, will also allow us to look for signatures of satellites around these planets. At the time of the EJSM-Laplace mission, this exploratory work should have resulted in a solid statistical knowledge of Jupiter-like exosystems. Among the detected exoplanetary systems, we may find a significant number of Jupiter-like objects, i.e. giant gaseous planets with a set of satellites whose individual sizes are comparable to the size of Earth-like planets, i/e/ either rocky or water-rich bodies similar to the terrestrial planets and icy moons of our solar system.

Exoplanet detection missions may thus identify a significant number of systems similar to that of Jupiter, both in terms of planet and satellite distribution, and in terms of the physical conditions prevailing. Also, space- and ground-based transit experiments will give us the opportunity to study in great detail transiting planets in the habitable zone of cool K and M dwarfs, for which planetary orbital periods in the habitable zone are just a few days. In these favourable cases, characterisation of the atmospheres of giant planets in close-in orbit is already possible, via on-off transit transmission or emission spectroscopy (e.g. Tinetti et al. 2010; Swain et al. 2010). Again, this will place the study of the Jovian atmosphere by EJSM-Laplace in a much broader context.

The detailed study of the Jupiter system provided by EJSM-Laplace will therefore be placed in a much broader perspective, and conclusions of EJSM-Laplace about habitability will be transposable on a more global, cosmic, scale.

2.4.2 Plasma Universe

The majority of matter within the visible Universe (including our own Solar System) exists in the plasma state. Thus, most astrophysical phenomena are controlled by a small number of fundamental processes that arise as the result of charged particle populations interacting with large-scale electromagnetic fields. A variety of processes with vastly different temporal and spatial scales may be coupled together, mediated by the effects of the magnetic field. Therefore, understanding the physics of "space plasmas" requires a combined effort of theoretical models and observations, with the latter providing a solid basis for us to take significant steps forward. *In situ* observations in different environments characterised by very different spatial and temporal scales, such as those in the magnetospheres of Mercury, Earth, Jupiter, Ganymede, and Saturn are required in order to make comparisons and thus deepen our understanding of the fundamental processes operating in the Plasma Universe.

Aurora seen in the skies of the polar regions of Earth indicate that the plasma filling the magnetosphere surrounding the planet is highly dynamic, just like the solar atmosphere that we see in the images taken in UV or X-ray wavelengths by a solar observing spacecraft. Whilst we cannot yet visit other stars or astrophysical environments, planetary magnetospheres provide unique laboratories in which to acquire *in situ* spacecracft observations of plasma processes creating such phenomena. *In-situ* data provide far more detailed information which is necessary for us to truly understand how the charged particles behave under the influence of the electromagnetic field. It is even possible to perform multi-point observations and see how the magnetospheric plasma behaves in time and space. One of the most important lessons we are learning is that, in space plasmas, processes at vastly different scales couple to produce fascinating effects such as explosive magnetic energy release or high-energy particle acceleration.

Of course, the Earth's magnetosphere is the most straightforward location to explore such possibilities, as formation-flying multi-scale terrestrial missions (e.g. Cluster) are more readily achievable. The Jovian magnetosphere is an important place to explore as it has the largest spatial scale among Solar

System objects. The Jupiter system bridges the gap between planetary plasma physics and astro-plasma physics. This large-scale system, sustained by the strong magnetic field of the planet, is the strongest particle accelerator in the solar system. A substantial fraction of the driving energy is tapped from the planet's fast rotation, coupled to the giant rotating circum-planetary magnetised disc. This mechanism gives insight to the way astrophysical magnetised discs work in general, an area which EJSM-Laplace will explore. Another attractive aspect of the Jovian magnetosphere which directly connects to astrophysics is the diversity of magnetised binary interactions between Jupiter and its moons. Io and Europa offer non-magnetised obstacles to the magnetospheric flow, and eject neutral particles into the surrounding magnetosphere where they are ionised and picked-up by the rotating plasma flow and magnetic field. This process adds significant plasma mass to the magnetosphere, and triggers an interchange motion that disperses the newly added component. Ganymede has its own internally driven magnetic field and interacts with the magnetospheric plasma forming a magnetosphere within a magnetosphere. These binary moon-magnetosphere interactions are recorded in the three auroral "spots" in Jupiter's atmosphere located at the magnetically mapped footprints of the moons. Through these binary interactions of the Jovian magnetosphere, EJSM-Laplace will explore the broad diversity of interactions of this kind in general terms, including the study of satellite obstacles in the Jovian magnetospheric flow with varying degrees of magnetisation, and a variety of Mach number conditions. This has important consequences on our understanding of the diversity of such binary interactions in the Universe, in particular in relation to exoplanetary systems.

Finally, one of the most spectacular results of magneto-plasma interactions everywhere in the Universe is the generation of intense non-thermal radio emissions. Jupiter is actually the most intense radio source in our sky, and produces a unique diversity of types of emissions, representative of the complexity of its internal and external interaction processes. By studying the Jovian radio emissions in detail close-by, and by crossing directly some of its source regions, EJSM-Laplace will build on the results of previous missions to Jupiter to lead to a comprehensive description of magnetospheric radio emissions and how they can be distinguished from stellar emissions. This will be a key element in our capacity to recognize planetary signatures in radio emissions from distant stars, and will contribute to giant exoplanets search and detection.

2.4.3 Planetary Atmospheres

The diversity of planetary atmospheres in our Solar System can be understood in terms of the different environmental conditions affecting their meteorology, bulk composition, cloud microphysics, complex chemistry and evolution. Atmospheric science has made significant advances in unraveling the mechanisms responsible for the bewildering range of atmospheric configurations arising from these initial conditions. By studying the plethora of planetary atmospheres - from the giant planets and their moons to rocky planets - we are able to put the complexity of Earth's own atmosphere into a larger context. EJSM-Laplace's exploration of Jupiter and its collection of icy satellites will provide access to a broad range of atmospheric processes, from large-scale atmospheric organization of jet streams, moist convection, storms, plumes, vortices, and lightning to sputtering and other processes maintaining the tenuous satellite exospheres.

Jupiter's atmosphere serves as a paradigm for atmospheric dynamics and chemistry on giant planets, both in our Solar System and beyond. Jupiter is often viewed as the best laboratory for studying fundamental fluid dynamics with its weather layer of alternating zonal jets, long-lived giant anticyclonic vortices and vertical and horizontal wave activity on a variety of scales. Several mysteries remain unresolved: How deep does the zonal motion penetrate – are zonal jets a weather-layer phenomenon, or a manifestation of deeper internal processes? What is the importance of moist convection in determining the transport of energy and material between different levels? What causes vertical and horizontal wave activity, and how do waves govern vertical stratification and energy transfer? What is the balance between solar radiation input and internal energy that governs the existence of belts, zones, eddies and vortices, and what maintains each of these features against dissipation? How does Jupiter's polar atmosphere, the apex of the planet-wide circulation, differ from the rest of the planet? And what cyclic global processes are responsible for 'upheavals' of the belt/zone structure and the variability of Jupiter's appearance?

The advanced instrumentation, broad wavelength coverage, long temporal baseline and synergistic capabilities of JGO and JEO will permit the most extensive study of gas giant dynamics and chemistry ever performed. The product will be a four-dimensional database of Jupiter's climate to inform circulation modeling and permit predictions of variability and allow us to study the mechanisms driving atmospheric variability on giant planets.

Finally, Jupiter's atmospheric composition can be compared to that on other planets in our Solar System to reveal how planetary atmospheres evolve. Indeed, the complement of heavy elements in the giant planets is thought to increase with radial distance from the Sun, a signature of the primordial planetary nebula from which the planets formed. As a constraint on the formational history of our Solar System, chemical studies of planetary atmospheres provides a window onto the past and helps us to understand the expanding range of planetary systems around other stars.

3 EJSM-Laplace Strategy

3.1 The EJSM-Laplace "formula"

The EJSM-Laplace mission would provide a thorough investigation of the Jupiter system in all its complexity with emphasis on the Galilean satellites, and their potential habitability. EJSM-Laplace has been tailored to observe all the main components of the Jupiter system and untangle their complex interactions. Central to this system, the four Galilean satellites span a broad range of possible internal structures, from pure silicate/metal bodies (Io) to dominantly icy ones (Callisto). They can be divided into two pairs, two dominantly rocky ones (Io and Europa), and two dominantly icy ones (Ganymede and Callisto). In order to place Europa and Ganymede, two of the three ocean-bearing moons, in the right context, and to fully understand the Galilean satellites as a system, our observation strategy with EJSM-Laplace can be described in three steps:

- Conduct an in-depth comparative study of these two pairs (Europa-Io and Ganymede-Callisto), with a special focus on the two ocean-bearing bodies, Europa and Ganymede, which JEO and JGO, respectively, will fully characterize. Then, extend our study to the whole satellite system (including Io, Callisto, small satellites and rings);
- Study the planet Jupiter and its giant, rotating magnetosphere;
- Study coupling processes inside the Jupiter system, with emphasis on the two key coupling processes within that system: gravitational coupling, which ties together Jupiter and its satellite system, and electrodynamic interactions which couple Jupiter and its satellites to its atmosphere, magnetosphere and magnetodisc.

3.2 EJSM-Laplace Investigation Strategy

The mission is built around two orbiters that are designed to operate independently first in orbit around Jupiter, and then in orbit around either Ganymede (JGO) or Europa (JEO). It will fully exploit the capability offered by two spacecraft operating simultaneously in the Jupiter system, including using an inter-spacecraft communication link to perform unique scientific investigations of the various elements of the Jupiter system, thus providing otherwise unattainable coverage of Jupiter's atmosphere, ionosphere and rings, and the Galilean moon environments. The two orbiters are nominally planned to be independently launched in early 2020. Both spacecraft would use a 6-year Venus-Earth-Earth gravity assist trajectory. On approach to Jupiter, long term monitoring of Jupiter's atmosphere and magnetospheric processes and dynamics using the powerful remote sensing capability of both platforms will be performed. In addition, we will take full advantage of the staggered arrival of the two spacecraft to undertake synergistic observations of the solar wind interaction with the coupled magnetosphere-ionosphere system, one spacecraft measuring the solar wind while the other investigates the magnetosphere. Following orbit insertion multi-year tours of the Jovian system are planned including: synergistic and complementary science from both spacecraft with multiple flybys each of Ganymede, Europa, Callisto, and Io, as well as dedicated orbital phases around Ganymede and Europa; continuous magnetosphere observations; regular monitoring of Jupiter's and Io's atmospheres; and observations of the Jupiter ring system. The current mission trajectory illustrates the opportunity for specific geometries, but should only be considered as an example trajectory which will eventually be designed during the implementation phase.

The model payload for the mission includes: from wide to narrow angle cameras; visible-infrared imaging spectrometers; ice penetrating radars; ultra-violet imaging spectrometers; sub-mm wave instrument; laser altimeters; magnetometers; plasma and particle instruments, ion-neutral mass spectrometers; radio and plasma wave instrument; radio science instruments; and a thermal instrument. Similar elements of the EJSM-Laplace model payload are carried by both spacecraft in order to ensure a thorough investigation of the individual moons targeted by each spacecraft, whereas some specific instruments are unique to each element to enhance the whole system science return. A minimum data volume of 1 Gbit/day is expected from each spacecraft.

3.3 Complementary and Synergistic Two Platform Science

The dual-platform architecture of EJSM-Laplace is an outstanding base for a comprehensive observation of the Jupiter system and its components, with emphasis on the two Galilean satellites Europa and Ganymede. The design of the two-spacecraft EJSM-Laplace mission enhances and emphasises each spacecrafts' contribution – ***providing complementary science return***. In addition, with two spacecraft working together in the complex coupled system EJSM-Laplace will produce results otherwise not obtainable from the individual spacecraft – ***providing synergistic science return***.

While JEO is tailored for an in-depth close orbital study of Europa, it will also perform several close fly-by observations of Io, as well as of the other Galilean satellites. JEO will therefore cover the two inner satellites, and the innermost part of the Jupiter magnetosphere and radiation belts. In a complementary way, JGO is tailored for an in-depth orbital study of Ganymede. It will also conduct a detailed study of Callisto, the outermost Galilean satellite, during a series of quasi-resonant orbits offering multiple encounters with this satellite. As such, JGO will cover the two outermost Galilean satellites, and the middle magnetosphere within which they are imbedded. This complementary mission design provides the basis for detailed comparisons between Ganymede and Europa, and between the four Galilean satellites in general. The staggered arrival of the two spacecraft into the system provides a prolonged temporal coverage of the satellites, the planet itself, and the magnetosphere which allows a clearer picture of the variation of the individual elements of the system with time. In addition, the complementary trajectories of JGO and JEO will enhance the coverage of the magnetosphere (for example with local time, radius, and time) and the atmosphere (in longitude, latitude and time) which allows a clearer understanding of the structure and dynamics of both. For both JGO and JEO, the orbital phases around Ganymede and Europa, respectively, will be the final phases of their mission. During the preceding phases – i) approach to Jupiter, ii) Jupiter orbit insertion, and (iii) the long duration Jovian orbit phase, both JGO and JEO will navigate inside the Jupiter system, providing observations of the planet and its system as well optimising the coverage by the individual platforms. As such the ***complementary*** EJSM-Laplace mission coverage would be maximized.

Simultaneous coordinated ***synergistic*** observations from two locations within the Jupiter system will also significantly enhance the overall science return with respect to both mission elements (JGO and JEO) considered individually. The final details of these synergistic opportunities will of course depend upon the mission profiles and instrument complement of the respective spacecraft. The joint timeline of the two spacecraft would be optimised to offer the maximum number of such opportunities, combining remote observations with in situ measurements, or observations of the same target from two viewpoints, at different angles, wavelengths, and resolutions (see Figure 3-1). Here we address the possibilities for such complementary and synergistic science possibilities in terms of satellite science, magnetospheric processes, and the Jovian atmosphere and local environment.

3.3.1 Satellite Science

The two EJSM-Laplace spacecraft will perform their individual orbit phases of Ganymede and Europa towards the end of the mission, as described above. In addition, the spacecraft will perform individual flybys of Io (JEO only), Ganymede, and Callisto to enhance the overall coverage of the Galilean satellites. The specific details of the synergistic opportunities possible for satellite science using both spacecraft can be outlined as follows:

- Satellite mapping, surface and atmosphere properties
- Active processes
- Internal structure of the moons

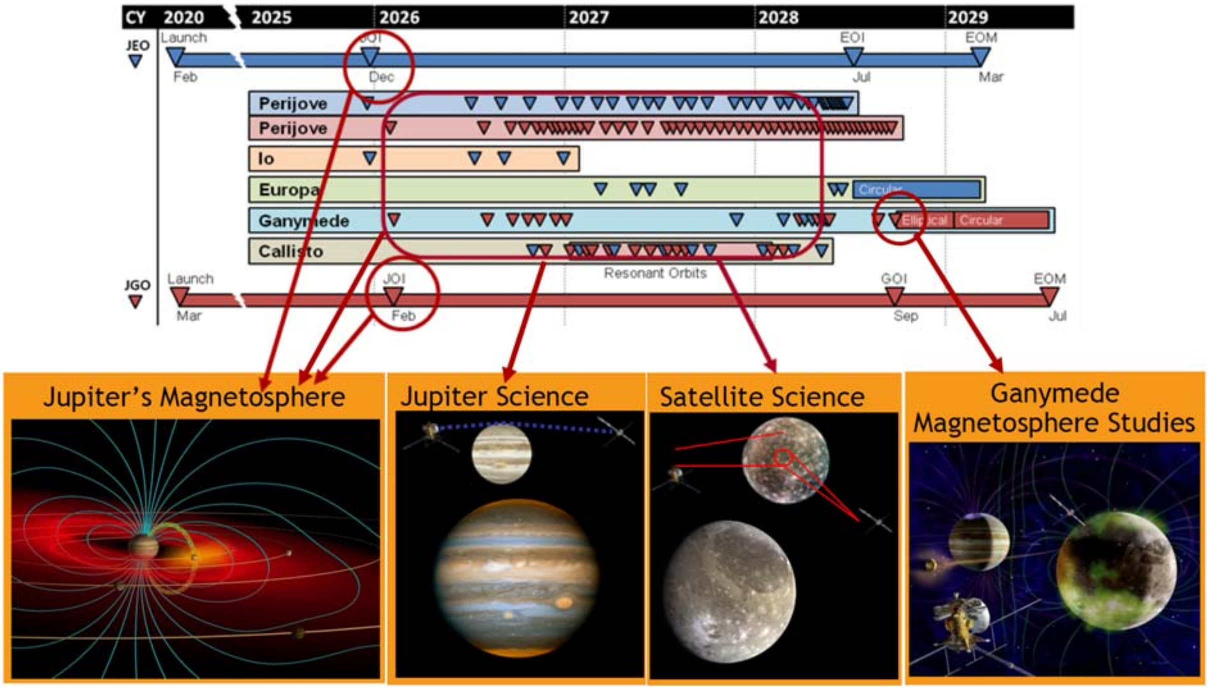


__Figure 3-1.__ Timeline of the EJSM-Laplace mission with JGO and JEO phases and events shown in red and blue respectively. Examples of synergistic science opportunities are illustrated in the bottom.

<u>*Satellite mapping, surface and atmosphere properties.*</u> The ability to obtain global maps of the icy moons would be greatly enhanced by the presence of two spacecraft performing separated tours of the Jovian system. This is especially true in the case of Callisto. Each spacecraft will have limited viewing geometries at various times in the tour. However, when the spacecraft data are taken in combination, high and moderate resolution observing opportunities are uniformly spread across the moon. The combined dataset provides nearly uniform coverage, which would only be achieved by both spacecraft working together.

The combined JEO and JGO suite of instruments would enhance the spatial and spectral coverage of atmospheric measurements. Synergistic measurements from the two spacecraft would allow for simultaneous observations in different wavelengths regimes, providing unprecedented spectral coverage of the atmospheres. In addition, full spatial coverage would likely not be achieved from isolated flybys. Observations using two spacecraft would enable much greater coverage to understand atmospheric asymmetries.

<u>*Active processes.*</u> Several satellite processes in the Jovian system are highly active. Deployment of two spacecraft in the system simultaneously would enable rapid follow-up on discoveries by one spacecraft with observations by the second spacecraft. This backup support would allow for longer observations of the event, but also for complementary observations with an additional set of instruments.

The trajectories of the two spacecraft would provide the opportunity for JGO to obtain distant observations of Europa and Io. Io is an ever-changing world. The overall duration of EJSM-Laplace would allow for increased temporal coverage in monitoring this active moon. JGO would improve the temporal resolution and spatial coverage for monitoring Io volcanism remotely. In particular, stereo imaging of plumes may be possible, and would provide a valuable constraint on plume dynamics. Outbursts on Io would also be monitored by both spacecraft for increased coverage. Finally, simultaneous imaging in eclipse from the two spacecraft could provide unique information on the 3-D plasma interaction.

Ganymede's auroral emissions vary spatially and temporally. Shared observations of this unique phenomenon, with simultaneous observations of the magnetically mapped auroral footprints in Jupiter's atmosphere, would probe both the atmospheric, magnetic, and Jovian magnetosphere interaction characteristics of the moon.

The presence of two spacecraft in the system would allow the unprecedented opportunity for dual spacecraft radio occultations of satellite ionospheres, to infer atmospheric conditions and study plasma interactions at a wide range of local times. Radio occultations involving the Earth are, in contrast, restricted to local times near dawn and dusk, thus limiting study of the diurnal variability of the satellite atmospheres.

Internal structure of the moons. It is not possible for a single spacecraft to investigate the deep structure of the three giant icy moons in great detail, simply because it would not have the opportunity to make close flybys of each moon. This does not, however, mean that three spacecraft are required. If flown in a coordinated fashion, the two spacecraft proposed for EJSM-Laplace can achieve this goal. As well as thoroughly investigating the two moons around which they will orbit, the proposed routes of the two spacecraft through the Jovian system will also provide good constraints on Callisto. Investigation of the internal structure of Callisto will be significantly strengthened by the presence of multiple spacecraft, because it will allow for a better determination of gravity fields by Doppler tracking of flybys. Two spacecraft could improve coverage by distributing closest approach positions more widely over the satellite and by altering the geometry of flybys, depending on the geometries of the spacecraft. This would help to break degeneracies in the inversion process, potentially allowing the determination of gravity coefficients at degrees larger than 2.

On Ganymede and Europa, phase coverage on induced magnetic field measurements could be significantly increased by multiple spacecraft encountering the satellite at different phases of Jupiter's magnetic field, potentially allowing the determination of the induced response at multiple periods. This additional information would be very valuable for understanding of the ocean characteristics. In addition, JEO flybys of Ganymede during JGO orbit would aid in assessing the interaction of the Jovian magnetospheric field with the intrinsic Ganymede field.

Finally, two spacecraft in the system provides the potential for extremely accurate spacecraft-to-spacecraft positioning by single beam interferometry, which would significantly improve satellite ephemerides. Nonetheless, such a technique would require significant antenna resources on the ground.

3.3.2 Magnetospheric Processes

The Jovian magnetosphere as revealed through previous single-point spacecraft measurements is a complex, coupled, 3-D and time dependent system. As this is also the case for magnetospheres in general, it is therefore a commonly accepted fact in the field of magnetospheric physics that single point measurements will never allow a full understanding of the system to be achieved. For example, with single point measurements it is not possible to distinguish between temporal and spatial variations (or gradients) in the magnetosphere. The solar wind interaction with the Jovian magnetosphere varies over time associated with changes in the solar wind velocity, density, and interplanetary magnetic field strength and orientation during a solar rotation. These variations alter the shape, structure, and size of the magnetosphere. In addition to this external effect, the moons in orbit around Jupiter provide a variable input of mass from their internal sources, i.e. the volcanic eruptions on Io filling the Io torus and the magnetosphere with plasma mass, and mass-loading near Europa from surface/plasma interactions. Jupiter's magnetic dipole tilt of ~10° with respect to the rotation axis also provides a varying interaction of the Jovian magnetosphere with the Galilean moons orbiting in the rotational equatorial plane. These effects in combination produce multiple time-scales with which the magnetospheric system is varying. In addition, magnetospheric spatial gradients exist in the plasma density, the thickness, and the electric current density which flows within the magnetodisc which physically dominates the middle magnetosphere. These spatial gradients occur in local time (azimuth) and radial distance from Jupiter.

In order to understand these complex temporal and spatial variations, more than one spacecraft is required. The presence of two spacecraft making simultaneous measurements in the Jovian magnetosphere will significantly enhance our understanding of the complex processes described above. Precise details would depend upon the final mission configuration, but there are a wealth of opportunities for synergistic science from JGO and JEO which can be outlined as follows:

- Solar wind driven magnetospheric dynamics
- Magnetospheric dynamics at Jupiter and Ganymede
- Local and global views of the magnetosphere and moons

Solar wind driven magnetospheric dynamics. As outlined above, with respect to the magnetosphere, there is a great advantage and significantly enhanced science return if two observations are made of the system simultaneously. There are a number of opportunities where this can be achieved in the Jovian magnetosphere, which will improve our knowledge of the coupled system. The first opportunity for EJSM-Laplace will arise when JGO is approaching Jupiter during interplanetary cruise and JEO has already achieved orbit insertion and is measuring the Jovian magnetosphere. Simultaneous observations of the Jovian system at this time will help to investigate how the solar wind directly affects Jupiter's magnetosphere, a topic of much debate over the last few decades. For example, a major solar disturbance such as a corotating interaction region (CIR) or a coronal mass ejection (CME) passing the Jovian magnetosphere will affect the boundary locations (bow shock and magnetopause), plasma flows, electric currents within the magnetosphere, producing enhanced radio and auroral emissions. Such solar disturbances are common (few per solar rotation) at the orbit of Jupiter and hence the chance of capturing such an event during the JGO approach phase is high. Therefore, JGO and JEO have an excellent synergistic opportunity to reveal the complex nature of the solar wind-magnetosphere interaction.

Magnetospheric dynamics at Jupiter and Ganymede. In addition to the solar wind-magnetosphere interaction, the presence of two spacecraft in the Jovian system would enhance observations of the dynamic coupling between the different magnetospheric regions (e.g. particle injections, reconnection processes) and would provide a clearer understanding of system periodicities which are present in these phenomena. Simultaneous two-point monitoring of reconnection processes in the magnetotail, but separated in magnetic local time, would provide important constraints on the global (or otherwise) nature of the reconnection processes present, the configuration of the X-line (i.e. the location of the reconnection across the system), and to what extent reconnection is driven externally or internally. During the phase when JGO is monitoring the middle magnetosphere and JEO is within the inner magnetosphere, it would be possible to study in detail the processes which transport plasma in the system. Simultaneous measurements in parallel from different locations in local time and/or radial distance from Jupiter would enable synergistic studies of particle drifts, diffusion processes, interchange motion, flux tube interchange, or acceleration processes during magnetospheric reconfiguration events.

An important synergistic opportunity arises when JGO is in orbit around Ganymede, during the elliptical and circular phases of the mission, and JEO is orbiting Jupiter sampling the magnetosphere in the vicinity via targeted flybys of Ganymede. Such a scenario would allow simultaneous internal and external observations of Ganymede's magnetosphere (e.g. morphology of the boundaries, convection and reconnections processes) and would enable the response of the Ganymede magnetosphere to upstream Jovian conditions to be elucidated. Such studies would also allow an understanding of the generation of the Ganymede aurora, and potentially simultaneous observations of the magnetically mapped auroral footprint of Ganymede (and the variability thereof) in the atmosphere of Jupiter.

Local and global views of the magnetosphere and moons. The local view of the magnetosphere in the vicinity of the moons (Ganymede, Europa, and Callisto, and Io) is obtained through the study of plasma transport between the moon itself and the magnetosphere while both spacecraft make flybys or are in orbit their respective targets. The global view of the Jovian magnetosphere is obtained through observations of the magnetodisc dynamics and large-scale transport while both spacecraft measure the magnetosphere during their Jupiter orbit phases. To obtain a synergistic view of the both the local and global views of the magnetospheres would involve, for example, remote sensing of auroral emissions in combination with in situ field and particle measurements. The method is twofold: simultaneous observations of the Jovian aurora would be made remotely while the two spacecraft would measure either the in situ satellite local environments (producing the auroral footprint emissions), or the magnetodisc (producing the main auroral oval).

Two spacecraft in the Jovian system would also be able to perform observations of the Io and Europa tori through in situ particle and field measurements (from JEO) while JGO would remotely sense perturbations and variations in the system. Finally, the ability to observe radio emissions from the Jovian system (with JGO) would allow EJSM-Laplace to have a global view of the electromagnetic environment of Jupiter, giving a radio perspective of the aurora, ionospheric currents, the magnetic field, the moon auroral footprints, torus emissions, Ganymede's magnetosphere, and the internal conducting layers of Europa and Ganymede.

3.3.3 Jupiter's Atmosphere and Local Environment

As stated above, the two-spacecraft mission architecture of EJSM-Laplace offers the unique opportunity to enable a spacecraft-to-spacecraft radio link. This will be particularly beneficial to Jovian atmospheric science. Overall the two-spacecraft EJSM-Laplace mission permits both synergistic and complementary atmospheric studies in three major areas:

- Radio science occultations from spacecraft to spacecraft
- Dual spacecraft views of atmospheric features, in addition to imaging from two vantage points
- Enhanced flexibility and expanded science instrumentation and wavelength coverage

Radio science occultations from spacecraft to spacecraft. The temperature, pressure, and density structure of the neutral atmosphere, the abundance of microwave absorbing gases, as well as the energetic electron distribution of the ionosphere, are typically probed by Earth-based monitoring the attenuation and frequency changes of a spacecraft signal as it passes behind the limb of a planet. For the outer planets, this means that spacecraft-to-Earth occultations only sample the dawn and dusk terminators, and only a narrow range of local times has ever been sampled. Although the neutral atmosphere is not expected to respond quickly to these local changes in insolation, the charged ionosphere may exhibit significant variability as a function of local time. EJSM-Laplace offers the unique capability for spacecraft-to-spacecraft occultations, permitting sampling of the full range of local times on Jupiter for the first time, from orbital geometries that are unique to EJSM-Laplace. Furthermore, the presence of two spacecraft performing earth and spacecraft occultations vastly increases the number of possible occultations in the 2+ year nominal tours of JGO and JEO. The frequent sampling of the same latitude at regular intervals will reveal the temporal variability of the atmospheric structure from the deep troposphere to the thermosphere. In particular, the presence of vertically propagating waves that evolve with time are thought to dominate energy and momentum transport between different vertical layers, and the extent of this vertical coupling is a key goal for EJSM-Laplace's study of Jovian dynamics and circulation. Note that JGO-Earth occultations occur only in the southern hemisphere, clustered at low and high latitudes. JEO-Earth occultations cover low to mid-southern latitudes. JEO-JGO occultations cover nearly the entire range of latitudes on the planet and offer significant northern hemisphere coverage.

In addition, the much shorter spacecraft-to-spacecraft distance compared with spacecraft-to Earth distance results in significant increase in the measurement signal-to-noise ratio (SNR). The increase varies from about one to three orders of magnitude, depending on the distance between the two spacecraft, with commensurate enhancement in measurement sensitivity and dynamic range. The on-board capabilities required in order to enable the spacecraft-to-spacecraft occultations (RF receivers) also enable comparable increase in measuring the SNR of "uplink" Earth occultations. These are occultations conducted using transmission from the Earth (of RF power up to 20kW from one of many Deep Space Network stations) and reception on-board the spacecraft.

Dual spacecraft views of atmospheric features, in addition to imaging from two vantage points. Ground-based observations and typical spacecraft missions provide a single view, or snapshot, of an atmospheric feature. But to fully understand the dynamics and vertical structure of the atmosphere we must study the evolution with time over many wavelengths, and if possible, viewing angles. Thus, we usually have to rely on the cloud particles observed at different times to act as true tracers of the flow, and on the intrinsic nature of the particles themselves (their reflectivity, size and shape), to turn two-dimensional data into a four-dimensional understanding. There are two distinct regimes of study under this category that can benefit from two spacecraft: atmospheric structure modeling and dynamical tracking. For the first, it is typically necessary to observe the same cloud features as they appear at different emission angles. However, the clouds are ever morphing into new configurations; coalescing, diffusing, and changing in the zonal wind shear. During the time elapsed between required multiple viewing geometries one cannot assume static atmospheric structure. In addition, structure modeling is dependent on *a priori* assumptions about cloud geometry and particle properties, and without enough data, some parameters are not uniquely retrieved. EJSM-Laplace offers a unique opportunity whereby two spacecraft can simultaneously view the same atmospheric feature from vastly different viewing geometries. For example, both narrow angle observations (e.g., looking in detail at the turbulence associated with a storm or plume) and contextual imaging can occur simultaneously, and such observations allow us to study the coupling between events over large horizontal distances. Ideally, with an identical instrument, or at least well cross-calibrated instruments, on each spacecraft, the same feature can be viewed in a sort of stereo, where one can produce a nadir view and the other at high emission angle. This will lend extra leverage, and therefore, accuracy, to vertical cloud retrievals.

For dynamical studies, cloud motions are usually tracked either "intensely" with several time steps over 30 minutes to a few hours, or with separations of one Jovian rotation to allow a longer time base for motion to become apparent. However, features evolve on timescales of minutes to days, showing divergence or convergence related to vertical motions, large-scale rotation, and lateral motions independent of the zonal flow field. With two spacecraft, a cloud feature, such as a convective thunderstorm or vortex, can be observed much more thoroughly on short timescales and continuously tracked for much longer periods to better measure three-dimensional flow. This is particularly true if we take Jupiter's ten-hour rotation into account: from a single spacecraft, a feature could only be tracked for a brief 5 hour period, with a 5 hour wait before it can be reacquired. On the other hand, the added flexibility of two orbiting platforms will allow regular wind and compositional measurements to extend over much longer periods.

Enhanced flexibility and expanded science instrumentation and wavelength coverage. The presence of two spacecraft permits multi-angle and multi-frequency observations of Jupiter's global circulation. Over the course of the mission, the two spacecraft will work together to sample the full phase angle coverage for scattering of Jovian clouds and hazes. By sampling the full phase curve (rather than the low phase angles that can be observed from Earth), we may break degeneracy in cloud structure retrievals to extract information on optical properties, such as scattering, particle shapes and sizes, optical depth and, ultimately, the composition of the Jovian clouds and hazes, which remain largely a mystery. If different instruments on a single spacecraft are unable to operate together, then the presence of similar instruments on the second spacecraft will provide added coverage. For example, visible imaging from one platform will be complemented by thermal and compositional mapping from the second. As the troposphere and middle atmosphere (stratosphere, mesosphere) are expected to act as tightly coupled systems, the simultaneous study of both regimes will greatly increase the potential science return relative to either dataset in isolation. Another example is the detection of lightning activity by one, simultaneously monitored by remote sensing instruments on the other. Finally, the interaction of the Jovian atmosphere with the immediate planetary environment can also be studied if magnetospheric and plasma instruments on one spacecraft observe phenomena in the magnetodisc that have direct manifestations on the upper atmosphere (e.g. auroral emissions) being studied by the second spacecraft.

Finally, JGO and JEO synergies can also be found where the two spacecraft are dissimilar. The Jovian tour geometries are different for the two spacecraft (a product of the flybys necessary to reach their satellite targets), with JGO providing more opportunities for long-range continuous monitoring than

JEO. By having both elements working together, we add considerable flexibility to the mission design while still meeting Jupiter science objectives. Furthermore, JGO and JEO will ultimately contribute different instruments to the mission (e.g., sub-mm instrumentation on JGO; thermal infrared instrumentation on JEO), which will work together to study Jupiter simultaneously across a broad wavelength range (from the radio to the UV) with a range of spatial and spectral resolutions.

3.4 The EJSM-Laplace Heritage and Legacy

EJSM-Laplace builds on the outstanding heritage of many past and current space missions to the outer planets, including Pioneer, Voyager, Ulysses, Galileo, Cassini-Huygens, and New Horizon fly-bys. At Jupiter the first multi-year orbital exploration by the NASA Galileo mission made many new discoveries despite its rather severe measurement capability limits, providing the first comprehensive description of its components. As a result, Galileo discoveries have driven the identification of the next generation of key scientific questions. Many of them relate to our quest for a better understanding of the Jupiter system as a whole; its components and their interactions, their origin, formation, evolution, and, ultimately, their habitability. Similar key outstanding science questions are resulting at the Saturn system from the NASA-ESA-ASI Cassini-Huygens mission. These two missions clearly demonstrate the requirement for orbiting spacecraft at the gas giant systems, in order to globally monitor and resolve spatial and temporal variations. Addressing such outstanding questions beyond these missions now requires a new generation of spacecraft tailored to focus on key scientific questions by utilizing an increased instrument capability, novel observation strategies, and synergistic science from two spacecraft.

The first mission of this new generation will be NASA's Juno mission, to be launched in 2011. Juno uses a specific mission profile to focus on a sub-set of the outstanding questions: for example Juno will investigate and partly untangle the question of the origin of Jupiter, its internal structure, the composition and dynamics of its atmosphere, as well as its polar magnetosphere and aurora. Using a near-polar, highly eccentric orbit with a perijove at 5000 km above Jupiter's cloud tops, Juno will measure the low-altitude polar and magnetic fields, probe atmospheric composition to retrieve the abundance of oxygen and other heavy species, and monitor the dynamics of the polar upper atmosphere and its coupling to the polar magnetosphere. Juno will neither focus on the low-altitude regions of the Jupiter system, where all regular satellites reside, nor investigate the Galilean satellites.

EJSM-Laplace is then the next logical step in our in-depth exploration of the geophysical and environmental characteristics of two of the major Galilean satellites, Ganymede and Europa and partial exploration of Callisto and Io, and would provide an in-depth understanding of Jupiter's atmosphere and magnetosphere. It would focus on Europa and Ganymede by flying the first orbiters around these objects, while also studying the whole system during their first mission phases in interplanetary space, and in Jovian orbit. In a way that is perfectly complementary to Juno, EJSM-Laplace would study the Jupiter system as a whole; focusing on the low latitude regions where the regular satellites and most of the magnetospheric plasma populations reside. EJSM-Laplace would revolutionise our understanding of the complexities of the Jupiter system, and prepare the ground for future in-situ exploration of the surfaces of the Galilean moons. This mission would make a significant step in characterizing the archetype gas giant of our solar system, and provide a cosmic connection to exoplanet systems. As such, the science return from EJSM-Laplace will be a major step forward in improving our perception of astrophysical objects in general.

EJSM-Laplace would build on and consolidate the extremely productive collaborations among the international planetary community, of which the most recent example is the highly successful Cassini-Huygens mission at Saturn and Titan. In this way it will lay the foundations for the next phases of outer planetary system exploration by continuing to forge an international outer planetary community.

4 Scientific Objectives

The Jovian system exemplifies the typical structure of outer planet systems. Besides the giant planet itself and its huge magnetosphere, it consists of (1) four small inner satellites (Metis, Adrastea, Amalthea, and Thebe), that are located in the equatorial plane of Jupiter inside Io's orbit, (2) a ring system, (3) four large satellites –the Galilean Satellites (Io, Europa, Ganymede, and Callisto), and (4) a group of numerous outer irregular satellites (currently 55 known). In addition, coupling processes arise in the system, especially the gravitation coupling between the Galilean satellites, and the interaction of the Galilean Moons with the Jovian magnetosphere.

This section describes the current state of knowledge, open questions and the goals of the EJSM-Laplace mission. Ganymede and Europa, the two primary targets of the mission, are identified for detailed investigation since they provide a natural laboratory for comparative analysis of the nature, evolution and potential habitability of icy worlds. The diversity of the satellite system will be studied via additional focus on the other two Galilean satellites, Io and Callisto, and eventually at the smaller moons. Broader studies of Jupiter's atmosphere and magnetosphere will complete the investigation of the Jovian system.

4.1 Exploration of the Habitable Zone: Europa and Ganymede

The main objective of EJSM-Laplace is the detailed investigation of Europa and Ganymede as planetary objects and possible habitats in the Jupiter system

4.1.1 Sub-surface oceans, icy crusts, and interiors

Overview: the oceans below the icy crusts

Voyager and *Galileo* data indicate that Europa and Ganymede possess important prerequisites to be considered habitable. *Galileo*'s detection of induced magnetic fields (Kivelson 2000; 2002) combined with imaged surface characteristics (Pappalardo, 1999) and thermal modeling of the moons' evolution (Spohn and Schubert, 2003), advocate the presence of liquid water oceans below the icy crusts of Europa and Ganymede. However, the depth and composition of the oceans, as well as the dynamics and exchanges between the oceans and the deep interiors or the upper ice shells, remain unclear. Furthermore, it is unknown whether liquid water reservoirs or compositional boundaries exist in the shallow subsurface ice and how the dynamics of the outermost ice shell is related to geologic features and surface composition. By investigating (i) the deep interior, (ii) the ice shells' shallow subsurface regions, and (iii) the icy surface characteristics, EJSM-Laplace will provide a broad understanding of the present state and evolution of the hydrospheres of Europa and Ganymede. ***Assessing the habitability of Europa's and Ganymede's subsurface oceans is a major goal of EJSM-Laplace.***

Science objectives

Oceans. Electrical currents in the oceans that contain salts –and hence provide excellent electrical conductors– can generate secondary magnetic fields in response to the external rotating Jovian magnetic field. Those induced fields were detected by the *Galileo* spacecraft at Europa, Ganymede and Callisto and provide strong evidence for present-day subsurface oceans (Kivelson et al., 2000,2002). ***Measurements by EJSM-Laplace at multiple frequencies will further constrain the electrical conductivity of the oceans and the depth at which the induced fields are generated.***

Furthermore, the tidal response of the satellites' icy shells strongly depends on the presence of oceans. The amplitudes of periodic surface deformation on Europa are in a range of 60 m in case of an ocean, and less than a meter if Europa is lacking an ocean. Albeit smaller, the equivalent numbers at Ganymede of 7 to 8 m (ocean) and a few tens of cm (no ocean) are still significant and could be measured (e.g. Moore and Schubert 2000,2003). Along with the tidal surface displacements, there is a time variability of the gravitational potential of the satellite because of the formation of the tidal bulge. ***Both surface displacements and variations of the gravitational potential will be measured by JEO and JGO when in orbit around Europa and Ganymede, respectively.***

The Galilean moons are locked in a stable 1:1 spin-orbit coupling. However, slight periodic variations in the rotation rate (physical librations) and the amplitudes associated with these librations can provide further evidence for subsurface oceans. ***EJSM-Laplace will measure precisely the rotation rates, pole-positions, obliquities, and libration amplitudes of Europa and Ganymede.*** This will further constrain the dynamical history of the satellites, e.g., de-spinning, resonance capture, or constraints on non-synchronous rotation of the icy shells, besides yielding information on the subsurface oceans and deeper interior.

EJSM-Laplace will be able to unambiguously detect oceans on Europa and Ganymede. By combining various independent techniques, EJSM-Laplace will furthermore characterize the extent of the oceans and the main physico-chemical properties (electrical conductivity, salinity etc.). Main objectives will be to measure the induced magnetic signal at multiple frequencies, the tidal variations (time-varying amplitudes and time-varying potential), the libration amplitudes and to search for liquid water in the subsurface (**Figure*****).***

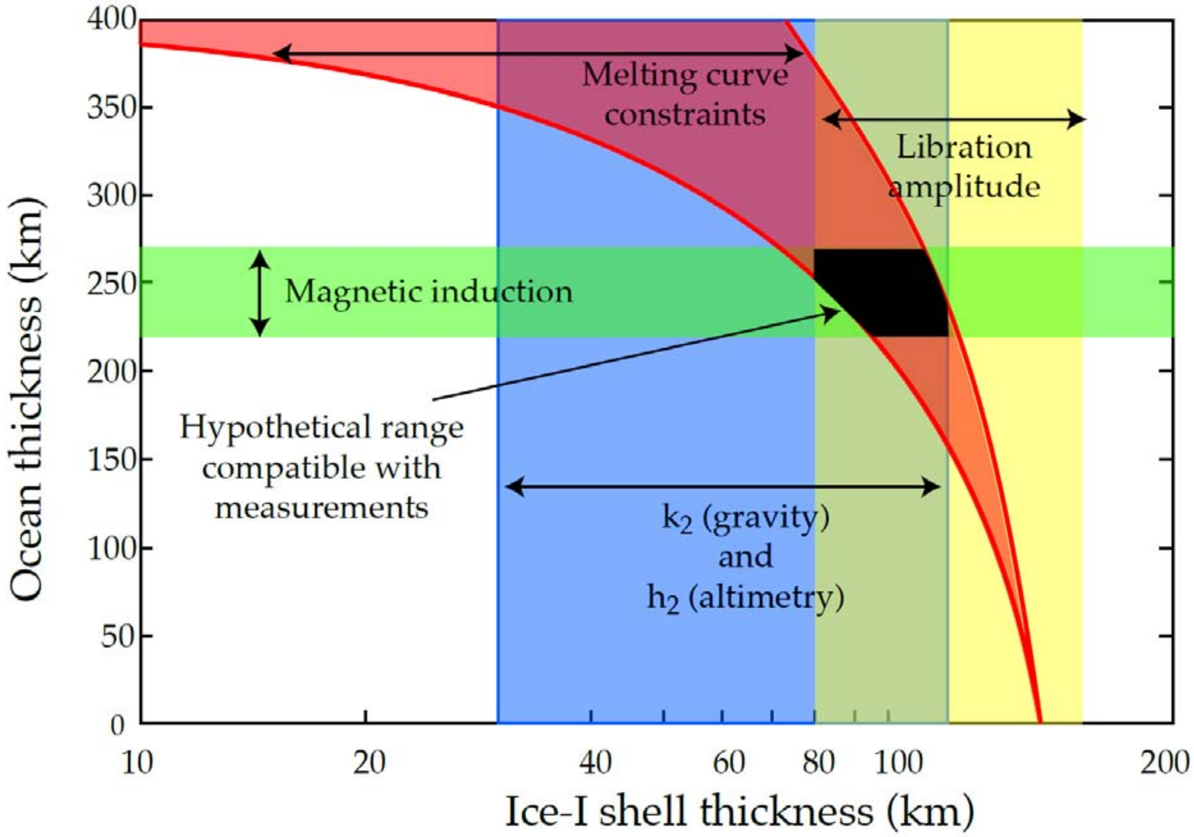


Figure 4-1. *Schematic view of the strategy to characterize Ganymede's icy crust and liquid layer by using combined techniques on JGO. The parameter space (ice-I shell thickness and ocean thickness) is bounded by the domain of stability of ices (red curves), but not fully constrained due to our poor knowledge of the temperature profile and the volatile content. JGO will provide the required additional constraints (resulting black area) by determining (a) the Love numbers h_2 and k_2 (main ambiguity: rigidity of ice-I), (b) the libration amplitude (main ambiguity: density contrast between ice-I and ocean), (c) the magnetic induction signal (main ambiguity: electrical conductivity of the ocean). In this schematic view very generous error bars have been assumed.*

Icy crust. Sub-surface radar sounding will be used to locate liquid water in the ice shell, to identify the stratigraphic and structural patterns, and in the case of Europa to detect the ice-ocean interface. By using subsurface sounding we seek to test hypotheses related to the origin (marine, convective, tectonic, or impact) of structures at the surface and in the shallow subsurface. The scientific goals are: identifying the stratigraphic and structural patterns, understanding the crustal behaviour, matching the surface geology with subsurface features and studying the global tectonic setting and geological evolution.

EJSM-Laplace will characterize the structure of the icy shell including its properties and the distribution of any shallow subsurface water on Ganymede and Europa. It will also correlate surface features and subsurface structure in order to investigate near-surface and inter processes.

Internal structures. By comparing Europa, Ganymede and Callisto we obtain information on physico-chemical processes of planetary evolution and in particular processes of differentiation of icy moons. *Galileo* data suggest that Callisto is partially differentiated while the other satellites, especially Ganymede, are highly condensed objects (Schubert et al., 2004). What does this imply for the structure, composition and evolution of the Jovian sub-nebula? The relevance of different energy sources, e.g., tidal heating in Ganymede and Europa during resonance passages or different impact rates after formation of the satellites is still unclear. Interior structure models of Europa and Ganymede are currently based on degree-2 measurements of the gravity fields using an *a priori* hydrostatic assumption (Schubert et al., 2004). Using polar flybys and/or the orbit phases at Ganymede and Europa EJSM-Laplace will improve the degree-2 fields without relying on the assumption of hydrostatic equilibrium (h.eq.). As a result the secular Love number k_{2s}, a major constraint for density profiles will be improved. High-order fields and deviations from hydrostatic equilibrium will be detected especially in orbit around Europa and Ganymede. Finally, EJSM will determine time-dependent variations of J_2, C_{22} and thus k_2 for the first time. Those values are indicative of liquid layers in the interior and will contribute to determining basic physical characteristics of the oceans, especially in orbit about Europa and Ganymede.

EJSM-Laplace will verify whether hydrostatic states are actually obtained by measuring the low-order gravity fields in different orbital geometries. Measuring the high-order fields, EJSM-Laplace will quantify mass anomalies, asymmetries in the mass distribution and other non-hydrostatic contributions to the satellites' gravity fields (Table 4-1).

Offsets between centre of mass and centre of the figure will be determined by combining gravity data with shape measurements offsets between center of mass and center of figure will be determined. The finite strength of planetary material and dynamic processes in the interior cause deviations of the surface from the equilibrium surface. EJSM-Laplace will perform global high precision topographic measurements of Europa and Ganymede thus providing the reference for local and regional high-degree topography. The time-varying tidal deformations will be related to the equilibrium shape. ***Analysis of the gravity and shape measurements will significantly improve our understanding of interior structure of Europa and Ganymede, thus providing important constraints for their evolution models.***

Table 4-1 *Summary of the gravity field determination by Galileo spacecraft (Schubert et al., 2004) and accuracy expected from the EJSM-Laplace mission.*

	J_2=-C_{20} (static)	C_{22} (static)	k_{2s} (static)	k_2 (time-dependent, due to tides)
Galileo				
Io	(1859.9+/-2.7) x 10^{-6}	(588.8+/-0.8) x 10^{-6}	1.3043+/-0.0019 (h.eq.)	-
Eu	(435.5+/-8.2) x 10^{-6} (h.eq.)	(131.5+/-2.5) x 10^{-6}	1.048+/- 0.020 (h.eq.)	-
Ga	(127.53+/-2.9) x 10^{-6} (h.eq.)	(38.26+/-0.87) x 10^{-6}	0.804+/-0.018 (h.eq.)	-
Ca	(32.7+/-0.8) x 10^{-6} (h.eq.)	(10.2+/-0.3) x 10^{-6}	1.103+/-0.035 (h.eq.)	-
EJSM				
Io	~ 10^{-6} or better	~ 10^{-6} or better	~ 10^{-3} (h.eq.) or better	~ 10^{-1} or better
Eu	~ 10^{-9} or better	~ 10^{-9} or better	~ 10^{-5} (h.eq.) or better	~ 10^{-3} or better
Ga	~ 10^{-9} or better	~ 10^{-9} or better	~ 10^{-6} (h.eq.) or better	~ 10^{-3} or better
Ca	~ 10^{-8} or better	~ 10^{-8} or better	~ 10^{-4} (h.eq.) or better	~ 10^{-1} or better
	No h.eq. assumed	No h.eq. assumed		No h.eq. assumed

Whether or not a planet generates a magnetic field depends on the presence of a core and its structure. Lateral variations of density can provide constraints on the differentiation history and on alternative dynamo models. The Earth, Mercury, and Ganymede are the only solid state bodies known so far to generate intrinsic magnetic fields in their metal cores (Kivelson, 2002).

EJSM-Laplace will carry out a detailed investigation of the magnetic field of Ganymede. This will provide important inputs to dynamo theories that, combined with thermal-evolution models, will tell us what conditions are required for generating and maintaining dynamo activity.

Outstanding questions that will be addressed by EJSM-Laplace

- Is there liquid water on Europa and Ganymede? If so, what is its spatial distribution? How thick are the ice layers and what are the properties of the liquids? What is the relationship between the surficial geologic units and the history of the liquid water?
- What are the chemical and biological potentials of Europa's and Ganymede's oceans?
- Is there material exchange between deep interior, ocean, ice shell, and surface? How do these cycles work? How is this related to non-water ice components at the surfaces?
- What are the characteristics of Ganymede's magnetic field and how is it generated?
- What is the density distribution within the moons? Are they in hydrostatic equilibrium?
- Does tidal heating occur in Europa's ice shell or in the silicate interior? What is the role of tidal heating in the evolution of Europa and Ganymede?

4.1.2 Geology

Overview: the diversity of geological features on Ganymede and Europa

The Galilean satellites Ganymede and Europa show a tremendous diversity of surface features. Each of these moons exhibits its own fascinating geological history – formed by the competition of external and internal processes. The factors influencing their origin and evolution are related to composition (volatile compounds), temperature, density, differentiation, volcanism, tectonics, the rheological reaction of ice and salts to stress, tides, and space interactions that are still recorded in the present surface geology. The record of geological processes span from possible cryovolcanism, through tectonism to impact cratering.

Ganymede. With its mix of old and young terrain, ancient impact basins and fresh craters, and landscapes dominated by tectonics, icy volcanism, or slow degradation by space weathering (Figure 4-2), Ganymede serves as an archetype for understanding many icy satellite processes throughout the outer solar system. Understanding this largest example of an icy satellite surface will provide insight into how this entire class of worlds evolves differently from the terrestrial planets. Ganymede's surface is subdivided into dark, densely cratered ancient plains (perhaps essentially primordial and grossly similar to the surface of Callisto), covering about 1/3 of its total surface and bright, less densely cratered, heavily tectonized, grooved terrain. In addition to craters, dark terrain also displays hemisphere-scale sets of concentric troughs termed furrows, which are probably the remnants of vast multi-ring impact basins, now broken up by subsequent bright terrain tectonism. This type of terrain appears dark due to the addition of a non-water ice contaminant that appears to be concentrated at the surface by a variety of processes including sublimation, sputtering and mass wasting [Prockter et al., 1998]. Bright terrain separates the dark units in broad, up to several hundred kilometers wide, linear or curved parallel, closely spaced grooves, termed *sulci*. The bright terrain units formed predominantly at the expense of dark terrain through a process termed tectonic resurfacing, causing the partial or total transformation of dark terrain into bright terrain by tectonism (e.g. Pappalardo et al., 1998). Generally, grooved terrain represents rifts created by extensional stress (Pappalardo et al., 2004). Several caldera-like, scalloped depressions termed *paterae* found in the bright terrain represent probable volcanic vents (Pappalardo et al., 2004) and ridged deposits in one of the largest of such paterae were interpreted as cryovolcanic flows (Head et al., 1998).

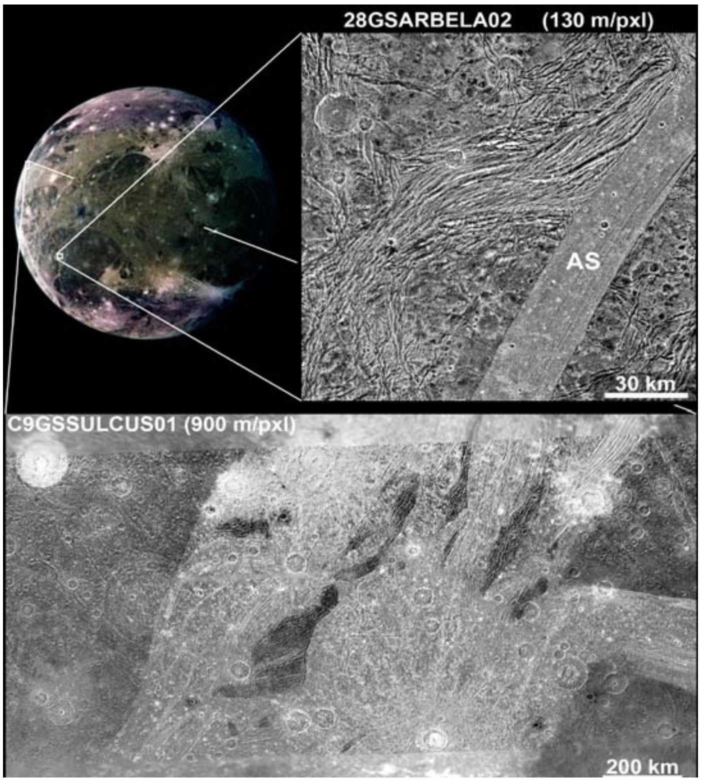


Figure 4-2. *Ganymede's surface is characterized by old, dark densely cratered plains, and by younger, bright and more ice-rich, tectonically resurfaced terrain. Bright terrain formed at the expense of dark terrain, mostly through extensional tectonism, (lower panel; Galileo C9GSSULCUS, 900 m/pxl). Bright, smooth bands (upper right panel; Galileo 28GSARBELA02, 130 m/pxl) indicate lithospheric spreading, involving extension as well as strike-slip movements, as, e.g. in Arbela Sulcus (AS).*

Smooth units which embay other surface units such as crater rims, in some parts less densely cratered, are thought either to represent cryovolcanic flows, extruded as icy slushes (Pappalardo et al., 2004) or to be issued from mass wasting processes along slopes (Prockter et al., 1998). The smoothest units also exhibit some degree of tectonics, inferring that cryovolcanism and tectonic deformation are closely linked (Head et al., 2002).

Although the ultimate driving mechanism for groove formation is uncertain, there are many intriguing possibilities that it may be tied to the internal evolution of Ganymede and the history of orbital evolution of the Galilean satellite system (Showman et al., 1997).

The impact features on Ganymede exhibit a wider range of diversity than those on any other planetary surface. They include vast multi-ring structures, low-relief ancient impact scars called palimpsests, craters with central pits and domes, pedestal craters, dark floor craters, and craters with dark or bright rays (e.g. Schenk et al., 2004). The subdued character of Ganymede's oldest impact craters imply a steep thermal gradient in Ganymede's early history, with more recent impact structures reflecting a thicker and stiffer elastic lithosphere (e.g. Shoemaker 1982). Such an interpretation indicates a much warmer shallow subsurface ocean early in Ganymede's history than at present.

Europa. Europa's surface can be subdivided into plains and mottled terrain and is thought to have undergone cryovolcanic resurfacing in its recent past, but the comparably low image resolution so far did not permit clear identification of cryovolcanic landforms (Figure 4-3). Linear ridges which are the most widespread landform on Europa possibly formed by intrusion of melt into fractures (Greenberg et al., 1998). The two major geologic units on Europa identified are (1) bright, (shown in color images as bluish plains), and (2) darker, brownish mottled units, which superpose the older plains (e.g. Greenberg et al., 1998; Greeley et al., 2004). The bright plains consist of a network of parallel ridges and troughs, similar to grooved terrain on Ganymede.

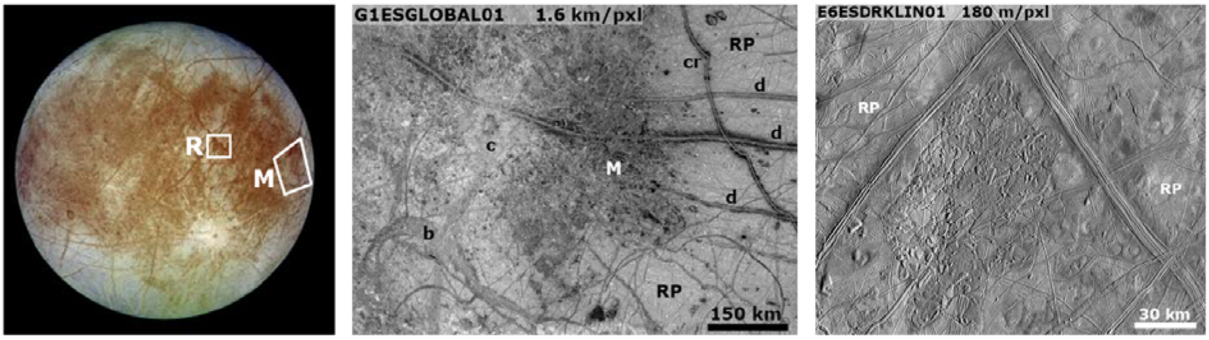


***Figure 4-3**. Europa's surface shows the widest range in colors of the three icy Galilean satellites (left) and exhibits two major surface units: bright, bluish plains, and dark, brown, mottled terrain. Bright plains consist of numerous parallel ridges and troughs (RP) superposed by mottled terrain (M) which at higher resolution (center of the right panel) is revealed as chaotic terrains (see text for details). Most features cutting plains and mottled terrain are double ridges, either linear (d) or cycloidal (cr) (middle panel), and bands (b). Very few impact craters (c) are observed.*

Ridges are predominantly double ridges with medial groove or trough (e.g Greeley et al., 2004) several hundred meters high. Depending on the depth of a liquid water layer underneath, several models of ridge formation are in discussion, involving rheological reactions of ice composites to compressional tectonism and diurnal tidal stresses, cryovolcanic and/or intrusive processes (e.g. Greenberg et al., 1998; Greeley et al., 2004). Bright plains are separated by dark bands, which are possible indications of crustal spreading, with brittle plates moving on a warmer, mobile substrate (e.g. Greeley et al., 2004). Chaos regions are characterized by broken plates of pre-existing terrain, such as ridged plains, which have been translated, rotated and tilted in a matrix of predominantly hummocky terrain, which in turn could be comprised or altered pre-existing terrain (e.g. Greeley et al., 2004). Widespread abundance of erosional or degradation features on Europa are absent.

Science objectives

Formation and characteristics of landforms. *Galileo* data have allowed us to describe for the first time the global geology of the moons. But it was not possible, except on a very few cases, to study regional and local geology, most of the data being at low or medium resolution (less than 1% of the surface was observed at a resolution better than 100 m/px; Figure 4-4). With its two orbiters, EJSM-Laplace will fully observe the moons at medium resolution (total coverage at a few 100 m/px) and will provide at least 50 times more high resolution imaging than Galileo. It will study the satellites' geological history using global, regional, and local mapping at different levels of resolution, and stereo imaging on regional and local scales. Colored maps down to 200 m/pix and 4-color coverage for selected large areas, up to 50 m/pix using spectral filters from about 350 nm to 1000 nm will be aquired to constrain mineralogical/chemical constituents of the near-surface layers and to correlate geologic features with compositional variations.

***EJSM-Laplace will provide a breakthrough in the geology of Ganymede and Europa by global imaging with moderate spatial resolution (<400 m/px) and high-resolution imaging (<5 m/px) of selected targets (Figure 4-4). Combined with spectral mapping, these observations will contribute to a comprehensive picture of the geological evolution of these satellites, constrain the role of cryovolcanism and tectonics in the geological history, and help researches to understand the origin of these bodies. EJSM-Laplace will also acquire detailed topographic profiles of tectonic features, grooved terrain, craters and cryovolcanic features by laser altimetry which, combined with imaging data, will enable identification of dynamical processes that cause internal evolution and near-surface tectonics**.*

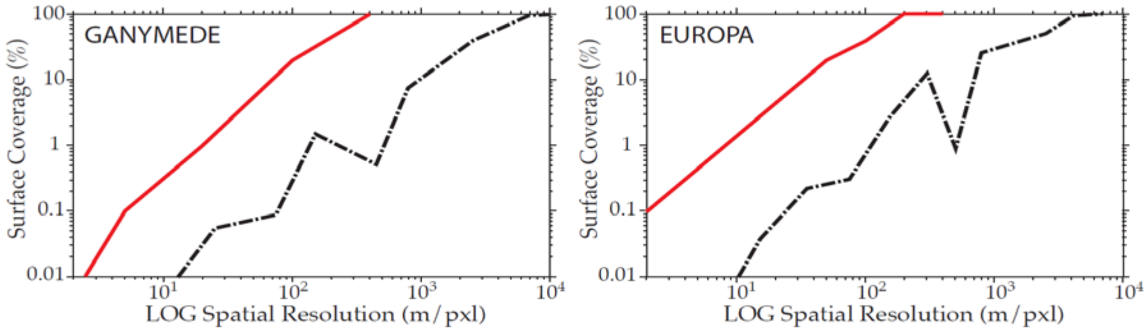


Figure 4-4. *Imaging coverage as a function of resolution as expected for EJSM-Laplace (red) in comparison to the Galileo SSI results (black) for Ganymede (left) and Europa (right).*

Using sub-surface radar sounding, EJSM-Laplace will probe Europa and Ganymede to assess the linkage of the ocean to the surface and the dynamics of the near-surface ice layers, by detecting compositional or phase boundaries between different intra-ice horizons and unconformities. The stratigraphic and structural data acquired will also provide information on crust formation and its possible destruction by deformational processes.

Global and regional surface ages. The morphology and distribution of craters of the icy Galilean satellites is significantly different from those on the terrestrial planets. Ganymede is a densely cratered object with a record of large impact features, including multi-ring structures, which imply an old surface age (e.g. Pappalardo et al., 2004). The widest range in crater morphology on any planet or satellite is found on Ganymede (e.g. Pappalardo et al., 2004). Europa's surface is characterized by a very low density of impact craters (only 16 crater with diameters of 3 – 27 km are identified), which suggest relatively young surface age (e.g., Greeley et al., 2004).

EJSM-Laplace will significantly improve the current estimate of Ganymede and Europa surface ages by measuring crater distributions from nearly global image coverage at 200-400 m/px resolutions plus sufficient high resolution target areas (5-50 m/px) and by monitoring the surfaces on a timescale of the order of hundreds of days up to years to identify potentially newly formed craters.

Outstanding questions that will be addressed by EJSM-Laplace

- What are the relative roles of tectonism and volcanism in shaping the terrains?
- What does the distribution of craters on Ganymede tell us about the evolution of the impactor population in the Jovian system through time?
- How is the geological evolution related to the impact, tectonic and cryovolcanic history?
- What is the age of certain geological units on Ganymede and Europa, and how will this finding contribute to our understanding the origin of the Jupiter system?
- What are the rheological reaction of ices and ice/salt/clathrate mixtures w.r.t. tectonic stress**?**
- To what extent are surfaces altered by cosmic weathering and what are the major exogenic surface alteration processes (micrometeorites, radiation, charged particles)?

4.1.3 Surface Composition

Overview: the complex chemistry of the icy surfaces

As revealed by the *Galileo* mission, there are substantial amounts of non-water-ice components present at the H_2O-ice dominated surface of Ganymede and Europa. The nature and origin of these species which may have been derived from a subsurface briny layer of fluid are widely debated. The detection and distribution of biologically essential elements (C, H, O, N, P, S) is critical in assessing habitability.

On Europa, *Galileo*'s spectra have distortions in several water ice absorption bands between 1 and 3 µm, indicating the presence of hydrate compounds concentrated in the visually dark and reddish regions. It has been hypothesized (e.g., McCord et al., 1998, 1999, Dalton, 2003; Dalton et al., 2005) that this material may be made up of hydrated salt minerals enriched in Mg and Na sulphates that form by the crystallization of brines erupted from the subsurface. Alternatively, this material was proposed to be due to hydrated sulfuric acid ($H_2SO_4{\cdot}nH_2O$), formed by the radiolysis of water and of the sulphur-bearing species, or by the decomposition of sulphate salts (Carlson et al., 1999). Later, Orlando et al. (2005) and Dalton (2007) reported that the Europa non-ice spectra would be actually best matched by mixtures of sulphuric acid hydrate together with hydrated salts, so both these chemical classes may be present on the surface with variable concentrations. Other non-ice species, like CO_2 and H_2O_2, were also found in the leading hemisphere at equatorial to mid-latitudes.

On Ganymede, various non-water-ice materials have also been identified with *Galileo* data and ground based spectra: carbon dioxide, sulphur dioxide, molecular oxygen, ozone and possibly cyanogen, hydrogen sulfate and various organic compounds (e.g., McCord et al., 1998) (Figure 4-5). Asymmetric and distorted water absorptions were found locally on Ganymede's trailing hemisphere and were interpreted as hydrated materials similar to those found on Europa (McCord et al., 2001). The source of the organic material could be formed in situ from radiolysis and chemical reactions within the contaminated icy crust, and from exogenic material falling onto Ganymede's surface.

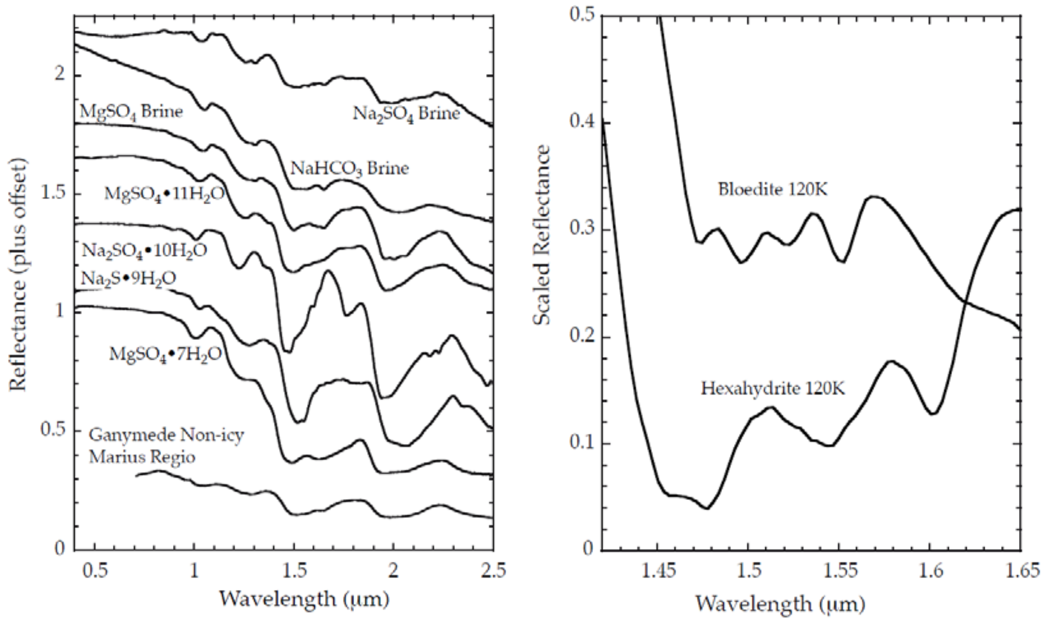


Figure 4-5. ***<u>Left:</u>*** *Spectra of several hydrates and brines, measured at 100 K in the range from 0.4 to 2.5 µm, compared with a NIMS spectrum of non-icy material of Ganymede.* ***<u>Right:</u>*** *Close-up of the spectra of hydrated minerals bloedite ($Na_2Mg(SO_4)_2{\cdot}4H_2O$) and hexahydrite ($MgSO_4{\cdot}6H_2O$) in the range from 1.42 to 1.65 µm, measured at 120 K. The narrowest feature here exhibits a FWHM of 7 nm. (Credits: J.B. Dalton)*

The *Galileo* mission has demonstrated that the surface of the moons is composed of water ices, but also many other compounds. But the composition and the distribution of these non-water-ice materials is still very poorly known, due to the poor spectral and spatial resolution of the Galileo spectro-imagers, and the limited coverage due to the small number of flybys.

EJSM-Laplace will make a breakthrough in our understanding of the surface composition and chemistry of Europa and Ganymede by near-global spectral imaging, mass spectroscopy of particles sputtered or ejected from the surface, and high-resolution spectral imaging of selected targets.

Science objectives

<u>*Characterize surface organic and inorganic chemistry.*</u> A reliable identification of all non-water-ice compounds is still missing on Ganymede and Europa, mostly due to the lack of high spatial resolution data with good signal-to-noise ratio (Figure 4-6), but also low spectral resolution. Hyperspectral imaging in a wide spectral range from UV to IR will be achieved by EJSM-Laplace at regional scale with spatial resolution of 2-3 km /px on at least 50 % of Ganymede and Europa surfaces, while very detailed compositional mapping (at spatial resolution of better than 100m/px) will be obtained on selected sites of interest. The spectral resolution will be 5 times better than the *Galileo* data in the near infrared range (better than 5nm/band between 0.4 and 2.5 µm).

EJSM-Laplace will provide almost complete spectral mapping of the moons' surfaces in the range from 0.1 µm to at least 5 µm, with a much enhanced spectral and signal-to-noise ratio. High spatial resolution spectral imaging of selected targets will allow reliable identification of non-water- ice material.

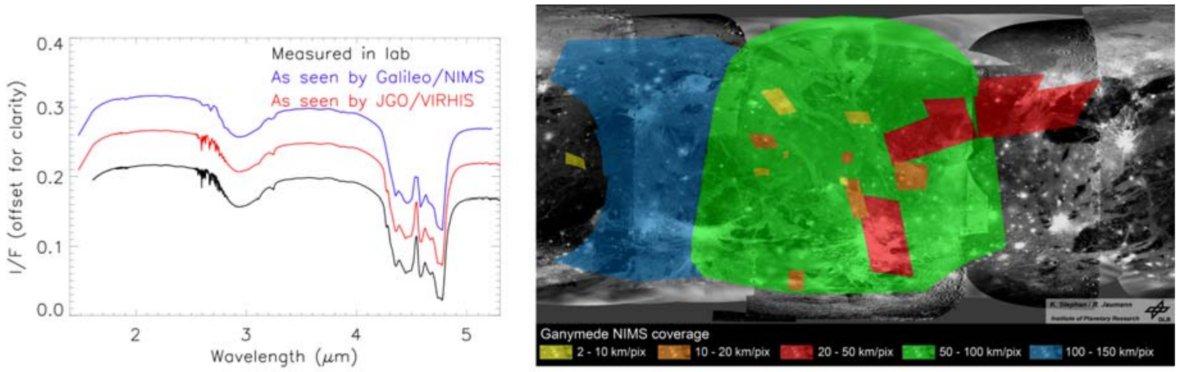


Figure 4-6. <u>Left:</u> *Comparison of IR spectra of mirabilite obtained i) in laboratory, ii) with the NIMS spectrometer onboard Galileo, and iii) expected with the VIRHIS instrument onboard JGO. The significant increase in spectral resolution will allow for a proper characterization of the non water-ice material on Ganymede and Europa.* ***<u>Right:</u>*** *Spatial coverage of Galileo NIMS on Ganymede superimposed on the mosaic obtained from the Galileo/ SSI images. The very low spatial resolution (> 20 km/px) of Galileo data did not allow proper investigation of composition and spatial distribution of non-water-ice compounds on the surfaces of the moons. (Credit: K. Stephan, R. Jaumann, DLR)*

Surface composition can also be inferred by measuring materials sputtered or ejected from the surface into the atmosphere using direct sampling, which is not affected by the physical properties of the material. Models predict that large molecules, such as hydrated Mg and Na sulphates and organics, may be sputtered to orbital altitudes at levels detectable for a sub-millimeter wave instrument or an INMS-type instrument. These observations, however, are limited in spatial resolution to approximately the height at which the measurement is made and by the necessity to infer the surface composition from the measured derived products through the processes of sputtering and radiation-induced chemistry. EJSM-Laplace instruments should be capable of achieving enough sensitivity to detect resultant products of H_2O (O, O_2, OH, H, H_2) and other minority species with mixing ratios of 1 ppm (Figure 4-7).

EJSM-Laplace will be able to measure the composition of the sputtered surface and the stable isotopes of C, H, O, and N in the major volatiles H_2O, CH_4, NH_3, CO, N_2, CO_2, SO_2, and the noble gases Ar, Kr, and Xe which would constrain the origin and evolution of the volatile inventories of Europa and Ganymede.

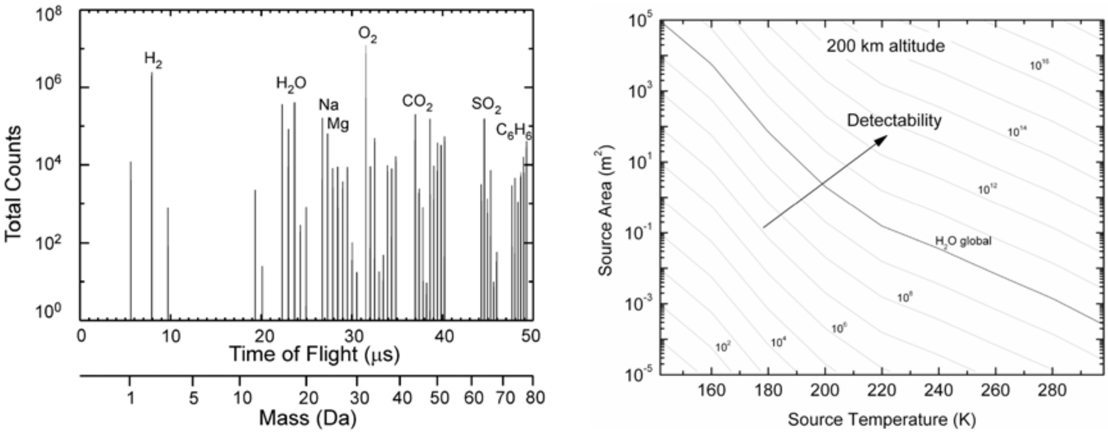


***Figure 4-7. <u>Left:</u>** a simulated mass spectrum of the anticipated Europa INMS results for neutral species at an orbit altitude of 100 km. The simulation is based on a surface composition made up by a mixture of hydrated salt minerals combined with the modeled atmospheric composition and 1% heavy organic. Credits: H. Waite, private communication, 2010. **<u>Right:</u>** Contour plot showing the water vapor density at 200 km altitude over a Ganymede super cooled liquid water surface source versus water temperature and exposed surface area. (Credits: B. Teolis, private communication, 2010).*

<u>Relate surface composition to geology.</u> The relationship of ice and non-ice materials and their distribution is crucial for understanding the origin and evolution of the surfaces of Europa and Ganymede. Surface material distribution can be linked to the internal activity of the moons but also to external processes (e.g. the effect of the Ganymede's intrinsic field shielding from high-energetic particles at equatorial to mid-latitudes). ***Combined with geological mapping, multi-wavelength spectral mapping and in situ measurements will lead to a consistent picture of surface chemistry and separate the relative contributions of endogenic subsurface geochemistry and exogenic magnetosphere-driven radiolysis, and assess the role of processes that exchange material between the surface and sub-surface.***

On Ganymede, bright terrains (typically grooved) are ice-rich compared to dark terrains. The composition of the non-water-ice material ranges from heavily hydrated at high latitudes, similar to that on Europa, to only slightly hydrated material associated with dark ray ejecta. However, most of the non-water-ice material, primarily associated with the dark regions, is a moderately hydrated material - possibly salt. It is worth noting that carbon dioxide, the most abundant of the trace materials, is also concentrated in these zones (Hibbitts et al., 2009), while no leading/trailing hemispheric asymmetry in the distribution of CO_2 exists nor the impact craters tend to be CO_2-rich (Hibbitts et al., 2003). It is also occasionally enriched in terrain containing larger grained ice in comparison with adjacent terrain of similar morphology and ice abundance.

On Europa, hydrated compounds are concentrated at the lineaments and chaotic terrains. Some young cryovolcanic flow units exhibit high proportions of hydrated salts and low abundance of sulfuric acid hydrate when compared to older surface units of the same type, or to surface units of different geologic origin. This suggests that for some units, we are observing an intermediate stage of the conversion of endogenically-produced sodium and magnesium sulfate salts into sulfuric acid hydrate by exogenically-driven radiolysis (Dalton et al., 2010). The presence of large quantities of brine and sulfate salts in certain deposits may reflect the composition of subsurface liquid source reservoirs (Dalton et al., 2010).

EJSM-Laplace will correlate distribution of non-water-ice material with geologic units in a wide range of spatial scales, up to very high spatial resolution (≤ 100 m) on selected targets, revealing sites where the surface is linked with the subsurface.

<u>Investigate the effects of radiation on surface composition and structure.</u> The Europa surface spectra could be matched by mixtures of sulfuric acid hydrate and hydrated salts. One mechanism might be that Na associated with some salts could be easily sputtered away and abundant H^+ could

take its place, forming sulfuric acid. Thus sulfuric acid hydrate abundance is linked to the magnetospheric charged particle energy flux, and could result from radiolytic processing of implanted sulphur from Io, or of sulphur emplaced as part of the surface deposits that came from the interior. Destruction of large molecules by the same radiation however suggests that there may be an equilibrium between creation and destruction that varies based on sulfur content and radiation flux. ***EJSM-Laplace will shed light on the contamination processes acting on the surface of Europa, mapping leading/trailing asymmetries due to implantation of exogenic material and revealing interactions with the subsurface material.***

Ganymede shows evidences of the presence of oxygen species, particularly solid O_2 and O_3 (Noll et al., 1996; Hendrix et al., 1999) in the trailing hemisphere, consistent with the preferential orientation of that side of the satellite with Jupiter's magnetosphere. Both of these species appear to be trapped within the ice matrix, and probably originate from ionic bombardment of the icy surface (the presence of CO_2 should produce also monomeric or polymerized H_2CO and an H_2CO_3 residue; species that have not been yet identified). The abundance of ozone varies with latitude, with the strongest concentration measured at higher latitudes. This was interpreted as being the result of plasma bombardment creating O_3 in the ice matrix and photodissociation destroying it, on a continual basis.

EJSM-Laplace will study the neutrals in the energy range 10 eV to 10 keV, produced by plasma-surface interaction, and provide 2D imaging of impacting plasma. It will also search for products of ionic bombardment on Ganymede and will allow a detailed mapping of the oxygen species over its surface. It will significantly enhance our understanding of ion bombardment processes and the dynamical response of the surfaces. Moreover, it will closely explore the physical processes involved in the cycling of oxygen species.

Outstanding questions that will be addressed by EJSM-Laplace

- What is the chemical composition of visually dark, non-water-ice materials on Europa and Ganymede?
- How do these materials correlate with the surface geology, in a wide range of spatial scales?
- Where is the non-ice material linked to the subsurface?
- What degree of contamination by exogenic material do the surfaces of Ganymede and Europa undergo?
- To what extent is the composition and physical state altered by radiation weathering effects?
- What is the temporal cycle of the oxygen species on Ganymede?
- In what way is the origin and evolution of these moons constrained by the current volatile composition?

4.1.4 Galilean moons and their interaction with Jovian magnetosphere

Overview: the complexity of the moon's environments

Ganymede is a unique moon: it has an intrinsic magnetic field, producing a magnetosphere about the size of Mercury's within Jupiter's magnetosphere. This field permits plasma access to the surface most easily at the poles, resulting in brightening of the polar caps (Khurana et al., 2007). Europa and Ganymede also have induced magnetospheres, and it is vital to separate their effects to study the sub-surface oceans. The two moons possess weak exospheres, ionospheres, and (in the case of Ganymede) exhibit auroral emissions. The aurora provides a visual representation of the electromagnetic interactions between Jupiter's magnetosphere and the moons, through processes which are not yet understood in detail. The thin exospheres are produced by sputtering processes, as their surfaces are bombarded by particles from Jupiter's radiation belt magnetosphere, and sublimation of the surface materials (McGrath et al., 2004). These processes, supplemented by volcanism at Io, also produce exospheres at Io and Callisto. Exospheric properties are thus indicative of processes at and composition of the surfaces (see also section 4.1.3).

EJSM-Laplace will characterize Ganymede's magnetosphere and investigate particle trapping and transport between Jupiter's and Ganymede's poles, along the flux tubes connecting both bodies. It will characterize the induced fields using dual measurements from JGO and JEO at the same time. The mission will also study the exospheres of Europa and Ganymede through remote measurements, multi-wavelength limb scans and stellar occultation, imaging of the aurora, and in-situ charged and neutral particle measurements from low orbits and fly-bys. Contemporary observations by JEO and JGO will unveil the transport of the particles within the magnetosphere.

Science objectives

Magnetic fields of the moons. A unique characteristic of Ganymede is its intrinsic magnetic field generated in the satellite's metallic core, and comparable to dynamo-activity in the Earth and Mercury (Kivelson et al., 2002). Ganymede is so far the only moon in the solar system to possess its own intrinsic mini-magnetosphere (about the size of Mercury's magnetosphere) embedded within the Jovian magnetosphere (Figure 4-8). Observational evidence for the presence of global water oceans on Ganymede and Europa has been indirectly obtained by the Galileo mission with the detection of an induced magnetic field generated at shallow depth in response to the time-variable rotating magnetosphere of Jupiter. However, the available data are inconclusive because of the complex interaction of the induced field, Ganymede's intrinsic field, Jupiter's magnetosphere and the plasma environment (Kivelson et al. 2002, 2004).

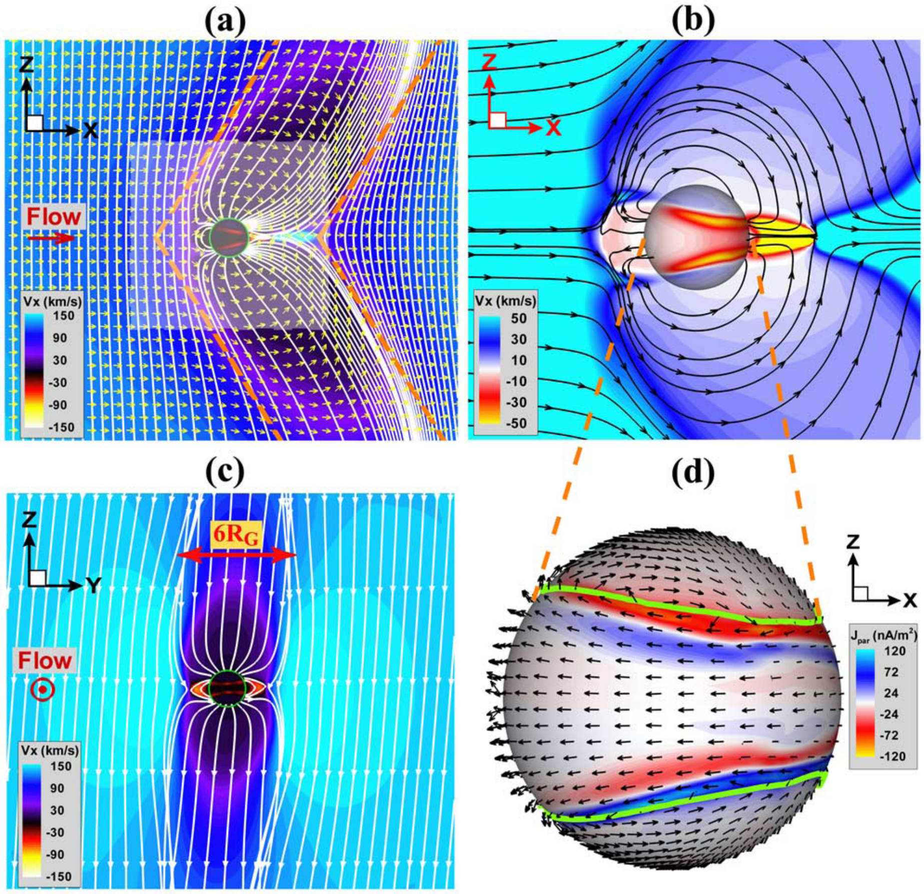


Figure 4-8. *Magnetic field of Ganymede immersed within that of Jupiter. (a) Flows and the projection of field lines (white solid lines) in the XZ plane at Y = 0. Color represents the V_x contours, and unit flow vectors in yellow show the flow direction. A theoretical prediction of the Alfvèn characteristics (orange dashed lines) is shown for reference. The projection of the ionospheric flow is also shown as color contours on a circular disk of $r = 1.08\ R_G$ in the center. (b) A zoomed-in view of the light area in (a). Flow streamlines are superimposed on color contours of V_x. Note that the color bar differs in order to illustrate the relatively weak flow within the magnetosphere. (c) Same as (a) but in the YZ*

plane at X = 0. (d) Field-aligned current density along with unit flow vectors shown on a sphere of radius r = 1.08 R_G. (from Jia et al., 2009)

EJSM-Laplace will investigate Ganymede's intrinsic magnetic field in detail and characterize the interplay between this intrinsic field, induced magnetic fields generated in the subsurface ocean, and the Jovian magnetosphere. It will establish the dimensions of Ganymede's magnetosphere and well as regions of open/closed field lines where particles are either trapped or transported, field-aligned, between the polar regions of Jupiter and Ganymede along the flux tubes connecting both bodies. Ocean currents will be sought in the induced magnetic signal. Long-term changes in the magnetic field may also be detected by comparison with Galileo data.

Particle populations and their interaction with Jupiter's magnetosphere. Many crucial parameters of the satellite/magnetosphere coupling have not been measured. During the close observation of icy satellites, plasma/surface interactions are key processes to be investigated. This includes processes associated with sputtering of surfaces and exospheres and with resurfacing due to intense bombardments by energetic particles. Given the complex composition of the environment of Jupiter, including sulphur ions, the understanding of plasma resurfacing is a necessity for the interpretation of the spectral signatures of the surfaces. The role played by charged particles in modifying the reflectance of moons' surfaces is not fully understood. It is also clear that energetic ions and electrons are the principal chemical agents in layers close to the surface of moons. However, the actual importance of these effects depends on the magnetic environment. Ganymede, as an example, possesses its internal dipolar magnetic field which interacts with the Jovian magnetic field thus permitting the plasma to impact the surface at specific regions resulting in a specific albedo distribution, with the polar regions being brighter than the equatorial belt (Khurana et al., 2007).

EJSM-Laplace will identify the particles near the moons and their interaction with Jupiter's magnetosphere by measuring the velocity-space distribution of thermal plasma and energetic particles from eV to MeV, plasma and radio waves, and neutral imaging of the impacting and ejected plasma from eV to keV (Figure 4-9).

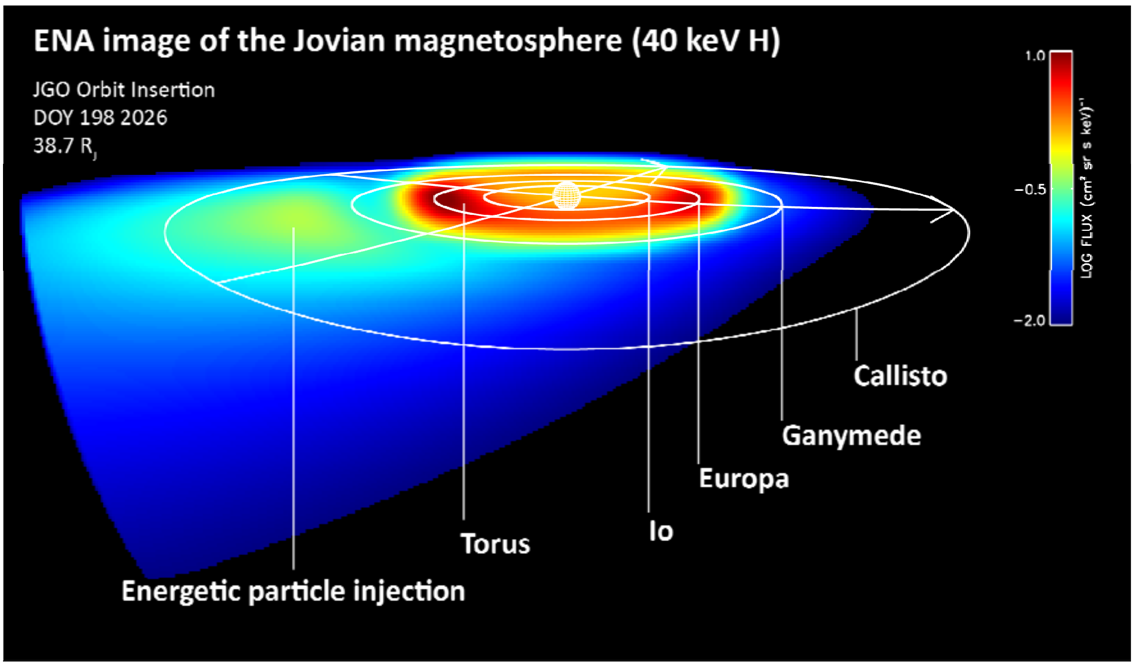


***Figure 4-9**. Numerical simulation of the ENA image taken in 40 keV Hydrogen of the Jovian system on approach to Jupiter during JGO Orbit Insertion. The Europa torus can be seen glowing in bright intensity. The fainter emissions to the left show one of the global injections suspected to be the giant particle accelerator for Jupiter's vast energetic particle population (Credit: P. Brandt).*

<u>The aurorae.</u> Different 'objects' move in the Jovian environment, each of them interacting with the magnetospheric plasma by a large variety of processes. Moons, with their exospheres, are conductive bodies. As they move trough the Jovian magnetic field, they create a specific current system (the unipolar dynamo). This electro-dynamical coupling is not stationary. It generates Alfvèn wave structures, called 'Alfvèn wings', that couple the Jovian ionosphere to the exospheres of moons. This coupling involves dissipation processes that convert electromagnetic energy into kinetic energy of accelerated particles. This is shown in the formation of particular auroral features and, in the Io case, by the generation of non thermal radio emissions.

Io, Europa, Ganymede and Callisto are in complementary situations. The magnetosphere interaction at Io is the most powerful. The coupling with Europa is thought to be less powerful even if it appears to be able to generate intense waves and a footprint in the auroral region of Jupiter. Ganymede, the only known magnetized moon, constitutes another unique situation. How this mini-magnetosphere interacts with the giant magnetosphere of Jupiter is a mystery. We only know that this interaction is powerful enough to create an auroral footprint in Jupiter's aurora.

EJSM-Laplace will study the aurorae using close-up imaging and the in-situ measurements of the particles producing them. It will measure the location and intensity of the footprints in the aurora of Jupiter remotely in combination with in-situ measurements of particles and fields in the field – aligned current systems.

<u>Sources and sinks of the ionosphere and exosphere.</u> All four Galilean satellites are known to have thin atmospheres / exospheres (McGrath et al., 2004), produced by sputtering processes and sublimation of the surface materials as well as volcanism at Io. Thus their properties are indicative of processes and composition at the surfaces (see also section 4.1.3). The presence of an O_2 atmosphere at Europa has been inferred from measurements of UV emissions; Na and K have also been measured at Europa, in ground-based observations. Ganymede also has a thin O_2 atmosphere, inferred from measurements of UV emissions, and a hydrogen exosphere, measured by the *Galileo* UVS in a limbscan.

EJSM-Laplace will significantly contribute to our understanding of the atmospheres of the icy satellites, their origin and evolution, as well as the composition of their surfaces, by observing the exospheres of Europa and Ganymede through remote monitoring, imaging of the aurora, multi-wavelength limb scans and stellar occultation, supported by in-situ measurements by particle packages from low orbits and fly-bys. Coordinated observations by JEO and JGO will unveil the transport of the particles within the magnetosphere.

<u>Outstanding questions that will be addressed by EJSM-Laplace</u>

- What are the characteristics of the intrinsic magnetic field of Ganymede (strength, size, variability)?
- Where is the boundary between open and closed field lines and how does the location of this boundary relate to surface and exosphere features?
- What are the particle distributions of various species around Ganymede and Europa?
- What neutral species are present in the exospheres?
- What are the morphology and dynamics of these weak, non-spherically symmetric exospheres?
- What role does Ganymede's magnetic field play in producing asymmetry in the plasma?
- What are the processes of production and loss of the exospheres and how do they vary in space and time?
- How do the exospheric particles escape and what effect do they have on the Jovian system?
- What is the nature of and controlling factors for the aurora on Ganymede, Europa and Io?
- What is the nature, structure and dynamics of Ganymede's and Europa's ionospheres?

4.2 Jupiter

EJSM-Laplace offers an unprecedented opportunity for study of Jupiter's atmosphere

Overview: the atmosphere of Jupiter

The exploration of Jupiter's dynamic atmosphere has played a pivotal role in the development of our understanding of the Solar System, serving as the paradigm for the interpretation of planetary systems around other stars and as a fundamental laboratory for the investigation of large-scale geophysical fluid dynamics and physiochemical phenomena. However, our characterization of this archetypal giant planet remains incomplete, with many fundamental questions about its nature unanswered. While the thin atmospheric 'weather-layer', the only region accessible to direct investigation by optical remote sensing, is only a tiny fraction of Jupiter's total mass, it provides vital insights to the interior structure, bulk composition, and formation history of our Solar System.

The EJSM-Laplace mission offers an unprecedented opportunity for study of Jupiter's atmosphere over long temporal baselines of 2 years or more, with simultaneous and complementary spectral and imaging coverage from the far-UV to the sub-millimetre and radio.

Jupiter is the end product of energetic accretion processes, thermochemistry, photochemistry, condensation processes, planetary-scale turbulence and gravitational differentiation. Its atmosphere is characterized by distinct latitudinal bands of differing cloud colours, vertical motions, temperatures and vertical mixing strengths separated by strong zonal winds and perturbed by long-lived vortices, storms, polar circulations, convective outbreaks, wave activity and variable large-scale circulation patterns (Rogers, 1995; Ingersoll et al, 2004; West et al., 2004). Although primarily composed of hydrogen and helium, Jupiter also contains small amounts of heavier elements found in their fully reduced forms (CH_4, PH_3, NH_3, H_2S, H_2O), providing source material for complex photochemical pathways powered by UV irradiation (Taylor et al, 2004, Moses et al., 2004). The abundances of most of these heavy elements are enriched over the solar composition, providing a window into the evolution of the primordial nebula material incorporated into the gas giants during their formation (Lunine et al., 2004). Jupiter's vertical atmospheric structure is governed by a delicate balance between solar, chemical and internal energy sources, and its layers are coupled by poorly understood dynamical processes which transport energy, momentum and material (Vasavada and Showman, 2005). Finally, Jupiter's atmosphere is intricately connected to the charged-particle environments of the ionosphere and magnetosphere (e.g., Yelle and Miller, 2004), and the local Jovian environment of the rings and icy satellites.

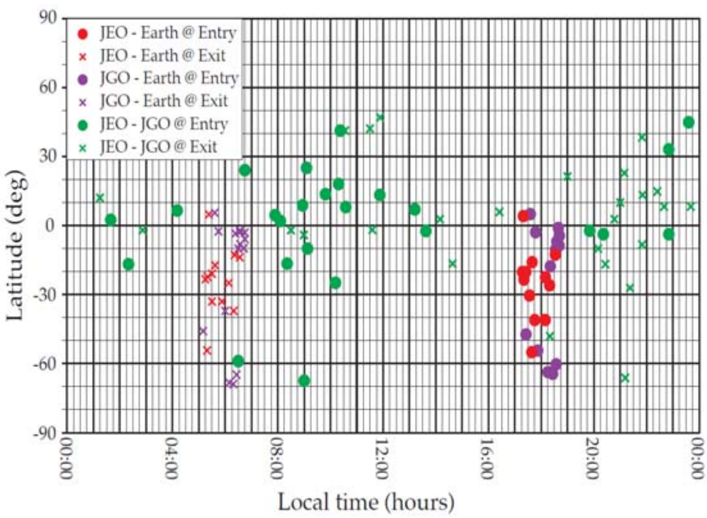
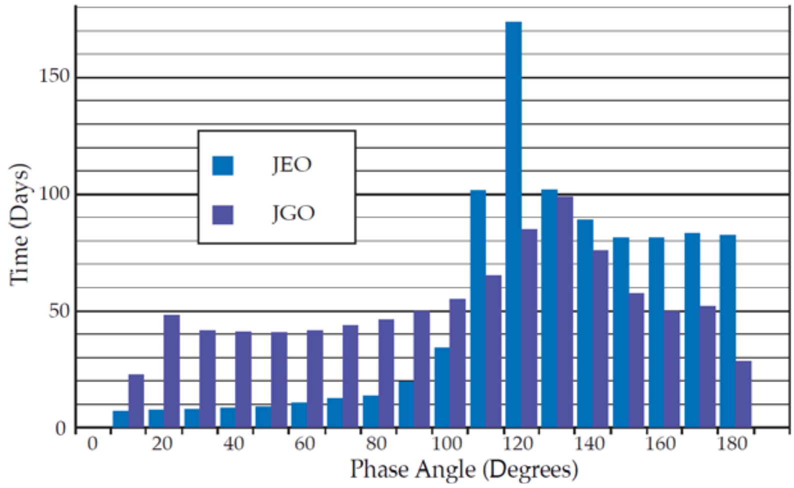


Figure 4-10*. Chart of the latitude/local time sounding for radio occultation during the full EJSM-Laplace mission for JEO and JGO. Even sampling in latitude and local time for atmospheric structure retrieval is important for deciphering Jovian variability in atmospheric structure.*

EJSM-Laplace will study Jupiter's plethora of atmospheric phenomena as a three-dimensional, highly coupled system that varies over a range of timescales, from hours to years.

The unique combination of two spacecraft (Figure 4-10), broad spectral coverage from advanced instrumentation, large data volume capacity, long approach phase, and 2+ year baseline of tour-phase observations (Figure 4-11), provides a significant potential for Jupiter atmospheric science. The combined knowledge from prior missions and EJSM-Laplace will revolutionize our understanding of Jupiter and its role in the evolution of habitable environments within our solar system. Furthermore, the fundamental insights into the origin, formation, and physiochemical processes on Jupiter will serve as the paradigm for the interpretation of planetary systems around other stars for decades to come.

__Figure 4-11.__ Cumulative time spent at varying Jupiter phases. Coverage in phase angle during the full EJSM-Laplace mission for JEO and JGO. Even sampling of phase angles is important for cloud scattering and composition studies (e.g. Nightside for lightning studies, Dayside for cloud tracking).



EJSM-Laplace will provide the first four-dimensional climate database for the study of Jovian meteorology and chemistry, and will investigate the atmospheric structure, clouds and composition from the thermosphere down to the lower troposphere to create a global picture of the many dynamical and chemical processes at work in Jupiter's atmosphere.

Science Objectives

The atmospheric science objectives of EJSM-Laplace fall into three categories designed to address the mysteries raised by previous missions to Jupiter. With advances in instrument sensitivity and resolution, as well as the long temporal baseline to permit the study of the dynamic atmosphere, EJSM-Laplace will enable new discoveries and address the fundamental physical and chemical processes at work on the outer planets (Figure 4-12).

Atmospheric dynamics and circulation. The variety of dynamical and chemical phenomena in Jupiter's visible atmosphere (the "weather-layer") are thought to be governed by a balance between solar energy deposition and forcing from deeper internal processes. Moist convection, eddies, turbulence, vertical wave propagation, and frictional damping are all believed to play a role in atmospheric circulation, transporting and mixing energy, momentum and material tracers transfer both horizontally and vertically (Vasavada and Showman, 2005; Salyk et al., 2006). Through imaging, spectroscopy, and occultations, EJSM-Laplace will study atmospheric motion from the troposphere to the thermosphere and its relation to the deep interior by measuring: vertical profiles of zonal winds and temperatures; dynamical tracers of circulation (e.g., potential vorticity, disequilibrium species, volatiles, cloud colours); and the distribution and depth of Jovian lightning. These observations will help to determine the importance of moist convection in driving Jovian circulation, and distinguishing between 'shallow' and 'deep' models for the origins of eddies, vortices and zonal jets.

Jupiter's atmosphere exhibits a wealth of time-variable phenomena, ranging from thunderstorms and lightning, formation and interaction of giant vortices, episodic plumes and outbursts, waves, and turbulence to quasiperiodic variations in the banded cloud patterns and storms. For example, wave

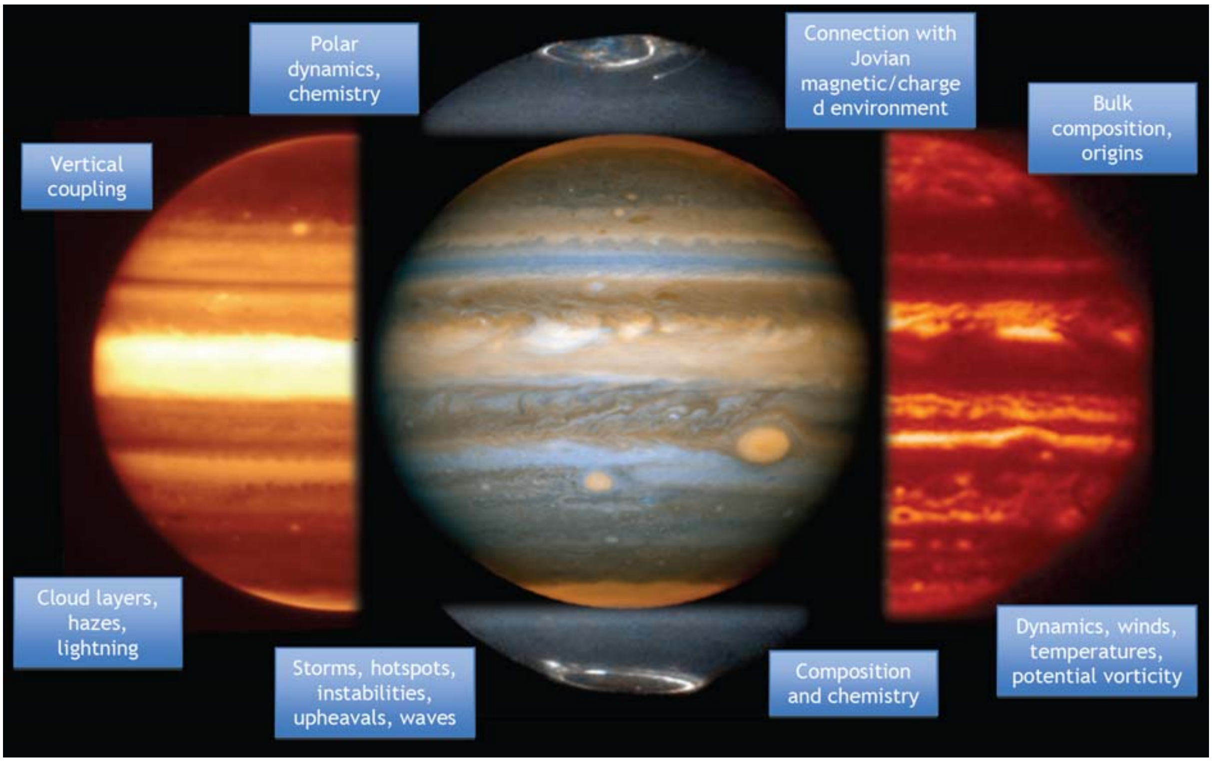


Figure 4-12. *Examples of the Jupiter science objectives of EJSM-Laplace. Each image shows Jupiter's appearance at a range of different wavelengths, from visible colouration and wind tracking (centre, HST, credit: NASA/ESA/A. Simon-Miller/I. de Pater) to cloud properties in the near-IR (left, Gemini/NIRI image, credit: Gemini Observatory/AURA/L.N. Fletcher); thermal structure and chemistry in the mid-IR (right, credit: NASA/IRTF/G.S. Orton, 5 μm image) and auroral properties in the UV (top and bottom, credit: NASA/ESA/J. Clarke).*

activity will be studied over a range of spatial scales, from (a) sporadic equatorial mesoscale waves; to (b) planetary-scale Rossby waves and the forcing of the Quasi-Quadrennial Oscillation (Leovy et al., 1991); and (c) gravity waves in the middle and upper atmosphere, which are thought to play an important role in energy transfer between different layers. Meteorological investigations of these phenomena will benefit from the long temporal baseline and broad spectral range offered by EJSM-Laplace, permitting global mapping at frequent intervals to identify the underlying dynamical causes for Jupiter's atmospheric variability.

EJSM-Laplace will provide a comprehensive investigation of Jovian circulation from the troposphere to the upper atmosphere, to create a four-dimensional climate database of the archetypal gas giant.

Composition and chemistry. Jupiter is the product of a myriad of thermochemical and photochemical pathways (Atreya et al., 2003). Atmospheric composition determines the structures of the cloud decks; radiative energy balance influences the troposphere and middle atmosphere; and condensation processes can provide the energy required for convective dynamics. Furthermore, Jupiter's bulk composition provides a window on the formation and evolution of the gas giant, and connects it directly to the nature of the satellite system. Primarily from UV through sub-mm spectroscopy, EJSM-Laplace will study (a) the 3D spatial distribution and variability of stratospheric hydrocarbons and exogenic oxygen-bearing species; (b) localized and non-equilibrium composition associated with discrete atmospheric features; and (c) the spatial distribution of volatiles to understand the importance of moist convection in cloud formation, lightning and chemistry.

EJSM-Laplace's survey of Jupiter's atmospheric composition will significantly advance our understanding of chemical processes in giant planet atmospheres.

<u>*Vertical structure of the atmosphere and interior.*</u> EJSM-Laplace's broad wavelength coverage from the radio to the far-UV will be used to characterize the vertical structure and coupling processes (e.g., wave propagation transporting energy and momentum; ion drag and meridional transport in the upper atmosphere) from the deep interior to the charged upper atmosphere. Studies of clouds and hazes at a range of observational geometries will constrain the global vertical structure and composition of the cloud decks and hazes from the millibar to ~5-bar level in Jupiter's atmosphere (West et al, 2004). EJSM-Laplace will determine the temperature, density, pressure and zonal wind structure from the troposphere to the thermosphere, and the charged particle distribution in the ionosphere and magnetosphere. Vertical coupling in the polar region (unique composition, auroral energy deposition, circumpolar waves and vortices, and north/south asymmetry) will be studied from the near-equatorial orbits.

EJSM-Laplace will study Jupiter's atmosphere as a coupled system, connected to both the deep interior and the immediate planetary environment, as a paradigm for gas giants in our solar system and beyond.

Finally, detection of internal waves that connect the troposphere to the interior of Jupiter would complete the picture that EJSM-Laplace could give of the Jupiter atmosphere from the uppermost layers to the deep interior. The challenging detection of internal oscillation modes (Jovian seismology) is one of the potential sources of activity observed in the upper layers, whose characterization by EJSM-Laplace might be a unique goal complementary to the data that will be returned by the JUNO mission.

<u>Outstanding questions that will be addressed by EJSM-Laplace</u>

A. Atmospheric dynamics and circulation
- How is the deposited solar energy redistributed in the Jovian atmosphere and what dynamical processes are involved in the energy transfer between atmospheric layers?
- How are localized processes (lightning, discrete vortices) on Jupiter related to the dynamics of the atmosphere?
- What is the time-variable three-dimensional flow field and how important is wave activity in the global circulation of Jupiter?

B. Composition and chemistry
- How is the spatial variation of composition of condensables related to the meteorology?
- How do non-equilibrium species vary spatially and relate to the global circulation?
- What is the composition of the stratosphere and how is it related to dynamical processes and photochemistry?

C. Vertical structure and interior
- What is the nature of coupling processes between Jupiter's deep interior and upper layers?
- What is the altitude, thickness and composition of the clouds and colored chromophores in the atmosphere of Jupiter ?
- What are the processes responsible for the formation of upper atmospheric haze at high latitudes?

4.3 The Magnetosphere and Magnetodisc

The EJSM-Laplace dual spacecraft mission offers the first opportunity to study the 3-D properties of the magnetodisc, plasma sources and mass loading coupling processes

<u>Overview: the outstanding properties of the Jovian magnetosphere</u>

The strong internal magnetic field of Jupiter (equatorial surface intensity of 4 Gauss) creates the largest and fastest rotating magnetosphere in the solar system. With an average subsolar magnetopause distance of 75 R_J, the magnetosphere rotates in less than 10 hours about its rotation axis. It is driven by the fast rotation of its central spinning object, Jupiter.

Its major plasma source is the volcanic moon Io, deep inside the magnetosphere, which releases about 1 ton/s of oxygen and sulphur and feeds with this Iogenic plasma an equatorial magneto-disc extending out over 100s of planetary radii. The Jovian magnetosphere is the most accessible environment for direct in-situ investigations of processes regarding: (i) the stability and dynamics of magneto-discs, and more generally, angular momentum exchange and dissipation of rotational energy (the 'fast rotator' theme), (ii) the electro-dynamical coupling between a central body and its satellites (the 'binary system' theme) including plasma/surface interactions, transport processes and turbulence in partly ionized media. Jupiter is also a powerful particle accelerator, its inner magnetosphere being the most severe radiation environment in the Solar System.

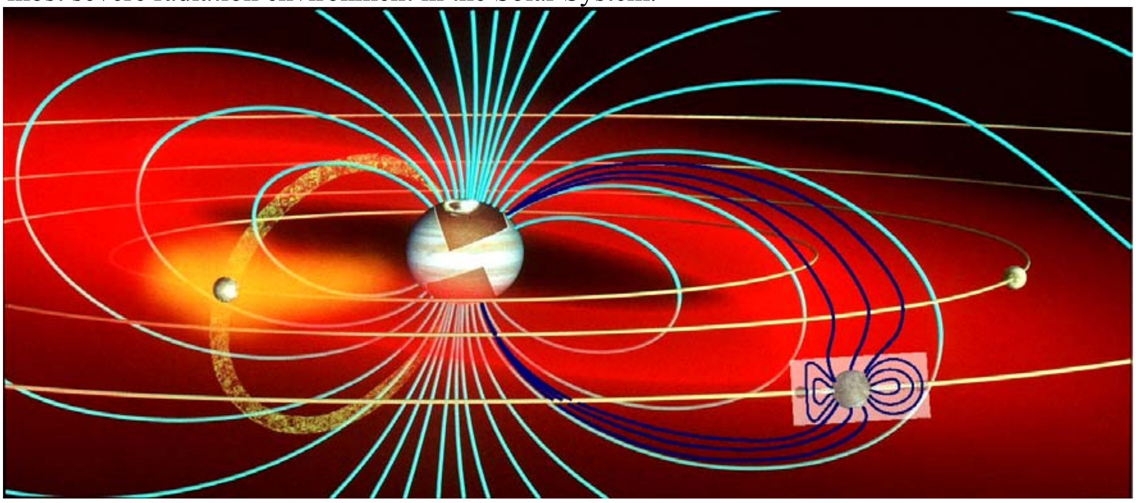


Figure 4-13. *Main objectives of EJSM-Laplace for the study of the Jovian magnetosphere. The scientific return of the mission is significantly enhanced by the opportunity to conduct dual measurements.*

EJSM-Laplace, providing for the first time the opportunity to conduct dual measurements in the Jovian system, will study the dynamics of the Jovian magnetodisc (with angular momentum exchange and dissipation of rotational energy), determine the electro-dynamic coupling between the planet and the satellites, and assess global and continuous acceleration of particles (Figure 4-13).

Science Objectives

The magnetosphere as a fast rotator. The magnetosphere of Jupiter has been traditionally divided into inner (<10 R_J), middle (10-40 R_J) and outer (>40R_J) magnetosphere. The inner region contains the synchrotron radiation belt of Jupiter ($1.1 < r < 3$ R_J) formed by energetic electrons gyrating around in the strong magnetic field and having energies in the range of a few tens of MeV to several hundred MeV. The inner region is also the location of the main plasma source of the magnetosphere, namely Io. It is believed that plasma is transported outwards from the inner magnetosphere by an interchange instability driven by centrifugal stresses (Brice and Ioanidis, 1970; Michel and Sturrock, 1974; Kivelson et al., 1997; Khurana and Schwarz, 2005). Further out, in the middle magnetosphere, the magnetic field becomes highly stretched as it acts to contain the plasma against the strong centrifugal and thermal pressure forces. The plasma temperature is quite high (>10 keV) and it is not fully understood what process or processes are responsible for energizing the warm plasma of the torus to such high values. In this region, the plasma corotation with Jupiter's magnetosphere gradually breaks down because the poorly conducting ionosphere of Jupiter is not able to impart sufficient angular momentum to the outflowing plasma. The radial currents, which enforce corotation on the magnetospheric plasma, generate aurorae in the Jovian ionosphere by accelerating electrons into the ionosphere from the action of large field-aligned potentials. In the outer magnetosphere, the azimuthal plasma velocity lags corotation by a factor of two or more. The outer magnetosphere on the dayside is extremely squishy. Depending on the solar wind dynamic pressure, the dayside magnetopause can be found anywhere from a distance of ~ 45 R_J to 100 R_J (Joy et al., 2002). An extremely disturbed region, known as the "cushion region", with a radial extent of ~ 15 R_J was discovered adjacent to the noon magnetopause in the magnetic field observations from Pioneer and Voyager spacecraft. It is not yet known whether this region is a permanent or a temporal feature of the magnetosphere. Finally, in the nightside outer magnetosphere, an additional current system exists that connects the magnetodisc current to the magnetopause currents. This current system creates a long magnetotail (length > 7000 R_J), which extends to the orbit of Saturn.

The fast rotation of the planet combined with the continuous supply of ion populations from Io's volcanism lead to the formation of a neutral and ion torus, and further out, of a magneto-disc. In the inner magnetosphere, the warm and cold plasma of the torus is confined to the centrifugal equator, a surface defined by the loci of points where each field line reaches its farthest distance from the rotational axis of Jupiter. Further out in the middle magnetosphere, the plasma subject to the mirror force collects in the region of field strength minimum (magnetic equator). In the outer magnetosphere, the magnetodisc essentially becomes parallel to the solar wind flow direction in the magnetotail. Observations show that the magnetodisc is extremely thin in the dawn sector (half thickness ~ 2 R_J but has a half-thickness exceeding 10 R_J in the dusk sector.

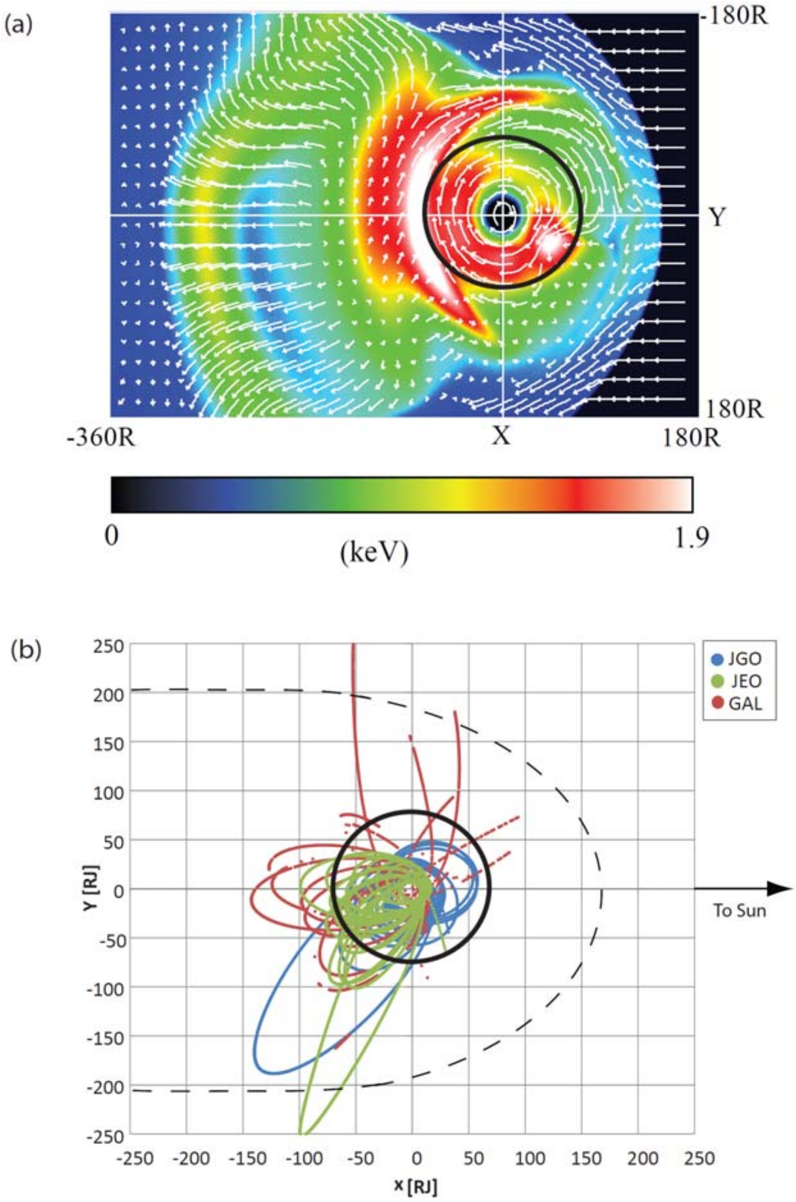


Figure 4-14.

a)*. This figure shows MHD model results for the temperature per AMU (as indicated in KeV by the colour bar), and plasma flow vectors (white) in the dawn-dusk meridian plane of Jupiter's magnetosphere. The figure shows the results for a solar wind dynamic pressure of 0.01 nPa and 0.105 nT IMF. Superposed is an example region (black circle) where the JGO or JEO spacecraft are expected to reside. This emphasises the importance of two spacecraft measurements in the magnetosphere, given the difference in the environment within this black circle at different local times. Adapted from Fukazawa et al. (2005).*

b). *A schematic showing the equatorial plane and the trajectories of JEO (green), JGO (blue) in comparison with Galileo orbits where particle data exist (red). The size if the magnetosphere is indicated by the black dashed line, representing a typical location of the bow shock. A similar black circle is show in panel (b), for comparison with the model results in panel (a).*

Various processes contribute to the radial transport of newly-formed plasma, from the Io torus to the external magnetosphere and to the interplanetary medium: microscopic diffusion, meso-scale interchanges, global sporadic disruptions and reconfigurations of the disk, magnetic reconnection...

The chain of processes involved in these phenomena, most likely common to any magnetized systems combining fast rotation and radial transport is still not quantified. Their full description and understanding at Jupiter will have immediate implications for other astrophysical disks. Their scales, temporal and spatial, are the fundamental parameters to determine, as they characterize the dynamical processes at work and guide any theoretical or simulation analysis.

EJSM-Laplace will investigate the global configuration and dynamical behaviour of Jupiter's magneto-disc along its trajectory inside the system. Simultaneous measurements of JEO and JGO will be particularly important (Figure 4-14).

The magnetosphere as a giant accelerator. The dynamics of Jupiter's magnetosphere is far from understood. The huge dimensions of the magnetosphere and the wealth of processes in the different regions makes it quite challenging to distinguish between them. Most of the knowledge we have about those processes stem from in-situ measurements inside the magnetosphere obtained by the *Galileo* spacecraft between 1995 and 2003 covering the regions especially in the Jovian magnetotail as far out as 150 R_J. Nevertheless, this is still a very small portion of the magnetosphere with a magnetotail extending over thousands of R_J.

The dominant feature of the entire Jovian magnetosphere is the motion of the plasma in the sense of corotation in a magnetodisc configuration as described above. The corotation of the plasma is highly dependent on the distance from the planet and on local time in the Jovian system. The distance where the rigid plasma corotating breaks down ranges from 20 R_J in the dusk sector up to 40 R_J and beyond in the dawn to predawn sector of the magnetosphere. The magnetosphere is subcorotating outside that distance and reaches a nearly constant velocity independent on local time of about 200 km/s in the magnetotail of Jupiter. The subcorotating flow is disrupted by dynamic changes in the outer magnetosphere on various time scales with periods of hours up to several days. Especially in the predawn sector so-called substorm-like radial flow bursts have been observed which change the global configuration of the entire magnetosphere.

One of the dynamical processes is the radial transport of the material released from Io. In this process the plasma is transported through the entire magnetosphere first radially outward where the interchange motion plays a major role; then radially inward through diffusion processes from the outer magnetosphere into the inner part violating the third adiabatic invariant and gaining energy up to MeV. Another dynamic process in the middle magnetosphere involves particle injections where hot plasma from the outer part in being injected into colder plasma further in. Finally in the outer part of the magnetosphere reconnection of magnetic field lines and associated particle acceleration takes place and influence the particle dynamic inside the magnetosphere.

EJSM-Laplace will significantly enhance our knowledge of the processes occuring in the magnetosphere with better time resolution, better directional information and especially with ability of simultaneous measurements in different regions of the magnetosphere (Figure 4-14).

Outstanding questions that will be addressed by EJSM-Laplace

A. The magnetosphere as a fast rotator

- What determines the shape and variability of a spinning mass-loaded magnetodisc?
- What mechanisms control the dissipation of angular momentum and rotational energy?
- What are the associated transport, acceleration and radiation processes?
- How do the global magnetospheric structure and activity depend on solar wind effects and mass-loading processes?
- How do the different electromagnetic emissions diagnose the state of the magnetosphere?
- How is energy transferred in the coupled thermosphere/ionosphere/magnetosphere system?

B. The magnetosphere as a giant accelerator

- Where do the high energy particles in the Jovian radiation belts come from?
- How are they produced in the most intense radiation environment in the Solar System?
- How do they affect moons (their surfaces, tenuous atmospheres/exospheres) and what are the effects in terms of habitability?

4.4 Io, Callisto, and Other Satellites

The EJSM-Laplace will characterize the moons and rings, yielding the pieces of information needed to constrain theories of the origin and evolution of the system.

Overview: A thorough study of the Jovian satellite system

The four Galilean Satellites, Io, Europa, Ganymede, and Callisto are very diverse with respect to their chemical composition, surfaces, internal structure, evolution, and their degree of interaction with Jupiter (Figure 4-15). In addition to the very thorough studies of Ganymede and Europa which have been described in the previous sections, EJSM-Laplace will explore in great details Callisto and Io.

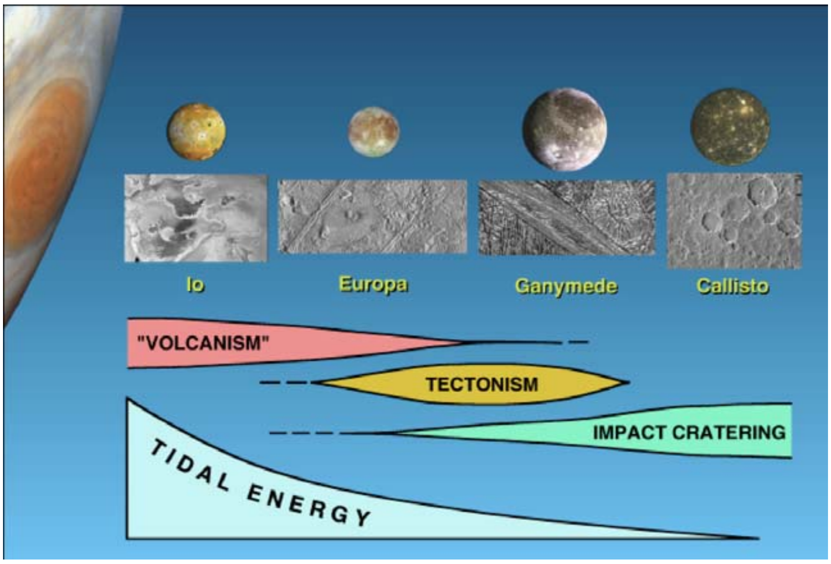


***Figure 4-15.** The diversity of processes and the degree of activity in the Jupiter system follows regular trends that are presumably closely related to the availability of tidal energy. The latter significantly decreases with increasing distance from Jupiter (Figure: R. Greeley).*

The bulk density decreases with increasing distance from Jupiter. This indicates different chemical compositions ranging from silicate rock + iron at Io to a 50% ice and silicate rock + iron mixture at Callisto. This trend reflects the conditions (mainly temperature) within the protojovian nebula at the time the satellites formed (Stevenson et al., 1986). However, this stands in contrast to the Saturn system which is lacking such trends. By studying all four Galilean moons, we seek to understand the relatively smooth evolution of such a regular satellite system from its origin to the present diverse surfaces and internal structures of the Galilean Moons related to their different energy budgets.

By studying Io, Callisto, and small bodies in addition to Ganymede and Europa, a broad variety of processes that has led to vigorous volcanism (Io), subsurface water oceans (Europa, Ganymede, Callisto), tectonism of icy surfaces (Europa, Ganymede), intrinsic magnetic field generation (Ganymede), early cratering record and erosion processes (Callisto) will be explored by EJSM-Laplace.

Tenuous rings are a distinct class of solar system structure that engenders considerable interest about its origin, dynamics and evolution. In all giant planets, small moons are intimately intermixed among the rings and may act as both sources or sinks for ring material. The Jovian ring system is faint and consists mainly of dust, and it can provide some clues about the origins of the Galilean moons.

EJSM-Laplace will study the diversity of the satellite system and the complex coupling processes in the Jovian environment that are key to understanding the evolution of the satellites.

Science objectives

Callisto as a witness of the early Jovian system. Callisto's geology is dominated by impact craters and surface degradation (Figure 4-16). The global true color image of low-resolution *Galileo* SSI images shows an old densely cratered surface with large multi-ring structures, such as Valhalla, characterized by bright circular spots in their centers and a large number of concentric troughs and/or ridges. Sublimation degradation of bright, topographically high-standing landforms, e.g. crater rims, is mainly caused by solar insolation changing over each diurnal cycle (16.689 earth days) and supported by compositional differences in the icy crust, and zones of weaknesses created by early tectonism (e.g. Moore et al. 2004). ***Imaging data of Callisto's surface is still sparse on regional and local scales. This will be significantly improved by mapping the surface at different resolutions with EJSM-Laplace during the Callisto flyby phases.***

Callisto also shows a strong signal of an induced magnetic field, presumably generated within a subsurface ocean (Khurana et al., 1998). ***Constraints on ice thickness and ocean characteristics on Callisto will be derived from magnetic field measurements at multiple frequencies and possibly from detecting the time-variable changes in the gravity field***.

In contrast to Ganymede, which is similar in bulk composition and size, Callisto is only partially differentiated (e.g., Schubert et al., 2004). Whether this different evolution is a consequence of the conditions in the Jovian sub-nebula or of later events (e.g., capture of Ganymede in the Laplace resonance) remains to be investigated.

EJSM-Laplace will address this issue mainly by gravity field, shape, and induced field measurements in different flyby geometries with both spacecraft. On the basis of improved gravity data in combination with the data on the induced magnetic fields, it will be possible to constrain the radial distribution of rocks, ice and liquid water.

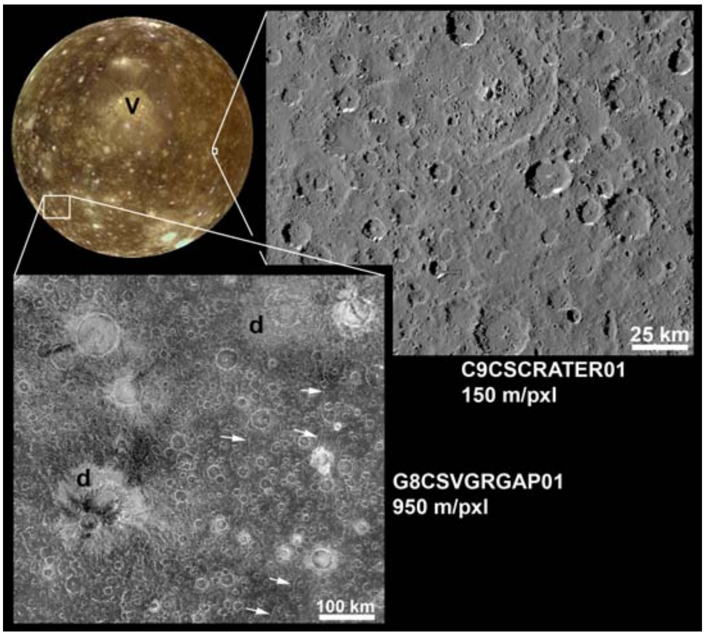


Figure 4-16. *Galileo images of Callisto. Upper left: Old densely cratered surface of Callisto with large multi-ring structures, such as Valhalla (V). Lower panel: SSI medium resolution image of a cratered plain including dome craters (d) and ring arcs of old, degraded multi-ring structures (arrows). Rigth panel: SSI high resolution image revealing the high state of surface degradation driven by sublimation.*

Callisto's surface composition is thought to be broadly similar to its bulk composition. Non-water-ice compounds include Mg- and Fe-bearing hydrated silicates, CO_2, SO_2, and possibly ammonia and various organic compounds (Moore et al., 2004; Showman and Malhotra, 1999), with abundances greater than those reported on Ganymede, and with an extreme heterogeneity at the small scale (1-10 km). CO_2 of varying concentrations appears to exist almost everywhere with slightly higher abundance on the trailing hemisphere, and in the interior, the rim and the ejecta of the impact basins and craters, with the youngest craters showing the largest abundance (Hibbitts et al., 2002). Since the impactor bodies cannot be the source of CO_2 as this compound would rapidly sublimate, trapping structures (e.g., ice clathrates, physisorption) which form a stable underground reservoir of CO_2 are envisaged.

EJSM-Laplace will have the ability to map a large portion of the surface of Callisto (Figure 4-17), acquiring high-resolution imaging and spectral data of selected targets in the overall range from 0.1 to at least 5 μm, which will allow a reliable identification of non-ice materials. Particle instruments will also be used during closest approach to sample volatile composition coming from

the surface. In particular, EJSM-Laplace will investigate the intriguing mechanism of replenishment of CO_2 taking place on Callisto.

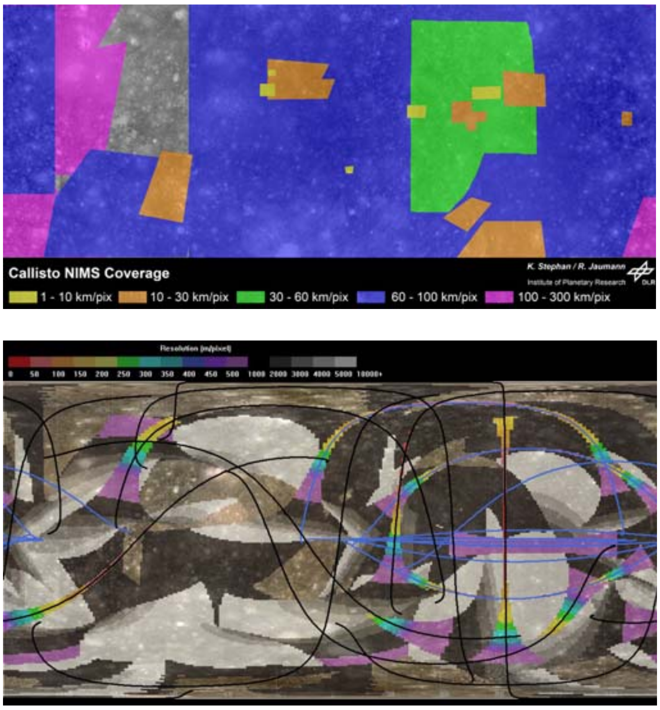


Figure 4-17.
<u>Upper panel:</u> coverage of Galileo/NIMS data on Callisto, superimposed to an optical mosaic by the Galileo/ISS camera. The colour code is related to the spatial resolution (yellow = best, blue = worst). Credits: K. Stephan and R. Jaumann, DLR.
<u>Lower panel:</u> Planned coverage of Callisto by VIS-IR spectrometers onboard JEO and JGO. Blue tracks are by JEO and black tracks are by JGO. The colour code of the imaged surface is related to the spatial resolution (red = best, grey = worst). Credits: R. Lock and E. Sturm, NASA/JPL

<u>*Study Io's active dynamic processes.*</u> Despite its relatively small size, Io is the volcanically most active body in the solar system (Figure 4-18). Its geology is dominated by widespread volcanism, driven by tidal forces. Most of the 400 volcanoes are paterae (caldera-like collapse depressions). Only few topographic edifices such as shields or stratovolcanoes are identified. Large lava flows reach lengths up to 300 km (e.g. McEwen et al., 2004). It is assumed that silicate volcanism is dominant at thermal emission enhanced hot spots, while secondary sulphur volcanism may be important at certain places (e.g. Greeley et al., 1984; Carr et al., 1998; McEwen et al., 2004) and is responsible for the dominance of SO_2 in Io`s atmosphere. Eruptions on Io can either last for many years or be very short. Long duration eruptions originate from paterae or fissures producing large lava flow fields or from central vents with gas plumes (S_2 as well as SO_2) . Short-lived eruptions display dark lava flows typical of high eruption rates and pyroclastic deposits. Rugged mountains appear as isolated peaks with heights ranging from a few to ~18 kilometers suggesting dominantly silicate structures, rather than sulfur-rich edifices.

Io's colorful appearance is the result of various materials produced by its extensive volcanism. Io contains little to no water, though small pockets of water ice or hydrated minerals have been tentatively identified (Douté et al., 2004). Io's surface is largely dominated by sulphur species: in particular, SO_2 frost is omnipresent (e.g. Douté et al., 2001), but there is also evidence for S_2, SO, SO_2 gas and NaCl erupted from plumes (Lopes and Spencer, 2006), as well as indications of Fe-bearing salts, silicates (feldspars and pyroxenes) consistent with high-temperature lava flows, FeS_2, and iron sulfide minerals.

EJSM-Laplace will determine the composition of different materials on the surface of Io through multi-wavelength imaging spectroscopy (in the overall range from 0.1 to at least 5 μm) and particle instruments, and it will characterize their bulk properties in a wide range of spatial scales, allowing reliable correlation with geologic features, particularly volcanic calderas.

Io's thermal activity is driven by tidal heating. Constraints on Io's dissipation rate which is closely linked to Io's thermal-orbital evolution can be derived from Io's surface heat flow.

EJSM-Laplace will investigate the nature and magnitude of tidal heating and heat loss on Io by measuring the thermal emission of the satellite. Further constraints on Io's evolution will be provided by determining global shape and gravity field from different flyby geometries.

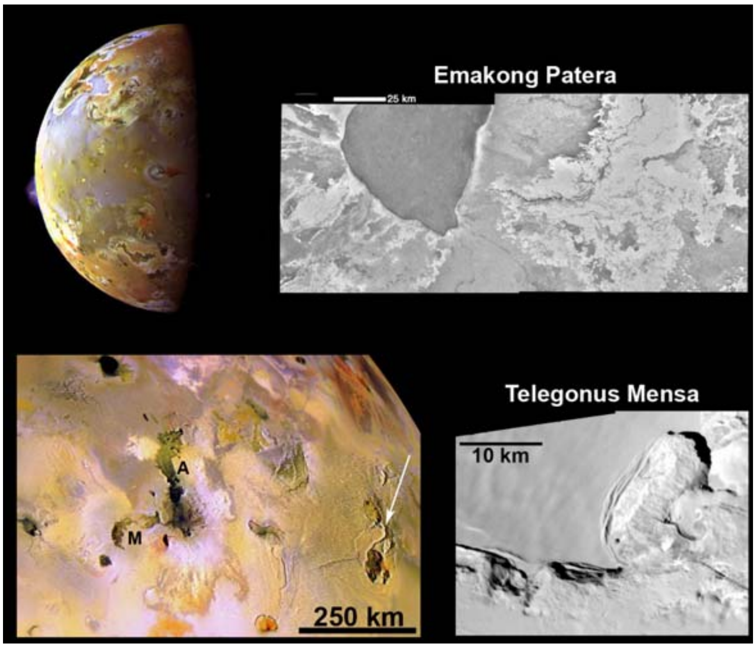


Figure 4-18. *The complexity of Io's geology. Upper left: Io's colored surface, caused by deposits of allotropes of sulphur and sulphur dioxide, and active plumes (limb on the left). Volcanic activity is indicated by lava flows such as those of Maui (M), Amirani (A), or from Emakong Patera, (lower left panel and upper right panel). Mountains are ubiquitous. Their heights can reach up to 18 km (lower left panel, arrow). High resolution images indicate active erosion and degradation processes (lower right panel - detail from Telegonus Mensa).*

<u>Study the rings and small satellites.</u> Jupiter's ring system is faint and consists mainly of micron-sized dust. It has three components. The main ring is the brightest one and is < ~30 km thick. Near its inner boundary at about 1.71 R_J, it expands into the vertically extended *halo* (Showalter et al. 1987; Ockert-Bell et al. 1999). Two "*gossamer*" rings stretch beyond the main ring, one immediately interior to Amalthea, another one interior to Thebe (Esposito, 2002; Ockert-Bell et al., 1999). Total mass of the ring system (including unresolved parent bodies) is poorly known, but it probably lies in the range from 10^{11} to 10^{16} kg. The composition of its components is uncertain due to lack of high-resolution, high signal-to-noise data in the near infrared range up to 5 µm. The age of the ring system is also unknown, but it may have existed since the formation of Jupiter. Small particles are readily destroyed by various processes in the Jupiter's fierce environs, and thus faint rings must be continually replenished from a population of parent bodies if they are long-lived features.

EJSM-Laplace will characterize the physical and chemical properties of Jupiter's rings, identifying the processes that define the origin and dynamics of the ring dust in all of the main components and characterizing their fine structure. To achieve this goal, global imaging of the entire ring system in 3D and in a wide range of solar phase angles (including <10° and >170°) is needed, as well as multiwavelength mapping of the ring particles' composition and photometric behaviour in the spectral range from 0.1 µm to at least 5 µm. The vertical structure of the main ring will also be determined through radio science measurements.

The small, regular satellites Thebe, Amalthea, Adrastea and Metis, revolve in the inner region of the Jupiter system ranging from 1.8 to 3.1 R_J, largely embedded in the Jupiter's ring system. They are believed to be parent bodies of the ring material (Burns et al., 1999). The leading sides of Thebe, Amalthea and Metis are significantly brighter than their corresponding trailing sides, suggesting that a common mechanism is governing the global albedo patterns (Thomas et al., 1998; Simonelli et al., 2000). Almathea and Thebe may have formed by accretion from the circumjovian nebula and should be composed of refractory, high-density materials (Pollack and Fanale, 1982). However, Amalthea's density is less than that of water (Anderson et al., 2005) and the moon shows deep, broad 3-µm signature diagnostic of hydrous minerals or organic materials (Takato et al., 2004), indicating that it cannot have formed in its current position, since the hot primordial subnebula would have melted it. Moreover, it has been argued (Hamilton et al., 2001) that both Amalthea and Thebe attained their relatively large inclinations during past resonant interactions with Io; these took place as the latter satellite evolved outward due to tidal interactions with Jupiter. The composition of the other ring-moons is largely unknown to date.

EJSM-Laplace will shed light on the physical shape and bulk composition of these small moons (at least the largest objects, Thebe and Amalthea), investigating the individual relationships between the inner moons and the ring system and constraining the origin of these bodies. EJSM-Laplace will also improve their orbital elements and look for new smaller moonlets.

In the framework of the processes shaping the moons of the giant planets, the most important influence the irregular satellites can have is that of contaminating the surfaces of the Galilean satellites, introducing exogenous elements with potentially different compositional features. The nature of the contaminants delivered depends on the composition of the irregular satellites, which is strictly linked to the formation regions of their parent bodies.

EJSM-Laplace will perform high-resolution imaging and multiwavelength spectroscopy of a satellite's surface, ideally during a close fly-by in the approach phase to Jupiter, otherwise with less demanding full-disk observations.

Outstanding questions that will be addressed by EJSM-Laplace

Callisto

- Is there a subsurface ocean on Callisto? How did it evolve?
- How thick is the ice-layer, and does liquid water exist within the ice?
- How are rock and ice distributed within Callisto's interior?
- What are the non-water ice components at the surface on Callisto and where are they most linked to the interior and exosphere?
- Are hydrated salt minerals and ammonia present on the surface of Callisto?
- What is the mechanism that allows CO_2 on Callisto to be continuously replenished and what are the rates of sublimation-degradation?
- How much material is exogenic? Where does it come from (Io and / or the outer Jovian system)?

Io

- What is Io's global heat flow and how is it related to the present-day tidal heating rate and how does the volcanic activity on Io vary spatially and on various timescale (minutes to x10 years)?
- What silicates are exactly present and is there evidence of hydrated minerals and iron sulfides?
- How variable is Io’s atmosphere (temporally and spatially) and does it drive plasma torus variability?

Small bodies and rings

- What is the origin and the physical nature of the irregular satellites?
- Are the small inner satellites the source of the material composing Jupiter's rings?
- Are there other smaller ring-moons revolving in the Jupiter system?
- Does the ring system evolve and, if so, on which timescale?
- What is the chemical composition of the three components of the ring system?
- What are the physical properties of the ring particles?

4.5 *Transverse Themes*

EJSM-Laplace will study the complex coupling processes in the Jovian environment that are key to understanding the evolution of the satellites.

4.5.1 Coupling Processes in the Jupiter System

Gravitational coupling – the Laplace resonance

Io, Europa, and Ganymede are locked in a mean-motion resonance unique in the solar system, the so-called Laplace resonance in which the orbital periods of the satellites are in the ratio 1:2:4 (Figure 4-19). It is still unclear how and when the resonance formed. A primordial origin was suggested by Peale and Lee (2002) and earlier by Greenberg (1987). An alternative is the 'classical' scenario (Yoder 1979; Yoder and Peale, 1981) in which the resonance is formed by more rapid tidal migration of the inner satellites and subsequent capture into resonance of the outer moons. ***By studying the tidal response of Ganymede and Europa, combined with astrometric observations, EJSM-Laplace will constrain possible evolution scenarios.***

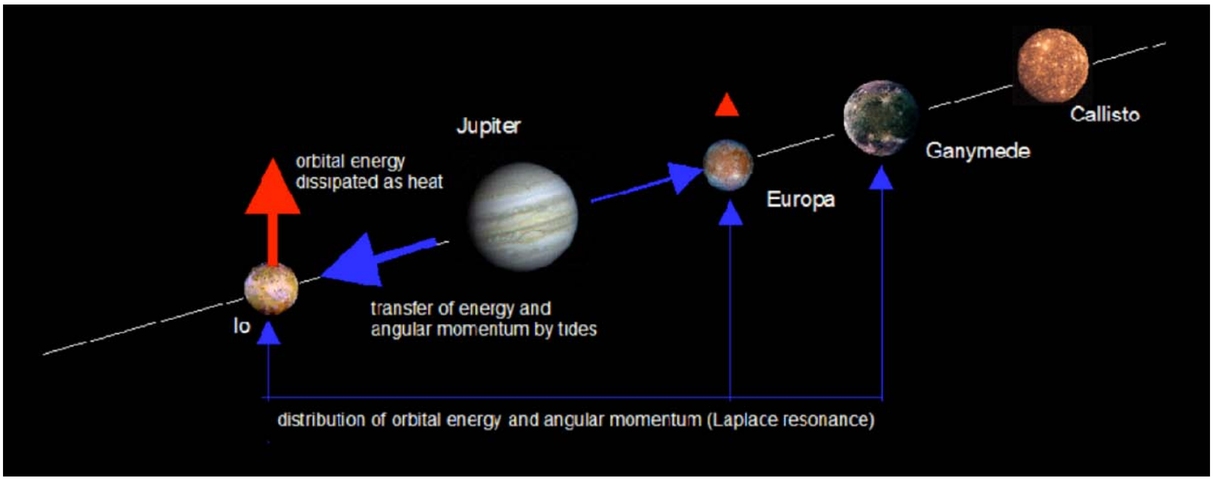


Figure 4-19. *The rotational energy of Jupiter is a huge reservoir of energy for the three inner Galilean satellites. Orbital energy gained by Io due to tidal torques exerted by Jupiter is distributed among Io, Europa, and Ganymede, due to the Laplace resonance. The resonance is therefore essential for ongoing tidal heating inside Europa, and may allow for the existence of an ocean inside Europa over billions of years.*

The Laplace resonance between Io, Europa and Ganymede plays an essential role in the redistribution of rotational and orbital energy between the Galilean moons and Jupiter and also in the tidal dissipation in the satellites since it maintains finite orbital eccentricities, required for tidal interactions, on geological timescales. As tidal dissipation can be an important heat source for the satellites, and is by far the largest energy source for Io, gravitational interactions can also drive the internal dynamics and the evolution of the satellite's interior and surface. Understanding the gravitational interactions between Jupiter and the Galilean satellites is therefore essential for many aspect of Jupiter system science, including the habitability in the subsurface oceans. In particular, the evolution of the Laplace resonance may be important for the future of volcanism on Io and for the subsurface oceans of Europa and Ganymede. A recent analysis of astrometric ground-based observations of the Galilean satellites (Lainey et al., 2009) suggests that Io is currently moving inwards to Jupiter whereas Europa and Ganymede are moving away from Jupiter and that the system is evolving away from the exact Laplace resonance.

EJSM-Laplace will complement the ground-based astrometric observations to accurately quantify tidal energy dissipation in the satellites and Jupiter, and provide new constraints on the evolution of the system.

Magnetospheric coupling

Electromagnetic coupling processes occurring within the Jovian magnetosphere may be divided into two categories: i) the processes which are the result of coupling between the planet, its rapidly rotating magnetosphere and the satellites (e.g. Io, Europa, Ganymede, and Callisto); ii) the processes which result due to the large-scale coupling between Jupiter and the magnetically connected solar wind-magnetosphere-ionosphere system.

In the first case, the Galilean moons interact with the field and plasma of the Jovian magnetosphere over many spatial scales. The interactions change the plasma momentum, temperature, and distribution function, and generate strong electrical current systems. Important intrinsic properties of the moons affect the interactions with the plasma that flows onto them, and simultaneously, the properties of the Jovian plasma at the orbit of the moon also affect the interaction. One of the most interesting interactions that takes place in this regard, is the interaction between Jupiter's magnetosphere and Ganymede. The internally generated magnetic field of Ganymede extends beyond the surface of the moon, and allows the creation of a miniature magnetosphere embedded within the rapidly rotating Jovian magnetosphere (as discussed in previous sections). The *Galileo* mission has provided much new information on the above properties and allowed many breakthroughs in our understanding, but there remain many open questions as we learn more about these complex interactions.

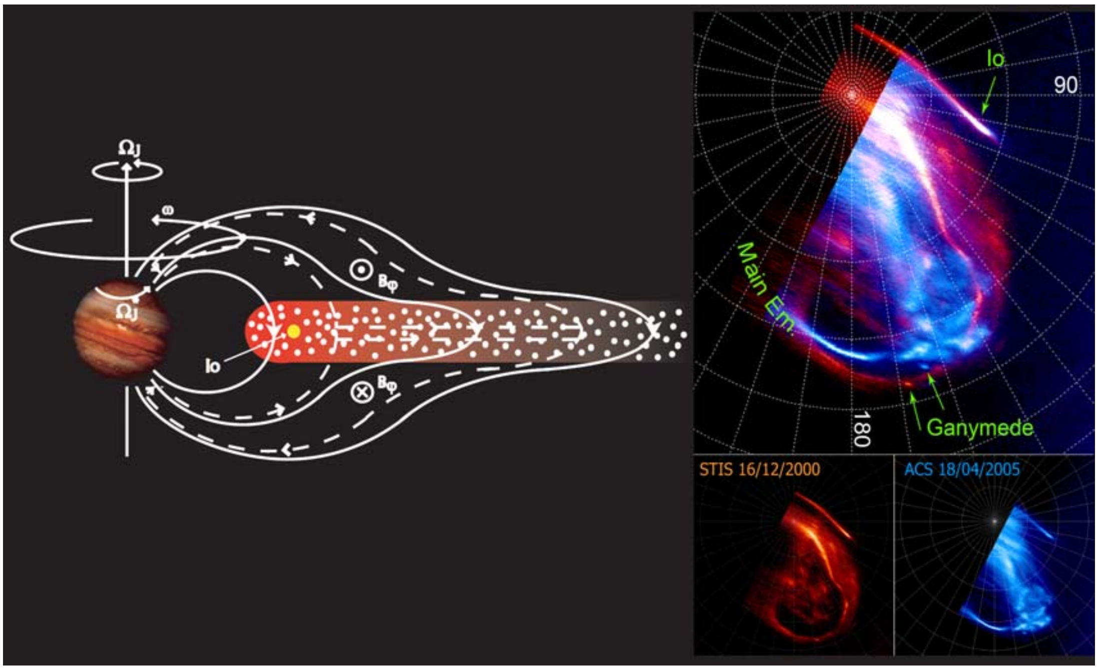


Figure 4-20. *Left: The magnetosphere-ionosphere coupling current system (After Cowley and Bunce, 2001).* ***Right:*** *The main auroral emissions, including the magnetically mapped moon footprints (Grodent et al. 2008).*

In the second case, Jupiter's middle magnetosphere is dominated by the effects of the rapid rotation of the planet. The magnetosphere-ionosphere coupling current system (Figure 4-20) is set up due to the sub-corotation of magnetosphere plasma, and generates a large-scale current system which links to the ionosphere via field-aligned currents. The upward currents in the magnetosphere-ionosphere coupling system are thought to relate directly to the main auroral emissions in Jupiter's atmosphere (see Cowley and Bunce, 2001), and as such the dynamics of the middle magnetosphere can be viewed through combined in situ plasma sheet and remote auroral observations.

In all cases, the interactions result in magnetic field perturbations, plasma signatures, radio waves, and/or auroral emissions (at UV, IR, visible, X-ray wavelengths). Analysis of previous data (e.g. Galileo), remote observations (e.g. Hubble Space Telescope (HST), Chandra/XMM, IRTF/UKIRT, and/or radio telescopes), and theoretical modeling and simulation studies are the main source of data in this field. However, there are major gaps in temporal coverage and spatial resolution.

EJSM-Laplace will provide systematic and long term investigations of the coupling processes in the Jupiter magnetosphere by measuring parameters of plasma and waves and monitoring aurora by two spacecraft.

Outstanding questions that will be addressed by EJSM-Laplace

Gravitational coupling

- How large are the tides of the Galilean satellites?
- Are the Galilean satellites rotating synchronously with their orbital motion?
- Do the Galilean satellites move inwards to Jupiter or away from Jupiter?
- Are Io, Europa, and Ganymede evolving away from the exact Laplace resonance?
- How important is the tidal heating of the Galilean satellites?

Magnetospheric coupling

- What is the origin of Ganymede's auroral emission, and how does it relate to the extent of the exosphere?
- How does the surrounding particle and field environment affect the surfaces of Ganymede and Europa?
- What drives the complex variability in the moon-magnetosphere coupling current systems, both locally and at the magnetically mapped moon footprints in Jupiter's ionosphere?
- How do the different components of Jupiter's auroral emissions relate to dynamics in the magnetosphere and/or solar wind?

4.5.2 Origin and Formation of the Jupiter System

One of the most important subjects of Solar System studies is the investigation of the processes which led to the formation of the gaseous giant planets and their satellite systems. ***EJSM-Laplace will supply new crucial information to address this topic by providing an unprecedented understanding of the internal structure and the surface properties of the Galilean satellites (especially Europa and Ganymede). EJSM-Laplace will allow us to infer the bombardment history on the Galilean satellites and to comparatively study the composition of the Jovian satellite system. This will include a chance to study one of the irregular satellites, which may be the remnants of the population of planetesimals from which Jupiter's putative core accreted.*** Along with a better understanding of Jupiter's composition, all these elements will combine together to improve our knowledge of the environment, i.e. the Solar Nebula and the Jovian sub-nebula, from which Jupiter and its satellites formed.

Chronology of events. The study of the impact craters, their sizes and distribution provides important information about the age of the surfaces of the satellites and helps to comprehend the evolution of the early Solar System, in particular the reality and the characteristics of the Late Heavy Bombardment that has been suggested to be triggered by the combined effects of the migration of the giant planets and their interactions with the residual planetesimal disk (Tsiganis et al., 2005). ***The cratering record on the surfaces of the satellites, which is crucial to understand the history and the chronology of the Solar System, will be thoroughly addressed by EJSM-Laplace due to its high imaging capabilities.***

From internal structures to models of evolution. Gravity and laser altimeter investigations from the quasi-polar, low circular orbits of JGO and JEO will strongly improve our knowledge of internal structure of Ganymede and Europa. Moreover, the limited dataset supplied by *Galileo* on Callisto will be significantly complemented by non-equatorial JGO fly-bys of the moon. The internal structures of the Galilean satellites result from their complex thermal histories that are in turn related to the amount and the nature of energy sources that were present during their evolution. As an example, if short-lived radioactive elements need to be included in the evolution modeling to explain the present internal structures that will be revealed by EJSM-Laplace, this will provide huge constraints on the processes and timescales of formation of the satellites and of the Jovian system as a whole. ***EJSM-Laplace will provide new constraints on the internal structure of the moons***.

Knowledge of the internal mass distribution and density profile of Jupiter is mandatory to determine the existence and the characteristics of the planetary core, which in turn would help solve the controversy between the two competing scenarios for the formation of giant planets (see Coradini et al., 2010, and Lunine et al., 2004; Coradini, Magni & Turrini, 2010, and references therein). To date, the internal structure of the giant planets has been investigated through the study of their gravitational momenta J_n. The contribution of EJSM-Laplace, with its model payload, to the evaluation of the Jovian gravitational momenta won't improve JUNO's measurements. But possible alternative solutions to investigate the interior of Jupiter are under evaluation. To this regard, the seismological approach is a potential new way to determine the interior of giant planets (Blanc et al., 2009; Coradini et al., 2010; §5.2.1 hereafter).

<u>*Composition constrains on the formation of the Jovian system.*</u> The physics and chemistry of the Galilean satellites can be directly related to the processes that led to the formation of the planets (see e.g. Coradini, Magni & Turrini, 2010, and references therein). Such processes are regular, and they are physically and chemically continuous. Determining the abundances of key elements can thus help in constraining the conditions in which the regular satellites system formed. ***EJSM-Laplace will investigate the ratios of stable isotopes of C, H, O, and N in the major volatile species*** (H_2O, CH_4, NH_3, CO, N_2, CO_2, SO_2, etc.). The measurement of the D/H ratio in H_2O and CH_4 is particularly important to determine the temperature at the time of the condensation processes of the satellites (see e.g. De Pater & Lissauer, 2001). In addition, to understand the origin and delivery of the volatiles, ***ion and neutral mass spectrometry in the tenuous atmospheres will give estimates of the bulk contents of the moons*** as well as sensitivity and mass resolution will allow.

The formation and survival processes of the small satellites (both inner and outer) are still unanswered questions. Some of the inner satellites, in fact, have hydrated silicates on their surface that are evidence of the presence of water. They could have formed *in situ* at some late stage of the evolution of the Jovian sub-nebula (see e.g. Coradini, Magni & Turrini, 2010) or in an outer region of the earlier Jovian sub-nebula, later migrating inward due to gas drag. They could also have been captured from the outer Solar System, again migrating to their present positions due to gas drag. ***By gathering information on the composition of Amalthea and Thebe, and possibly the other small inner satellites, EJSM-Laplace could help answering when and where such small bodies formed.***

The investigation of the outer small satellites, i.e. the irregular satellites, is of interest, in the context of EJSM-Laplace mission, for two reasons. First, this population of captured objects represents a sampling of the planetesimals which populated the early outer Solar System. Second, there is observational evidence indicating that dust generation processes take place between the irregular satellites and that the dust particles travel inwards toward the inner satellites, likely contaminating their surfaces (see e.g. Tosi et al., 2010; Coradini et al. 2010, and references within). ***Depending on the mission profile, one S/C of EJSM-Laplace may have the opportunity to investigate the composition of an irregular moon, which would add new constraints on the models of formation of the Jovian system and on the presence of exogenous material on the surfaces of the regular satellites.***

<u>**Outstanding questions that will be addressed by EJSM-Laplace**</u>

- What were the environments from which Jupiter and its satellites formed?
- How did their secular evolution modify their primordial features?
- What is the origin of the small (regular and irregular) satellites of Jupiter?
- Are inner and outer irregular satellites similar?
- What the Jupiter and satellites origin can tell us about the early Solar System?

5 Scientific Requirements and Mission Scenario

The two *EJSM-Laplace* spacecraft will carry the most powerful remote sensing and in-situ payload complement ever flown to the Outer Solar System. Following the formulation of the mission goals, this section identifies experiment techniques required to address the science objectives and translate science objectives into payload requirements in terms of resolution, coverage, sampling rate, spectral properties etc. We note that this section describes the measurement techniques outlined by the JSDT to define the model payload, but does not exclude additional or alternative ones that are worth considering during the AO process. The section also outlines the main requirements placed by science on the mission, its scenario and budgets, and the required spacecraft capabilities. The organization of this section follows that of the Science Requirement Matrix [14] and refers to it for details of the measurement requirements.

5.1 Ganymede and Europa

5.1.1 Subsurface ocean, ice shell, and interior

EJSM-Laplace investigations. Investigation of the subsurface ocean on Europa and Ganymede and its properties, ice shell and deep interiors is one of the main mission objectives that would eventually lead to important conclusions about the existence of habitable environments on the Galilean moons.

Proposed experimental techniques. EJSM-Laplace will exploit several methods to investigate the icy crusts, the sub-surface oceans, and the deep interiors of Europa and Ganymede. Oceans will be characterized by the combined observations of the gravitational tides, the surface motions, the dynamical rotation state, and the induced magnetic field. The same techniques will be used for the investigation of the deep interiors. The amount of knowledge will ultimately depend on the degree of precision that will be achieved on each measurement. ***Radio tracking*** of the spacecraft with range-rate accuracy in the range of 0.015 mm/s and 0.1 mm/s at 60 sec integration time will yield precise determination of gravity fields up to degree 12. The same technique will provide ranging from Earth to spacecraft to determine the position of the moons' centre of mass relative to Jupiter with an accuracy better than 10 m. Tidal deformations of the icy crust will be monitored by ranging the spacecraft distance to the moons' surface at crossover points globally distributed with an accuracy of 1 meter. This is achievable with ***laser altimetry*** by doing contiguous global ranging to the surface with 10-cm shot accuracy. ***Wide-angle and narrow-angle imaging*** with resolution of ~100m/px and ~10m/px respectively in combination with ***laser altimetry*** and ***radio sounding*** will be required to build an altimetry corrected network on the satellites' surfaces to characterize their dynamical rotation state (forced libration, obliquity and nutation). Finally, the magnetic induction response from the ocean will be characterized by measuring continuously the ***magnetic field vector*** with an accuracy of 0.1 nT by 8 to 32 Hz at multiple frequencies. These measurements must be supported by ***plasma and wave observations*** to constrain contribution from currents not related to the subsurface ocean.

EJSM-Laplace will study the icy shells. It will investigate their structure and their physical properties, their interaction with the ocean, and the correlation between the surface features and the subsurface. All these objectives require global mapping of the satellites by a ***radar sounder***. This has the ability to penetrate the surface and to perform a sub-surface analysis with penetration of a few kilometers (for an averaged frequency ranging within 20 and 50 MHz) with a vertical resolution of some meters. Composition mapping of the moons' surface by ***imaging spectroscopy*** in UV to IR range is necessary to complement subsurface sounding to correlate near-surface and interior processes. Characterization of the surface thermo-physical properties and heat budget require measurements in the thermal infrared and sub-mm range. ***Spectro-imaging*** at wavelengths >5 µm will measure thermal emission from the surface to characterize heat budget. ***Sub-millimeter sounding*** at longer wavelength (200-600 µm) with polarization capabilities is required to penetrate a few centimeters into the soil and derive temperature gradient in the subsurface. Combination of both techniques will characterize thermal inertia of the upper layer.

5.1.2 Geology

EJSM-Laplace investigations. For Ganymede and Europa, EJSM-Laplace will determine the formation and characteristics of magmatic, tectonic, and impact features, constrain global and regional surface ages, and investigate the processes of erosion and deposition.

Proposed experimental techniques. A suite of ***imaging instruments*** covering a broad range of parameters (field of view, spatial resolution) is required for both JGO and JEO spacecraft. ***Wide-angle imaging*** will provide context coverage of at least 80 % of the satellites' surfaces at 200 and 400 m/px for Europa and Ganymede respectively. ***Narrow angle imaging*** will investigate selected targets with spatial resolution from 20 m/px down to 1 m/px. The imaging should be supported by ***laser altimetry*** with at least 10 m vertical and better than 1 km horizontal resolution to create precise topographic maps on selected areas. The cameras should have both panchromatic and narrow band channels in the visible and near-IR range to reconstruct color images of the surface.

In order to constrain the ages of the surfaces and the erosion processes, additional techniques to those listed above should be used. The ***sub-surface radar*** sounding with the same approach described in section 5.1.1 will provide the third dimension to the geology investigations. Both UV and IR imaging spectroscopy with high spatial resolution (better than 100 m/pxl at local scale) and high spectral resolution will emphasize spectral differences between geologic features (grooves, calderas and craters) and the surrounding areas. At medium spatial resolution (better than or equal to 5 km/pixel), these techniques will also map on large areas leading/trailing asymmetries due to contamination by exogenic material. The ***particle and plasma instrument*** will contribute to investigate the processes of erosion and deposition by determining the precipitation flux of electrons and ions (with composition) in the eV to few MeV energy range.

Complementary techniques. A thermal instrument onboard JGO would make possible thermal mapping of the surface of Ganymede, which would help to constrain the geologic activity and the physical properties of the surface. This measurement could be made partly by the thermal instrument onboard JEO during the close flybys of the moon.

5.1.3 Surface Composition

EJSM-Laplace investigations. On Ganymede, the mission will characterize the surface organic and inorganic chemistry, relate material composition and distribution to geological processes, investigate the composition on open vs closed magnetic field line regions, and determine the volatile content near the moons to constrain their origin and evolution. For this purpose, EJSM-Laplace will provide nearly-global, multiwavelength spectral mapping and mass spectroscopy of the surfaces, complemented by high-resolution spectral imaging of selected targets. The composition observations will have important synergy with surface imaging and subsurface investigations that would provide geological and morphological context (section 5.1.2).

Proposed experimental techniques. ***Imaging spectroscopy*** in the broad spectral range from UV to infrared will be the main remote sensing technique of EJSM-Laplace to study the surface composition of the moons. On Ganymede, the mission goals require at least 50% of the surface coverage with resolution of 2-3 km/px and mapping of selected target sites with resolution of at least 100 m/px. Spectral resolution should be high enough to resolve characteristic features of surface ices/minerals (Dalton, 2003). Remote sensing will be complemented by ***ion and neutral mass-spectrometry and particle/ plasma analysis*** of the moons' exospheres that originate from sputtering and sublimation of surface material. This technique should allow one to measure major volatiles (H_2O, CH_4, NH_3, CO, N_2, CO_2, SO_2, etc.), stable isotopes of C, H, O, as well as the noble gases Ar, Kr, and Xe with mass resolution better than 500 and sensitivity to measure partial pressures at 10^{-17} mbar for one orbit accumulation time at Ganymede. To achieve exospheric profiling during fly-bys a sensitivity of 10^{-14} mbar would be sufficient provided the spacecraft is sufficiently clean. ***Particle analyser*** should be able to measure three dimensional distribution function of ions in the energy range ~1 eV to ~1 MeV with the 4π coverage and map directly the backscattering neutral flux from the surface in the energy range 10 eV to 10 keV at a velocity resolution better than 30% and angular resolution less than 7 degrees. ***Sub-millimeter sounding*** will support spectro-imaging investigations of the physical and thermophysical properties of the surface (grain size, porosity, thermal inertia, etc.). This technique will be especially effective if working at 200-600 μm with polarization capabilities. ***Bistatic radar*** experiment would be required to determine dielectric permittivity of the surface as well as average roughness of medium scale features.

Complementary techniques. The science return could be complemented by an extension of the infrared spectral range beyond 5 μm. This would give access to absorption bands of organic materials, provided that the SNR is sufficiently high (>30) in that spectral region.

5.1.4 Local Environment and Interaction with the Jovian Magnetosphere

EJSM-Laplace investigations. EJSM-Laplace will characterize Ganymede's intrinsic and induced magnetic field and its interaction with Jupiter's magnetosphere, investigate the particle population and its interaction with the Jupiter magnetosphere, study the aurorae, and determine the sources and sinks of the ionospheres and exospheres.

Proposed experimental techniques. The characterization of the magnetic fields requires precise measurements of ***3 axis magnetic and electric field*** vectors with high sampling frequency, combined with ***plasma and wave observations,*** and in broad range of distances to the moons. ***Measurements of thermal plasma and energetic particles***, including ***neutral imaging of impacting and ejected plasma*** will play an important role.

The processes of particle acceleration, transport, and interaction with the moon cause auroral emissions, the study of which requires combination of remote sensing and *in situ* techniques. In addition to the in situ technique, ***multi-wavelength monochromatic and spectral imaging*** in the range from 0.1 to at least 5 microns of aurorae at 1-min temporal resolution and maximum spatial resolution will be utilized.

The study of tenuous atmospheres requires ***imaging spectroscopy*** from UV to IR (0.1- to >5 microns). These techniques will provide column densities of atmospheric species at better than or equal to 1 km spatial resolution , and will constrain the amount of some specific compounds from limb scans and during stellar occultations. This investigation also needs ***sub-millimeter observations*** to characterize the vertical temperature profile from ground to 300- to 400-km altitude with about 5 km vertical resolution by multiple water line observations in the 500- to 600-μm and 230- to 270-μm wavelength range and also to map the concentration of water vapour. It will be complemented by ***ion and neutral mass spectrometry*** of plasma particles, ***radio occultations*** to measure the neutral atmosphere and ionosphere, and ***plasma wave measurements*** to constrain plasma density and temperature of the ionosphere.

5.1.5 Requirements to the Mission

Most of the objectives described above will be fulfilled during the dedicated phases of JEO and JGO around Europa and Ganymede, respectively. The observation techniques impose certain requirements during these phases, which are discussed below. All these constraints have been taken into account for defining the best observation strategies during the dedicated phases [11].

Illumination: ***Imaging*** needs optimal illumination conditions, i.e. β-angle (angle between the orbital plane and the Sun) should not be below ~50 degrees. Secondly, high-resolution imaging from low orbit (<1000 km) is incompatible with yaw-steering usually implemented on spacecraft to keep solar panels fully illuminated. ***Spectroscopy and imaging spectroscopy***, especially in the IR, requires also optimal illumination conditions, i.e. β-angle should not exceed ~60 degrees.

Pointing accuracy: high-resolution imaging is incompatible with yaw steering and would require suspending of yaw-steering above selected targets.

Orbits: Laser altimetry and sub-surface radar investigations can effectively sound the moons' surfaces from an altitude below ~500 km. In addition, the study of tidal deformation of the moons requires the existence of cross-over points over which the spacecraft passes several times during the mission at different phases of the expected tide. Plasma environment investigations require field measurements at wide range of distances to the moon including observations both inside and outside of the magnetosphere. Detection and study of the induced component requires field measurements from low orbit over the time of several rotations of Jupiter. Even lower orbit (< 200 km) is needed for particle investigations by neutral/ion mass-spectrometry. It also requires access to both leading and trailing hemispheres. In order to study the exospheres of the moons, both spacecraft should be capable to perform stellar occultations.

Downlink capabilities: During the circular phase around Ganymede, the capability to downlink data will be limited (1 Gb/day with a conservative approach). High resolution imaging and spectro-imaging will produce a huge amount of data and a trade-off has to be found between the downlink capabilities and the duration of observations.

Two-spacecraft observations: Investigation of the plasma environment would strongly benefit from coordinated two spacecraft observations.

Magnetic cleanliness: Magnetic field sensors should be positioned away from the main sources of stray magnetic field accomplished ideally with a dedicated MAG boom. The length of this boom will be dependent on being able to meet the stringent science measurements requirements as well on the magnetic cleanliness requirements placed on the spacecraft.

5.2 The Jupiter System

5.2.1 The Jovian Atmosphere

EJSM-Laplace investigations. EJSM-Laplace investigations goals for the Jovian atmosphere are:

1) To characterize the atmospheric dynamics and circulation of Jupiter (investigate the dynamics of its weather layer, its auroral structures and energy transports, study the relationships of the ionosphere and thermosphere, quantify the roles of wave propagation and atmospheric coupling).
2) To study the chemistry of the atmosphere (bulk elemental abundances, 3D composition measurements from the stratosphere to the low thermosphere, study of the localized and non-equilibrium composition, moist convection processes).
3) To explore the atmospheric vertical structure of the giant planet (3D structure from upper troposphere to lower thermosphere, structure and dynamics below the upper troposphere, coupling processes across the layers).

Baseline experimental techniques. EJSM-Laplace is going to address these investigations using a favorable combination of remote sensing techniques traditionally used in planetary physics: imaging, spectroscopy, and radio-occultation. It will benefit greatly from the unique opportunity to have dual observations with complementary payloads during almost two years.

The study of the cloud morphology and atmospheric dynamics requires systematic ***imaging*** of Jupiter in the visible through infrared range with few tens of km spatial resolution and repetition time from days to years in order to characterize variable phenomena like waves, eddies etc. and reconstruct wind field from tracking of cloud features. ***Spectral imaging*** in the visible through infrared range with moderate resolving power of at least 400 is needed to monitor the distributions of minor species in the Jupiter's troposphere and use them as dynamical tracers. Observations in the ultraviolet will be used to study auroral emissions. ***Sub-millimeter spectroscopy*** thanks to very high resolution ($\lambda/\delta\lambda \sim 10^6$) will provide profiling of trace gases (CO, H_2O, CH_4, HCN) thus adding vertical dimension to the temperature sounding, composition studies as well as determination of oxygen and hydrogen isotope ratios. This technique will also enable pioneering direct Doppler measurements of winds in the Jovian stratosphere. ***Radio-occultation*** – an ideal technique to sound stratospheric temperature structure – will be used in both traditional spacecraft-to-Earth and novel Earth-to-s/c and s/c-to-s/c modes. ***Stellar occultation*** will complement by sounding stratospheric composition and upper haze distribution.

Complementary techniques. The science return can be strongly complemented by several other observation techniques. ***High-resolution Doppler spectrometry*** would enable direct wind measurements at the cloud level. It is also the only way to explore Jupiter's interior density structure and dynamics below the upper troposphere. Mid-IR observations (8-12 microns) are needed to determine the distribution of PH_3 in the 0.1- to 0.8-bar region. Far-IR measurements (15-250 microns) could be used to measure the ortho/para-H_2 ratio, and methane distribution. ***High-resolution thermal IR spectrometry ($\lambda/\delta\lambda$ > 1000)*** is also highly desirable to study composition, structure and dynamics of the Jupiter weather layer and to address questions about the origins and evolution of Jupiter's atmosphere.

5.2.2 The Jovian Magnetosphere

EJSM-Laplace investigations. EJSM-Laplace will investigate the global configuration and dynamics of the Jovian magnetodisc (structure and stress balance, exchange and coupling processes, response to solar wind and planetary rotation), determine the electro-dynamic coupling between the moons and the magnetospheric plasma (exchange processes in the plasma and neutral tori, interactions between Jupiter's magnetosphere with the moons) and characterize the global and continuous acceleration of particles (particle characterization, study of the loss processes, dynamics of electron synchrotron emissions).

Baseline experimental techniques. The experimental techniques required to fulfill the task are quite similar to those proposed for the study of the magnetosphere of Ganymede (sections 5.1.1 and 5.1.4). The goal requires measurements of ***3 axis magnetic and electric field*** vectors with moderate sampling frequency. ***Measurements of thermal plasma and energetic particles*** will characterize three dimensional distribution functions of ions and electrons, as well as mass spectra of ions and neutrals. They will be complemented ***by measurements of the plasma density, electron temperature, plasma waves and electromagnetic emissions***. ***Imaging and spectro-imaging*** are required to monitor Io volcanic activity, which is the main source of material in the Jupiter magnetosphere. ***Imaging and imaging spectroscopy*** are also necessary to conduct robust observations of auroral emissions.

5.2.3 Study the Jovian Satellite and Ring Systems

EJSM-Laplace will study Io's active dynamic processes, characterize Callisto as a witness of the early Jovian system, and explore the rings and small satellites. The study of these other bodies of the Jovian system will strongly complement detailed investigations of Ganymede and Europa and would complete the survey of the Jovian system. Experimental techniques for these moons and rings are similar to those described in section 5.1 with the difference that they will be studied from fly-by trajectories (Io and Callisto) or very remote observations (small bodies and rings), resulting in that their investigations would not be as detailed as surveys of Ganymede and Europa.

5.2.4 Requirements to the Mission

The most stringent requirements imposed by the measurements have been identified during the phases dedicated to the observation of Ganymede and Europa (section 5.1.5). Since there is no additional instrument in the model payload which is related to an investigation in the Jupiter system, the requirements are basically similar to those described previously. The specific requirements, which can be mentioned here, are:

Pointing: For Jupiter, the radio-occultation sounding requires pointing capabilities and attitude stability of both spacecraft, at levels which could guarantee the ability for the two spacecraft to communicate with each other to implement spacecraft-to-spacecraft radio-occultation experiments.

Two spacecraft observations. The study of the Jovian magnetosphere will be significantly enhanced if the two S/C are in the system at the same time. It is worth noting that a significant amount of measurements (50 %) required for this goal will strongly benefit from two spacecraft observations [14]. Similarly, Jupiter's observations will strongly benefit from the opportunity to make two spacecraft observations (both in space and time). Specific strategies during the tour need to be looked for in order to optimize the science return for these two objectives.

5.3 Baseline Science Scenario

In this section we provide a high level description of the science activities of the ESA flight element (JGO) and focus on the science targets and priorities of each of the mission phases. The JGO science scenario is divided in 7 phases which will be also described in section 7 from the point of view of flight dynamics. Their main features including science priorities of each phase are listed in table 5-1.

Table 5-1. *Science phases of the JGO mission*

	Phase	Start	End	Duration	Science priorities
1	Cruise	03.2020	02.2026	5.9 years	
	Jupiter Tour				
2	Jupiter orbiter	02.2026	02.2027	~365 d	• Monitoring of the Jovian atmosphere, its structure, composition, and dynamics. • Characterization of the Jovian magnetosphere as a fast magnetic rotator and giant accelerator. • Preliminary studies of the outer moons during close flybys. • Remote observations of the inner Jovian system.
3	Callisto pseudo-orbiter	02.2027	03.2028	~388 d	• Characterize the Callisto internal structure, surface and exosphere. • Monitoring of the Jovian atmosphere and magnetosphere. • Remote observations of Ganymede, Europa, Io, and small moons.
4	Transfer to Ganymede	03.2028	09.2028	~240 d	• Study of interactions of the Ganymede magnetic field with that of Jupiter. • Monitoring of the Jovian atmosphere and magnetosphere
	Ganymede Tour				
5	Elliptical/ high altitude (5000 km) circular orbit (GEO)	09.2028	01.2029	120 d	• Global mapping to investigate surface - subsurface characteristics • Search for past and present activity. • Determine global composition, distribution and evolution of surface materials. • Characterize the local plasma environment and its interactions with Jovian magnetosphere.
6	Middle altitude (500 km) circular orbit (GCO-500)	01.2029	05.2029	120 d	• Understand geology, composition and evolution of selected targets with very high resolution. • Study the plasma environment and its relation to the deep interior
7	Low altitude (200 km) circular orbit (GCO-200)	05.2029	07.2029	60 d	• Characterize the extent of the ocean and its relation to the deep interior. • Characterize the structure of the ice shell including distribution of

					subsurface water. • Determine sinks and sources of the ionosphere and exosphere.

Figure 5-1 illustrates the timeline of the JGO and JEO missions.

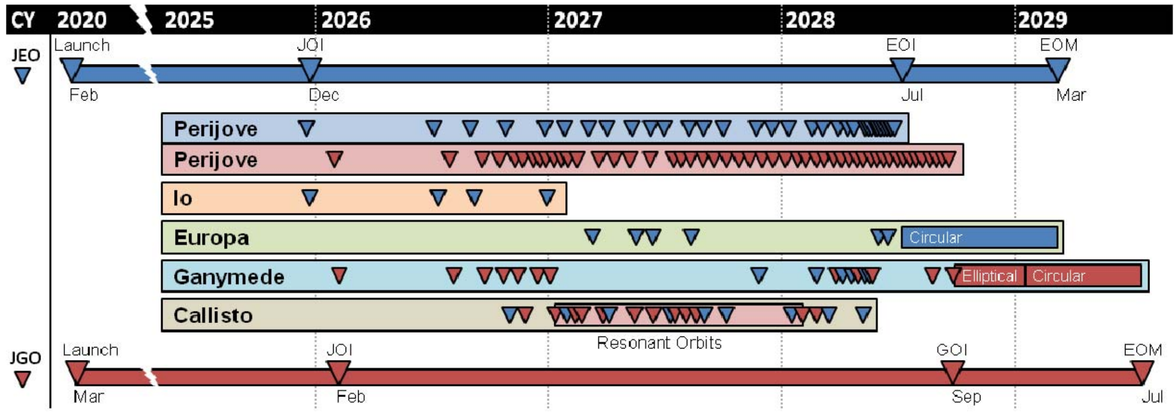


Figure 5-1. *Illustrative timeline of JGO and JEO science missions. JGO and JEO related events and phases are shown in red and blue correspondingly.*

5.3.1 Jupiter Tour

After the Jupiter orbit insertion (JOI) in February 2026 (Figure 5-1) JGO will stay for about one year in evolving elliptic orbit around Jupiter outside the Ganymede orbit and thus radiation belts (Figure 7-2). The orbit will allow detailed investigations of the inner magnetosphere of the giant planet (Figure 4-13). This phase will be also focused on monitoring of the Jupiter atmosphere and coupling processes. Seven flybys of Ganymede would allow starting of investigation of the moon and in particular interaction of the Jovian magnetosphere with that of Ganymede.

During the *Callisto pseudo-orbiter phase* that would last for ~13 months JGO will perform 10 flybys of this moon. Investigations will be focused on characterisation of the Callisto internal structure, surface and exosphere. The time between Callisto flybys will be devoted to continuous monitoring of Jupiter's atmosphere and magnetosphere, rings and dust environment, and remote observations of the other moons. The following 6 months of *transfer to Ganymede* will again be favourable for the studies of interaction of the Jovian magnetosphere with the intrinsic magnetic field of the moon, together with remote observation of the giant planet and the icy moons.

5.3.2 Ganymede Tour

The JGO mission at Ganymede consists of three phases (Table 5-1). They are designed in such a way that the spacecraft avoids solar eclipses at least in the nominal mission. This allows us to simplify the power system design and, hence, to reduce the size of the solar panels (section 7, figure 7-4). Science priorities are distributed between the mission phases so that to allow imaging instruments to complete mapping of the surface at optimal illumination conditions (phases 5, 6) while giving priority in the phase 7 to the geophysical, exospheric and plasma investigations that require to be as close to the moon as possible.

In the current scenario JGO would be inserted into highly elliptical orbit around Ganymede with inclination i ~ 83° and at β ~ 25° (Figure 5-2). (β is defined as the angle between the JGO orbital plane and Ganymede-Sun vector.) The first elliptical orbit sub-phase will be used for high-resolution spectro-imaging and plasma investigations during pericentre flybys at close to noon conditions (Figure 5-2). Elongated orbit would enable investigations of interaction of the Ganymede magnetosphere with the Jovian magnetic field. The following sub-phase with high circular orbit of ~5000 km altitude will be devoted to the global imaging and spectro-imaging taking advantage of optimal illumination conditions. β-angle of the orbit with the selected inclination will evolve at such a rate that JGO will arrive at the second elliptical phase at β ~ 50°. Again pericentres of this elliptical orbit will be used for high resolution imaging, spectro-imaging and plasma investigations at morning (evening) conditions.

The phase 6 will start with transition to the circular orbit GCO-500 with 500 km altitude at β ~ 55° that would again keep the spacecraft out of eclipses (Figures 7-6, 5-2). JGO will stay in this orbit performing high-resolution imaging at β = 55° - 70°. Since the orbit inclination can be slightly modified in transition from GEO to GCO, the rate of β angle evolution (and thus duration of the high resolution imaging period) can be tuned.

The Ganymede tour will enter phase 7 (table 5-1) after the orbit reaches β ~ 70° and illumination conditions become not favourable for imaging. JGO will be transferred to the 200 km orbit (GCO-200), as from that value of β onwards eclipse can also be avoided at lower altitudes (figure 7-4). The remainder of the mission will be devoted to the geophysical (laser altimetry, gravity, sub-surface radar), exospheric and plasma and fields (INMS, MAG, RPWI) investigations.

At the end of the mission there may be an opportunity for JGO to probe lower altitudes during the orbital decay that would allow sounding the Ganymede exosphere at different altitudes. This should be considered as an optional case. Alternatively JGO can be kept in low 200 km orbit for an extended mission. However when β-angle start decreasing JGO will enter in eclipse phase thus resulting in limited science operations. There will be enough power for JGO to survive eclipses. Radiation dose will be the factor that limits the spacecraft lifetime.

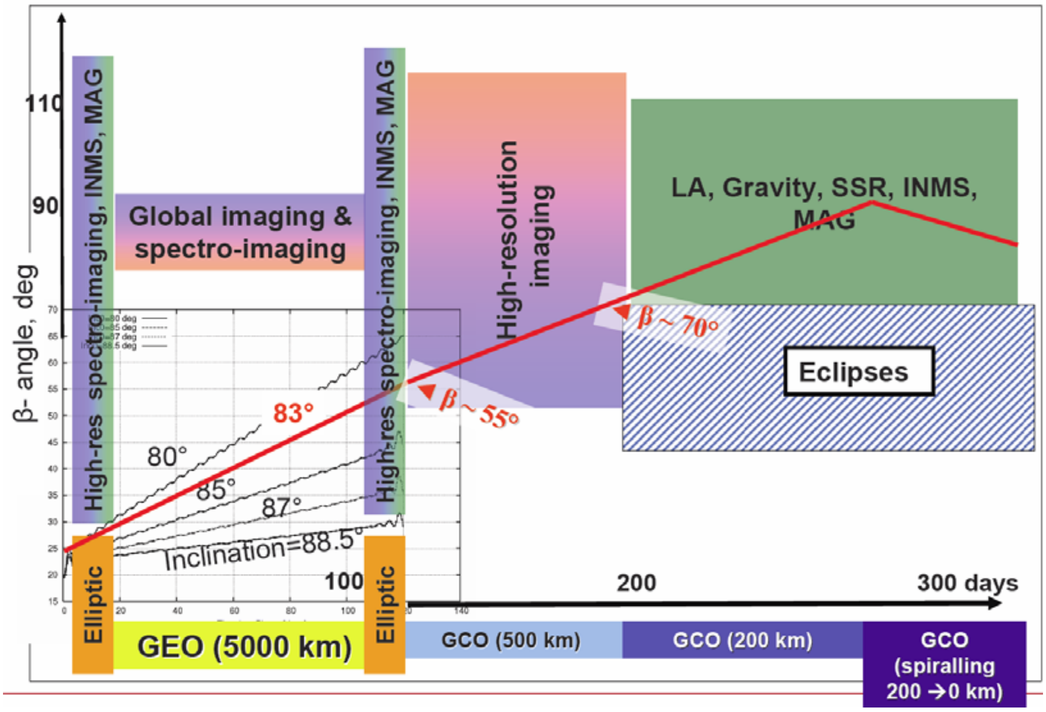


Figure 5-2. *Sketch of the proposed scenario. The red line shows the evolution of the β-angle with mission time for the selected inclination of ~83° in GEO phase and ~85° in the GCO phase (note the small kink on the red line at β~55°). Colored rectangles mark various remote sensing priority investigations.*

We note that the science scenario described here (red line in Figure 5-2) assumes an evolution of the β angle with time starting from β~25º at the beginning of the Ganymede tour, which is favourable for the spectro-imaging investigations and assumes an orbit inclination of 83º. The current flight dynamics simulations (see section 7.5.2, Figures 7-5, 7-6) resulted in initial β~40º with an orbit inclination of ~88º thus providing slightly worse signal-to-noise ratio for spectroscopy and slower rate of β angle evolution with time. More detailed flight dynamics analysis will be carried out during future studies with the aim of extending the initial β angle on arrival at Ganymede towards lower values.

6 EJSM-Laplace Model Payload

The model payloads for both EJSM-Laplace spacecraft (JEO and JGO) were chosen by the EJSM-Laplace Joint Science Definition Team (JSDT) to address the mission science objectives (section 4) and to fulfil measurements requirements (section 5). Attention was paid, when justified, to have synergistic capabilities in the model payload on both JEO and JGO, but also to include model payload instrument with unique capability on either JEO or JGO. The model payloads were also used to identify the key drivers of the payload towards the engineering aspects of the mission and spacecraft design as well as reference operational scenarios. The purpose of the model payload suite was twofold: 1). to demonstrate that reaching the mission goals is well within capabilities of the modern space instrumentation and 2). To have a representative payload suite for the spacecraft design assessments. It is underlined that the model payload complement for both JEO and JGO are notional payload. The model payload instruments were used to show proof of concept only, and should not be considered as final selections. Alternative and complementary instrument concepts and techniques may be proposed and selected via the NASA/ESA coordinated Announcement of Opportunity process to meet the mission objectives.

One common challenge for both the JEO and JGO instruments is their performance under harsh Jovian radiation environment. It is recognised that the radiation conditions for JEO are more challenging due to higher radiation flux and total dose. Also the planetary protection requirements are more stringent for JEO. NASA pays special attention to the JEO instruments due to the higher radiation flux and total dose. NASA's approach to develop the JEO model payload was to use only publicly available information in the concept designs. ESA's approach was similar, but at the same time, ESA initiated through the Call for Declarations of Interest in Science Instrumentation (DOI), instrument concept design studies and initial technology development for instruments of interest to be proposed for EJSM-Laplace. The intension was also to give experimental teams the ability to identify critical elements of their instruments and to prepare for later AO. This also gave The instrumental studies were run in parallel with mission industrial studies. Feedbacks on the model payload related issues were provided by the 3 contractors (Section 7), and allowed to improve the model payload definition, define preliminary instruments-to-spacecraft interfaces, and to identify the resources requirements for the model payload.

Both JGO and JEO include 11 model payload instruments. Table 6-1 presents the model payloads, their primary science contribution and key characteristics. The mass of the JEO payload is 106 kg and the JGO payload is ~104 kg. Both masses are given without 20% system margin and shielding. Mass for shielding is estimated separately.

6.1 Model Payload Definition

Table 6-1 summarizes principal science goals and characteristics of the 11 JGO and JEO model payload instruments. In this report intended primarily for the ESA down-selection process, we provide description of the JGO model instruments according to the Payload Definition Document followed by a brief overview of the JEO model payload.

Table 6-1. *Main characteristics of the EJSM-Laplace model payload for both JGO and JEO*

Model Payload	JGO		JEO	
	Science Contribution	Characteristics	Science Contribution	Characteristics
Laser Altimeter	Tidal deformation of Ganymede; Quantitative morphology of Ganymede surface features	Single Beam @ 1064 nm 20 m spot @ 200 km 20 to 90 Hz pulse rate	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
Radio	Interior state of	2-way Doppler with	Interior state of Io,	2-way Doppler with

Science Instrument	Ganymede, presence of a deep ocean and other gravity anomalies. Ganymede and Callisto surface properties. Atmospheric science at Jupiter, Ganymede and Callisto. Jupiter rings.	Ka-Band transponder Ultra-stable Oscillator	Europa, Callisto and Ganymede, presence of a deep ocean and other gravity anomalies. Atmospheric science at Jupiter, Europa and Io. Jupiter rings.	Ka-band transponder Ultra-stable Oscillator
Ice Penetrating Radar	Structure of the Ganymede subsurface & identify warm ice water "pockets" and structure within the ice shell and search for ice/water interface.	Single frequency: 20-50 MHz Dipole antenna: 10 m	Europa ice/water interface and identify warm ice and/or water pockets within the ice shell	Dual frequency: 5 and 50 MHz, Vertical depths: 3 and 30 km Dipole antenna: 3 and 30 m
Visible-IR Hyperspectral Imaging Spectro-meter	Composition of non-ice components on Ganymede & Callisto; State & crystalinity of surface ices. On Jupiter: tracking of tropospheric cloud features, characterization of minor species, aerosol proper - ties, hot spots and aurorae.	Pushbroom imaging spectrometer with two channels with scan system λ= 400-5200 nm dλ= 2.8nm @ <2.5µm dλ=5.0 nm @ >2.5 µm IFOV: 0.125-0.25 mrad FOV: 3.4°	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 λ= 400-5200 nm dλ= 5 nm @< 2.6 µm dλ=10 nm @> 2.6 µm ifov:0.25mrad @ <2.6µm ifov:0.50mrad@ >2.6 µm FOV: 9.2°
UltraViolet Imaging Spectro-meter	Composition & dynamics of the atmospheres of Ganymede & Callisto	EUV and FUV+MUV grating spectrometers λ= 50-320 nm IFOV: 0.01 mrad FOV: 2°	Composition & dynamics of the atmospheres of the Galilean satellites	EUV grating spectrometer with scan system for stellar occultations λ= 70-200 nm IFOV: 1.0 mrad FOV: 3.7°
Ion and Neutral Mass Spectro-meter	Integrated within the plasma and particles Instrument (PPI-INMS)		Composition of sputtered products from Europa	Reflectron Time-of-Flight Mass range: 1-300 Daltons Mass res: >500
Thermal Instrument	N/A	N/A	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°
Narrow Angle	Local-scale geologic	Pushbroom imaging in orbit around Ganymede;	Local-scale geologic processes on Europa,	Orbital Mode: Panchromatic pushbroom

Camera	processes on Ganymede & Callisto; Io Torus imaging, Jupiter cloud dynamics & structure	framing imager for distant targets. Color and multispectral imaging capability with filter wheels (12 colors); 1024 *1024 sensor FOV: 0.30°. Pixel IFOV: 0.005 mrad	Ganymede & Callisto; Io volcano monitoring; Jupiter cloud dynamics & structure	imager OpNav Mode: Panchromatic framing imager. Jovian Science Mode: 9 color framing imager (filter wheel) IFOV: 0.01 mrad FOV: 1.2°
Wide Angle Camera	Wide only: Global morphology of Ganymede; Global to regional scale morphology of Callisto	Wide only: 12 filters Framing IFOV: 2 mrad FOV: 117 deg	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
Magneto-meter	Ganymede's intrinsic magnetic field and its interaction with the Jovian field	Dual tri-axial fluxgate sensors; boom length to meet magnetic clean-liness requirements (as measured by the outboard sensor): S/c DC field: <2nT S/c AC field: 0.1 nT rms in the range DC-64Hz.	Induction response from the Europa Ocean; Presence and location of water within Ganymede & Callisto	Dual tri-axial fluxgate sensors 10 meter boom
Plasma and Particles Instrument-Ion and Neutral Mass-spectro-meter	Jovian magneto-sphere. Interaction between Jovian magnetosphere and Ganymede and Callisto. Exospheres and ionospheres of the moons.	***Plasma Analyzer*** Electrons: 1 eV– 20 keV Ions: 1 eV – 20 keV ***Particle Analyzer*** Electrons: 15keV-1MeV; Ions: 3 keV - 5 MeV, ENA: 10 eV – 100 eV ***INMS*** Mass range: 1-300 amu M/dM >1000 Sensitivity: 10^{-14} mbar @ 5s measurement	Interaction between icy satellites and the space environment to constrain induction responses; Composition and transport in Io's plasma torus	Plasma Analyzer Electrons:10eV – 30 keV Ions: 10 eV – 30 keV Particle Analyzer Electrons:30keV- 1 MeV Ions: 30 keV-10's of MeV High-energy Electrons >2, >4, >8 and >16 MeV
Submilli-meter Wave Instrument	Dynamics of Jupiter's stratosphere; Vertical profiles of wind speed and temperature	2 channels Spec. range: 550-230 µm FoV: 0.15° – 0.065°	N/A	N/A
Radio and Plasma Wave Instrument	Ganymede ocean, exosphere and magnetosphere; Callisto Induced magnetic field and plasma envi-ronment; Jovian magnetosphere and satellite interactions	Plasma density (0.001-10^6 cm^{-3}) and temperature (0.01-20eV); S/c potential (± 50V) Near DC E-Field (up to 3 MHz), E (1kHz-45 MHz) and B (0.1-600 kHz) plasma and radio wave detectors	N/A	N/A

6.2 JGO Model Payload

The definition of the instruments for the JGO model payload was done by the Joint Study Science Definition team, based on the Payload Definition Document [1] put forward prior to the start of the JGO industrial study phase. The JGO model payload consists of 11 instruments which characteristics are summarized in Table 6-1. Note that the names of the model experiments in this section are not associated with any particular instrument but rather represent measurement techniques. As the industrial study progressed, the Medium Resolution Camera was removed from the model payload since its objectives could be accomplished by two other cameras. Instrumental DoI studies that ran in parallel with industrial activities demonstrated sufficient maturity of the model payload [10].

6.2.1 Narrow Angle Camera (NAC)

Science goals and measurements. Narrow Angle Camera (NAC)[1] will provide high resolution images of Jupiter and its moons. Global imaging from the high orbit and imaging of selected targets with resolution of few meters per pixel from the low orbit at Ganymede will make a breakthrough in understanding of geology of the icy satellite and history of its surface. At Jupiter NAC will investigate dynamics and morphology of the Jupiter cloud layer. The main measurements expected from NAC are as follows:

- Global imaging of the Ganymede surface with at least 400 m/px resolution
- Detailed characterization of the morphology of the surface of icy moons at regional and local scales with few m/px resolution
- Day side imaging of Jupiter with 15 km/px resolution to study cloud properties and dynamics
- Monitoring of lightning flashes on the night side
- Jupiter limb imaging with ~30 km vertical resolution to study aurora and hazes
- Astrometric, geodetic, geologic and morphologic observations of Io and other moons
- Monitoring of volcanic activity and related surface changes on Io
- Study of the Jupiter ring

NAC will provide context imaging vitally important for the other experiments. Several goals will be achieved in synergy with other instruments of JGO's model payload in particular with the Wide Angle Camera (WAC), the imaging spectrometer VIRHIS and the Laser Altimeter.

Performance requirements. The NAC goals and required performance in the Ganymede Circular Orbit phase (GCO-500 and GCO-200) drive the parameters of the instrument. The camera has to achieve high spatial resolution (< 10 m at 500 km altitude) with very low solar illumination levels at more than 5 AU distance away from the sun. The baseline performance requirements of the NAC camera are summarized in Table 6-2.

Table 6-2. *Baseline NAC performance requirements*

Parameter	Value
Type of instrument	Camera
Optics	
Spectral range, nm	350-1050
FOV, deg	0.293
Ifov, mrad	0.005 <10 m/px @ 500 km <5 km/px @ 1 Mkm
Focal length, mm	3000
Filters	12 (filter wheel)
Detector	
Type of detector	CMOS Star1000
Lines*Arrays	1024*1024
Pixel size, µm	15
Exposure time, msec	0.3-2000
Full well capacity, Ke^-	135

Possible instrument concept. Low illumination and extreme radiation at Jupiter impose severe constraints on the selection of instrument sensors and electronics. Fast motion in orbit around Ganymede prohibits long exposures and imaging experiments require some strategy for motion compensation. A 1024x1024 px CMOS APS detector is baselined for NAC. An alternative solution could be a CCD detector with 2048x2048 px and smaller pixel size (Bepi Colombo heritage) or a

[1] In the PDD [1] this instrument is called High Resolution Camera (HRC).

EJSM-Laplace customized detector. However, CMOS APS is preferred, because the dedicated region-of interest read-out of the APS would allow operating the detector in either pushbroom or framing mode. Further advantages are the high radiation tolerance of CMOS APS detectors and tolerant design with integrated electronics. Multi-spectral imaging capability will be provided by a motorized filter wheel with 12 filter positions, similar to that used by the Panoramic Camera on Beagle2 and ExoMars. Stereo imagery of Ganymede is obtained by two observations at different viewing angles provided by tilting the spacecraft. Figure 6-1 shows the framing camera for the DAWN mission that provides heritage for the NAC camera.

Figure 6-1. *Framing camera for the DAWN mission as representative instrument, providing heritage for NAC (Credit: MPS, DLR)*

Orbit, operations, pointing and other mission requirements. NAC will operate during the Jovian tour, Callisto flybys, and in orbit around Ganymede. The pointing prediction shall be sufficiently accurate to point the camera at selected targets and to guarantee sufficient image overlap for mosaicing. The camera shall maintain nadir-pointing. For low illumination at Jupiter exposure time will exceed dwell time to obtain sufficient SNR. Two possibilities have been considered to increase the exposure time: (1) TDI like technique by on-chip shifting or co-adding in analogue chain; (2) Mechanical compensation along the scan (velocity) direction by a piezo-driven system. The baseline method is the TDI-like technique as piezo elements are seriously affected by temperature variations. Both methods directly depend on the ground velocity of the LOS in combination with the spatial resolution (i.e. spacecraft height above real ground, not above reference ellipsoid). Most appropriate would be to obtain real-time information by the spacecraft concerning time, velocity and height. As this has not been considered during the assessment phase, the duration of TDI time steps (or velocity of motion compensation) has to be commanded based on the a-priori orbit and pointing knowledge.

Data volume and data rate considerations prohibit operating the NAC throughout an entire orbit in Ganymede Circular Orbit. Instead, NAC will acquire short image strips of a few kilometres only per imaging sequence which will be covered in a push-frame mode. High resolution imaging from close distances (Ganymede circular orbit) requires scan line to be perpendicular to the flight direction, that precludes using of “yaw steering” mode of the spacecraft. For astrometric and distant observations, NAC will be operated like a framing device. The instrument operation schedule should allow for geometric and radiometric calibration, instrument alignment cross-calibration and performance tests.

6.2.2 Wide Angle Camera (WAC)

Science goals and measurements. The Wide Angle Camera will provide multispectral context imaging of Jupiter and its moons to address the goals in geology, geodesy, geophysics and meteorology. The main measurements expected from WAC are listed below:

- Context imaging of the Ganymede surface with at least 400 m/px resolution
- Multispectral mapping of Ganymede to investigate topography, morphology, geology and history of its surface

- Imaging of Jupiter to study cloud morphology, particle properties, and dynamics
- Mapping of other satellites and ring

WAC will provide context imaging vitally important for the other experiments. Several goals will be achieved in synergy with other instruments of JGO's model payload in particular with the Narrow Angle Camera (NAC), the imaging spectrometer VIRHIS, and the laser altimeter (LA).

Table 6-3. *Baseline WAC performance requirements*

Parameter	Value
Type of instrument	Camera
Optics	
Spectral range, nm	350-1050
FOV, deg	117
Ifov, mrad	2
Focal length, mm	8
Detector	
Type of detector	SMOS Star1000
Lines*Arrays	1024*1024
Pixel size, µm	15
Exposure time, msec	1-2000

Performance requirements. The WAC goals and required performance in the Ganymede Circular Orbit phase drive the parameters of the instrument. The camera has to perform wide-angle imaging with very low solar illumination levels at more than 5 AU distance away from the sun. Table 6-3 shows baseline WAC performance requirements.

Possible instrument concept. Like in the case of NAC low illumination and extreme radiation at Jupiter impose severe constraints on the selection of instrument sensors and electronics. Fast motion in orbit around Ganymede prohibits long exposures and imaging experiments require some strategy for motion compensation. The basic concept of the instrument is very similar to that of NAC with the difference in optics that has much wider field of view and much smaller focal length. Figure 6-2 shows the HRSC-SRC camera for the Mars Express mission as representative instrument, providing heritage for WAC.

Orbit, operations, pointing and other mission requirements. WAC will operate during the Jovian tour, Callisto flybys, and in orbit around Ganymede. Requirements to WAC are very similar to those for NAC (section 6.1). The camera shall maintain nadir-pointing. For low illumination at Jupiter exposure time will exceed dwell time to obtain sufficient SNR. Exposure time will be increased by using TDI motion compensation technique. Data volume and data rate considerations prohibit operating the WAC throughout an entire orbit in Ganymede Circular Orbit. Instead, WAC will acquire short image strips of a few kilometres only per imaging sequence which will be covered in a push-frame mode. Imaging from close distances (Ganymede circular orbit) requires scan line to be perpendicular to the flight direction, that precludes using of "yaw steering" mode of the spacecraft. For astrometric and distant observations, WAC will be operated like a framing device. The instrument operation schedule should allow for geometric and radiometric calibration, instrument alignment cross-calibration and performance tests.

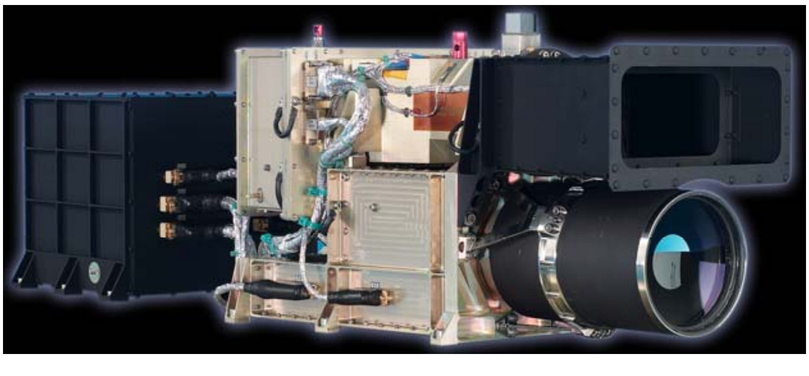


Figure 6-2. *HRSC-SRC/Mars Express camera as representative instrument, providing heritage for WAC (Credit: DLR, INAF)*

6.2.3 Visible InfraRed Hyperspectral Imaging Spectrometer (VIRHIS)

Science goals and measurements. The instrument will provide spectral imaging of the Galilean satellites and Jupiter atmosphere with moderate spectral resolution in the UV to thermal IR wavelength range. VIRHIS main goals are to study composition of the moons' surfaces and composition, dynamics, structure and morphology of the Jupiter atmosphere. The main measurements expected from VIRHIS are listed below:

- Characterization of composition, physical properties, geology and history of Ganymede and Callisto surfaces with emphasis on presence of organic materials, salts and weathering products as well as Io volcanic activity
- Composition, structure and dynamics of the Jupiter atmosphere and exospheres of its moons
- Monitoring of auroral and other non-LTE emissions on Jupiter and its moons
- Composition and physical properties of the small moons and dust

Several goals will be achieved in synergy with other instruments of the JGO model payload in particular with cameras, ice penetrating radar sounder, sub-millimeter instrument and radio science.

Table 6-4. *Baseline VIRHIS performance requirements.*

Parameter	**Value**
Type of instrument	Imaging spectrometer
Optics	
Spectral range, μm	0.4-5.2 (6 tbc)
Spectral sampling, nm	2.8-5.0
FOV, deg	3.4
Ifov, mrad	0.125-0.250
Focal length, mm	192
Detector	
Type of detector	HgCdTe CMOS multiplexer
Lines*Arrays	640*480
Pixel size, μm	27
Exposure time, msec	< 60000
Full well capacity, Ke^-	2000
Operating T, C	< -173

Performance requirements. The VIRHIS goals and required performance in the Ganymede Circular Orbit phase drive the parameters of the instrument. VIRHIS has to perform spectral imaging with very low solar illumination levels at more than 5 AU distance away from the Sun. The baseline VIRHIS performance requirements are shown in Table 6-4.

Possible instrument concept. VIRHIS is innovative and highly capable imaging spectrometer operating in UV though near-IR range. A Three Mirror Anastigmatic (TMA) telescope is joined to the entrance slit of an Offner spectrometer. A dual-region convex grating splits and reflects the diffracted optical beam to two focal planes. The image of the slit is built on two 2-D sensors optimized for Vis-NIR and IR spectral ranges. Thus, an instantaneous acquisition in each focal plane consists of spectral image of the 1-D entrance slit. The second spatial dimension is created by scanning mirror inside the telescope or by using the spacecraft motion (pushbroom mode). Figure 6-3 shows the optical module the VIRTIS/Venus Express – the heritage instrument for VIRHIS.

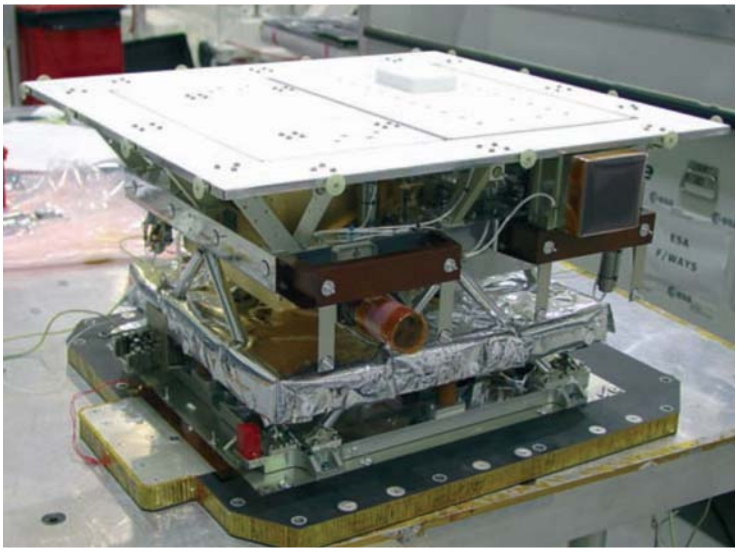


Figure 6-3*. The optical module of the VIRTIS/Venus Express as representative instrument, providing heritage for VIRHIS (Credit: INAF, LESIA)*

Orbit, operations, pointing and other mission requirements. VIRHIS will operate during the Jovian tour, Callisto flybys, and in orbit around Ganymede. The Ganymede low circular orbit is the most demanding part of the mission. Optimal β-angles for the imaging spectrometer are < 60 degrees. Nadir pointing is the main mode of observations. Observation strategy will include both nearly global mapping of the Ganymede surface from elliptical orbit and mapping of selected regions with high spatial resolution. VIRHIS' onboard software will be able to handle different operation and compression modes. A motion compensation mechanism is foreseen to increase effective exposure time. Imaging from close distances (Ganymede circular orbit) requires the rotation axis of the entrance mirror to be perpendicular to the flight direction that precludes using of "yaw steering" mode of the spacecraft. The IR detector operates at low temperatures (90-100 K). If passive cooling by radiator would not be enough, the use of an active cooler may be necessary. This would require extra time before the start of the observations, implying higher complexity operations.

6.2.4 Ultraviolet Imaging Spectrometer (UVIS)

Science goals and measurements. The Ultraviolet Imaging Spectrometer (UVIS) is expected to provide a wide variety of spatial, temporal and spectral observations of Ganymede, Callisto, Europa, and Io, and of Jupiter itself. Targeted observations of the Galilean moons will allow close study of the variability of their atmospheres, their interaction with the Jovian magnetosphere, and monitor any auroral emissions which exist (e.g. at Ganymede), as well as providing information on the detailed composition and chemistry of their surfaces. Within the magnetosphere, UVIS will offer observations of plasma sources and sinks through remote observations of torii. At Jupiter, UVIS will provide information on the interaction between Jupiter and the moons through high resolution observations of the magnetically mapped moon footprints, as well as global monitoring of the main emissions linked to a wide volume of the magnetosphere. Occultation measurements of the Jovian atmosphere will lead to high resolution information on the stratospheric temperatures, and atmospheric composition and chemistry. The main measurements expected from the UVIS instrument are as follows:

- Detailed investigation of the interaction between Ganymede's and Jupiter's magnetospheres and magnetospheric dynamics, understanding sinks and sources of plasma, ionospheres and exospheres
- Monitoring of volcanic activity and related surface changes on Io
- Surface reflectance observations to characterise the Ganymede and Callisto surfaces and to map non-water ice materials
- Understanding of surface composition variations due to interactions with plasma
- Observations of Jupiter's stratospheric temperatures, composition and their variations to understand coupling between atmospheric layers.

UVIS will provide context spectral-imaging to complement many other instruments measurements, including observations at visible, infrared, and radio wavelengths, and in combination with in situ field and particle data.

Performance requirements. The UVIS goals and required performance relate to the wide variety of UV emissions which occur in the Jupiter system. As such, they are a wide variety of spatial, spectral and temporal resolution requirements. The baseline UVIS performance requirements are summarized in Table 6-5.

Table 6-5. *Baseline UVIS performance requirements*

Parameter	Value
Type of instrument	EUV/FUV/MUV Imaging Spectrometer
Optics	
Type of optic	Off-axis parabolic mirror/ slit/ grating/detector
Spectral range, nm	110-320 nm (EUV:50-110 FUV/MUV: 110-320)
FOV, deg	0.1(spectral) x 1(spatial)
Ifov, deg	> 0.01
Focal length, mm	170
Detector	
Type of detector	Microchannel plate (MCP) + Position sensitive anode
Lines*Arrays	512*512
Pixel size, µm	80
Exposure time, msec	1000

Possible instrument concept. The UV imaging spectrometer experiment is made up of a detector and electronics unit. The detector unit includes a telescope, a spectrograph, two 2-D MCP detectors, and associated high voltage detector power supply. The electronics unit includes the data acquisition, processing and buffering electronics and the power, command and data interface with the JGO systems. The optics consists of a clear aperture off-axis paraboloidal mirror (OAP). The OAP collects the incoming light (from limb and/or nadir) and directs it toward the entrance slit of a imaging spectrograph with a reflective holographic diffraction grating. The grating disperses the radiation onto the focal plane, where an UV-sensitive microchannel plate detector records the spectrum. The electronics unit includes the data processing and buffering electronics and the power, command and data I/F to the JGO systems. Figure 6-4 shows structural and thermal model of the Phebus/BepiColombo UV spectrometer as representative heritage instrument for UVIS.

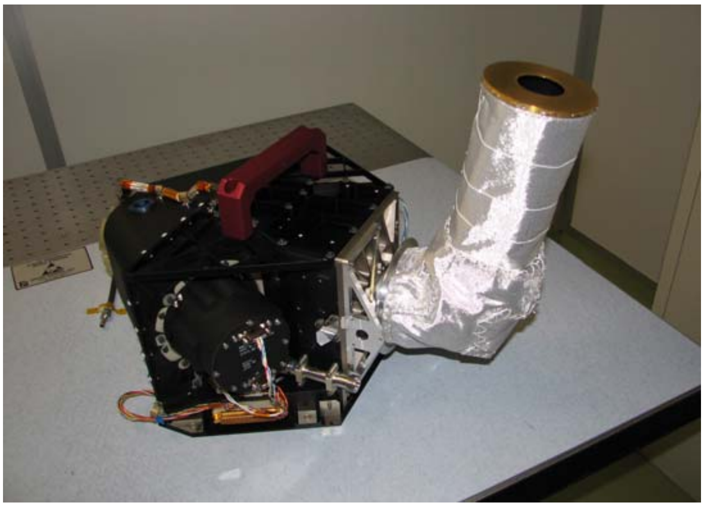


***Figure 6-4**. Structure thermal model of the Phebus/Bepi Colombo as representative instrument, providing heritage for UVIS (Credit LATMOS)*

Orbit, operations, pointing and other mission requirements. UVIS will operate during the Jovian tour, Callisto flybys, and in orbit around Ganymede. The pointing prediction shall be sufficiently accurate to point the instrument at selected targets (see Table below). The camera should ideally have common viewing direction as the other remote sensing instruments to provide complementary measurements. The Sun should be at least 30° away from the field of view of the instrument. This value is conservative, and may be reduced once the dimension of the baffle is decided. The UVIS instrument is capable of handling yaw steering. The maximum angular speed of the spacecraft during operations is 0.1 deg/s. There is no restriction outside operational mode. The operational modes for UVIS include 1) Nadir pointing for imaging the moon's and Jupiter's atmospheres and surfaces, requiring ~0.1°/s stability with 2 sigma accuracy, 2) Limb pointing for spectroscopy of Jupiter and the moons, requiring ~0.1°/s stability with 2 sigma accuracy, 3) Stellar occultation for spectroscopy of Jupiter/ Galilean moon atmosphere (especially Callisto and Io), requiring ~0.1°/s stability with 2 sigma accuracy, 4) Solar occultation for spectroscopy of Jupiter/Galilean moon atmosphere with ~0.01°/s stability with 1 sigma accuracy.

6.2.5 Sub-millimeter Wave Instrument (SWI)

Science goals and measurements. The main objective of a submillimeter wave instrument is to investigate the structure, composition and dynamics of the middle atmosphere of Jupiter and exospheres of its moons, as well as thermophysical properties of the satellites surfaces. SWI observations for the first time in the Jupiter system will provide pioneering direct measurements of wind speeds in the middle atmosphere of the giant and high-sensitivity composition measurements. The main measurements expected from SWI are as follows:

__Table 6-6.__ Baseline SWI performance requirements

Parameter	Value
Type of instrument	Heterodyne microwave spectrometer
Optics	
Spectral range, μm	Two bands: 550, 230
Resolving power, λ/Δλ	10^7
FOV, deg	0.15-0.065
Filters/ bandwidth	CTS/ 100 KHz
Scanning mirror	2-D: (±65°) * (±4°)
Detector	
Type of detector	Schottky
Exposure time, s	1-300
Operating T, °C	-20…+20, -150

- Characterization of the structure, composition and dynamics of the Jupiter middle atmosphere
- Study of the composition and structure of the exospheres of the Jovian moons
- Determination of the thermosphysical properties of the surfaces of the Jovian moons

SWI will have strong synergy with VIRHIS and PP experiments.

Performance requirements. The SWI objectives in atmospheric observations in the Jupiter system drive the selection of wavelength range and spectral resolution. SWI will perform point observations in two bands: 530-600 GHz and 1075-1275 GHz with very high resolving power. The baseline SWI performance requirements are shown in Table 6-6.

Possible instrument concept. SWI is a passive microwave heterodyne spectrometer. The sensor unit includes a 60-cm telescope (antenna) with a mechanism for along- (±65°) and cross (±4°) track scanning. After the antenna the beam is split and detected by two independent receivers for 600 and 1200 GHz bands (Figure 6-5). The front ends include feed horns, sub-harmonic mixers, low noise amplifiers and the submillimeter part of the local oscillator (LO) chain. The mixer and the first low-noise amplifier on each band are designed to work at -150°C providing enhanced sensitivity. We note that this cold temperature is required only for a small part of the instrument and could be reached by passive cooling using instrument specific radiator. The two electronic units are placed inside the S/C vault and expected to operate around 0°C. Figure 6-5 shows the flight model of the MIRO/ Rosetta instruments which is the heritage instrument for SWI.

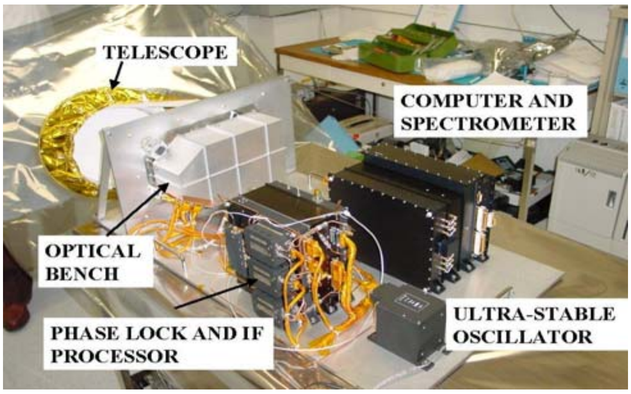


***Figure 6-5**. The flight model of the MIRO/ Rosetta as representative instrument, providing heritage for SWI (Credit: JPL, MPS)*

Orbit, operations, pointing and other mission requirements. SWI will operate during the Jovian tour, Callisto flybys, and in orbit around Ganymede. The 2-d scanning mirror provides sufficient pointing flexibility, but requires unobstructed FOV in the nadir, limb and space directions. SWI requires radiator to cool detectors down to -150°C. Although the instrument performance will be investigated on ground, an in-flight calibration which would consist of observations of internal black body and cold space is necessary.

6.2.6 Laser Altimeter (LA)

Science goals and measurements. A Laser Altimeter (LA) will contribute to the characterization of the icy moons. It will provide data about the topography, shape and tidal deformation of the icy surfaces. It will also be crucial for studies of the spacecraft orbit in the gravity field of a satellite by providing accurate range data. The main measurements expected from the Laser Altimeter are as follows:

- Derive topographic profiles
- Determine tidal deformations
- Determine satellite's dynamical rotation state
- Assist in orbit determination and gravity data modelling
- Measure surface roughness and albedo.

***Table 6-7.** Baseline LA performance requirements*

Parameter	Value
Type of instrument	Laser altimeter
Spectral range, nm	1064 nm
FOV, mrad	0.2
Ifov, mrad	0.2
Focal length, mm	1250
Filter bandwidth, nm	≤1
Spatial resolution, m	20m @ 200km
Type of detector	Avalanche Photo Diode (Si or InGaAs)
Receiver	Cassegrain
Transmitter	Galilean beam expander

LA will provide topographic measurements extremely important for the other experiments related to the geophysical and geo-morphological characterization of the moons. Several goals will be achieved in complementarity with other instruments of JGO's model payload in particular with the Radio science instrument, and the two cameras WAC and NAC and the sub-surface radar instrument.

Performance requirements. The LA goals and required performance in the Ganymede Circular Orbit phase (GCO-500 and GCO-200) drive the parameters of the instrument. The laser altimeter has to achieve a high signal-to-noise ratio for reliable pulse detections during night and day from a typical range of < 500 km at Ganymede. Its range accuracy should be lower than 0.5 m. It must allow for surface roughness modelling, slopes and albedo measurements during the sequence of observation at very high resolution of targeted areas. The baseline LA performance requirements are shown in Table 6-7.

Possible instrument concept. The instrument will measure the two-way travel time of a Laser pulse travelling from the instrument to the reflecting surface and back. Travel time measurements, combined with additional information on pointing and location of the Laser at the time of each pulse, will be used to construct geo-referenced topographic profiles along the ground track of the spacecraft. Two concepts or one combined concept are conceivable.

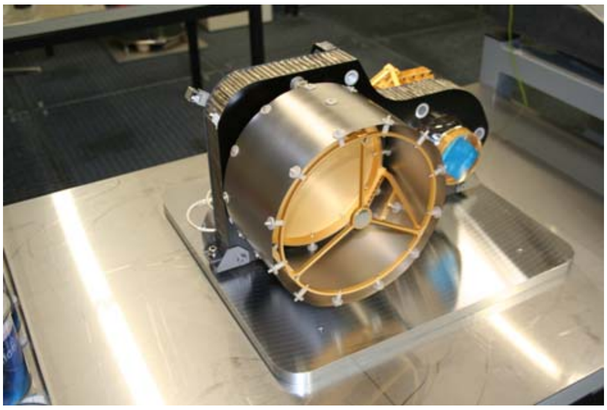


***Figure 6-6**. Structural and Thermal Model (STM) of the Bepi Colombo laser altimeter BeLa as representative instrument, providing heritage for LA (Credit: BeLa Team UBE/DLR/MPS).*

- a 'classical' laser altimeter with time-of-flight measurement and pulse-waveform analysis capability. The former measures the range from the spacecraft to the satellite's surface, the latter allows for determination of surface characteristics. This classical (BELA/BepiColombo-type) concept is the assumed baseline.
- A single-photon counting (SPC) detector allows for lower laser pulse energy at even higher ranges. This extends the measurements towards high orbits at Callisto and Ganymede. However, besides the development and space qualification of the SPC detector, dedicated pulse detection and processing schemes must be developed. In addition, false detections due to radiation may be a critical issue.

The laser altimeter is composed of a transceiver unit and an electronic unit. The transceiver unit contains the complete laser subsystem and the optical chain of the receiver. The start pulse of the clock is provided by an optical signal from the beam expander optic to the APD of the receiver. The electronic unit is connected via electrical harness to the transceiver unit and contains the rangefinder, the digital processing module and the power converter. This unit has an interface to the spacecraft (data, power). The complete instrument is cold-redundant. BeLa/ Bepi Colombo instrument as the heritage for LA instrument is shown in Figure 6-6.

Orbit, operations, pointing and other mission requirements. The instrument will operate during the spacecraft orbit phase around Ganymede and at flybys at Ganymede and Callisto whenever the distance is small enough to detect the reflected signal (here assumed value < 500 km at Ganymede and < 300 km at Callisto - smaller because of the lower albedo). With single photon counting higher ranges are possible. To obtain the dynamical tides (varying tidal deformation of the satellite along its orbit around Jupiter) measurements at same locations on the surface of the satellite at different orbital longitudes of the satellite are required (cross-over points). The laser will typically fire at a rate of 20 to 90 Hz depending on the orbit. Nighttime observations and daytime observations (which have to overcome the solar background noise) are equally possible. The pointing shall be accurate to within the size of the Laser footprint.

The pulse repetition rate of the laser will be adjustable during the mission between 1 and 90 Hz in order to save power and data volume. Global shape of the moons should be acquired at a moderate pulse repetition rate with low data rate for each pulse (260 bit / pulse). In this mode, the instrument will extract only the topography along the track. For surface characteristics of targeted regions, the laser altimeter will use the highest rate with full data rate in order to provide also measurements of albedo, slopes, and roughness of the areas.

The instrument should also be capable for 2-way (offline) range measurements to terrestrial Laser stations for instrument alignment calibration, performance tests, and also, for clock calibration. Range measurements could also support the tracking of the spacecraft and gravity field modelling. Ranging between the JEO and JGO spacecrafts could be supported by dedicated operation modes of the instrument and laser retro-reflectors on both spacecraft.

6.2.7 Ice Penetrating Radar (IPR)[1]

Science goals and measurements. The study of Ganymede's subsurface (and partially of Callisto's sub-surface) with a radar sounder instrument will bring new data of the icy crust of giant moons. It will explore for the first time the inner layers of the icy crust. This is mandatory to identify the stratigraphic and structural patterns, the crustal dynamics, and the relationships between the surface features and the subsurface. The main measurements expected from the subsurface radar are as follows:

- Global identification and local characterization of physical and dielectric subsurface horizons
- Obtain distributed profiling of subsurface thermal, compositional and structural horizons
- Identify thermally-controlled subsurface horizons within the ice shell

The ice penetrating radar will identify and locally characterize physical subsurface horizons by obtaining sounding profiles of subsurface thermal, compositional, or structural down to a few kilometres at relatively high vertical resolution (in the order of 10 m in free space). Several goals will be achieved complementarily with other instruments of JGO's model payload, in particular with the laser altimeter.

Performance requirements. The Ice Penetrating Radar (IPR) should be a radar sounder system at low frequency. A single frequency sounder will be appropriate for JGO because it is a good trade - off between the scientific goals and the complexity of the system. A radar sounder, thanks to the relatively low frequency of its pulse, has the capability to penetrate the surface and to perform a sub-surface analysis with a penetration ability of a few kilometers (depending on the selected central frequency of the pulse) with a vertical resolution of some meters depending on the bandwidth of the signal. The choice of the central frequency will depend on the two factors: a) the radiation noise is sensibly higher at frequencies below 20 MHz. As a consequence, for the design of a relatively simple system (good SNR with limited DC power), a frequency between 20 MHz and 50 MHz should be used. b) A higher frequency results in less critical constraints for the design of the antenna than a lower frequency. The geometrical resolution depends on the orbiter altitude. Thus, different resolutions are expected depending on the operational mode (circular orbits around Ganymede, and flybys). The radar sounder could also be used in altimetry mode with a moderate resolution. The baseline performance characteristics are summarized in Table 6-8.

Table 6-8. *Baseline IPR performance requirements*

Parameter	Value
Type of instrument	Radar sounder
Transmitted central frequency	In the range 20 – 50 MHz
Transmitted bandwidth	10 MHz
Alongtrack resolution	1 km
Acrosstrack resolution	< 5 km
Penetration depth	from 3 km to 9 km
Vertical resolution, m	From 10 m to 1 % of the target depth

Possible instrument concept. The instrument has an architecture similar to the radar sounder SHARAD (Figure 6-7). It is made up of an antenna, a transmitter, a receiver, and a digital system. The antenna is a dipole of 10 meters (two arms of 5 m), assuming a central frequency of 20 MHz. Its exact length can still vary because it depends on the central frequency chosen, which in turn is affected by the complete spectral characterization of the Jupiter noise and a complete modeling of the Ganymede

[1] This instrument is called Sub-Surface Radar (SSR) in the PDD document [1].

surface and sub-surface. The length of the antenna could be reduced by increasing the central frequency (e.g. at 50 MHz the length would be ~4 m.

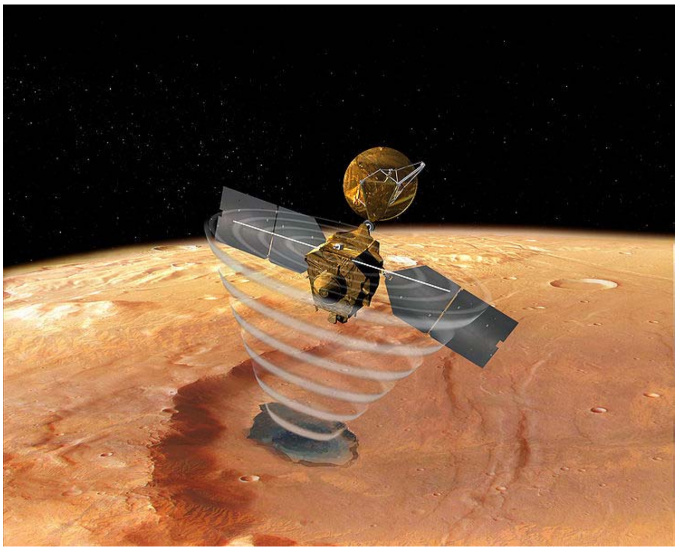


Figure 6-7. *Pictorial view of Mars Reconnaissance Orbiter using SHARAD radar at Mars (Credit: NASA/JPL)*

The sounder can investigate different intervals of depths depending on the choice of the central frequency. A minimum depth of about 3 Km at about 50 MHz is expected. Lower depths at very high resolution are not compatible with the radar sounder which is foreseen on JGO. But this very high resolution will be achieved on some specific targets using the radar sounder of JEO during flybys of Ganymede and Callisto.

Orbit, operations, pointing and other mission requirements. The radar instrument will be a nadir-looking sounder with accuracy of ±5°. The antenna should illuminate the surface according to a nadir view. An important requirement is to have always the antenna parallel to the ground during measurements. Concerning yaw, a deviation from parallelism to the ground should be less than 1°. It would be also important to have a small roll (<10°) in order to have the maximum antenna beam pattern at nadir.

The expected processed data rate being of about 300 Kbps, it is expected that the IPR instrument does not operate continuously in order to limit the data volume. The best option for the reduction of the clutter in radar measurements is to have the antenna in the across-track direction (perpendicular to flight direction). Nonetheless, the across-track direction may generate problems of interference with the solar panels. Thus, IPR might be in the along-track direction. In that case, the antenna beamwidth is very broad resulting in much ambiguous energy being returned to the sensor. But these returns have slightly different Doppler shifts from those coming back from the nadir direction. A Doppler processing can be applied to sharpen the horizontal resolution and cut off along track clutter echoes. A high pulse repetition frequency (PRF) is then required to correctly sample the surface Doppler spectrum.

6.2.8 Magnetometer (MAG)

Science goals and measurements. The MAG instrument will characterise the permanent internal/intrinsic magnetic field of Ganymede; establish and characterise magnetic induction signatures in possible sub-surface oceans at Ganymede and Callisto; investigate Ganymede's mini-magnetosphere which is embedded within the Jovian magnetosphere; observe magnetic field signatures within the Jovian magnetosphere and aid in characterising the dynamics within this magnetosphere. The main goals expected from MAG measurements, which will consists of measuring the three-axis magnetic field components with an absolute accuracy of 0.2 nT, are as follows:

- Determine the magnetic induction response from Ganymede's ocean at multiple frequencies
- Globally characterise Ganymede's intrinsic and induced magnetic field with implications for the deep interior
- Within Jupiter's magnetosphere: understand the structure and stress balance; investigate plasma sources and sinks, composition and transport; characterise large scale coupling processes; characterize the magnetospheric response to solar wind variability and planetary rotation effects

  understand the moons as sources and sinks of magnetospheric plasma.

In addition to its prime science goals, MAG will also provide the context for the behaviour of the global magnetic field which is vitally important for understanding other fields and particles data sets; and as such several of the goals will be obtained in synergy with other JGO model payload instruments.

Performance requirements. The primary MAG science goals of resolution of Ganymede's intrinsic magnetic field and characterising magnetic induction signatures at multiple frequencies drive the parameters of the instrument. MAG needs to achieve a stability of 0.1nT and an absolute accuracy of 0.2nT with a noise floor less than 10pT/Hz. The baseline performance characteristics are shown in Table 6-9.

Table 6-9. *Baseline MAG performance requirements*

Parameter	Value
Type of instrument	Dual tri-axial fluxgate magnetometer
Preferred location on spacecraft	Sensors boom-mounted with electronics on main equipment platform
Type of detector	Two fluxgate sensors
Operating temperature	-80C …+70C
Field range and resolution	Numerous ranges bracketed by: +/- 128nT @ 4pT resolution +/-65536nT @ 2nT resolution

Possible instrument concept. The MAG instrument should consist of two sensors, which would be boom mounted in order to minimise magnetic interference from the spacecraft, with the associated electronics located on the main equipment platform. Two sensors are required in order to facilitate operation as a gradiometer in order to separate the very small target ambient field from any magnetic disturbance field due to the spacecraft fields. The sensors could be miniaturised fluxgates which would draw on considerable space heritage and currently have a high TRL. The sensor electronics would be either of a digital FPGA based design which is in development, or of an ASIC based design which although further specific development would be required would offer considerable reductions in instrument power. The electronics would be composed of the sensor front end electronics, DC/DC converter and data processing and interface unit. Figure 6-8 shows the flight model of the Double Star magnetometer which is one of the heritage instruments.

Orbit, operations, pointing and other mission requirements. MAG should operate all the time. Data gaps will greatly complicate resolving the different frequencies driving the induction signatures in the ocean as well the as detailed intrinsic magnetic field at Ganymede. Operational requirements are minimal, and could be limited to simple power-on/power-off and data rate commands if necessary. MAG electronics would feature the capability to auto-range and over-sample within the MAG electronics, delivering telemetry to the main DPU. It is desirable that MAG be switched on before any other payload so that any unwanted magnetic signatures from other orbiter instruments may be properly characterised. MAG has no specific pointing requirements but knowledge of spacecraft attitude is required to an accuracy of < 0.1 degree. Knowledge of sensor to spacecraft mounting orientation is also required to the same accuracy hence sensor orientation in flight should be known to better than 0.2 degree. Stable alignment between sensor mounting and nominal probe pointing axis has been demonstrated on numerous missions through the use of rigid magnetometer booms. MAG has no inclination requirements. For assistance in

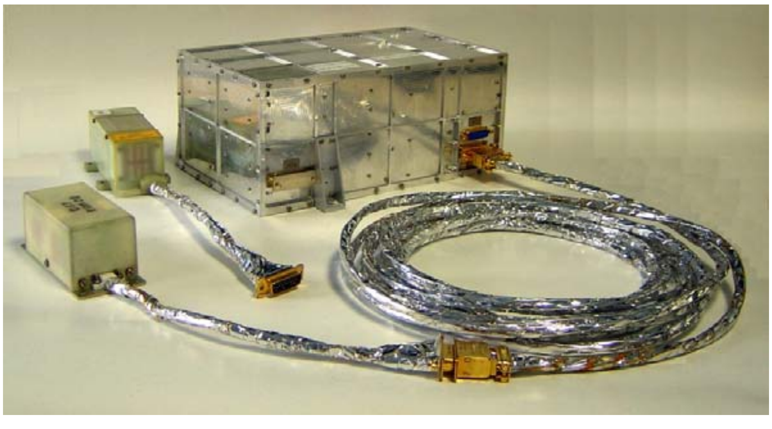


Figure 6-8. *Double Star magnetometer, with electronic box, in and outboard sensors and boom cable, as representative instrument, providing heritage for MAG (Photo courtesy Imperial College, London)*

calibration efforts once in flight, a spacecraft command timeline during operations would be extremely helpful.

MAG would operate in different modes to allow for different sampling rates and in different ranges depending on the required measurement range; examples of sampling rates would range from a normal mode of 32 vectors per second up to burst mode of 128 vectors per second.

MAG sensors should be positioned away from the main sources of stray magnetic field and away from ferromagnetic materials, accomplished ideally with a dedicated MAG boom. The length of this boom is dependent on being able to meet the stringent science measurements requirements.

The need for dedicated MAG sensor heaters is TBD depending on thermal models and sensor technology developments. MAG should be calibrated on the ground prior to launch. In-flight calibration will determine the spacecraft induced magnetic field, verify the extent to which the ground calibration remains valid and also quantify changes in calibration parameters. Minimization of the magnetic interference at the site of the MAG sensors is highly desirable to maximise the scientific return from the instrument.

6.2.9 Radio and Plasma Wave Instrument (RPWI)

Science goals and measurements. RPWI consists of a set of sensors that measures the near dc electric field (two E-field dipole sensors), electric component of plasma waves (E-field sensors and use of the radar antenna), magnetic component of electromagnetic waves (Search Coil Magnetometer), radio emissions (triad of radio antennae) as well as detailed characteristics of the thermal plasma (Langmuir Probes) including electric conductivity. Most of the proposed measurements have never been carried out before around Jupiter and its moons, and instrument characteristics are defined to fully address the scientific objectives stated in the above sections. In addition to passive measurement capability, the E-field sensor includes an active measurement technique for ambient plasma studies, but also to determine the effective antenna lengths, deployment lengths and electric sensor calibration in order to increase the accuracy of the passive RPWI measurements.

RPWI will primarily address two EJSM-Laplace science topics: i) the Jupiter moons - magnetosphere interaction (Ganymede and Callisto) with the objective to contribute significantly to the characterization of the sub-surface oceans; ii) the Jupiter magnetosphere, its dynamics and acceleration of particles as well as radio wave emission sources.

Table 6-10. *Baseline RPWI performance requirements*

Measured Quantity	Range
LP-PWI	
Electron density (n_e, $\delta n/n$)	0.001 – 10^6 cm^{-3}, 0(dc)-10 kHz
Ion density (n_i)	1–10^6 cm^{-3}, <1 Hz
Electron temperature	0.01 – 20 eV, <100 Hz
Ion drift speed	0.1–200 km/s, <1 Hz
Ion temperature	0.01 – 20 eV, <1 Hz
Spacecraft potential	±50 V, <100 Hz
Electric field vector, $\delta\mathbf{E}$(f)	0(dc) – 3 MHz (waveform), ±1 V/m Bit resolution: 0.015 mV/m
Integrated solar EUV flux	Resolution 0.05 Gphotons/cm^2/s
Active Measurements	
Electron density (n_e)	0.001 – 1000 cm^{-3}
Electron temperature	0.1 – 100 eV
RWI	
Electric field vector, $\delta\mathbf{E}$(f)	10 kHz – 45 MHz
SCM	
Magnetic field vector, $\delta\mathbf{B}$(f)	0.1 Hz – 20 kHz (one coil up to 600 kHz)
RA-PWI	
Electric field, δE(f)	1 kHz – 45 MHz

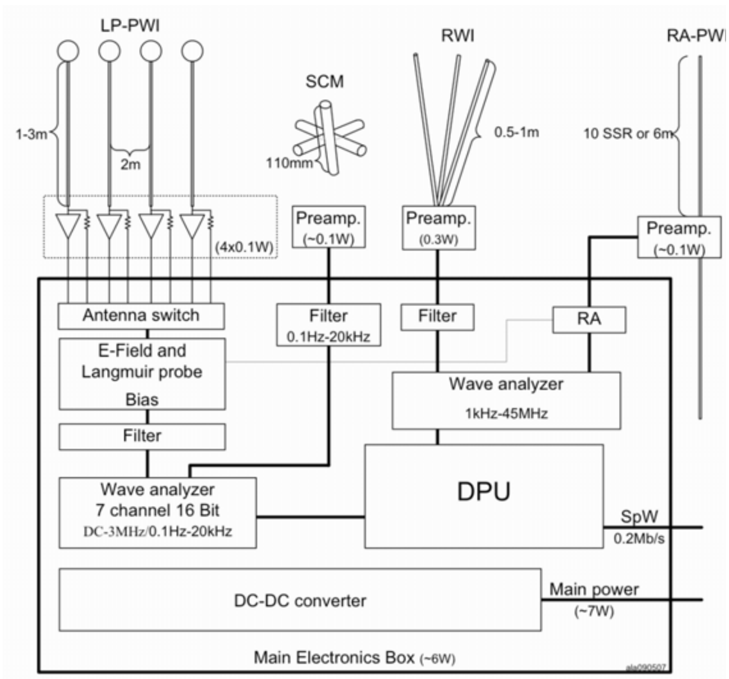
RPWI will contribute to a range of science objectives in the Science Traceability Matrix [14], for example:

- Determine the electrical conductivity of the ionized exospheres of the moons, the DC E-field and the current systems induced by the interaction with Jupiter's co-rotating magnetosphere

- Characterise particle populations within Ganymede's exosphere and magnetosphere and Callisto's exosphere and the interaction of these two moons with Jupiter's magnetosphere, and investigate the generation mechanisms of Ganymede's aurorae
- Contribute to investigate the surface composition of both icy satellites and the role of the internal (at Ganymede) and induced magnetic field in controlling surface sputtering processes, and investigate sub-surface outflow processes through direct *in situ* measurements of the ionized component of exhaust plumes if they do exist
- Contribute to the study of processes acting in Jupiter's magnetodisc, study the large scale coupling processes between Jupiter's magnetosphere, ionosphere and upper atmosphere, and study response to solar wind variability and the role of solar wind and planetary rotations on magnetospheric dynamics
- Contribute to the characterisation of the Jovian radiation environment and its time variability; study Jupiter radio emissions and their time variability; and contribute to the study of the auroral foot print of the moons.

Performance requirements. The electron number density (n_e), a critical parameter, will be determined through several independent techniques: i) Langmuir probe technique (for densities > 10 cm^{-3}); ii) measurements of the upper hybrid emissions (f_{uh}); iii) measurement of the spacecraft potential combined with f_{uh} measurements (or possibly an electron spectrometer on board S/C); continuous sampling of Langmuir probe current at ms time resolution; v) active mutual impedance measurements. The radio and plasma waves measurements by RPWI will allow for the determination of: i) wave polarization; ii) wave Pointing flux/Radio flux; iii) electric field vector in frequency range from near dc to 45 MHz; iv) magnetic field vector and/or spectrum in the frequency range 0.1 Hz to 600 kHz; i) interferometry and wave group speeds, plasma drift speeds, and plasma density inhomogeneities ($\delta n/n$); iv) convection electric fields (**E**×**B** drift); v) Electric fields of structures and waves responsible for accelerating charged particles; vi) Direction finding ; vii) Dust distribution (above about 1 μm size); viii) Signatures of dust-plasma interactions. Table 6-10 summarizes the RPWI performance requirements.

Figure 6-9. *Block diagram of the potential RPWI instrument [1]*



Possible instrument concept. The RPWI instrument concept is based on a set of dedicated sensors connected to a central processing unit (Figure 6-9). Some sensors need to be deployed at the tip of supporting booms; other sensors consist of a set of deployable antennae. The sensors include a set of (4) Langmuir probes/E-field monopoles which can either be accommodated on spacecraft-body mounted deployable booms (reference accommodation) or possibly at the tip of the solar panels, an alternative accommodation that has been briefly addressed during the present study and which may deserve a further study in the next study phase. This set of sensors cover the frequency range from DC to 3 MHz. The E-field dipole will allow measurements of two components of the E-field. The third component measurement will be made by using the radar sounder antenna dipole (2 x 5m); its sensitivity will also allow to perform Quasi-Thermal Noise measurements, a complementary method to that of the Langmuir Probe and that of the active mutual impedance technique to measure the local plasma parameters (density and temperature). Radio measurements will be made with a 3-axis radio antenna that will measure the 3 components of the wave electric field in the range up 1kHz to 45 kHz. Low frequency AC magnetic field measurements in the frequency range 0.1 Hz to 10 kHz (possibly up to several hundreds of kHz) will be made with a tri-axial search coil magnetometer. The combined set of E-field and B-field AC measurements should allow gonio-polarimetric measurements.

Orbit, operations, pointing and other mission requirements. RPWI measurements shall be performed during all science phases of the mission. The instrument sensitivity will be designed to fulfill the science objectives during 200-km altitude flybys of Ganymede and Callisto and during all three orbital phases at Ganymede. The instrument sensitivity would greatly benefit if the trajectory at Callisto and Ganymede would go lower than 200 km on a few occasions. The four spherical sensors of the Langmuir Probes should be in the plasma-ram hemisphere of the spacecraft with unobstructed view of the plasma flow when *in situ* plasma measurements are made. The central processing unit should be located inside the payload radiation vault, but preamplifiers for all sensors must be located near the sensors, and will therefore be designed to meet the expected high-radiation environment of the mission. The instrument is not expected to be sensitive to yaw steering, especially as it will make its prime measurements during the *in situ* measurement observation mode.

6.2.10 Particle and Plasma Instrument – Ion Neutral Mass Spectrometer (PPI-INMS)

Science goals and measurements. The main science objectives for the JGO plasma and particle package are as follows:

- Determination of the plasma dynamics around the moons and its interaction with their magnetic field and surfaces including aurora on Ganymede
- Investigation of the structure and composition of exospheres & ionospheres
- Characterization of the moons as plasma sources for the Jovian magnetosphere and dynamics of tori
- Study of the effects of magnetosphere interactions on the moons surfaces, loss of volatiles, chemical and radiation weathering
- Characterization of the dynamics of

Table 6-11. *Baseline PPI-INMS performance requirements*

Parameter	**Value**
Type of Package	Plasma physics, particle measurements, Ion and Neutral gas Spectrometer
Type of optics	Electrostatics, geometrical
Spectral (energy) range	ELS: 1 eV – 20 keV HPS: 1 eV – 10 keV MPS: 1 keV – 60 keV EPS: 3 keV- 5 MeV (i) EPS:15 keV–1MeV(e) ENA: 10 eV – 10 keV LAP: < 10 eV
Mass range	HPS, MPS: 1-60 INM; 1-300
Mass resolution, M/ΔM	HPS: > 5…10 MPS: > 40 INM: > 1000
FOV	ELS: 90° x 360° HPS: 90° x 360° MPS: 10° x 160° EPS: 12° x 160° ENA: 5° x 90° LAP: hemisphere
Angular resolution (ifov)	ELS: 10° x 22.5° HPS1/2: 20° x 45° MPS: 5° x 20° EPS: 12° x 25° ENA: 5° x 5° INM: 10° x 2°
Preferred location on s/c	MU: nadir plane DU: anti-nadir plane LAP sensor: ram direction for nadir pointing INM: ram direction

Jupiter's magnetosphere, structure of the magnetodisc, processes in it, and interaction with the solar wind

Performance requirements. Distribution functions of the electrons and dominant ion species (from Hydrogen to SO_2), from energies of a few eV to a few MeV. For plasma measurements, coverage of the whole sphere (4π) is highly desirable. This is required for plasma measurements (ions and electrons) at low energy (below ~10 keV) and around moons, since although the corotation and ram directions are important, other directions are important also. Characterization of cold (down to a fraction of an eV) plasma is required to provide the spacecraft potential, needed to aid the interpretation of electron and ion measurements at low energies (a few eV), and to intercalibrate sensors.

A high sensitivity instrument for neutral gas measurements is necessary to measure a full mass spectrum in, ~1 minute, with the smallest identified peaks at the 10^{-14} mbar level or better. The time resolution arises from the spatial resolution together with the spacecraft speed in orbit. The instrument sensitivity for the ionospheric ions should be sufficient to record a full mass spectrum with a dynamic range from 10^{-1} to 10^{4} ions/cm^3 in one minute. Mass resolution should be at least $M/\Delta M = 1000$, however larger mass resolutions would be helpful for isotope analysis (to resolve CO and N_2 one would need $M/\Delta M = 2500$).

Global imaging (via energetic neutral atoms (ENA)) is required to image the whole moon magnetosphere interaction region at once to separate time and spatial variations of the plasma population. This is a critical requirement for observations limited by fly-bys because no comprehensive statistics can be accumulated. The ENA imaging also provides patterns of ion precipitation onto the moon's surface to understand surface albedo variations and particle surface release processes. Table 6-11 summarizes the PPI-INMS performance requirements.

Possible instrument concept. To cover the measurement requirements PP would consist of seven sensor types, dedicated to the measurement of specific species - electrons, ions and neutrals - in different energy ranges (Table 6-11, Figure 6-10). From low to high energy, a possible arrangement could be:
1) Langmuir probe (LAP), to measure plasma density and temperature down to a <1 eV.
2) Electron Spectrometer (ELS), to measure electron distributions from a few eV to 20 keV.
3) Hot Plasma Spectrometer (HPS), to measure ion distributions, with composition (up to sulphur), from ~ eV to a ~10 keV/q with low mass resolution ($M/\Delta M \approx 5$), high sensitivity and time resolution.
4) Medium energy Plasma Spectrometer (MPS), to measure ion distributions, with composition (up to sulphur), up to few keV with high mass resolution ($M/\Delta M \approx 50$).
5) Energetic Plasma Spectrometer (EPS), for ion and electron distributions, from few keV to few MeV.
6) Energetic Neutral Analyzer (ENA), to characterize neutrals from a few eV to a ~10 keV.
7) An ion and neutral gas mass spectrometer (INM) with mass resolution of $M/\Delta M > 1000$.
To save mass and power, and improve mutual shielding, it is desirable to adopt a highly integrated architecture. Common DPU and power converters are anticipated. Electronic parts could be protected by the same shielded box. To cover the full 4π, the ELS and HPS each have a second unit mounted in a secondary PPI-

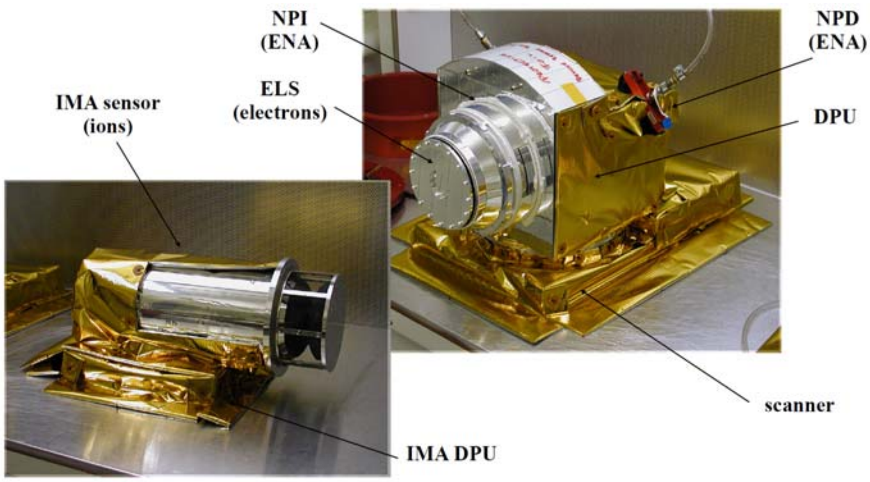


Figure 6-10. *ASPERA-4/Venus Express as representative instrument providing heritage for PPI-INMS (Credit: IRF)*

INMS unit on the other side of the spacecraft. Figure 6-10 shows the sketch of the PPI-INMS instrument.

Orbit, operations, pointing and other mission requirements. Continuous operations of the plasma instruments are required to fulfill the scientific objectives. The field of view of the ELS, HPS, MPS and EPS must include the corotation direction. The aperture of the INM, ELS and HPS instruments must include the spacecraft ram direction. Pointing accuracy is of order 1°. A conducting spacecraft surface is required due to the sensitivity of the low energy measurements to spacecraft potential.

6.2.11 Radio Science Experiment (JRST & USO)

Science goals and measurements. The Radio Science instrument uses the spacecraft telecommunication subsystem with added hardware capability: a Radio Science Transponder at Ka-band (RST), an Ultrastable Oscillator (USO), and additional functionalities within the X-band Transponder (AddX-TR). The radio science has the following goals:

- Chracterisation of internal structure and sub-surface oceans on Ganymede and Callisto by tracking JGO using RST
- Estimation of the surface roughness and dielectric constant at Ganymede and Callisto by bi-static radar sounding
- Sounding of the structure of the neutral atmospheres and electron density in ionospheres of Ganymede and Callisto by radio-occultation at dual frequencies
- Determination of the radial and vertical structure of the Jupiter ring on scales of ~1 km and sizes of the parent bodies in centimetre to meter size range by radio-occultation
- Study of tides and interactions within the Jovian system by tracking JGO using RST.

Possible instrument concept and performance requirements. The Radio Science Instrument will provide dedicated additional on board hardware interfaced with the telecommunication subsystem, namely a Radio Science Transponder at Ka-band (RST), additional functionalities in the X-band Transponder (AddX-TR) and an Ultrastable Oscillator (USO). The RST will provide a two-way coherent link at Ka-band from/to an Earth Deep Space antenna and will allow receiving a carrier frequency at Ka-band from JEO, in the Satellite-to-Satellite link (SSL) mode, and from the Earth, in the so-called one-way uplink mode. AddX-TR will expand the capabilities of the standard X/X/Ka-band Deep Space Transponder (DST) by allowing receiving a carrier frequency at X-band from JEO, in the SSL mode, and from the Earth, in the so-called one-way uplink mode. The USO will provide a precise frequency reference on-board to (a) carry out down-link one-way measurements at X- and Ka-band using the DST only and (b) carry out SSL and up-link one-way measurements using the RST and the AddX-TR.

When used in two-way mode, both the DST and the RST do not produce any telemetry (but a few housekeeping data) as the measurements are actually carried out by the ground station. The same applies also to spacecraft-to-Earth one-way measurements carried out at X- and Ka-band.

On the other side, when SSL or Earth-to-spacecraft one-measurements are carried out (through the AddX-TR at X-band and through the RST at Ka-band) telemetry data will be generated on-board (the in-phase I and quadrature Q components of intermediate frequency samples) as the AddX-TR and RST will mimic the functions usually performed by a ground station. These data will need to be stored on-board and then transmitted to ground through the telemetry channel. Figure 6-11 shows a possible architecture for JGO communication system, capable of fulfilling the science goals listed above.

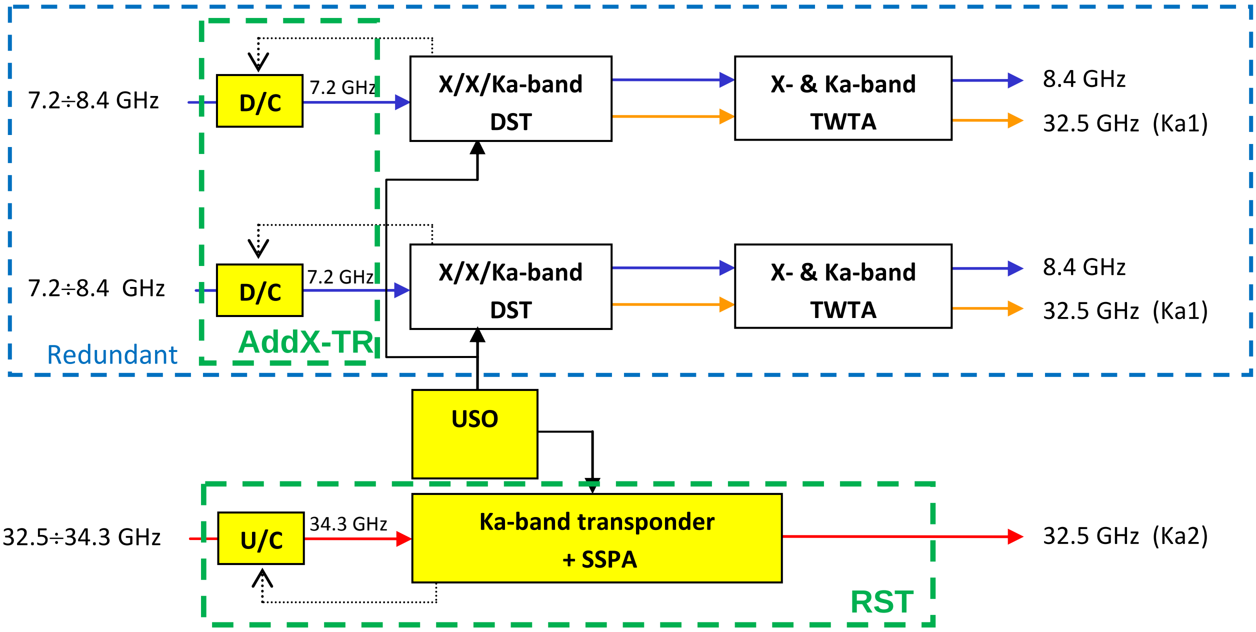


Figure 6-11. *JGO Radio Science payload (in yellow) integrated with the TT&C system [1]*

<u>Orbit, operations, pointing and other mission requirements.</u> For estimation of the gravity field of Callisto and Ganymede, it will be required to operate the RST during dedicated periods in several mission phases: the Callisto resonance orbits, and the Ganymede elliptical and circular phases. The best performance of the RST is obtained when simultaneous transmission and reception both at X-band and Ka-band are carried out, following the scheme illustrated in Figure 6-12.

In order to allow the previous scheme to be implemented, the Ground Antennas must be capable of simultaneous transmission and reception at X- and Ka-band. For the atmospheric science at Jupiter, Ganymede and Callisto, dual frequency one-way signals are essential to discriminate the effects on signal properties due to charged particles (ionospheres) or neutral atmospheres. For bistatic radar observations, dual polarization signals shall be sampled at the receiver (the Ground Station for downlink experiments and the spacecraft for uplink and SSL experiments) as this is needed to estimate the satellite surface dielectric constant. Science return of the radio experiment will be significantly higher if a radio link between JGO and JEO is provided.

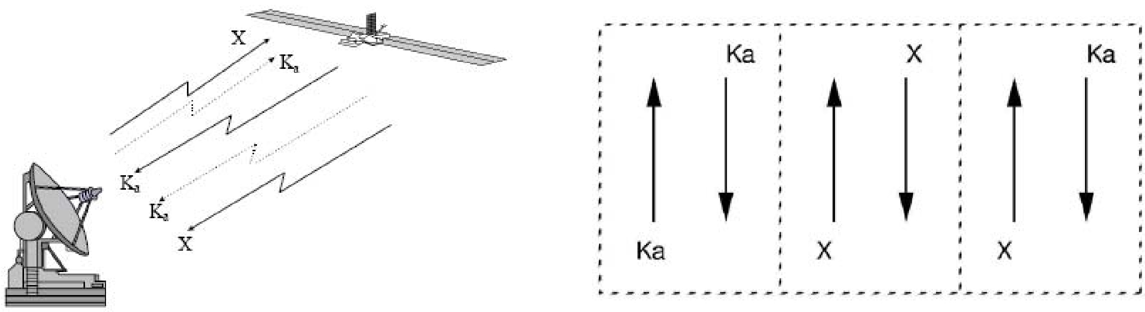


Figure 6-12. *Triple link - X/X, X/Ka (Ka1) and Ka/Ka (Ka2) - operations proposed for the JGO*

The duration of a radio science observation sequence will depend on the target, but all but one set of radio science observation will be compatible with the assumed availability of one Ground-station per day. The exception is during Callisto, and possibly Ganymede flybys, when a gravity pass will require coverage using 3 consecutive Ground-stations (combination of ESA and NASA stations may be possible).

Pointing requirements. During JGO one- and two-way tracking from Earth the following requirements apply:

- The S/C shall be three axis stabilized, controlled, during two-way gravity observations, by momentum wheels (no thruster firings) in order to avoid introducing un-modelled ΔV on the S/C centre of mass;
- Momentum wheels unloading (de-saturation) manoeuvres shall be executed outside tracking intervals dedicated to Radio Science;
- The High Gain Antenna shall be constantly pointed toward the Earth (for two-way tracking) or toward its "virtual position" identified by the direction which allows, after atmospheric bending of the RF signals, to reach the Earth, throughout the entire RS observations in order to guarantee continuous tracking;
- The S/C angular speed around the HGA axis shall be controlled to zero angular velocity during RS observations in order to avoid introducing Doppler signatures due to circular polarization of the radio signals. If a spin rate around the HGA is required, its knowledge must be such that it will not introduce any Doppler uncertainty in the observables. There is no requirement on the (namely constant) attitude angle about the HGA antenna, so this can be optimized for other S/C requirements.

During JEO-JGO SSL communications, for one-way atmospheric, ring and bistatic radar observations the following requirements apply:

- Both S/C (JEO and JGO) shall be three axis stabilized, controlled possibly by momentum wheels for higher pointing accuracy;
- JGO High Gain Antenna shall be constantly pointed toward JEO or (during atmospheric occultations) toward its "virtual position" identified by the direction which allows, after atmospheric bending of the RF signals, to reach JEO. This is common practice in all atmospheric occultations radio science experiments.
- JEO High Gain Antenna shall be constantly pointed toward JGO or (during atmospheric occultations) toward its "virtual position" identified by the direction which allows, after atmospheric bending of the RF signals, to reach JGO.
- For both S/C the angular speed around the HGA axis shall be controlled to zero angular velocity during RS observations in order to avoid introducing Doppler signatures due to circular polarization of the radio signals. If a spin rate around the HGA is required, its knowledge must be such that it will not introduce any Doppler uncertainty in the observables. There is no requirement on the (namely constant) attitude angle about the HGA antenna, so this can be optimized for other S/C requirements.

6.2.12 JGO Model Payload Summary

Table 6-12 summarizes interface parameters of the model instruments as they are presented in the Payload Definition Document [1]. Table 6-13 shows the correspondence between the science goals and the model payload instruments that address them.

Table 6-12. *JGO model instruments interface summary*

Instrument	Acronym	Mass [kg]	Size [cm]	Power [W]	TM [kbps]	Heritage
Narrow Angle Camera	NAC	10	50 x 20 x 20	15 (incl. DPU)	75	SRC/Mars Express PanCam/ ExoMars DAWN camera
Wide-Angle Camera	WAC	4.5	10 x10 x10	3 (excl. DPU)	5000	SRC/ Mars Express
Laser Altimeter	LA	11	30 x 22 x 23 cm + 20 x 18 x 15 cm	24	30	BeLa/ BepiColombo
Magnetometer	MAG	1.8	10 x 6 x 6 sensors; 16 x 16.5x12 e-box	2.0 (excl. Heaters)	7-70	Cassini, Double Star, Venus Express
Ice Penetrating Radar	IPR	10	37x25x13	20	300	MARSIS/Mars Express, SHARAD/ MRO
Radio Science Instrument	JRST	2-2.5	17x19x10 (TBC)	26	very low, HK data only	Cassini, BepiColombo, Juno
Ultrastable Oscillator	USO	1.5	15.2x9.0x13.0	5	low HK only	ERS, Rosetta, Venus Express
Submm Wave Instrument	SWI	9.7	70x52x41	39	10	MIRO/Rosetta
UV Imaging Spectrometer	UVIS	6.5	30 x 30 x 20 (no baffle)	20	30	PHEBUS/ BepiColombo
Visible InfraRed Hyperspectral Imaging Spectrometer	VIRHIS	17	Optical Head: 50×40×30 ME: 30×25×20	20	5000	VIMS-V/ Cassini VIRTIS/ Rosetta/ VEX
Particle and Plasma Instrument – Ion Neutral Mass Spectrometer	PPI-INMS	18.2	Main unit: 35x40x25cm Additional Unit: 25x25x70cm (incl boom)	50	5-50	ASPERA/MEX,VEX, ROSINA/Rosetta
Radio and Plasma Wave instrument	RPWI-E	3.0	15x15x8 cm	7+3		
	LP-PWI	2.0	4x 5cm probes on tip of 1-3m booms5		Min: 64 bps Max: 1 kbps	RPWS/Cassini, LAP/Rosetta CEFI/Swarm
	RWI	1.5	Triad of 50cm-1m antenna8		1-100 kbps	RPWS/Cassini Waves/STEREO
	SCM	1.0	11x11x11cm		See LP-PWI	PWI/BepiColombo RPWS/Cassini
	QTN	3.7	2x6m dipole		From 50 bps to 2kbps	RPWS/Cassini PWI/BepiColombo

Table 6-13. *Addressing of the EJSM-Laplace science objectives by the model payload.*

Objective		Science Investigation	WAC	NAC	VIRHIS	UVIS	LA	IPR	SWI	PPI-INMS	RPWI	MAG	RSI
GANYMEDE													
GA. OCEAN Characterize the extent of the ocean and its relation to the deeper interior.	GA.1	Determine the amplitude and phase of the gravitational tides.					X						X
	GA.2	Characterize the space plasma environment to determine the magnetic induction response from the ocean.								X	X	X	
	GA.3	Characterize surface motion over Ganymede's tidal cycle.					X						X
	GA.4	Determine the satellite's dynamical rotation state (forced libration, obliquity and nutation).	X	X			X						X
	GA.5	Investigate the core and rocky mantle.					X			X		X	X
GB. ICE Characterize the ice shell.	GB.1	Characterize the structure of the icy shell including its properties and the distribution of any shallow subsurface water.	X				X	X					
	GB.2	Correlate surface features and subsurface structure to investigate near-surface and interior processes.	X	X	X	X	X	X	X				
GC. LOCAL ENVIRONMENT Characterize the local environment and its interaction with the jovian magnetosphere.	GC.1	Globally characterize Ganymede's intrinsic and induced magnetic fields, with implications for the deep interior.								X	X	X	
	GC.2	Characterize the particle population within Ganymede's magnetosphere and its interaction with Jupiter's magnetosphere.				X				X	X	X	
	GC.3	Investigate the generation of Ganymede's aurorae.			X	X				X	X	X	
	GC.4	Determine the sources and sinks of the ionosphere and exosphere.			X	X			X	X	X	X	X
GD. GEOLOGY Understand the formation of surface features and search for past and present activity.	GD.1	Determine the formation mechanisms and characteristics of magmatic, tectonic, and impact landforms.	X	X			X						
	GD.2	Constrain global and regional surface ages.	X	X	X	X		X					
	GD.3	Investigate processes of erosion and deposition and their effects on the physical properties of the surface.		X	X					X		X	
GE. COMPOSITION Determine global composition, distribution and evolution of surface materials.	GE.1	Characterize surface organic and inorganic chemistry, including abundances and distributions of materials.		X	X	X			X				X
	GE.2	Relate compositions and properties and their distributions to geology.	X	X	X	X	X	X	X	X	X		
	GE.3	Investigate surface composition and structure on open vs. closed field line regions.	X	X	X	X				X	X	X	
	GE.4	Determine volatile content to constrain satellite origin and evolution.			X	X			X	X			
MAGNETOSPHERE													
MA. Characterize the magnetosphere as a fast magnetic rotator.	MA.1	Understand the structure and stress balance of Jupiter's magnetosphere.								X		X	
	MA.2	Investigate the plasma processes, sources, sinks, composition and transport in the magnetosphere and characterize their variability in space and time.	X	X	X	X				X	X	X	
	MA.3	Characterize the large-scale coupling processes between the magnetosphere, ionosphere and thermosphere, including footprints of the Jovian moons.		X	X	X				X	X	X	
	MA.4	Characterize the magnetospheric response to solar wind variability and planetary rotation effects.	X	X	X	X				X	X	X	
MB. Characterize the magnetosphere as a giant accelerator.	MB.1	Detail the particle acceleration processes.				X				X	X	X	
	MB.2	Study the loss processes of charged energetic particles.	X	X	X	X				X		X	
	MB.3	Measure the time evolving electron synchrotron emissions.								X	X	X	X
MC. Understand the moons as sources and sinks of magnetospheric plasma.	MC.1	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.	X	X	X	X				X	X	X	
	MC.2	Study the interactions between Jupiter's magnetosphere and Io, Europa, Ganymede, and Callisto.		X	X	X				X	X	X	
	MC.3	Study the interactions between Jupiter's magnetosphere and small satellites.								X	X	X	
JUPITER													
JA. Characterize the atmospheric dynamics and circulation.	JA.1	Investigate the dynamics of Jupiter's weather layer.	X	X	X				X		X		
	JA.2	Determine the thermodynamics of atmospheric phenomena.			X	X			X				X
	JA.3	Quantify the roles of wave propagation and atmospheric coupling.	X	X	X	X			X				X
	JA.4	Investigate auroral structure and energy transport.		X	X	X							
	JA.5	Understand the interrelationships of the ionosphere and thermosphere.			X	X			X				X
JB. Characterize the atmospheric composition and chemistry.	JB.1	Determine Jupiter's bulk elemental abundances.			X				X				X
	JB.2	Measure the composition from the stratosphere to low thermosphere in three dimensions.			X	X			X				X
	JB.3	Study localized and non-equilibrium composition.			X	X							
	JB.4	Determine the importance of moist convection in meteorology, cloud formation, and chemistry.			X	X							X
JC. Characterize the atmospheric vertical structure.	JC.1	Determine the three-dimensional structure from Jupiter's upper troposphere to lower thermosphere.	X	X	X	X			X				X
	JC.2	Explore Jupiter's interior density structure and dynamics below the upper troposphere.											
	JC.3	Study coupling across atmospheric layers.			X	X			X				X

6.3 Conclusions and Recommendations

Preliminary studies of the model instruments [10] as well as mission and JGO spacecraft design (section 7) proved that the model payload can achieve the EJSM-Laplace science goals within available mission resources. The model payload is mature: most of the instruments have flight heritage. However the existing flight experience does not expand to the harsh radiation environment that is expected at Jupiter. This emphasizes the need for radiation mitigation and protection and stressing importance of careful use of existing resources.

7 Mission Design

EJSM-Laplace would be a joint NASA-ESA mission comprising two spacecraft, a NASA provided Jupiter Europa Orbiter (JEO) and an ESA provided Jupiter Ganymede Orbiter (JGO). The discussion of the following sections focuses on the ESA element, the JGO spacecraft. Details on the JEO spacecraft are available at the JPL study report [1].

7.1 JGO Mission Profile

The configuration of the JGO spacecraft is driven by the long distance to Jupiter, the high Δv, the need to protect equipment from the intense radiation field, resulting in grouping of instrument and spacecraft hardware, and by the requirement of using solar electric power generation, resulting in a large area of solar arrays. Furthermore, to optimize the data downlink rate, a large high gain antenna is included in the baseline. Due to its remote sensing and *in situ* exploration requirements, a three-axis stabilized spacecraft is assumed.

Savings of the propellant consumption are achieved for the interplanetary trajectory by gravity assists (Venus-Earth-Earth and Earth-Venus-Earth-Earth for baseline and backup launches, respectively), and following Jupiter Orbit Insertion (JOI), by using the two outer Galilean moons, Callisto and Ganymede for shaping the trajectory within the Jupiter system. Science observations are assumed to be carried out during the flybys of the Jovian moons. In addition to allow for an extended exploration of Callisto and allowing for extended exploration of the Jupiter magnetosphere in this key region, a series of resonant orbits with Callisto is assumed, which is designed such that at least 9 Callisto flybys will be performed.

Finally the spacecraft will be transferred into an elliptical orbit around Ganymede, which will be circularized and reduced in altitude, until final deposition on Ganymede's surface. A detailed mission analysis is presented in [4], and is summarized here after.

7.2 Mission Phases

The following phases were identified from the point of view of the mission design:

1. Launch and interplanetary trajectory (5.9 years, 7.1 years for the backup launch date)
2. Jupiter orbit insertion, and energy reduction for transfer to Callisto (179 days)
3. Callisto phase (388 days)
4. Transfer to Ganymede (240 days)
5. Ganymede phase (300 days)

7.2.1 Launch and Interplanetary Trajectory

Launch is foreseen on an Ariane 5 ECA with direct escape towards a Venus gravity assist. In the baseline mission, with a launch date in March 2020, a Venus-Earth-Earth gravity assist sequence is planned, leading to a JOI, preceded by a Ganymede gravity assist manoeuvre, in February 2026, after 5.9 years. The mass injected into the Earth escape trajectory would be 4172 kg, with a hyperbolic escape velocity of 3.38 km/s, which increases to 5.5 km/s after the last Earth swing-by. In this baseline transfer scenario, the launch declination is 0°, which is optimal for launch-to-orbit mass performance.

For the main backup launch that was considered during the study, an additional Earth gravity assist is required extending the transfer time to Jupiter by about 1 year. Due to the relative alignment of Venus and Earth, the Earth departure and Venus arrival conditions are different and are depending on the launch opportunity influencing the direct escape conditions. The declination needed for the direct escape to Venus is low (close to 0°) for 2020, and high (close to about 45°) for 2022 launch opportunities. As the performance of Ariane 5 quickly degrades for non-zero declination, an additional Earth swing-by was introduced allowing for a close to zero degree declination launch, resulting in an Earth-Venus-Earth-Earth sequence. Due to this additional initial Earth gravity assist, the launch mass is considerably increased, partly being used by higher propellant mass required for an additional deep space manoeuvre for targeting Earth, partly resulting in higher dry-mass. Table 7-1 provides a summary of the launcher performance for the primary and for the backup launch considered.

Table 7-1 *Summary of launch mass and transfer duration for primary and backup launch dates. For the purpose of this table the propellant mass is calculated based on an assumed* I_{sp} *of 312 s.*

Launch Date	Launch Mass	Dry Mass	Propellant Mass	Transfer Duration
March 2020	4172 kg	1687 kg	2425 kg	5.9 yrs
May 2022	4641 kg	1701 kg	2872 kg	7.1 yrs

These launch dates were the best opportunities that were found and analysed in detail for the purpose of this study. They are very similar in dry mass and the backup opportunity has a more than one year longer transfer duration. For the purpose of constraining the design of the JGO spacecraft, the worst cases of the two options were taken as the baseline for the spacecraft design: maximum allowed dry mass (including maturity margins) being 1687 kg, and the size of the propellant tanks such that the Δv equivalent to the backup launch can be supported. The mission properties for operations in the Jupiter system are identical in both options. The total Δv budget is 2465 and 2771 m/s for the 2020 and 2022 launch opportunities, respectively.

Additional launch opportunities can be found at the cost of either mass or extended interplanetary transfer duration. These were not studied in detail. It was however verified that no larger Δv than for the nominal backup launch would be required.

7.2.2 Jupiter Orbit Insertion and Transfer to Callisto

The JOI is the most critical manoeuvre of the mission. All other manoeuvres are either without thrusting (Venus and Earth gravity assists), or occur while the spacecraft will be in a bound orbit around Jupiter, when sufficient repetitive opportunities for failure recovery exist. The JOI manoeuvre will require an operation of the main engine for almost 2 hours to deliver 874 m/s.

This Jupiter orbit insertion manoeuvre will be preceded by a Ganymede gravity assist. While from a purely kinetic energy point of view, it would be most efficient having a gravity assist as close as possible to Jupiter, this would significantly increase the encountered radiation dose, and it was therefore decided to limit the closest approach to about the Ganymede orbit (15 R_J). The Ganymede gravity assist foreseen prior to JOI reduces the required Δv by about 300 m/s.

The JOI manoeuvre will insert the spacecraft in a 13x243 R_J orbit, the perijove being defined by the orbit after Ganymede gravity assist, and the apojove being a consequence of the optimization for the following Ganymede gravity assist (this orbit is in 25:1 resonance with Ganymede). A perijove raising manoeuvre of 63 m/s will be performed at apojove to reduce the radiation dose upon the next Jupiter approach, and to reduce the relative velocity prior to the next Ganymede gravity assist. The geometry of this initial orbit around Jupiter is shown at Figure 7-1, where the orbits of Callisto, Ganymede and Europa are also indicated. This single orbit will take 179 days.

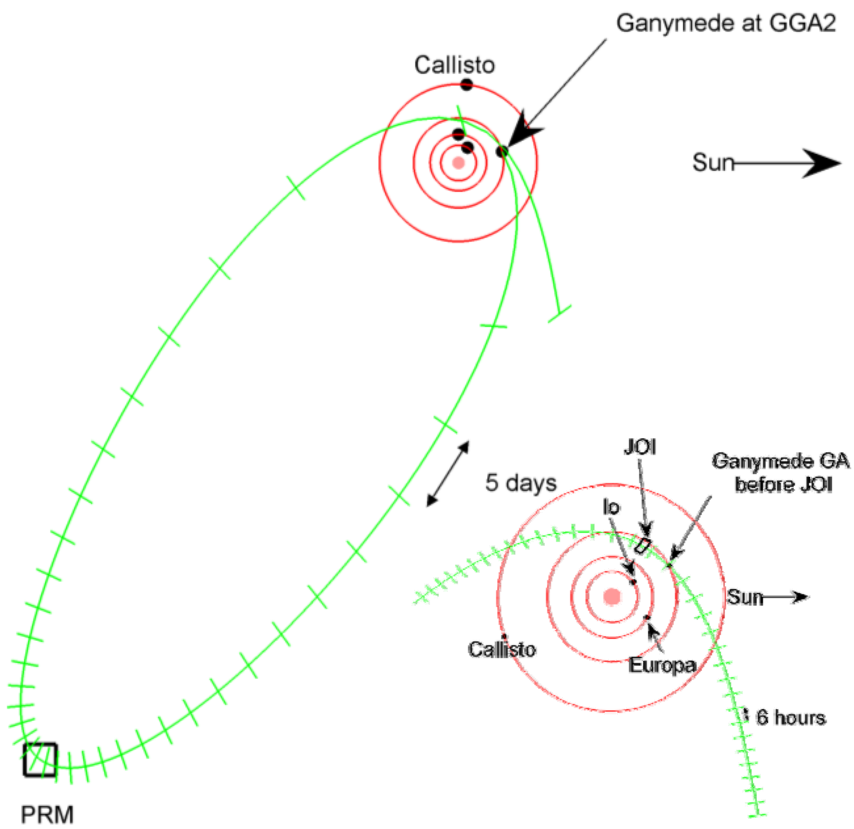


Figure 7-1. Trajectory of the first Jupiter orbit also showing the positions of Callisto, Ganymede, Europa and Io. The inset shows the JOI together with the preceding Ganymede gravity assist.

The orbit will further be reduced by three more Ganymede gravity assists (7:1, 4:1, 3:1 resonances), and the inclination will be reduced from the initial value of –7.4° with respect to the Jupiter equatorial plane. The total required deep space Δv is 23 m/s, and the final apojove and perijove are 50 R_J and 12.2 R_J, respectively (duration 120 days). Finally the spacecraft will be brought into a Callisto resonant orbit through a sequence of Callisto-Ganymede-Ganymede-Callisto gravity assists, which takes 58 days. The entire duration of this phase starting with the JOI and ending with the arrival at Callisto takes 357 days.

7.2.3 Callisto Phase

The exploration of Callisto will be achieved through a series of flybys. The spacecraft will be placed into a resonant orbit with Callisto, and 10 flybys are performed allowing to achive the science objectives at Callisto. The flybys are arranged to allow for (a) studies of the interior structure through one polar and one equatorial flyby; (b) filling gaps from Galileo and Voyager surface observations; (c) remote sensing observations of special targets; (d) geology observations of the leading or trailing equatorial regions. All flybys are targeted at 200 km altitude, except the final one, which is constrained by the transfer to Ganymede and has a higher altitude (~1200 km). From the mission analysis point of view, it is also possible to achieve lower altitude flybys, but due to navigation uncertainty a conservative altitude of 200 km was assumed in this study. A lower flyby altitude may be considered during the last flybys, if navigation accuracy has improved, as it would allow performing *in situ* measurements deeper in Callisto's exosphere.

The orbit during this Callisto phase is shown in Figure 7-2 in Jupiter Solar Orbit (JSO) coordinates, where the sun is at the right. The apojove of most of the orbits with higher eccentricity is opposite to the Sun, which is advantageous for magnetospheric *in situ* measurements. A more detailed summary of the remote sensing opportunities is shown in Figure 7-3, where the ground tracks for each flyby are drawn on a cylindrical map of Callisto's surface. Local time and specific areas and targets of interest are also indicated. The duration of this phase is 388 days.

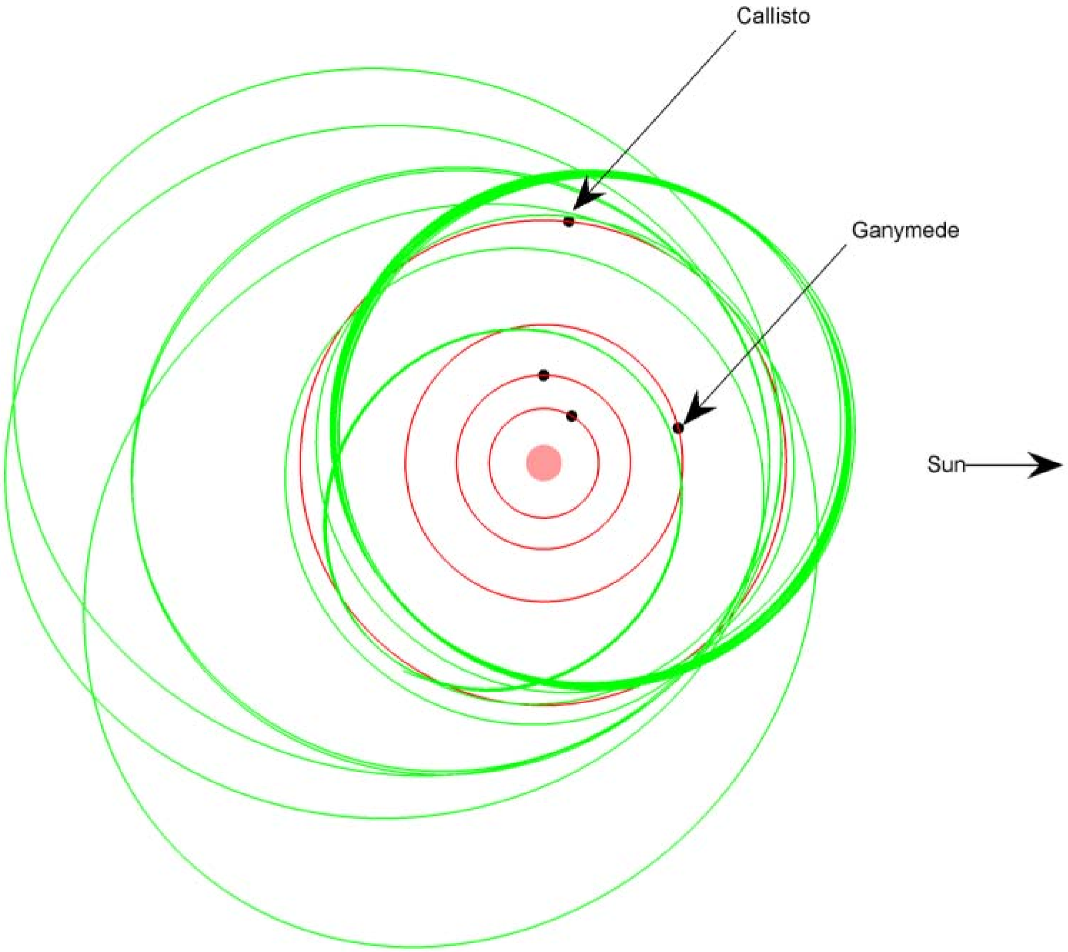


Figure 7-2. *The spacecraft trajectory (green) during the Callisto phase in Jupiter Solar Orbital (JSO) coordinates: Jupiter is located at the centre, as seen from the north celestial pole; the direction to the sun is to the right; direction to dawn is up. The orbits of Callisto, Ganymede, Europa and Io are also indicated. This trajectory includes 10 targeted flybys.*

For the Callisto flybys a Δv budget of 10 m/s per flyby was allocated for navigation corrections. This is limiting the number of flybys that are considered in the baseline. Further navigation analysis will be carried out during the next phase to investigate among others, whether this average amount of Δv could be reduced, thereby allowing for the number of flybys being increased. No changes to the implementation of the spacecraft would be required in this case.

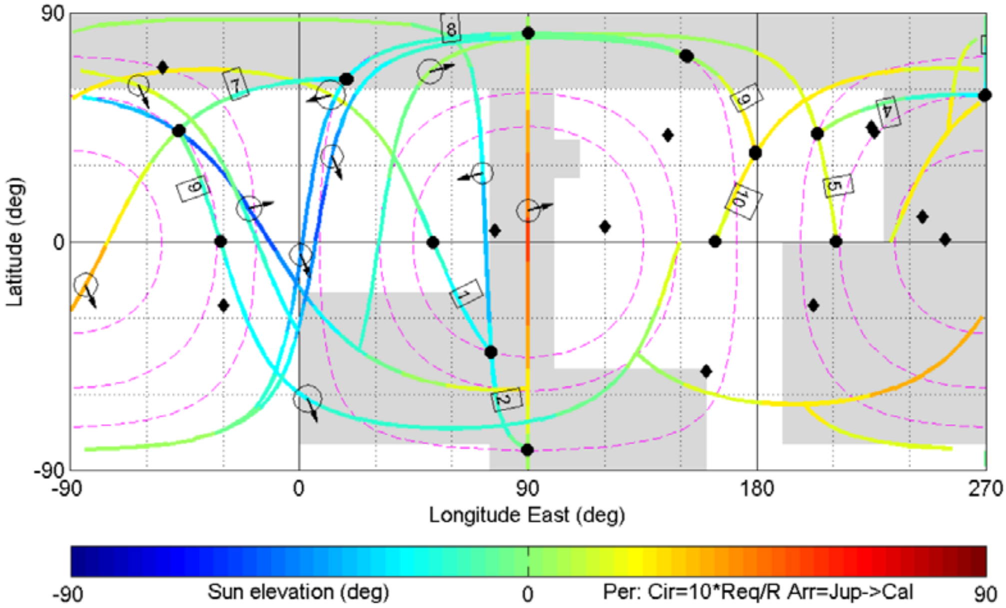


Figure 7-3. *Ground track of the Callisto flybys for altitudes <5000 km. The color scale indicates local Sun elevation of the sub-nadir point in degrees (values <0° refer to local night). Numbers indicate the sequence of the flyby. The shaded areas correspond to the scientific target areas to fill gaps from Galilieo and Voyager data. The black diamonds correspond to specific target locations. The black circles along each flyby trajectory correspond to the pericentre location (the size of the circle is linear with the pericentre altitude; the arrow gives the Jupiter-Callisto direction in the Jupiter equator of date).*

7.2.4 Transfer to Ganymede

The transfer will be performed by using the moon resonance strategy, which significantly reduces the Δv spent compared to the gravity assist strategy, at the cost of added transfer time, which however can be used for science observations, as the region between Callisto and Ganymede is particularly interesting for magnetospheric/plasma physics. The transfer takes 240 days and 92 m/s, and will be completed by the Ganymede orbit insertion manoeuvre, consuming 144 m/s.

7.2.5 Ganymede Phase

The Ganymede phase will comprise three different types of orbits, which are driven by the requirements of remote sensing at specific illumination conditions, magnetospheric sampling, and the constraint to avoid Ganymede eclipses that would require oversizing the solar panels. Obviously, the eclipse duration in Ganymede orbit is a consequence of the combination of spacecraft altitude and sun declination relative to the plane of its orbit (called β-angle), resulting at given altitude in longer eclipse durations for smaller sun declination values (see Figure 7-4). For close to polar Ganymede orbits, the orbital plane of the spacecraft will rotate around the pole as a function of inclination due to the influence of Ganymede's oblateness and Jupiter's attraction. This was used to design the orbit such that lower altitudes could be realized later during this phase, while still avoiding sun eclipses, allowing for a sequence of orbits with decreasing altitudes as summarized in

Table *7-2*.

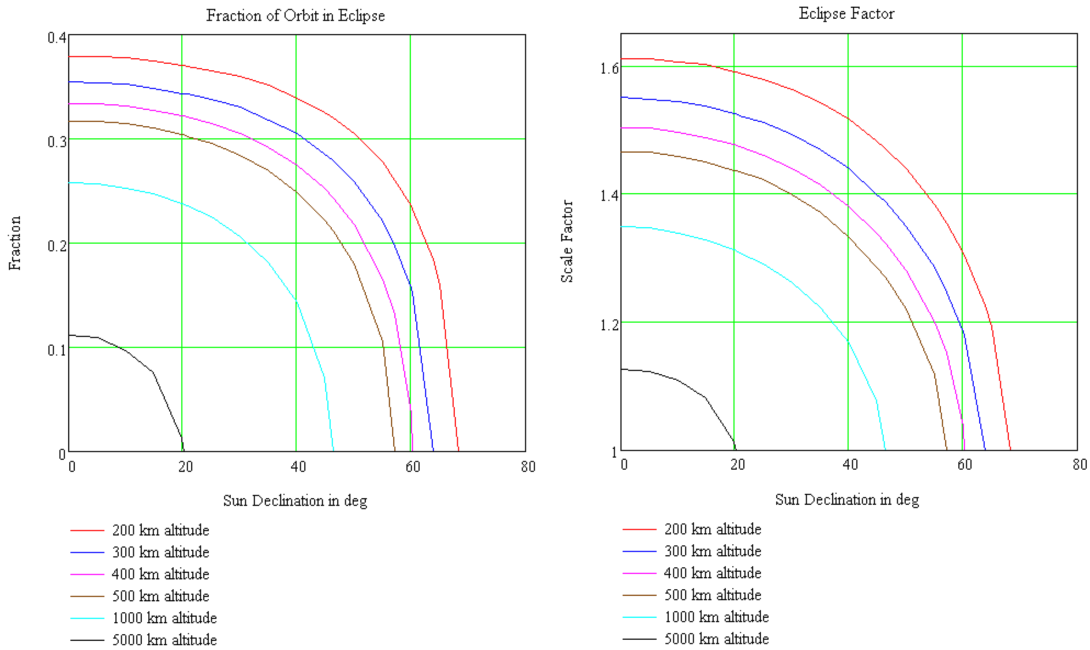


Figure 7-4. *Influences of eclipses by Ganymede on the spacecraft design. Left: the fraction of time spent in eclipse as a function of Sun declination to the orbital plane for circular polar orbits with altitudes from 200 to 5000 km. Right: the scale factor of increase of the solar panel for additional power generation.*

Table 7-2 *Paramters of the orbits around Ganymede.*

Phase	**Altitude, km**	**Sun Declination (β-angle), deg**	**Duration, days**
Elliptical*	200x10,000 to 5000 circular	40	120
High Circular	500	62	120
Low Circular	200	71	60
End	200	76	n/a

*) Note that in this phase an elliptical orbit is only available for limited time.

Due to the high apocentre of the elliptical orbit, perturbation by Jupiter is significant, and will cause the orbit to quickly evolve. The argument of pericentre was chosen such that this evolution leads to a circular orbit within about 20 days, where it will remain at an altitude of 5000 km, which will be maintained for about 80 days, and then the eccentricity will increase until a suitable point for injection into a 500 km altitude circular orbit is reached. The evolution of the most important parameters such as apocentre and pericentre altitudes, inclination, argument of pericentre, and sun declination are shown in Figure 7-5.

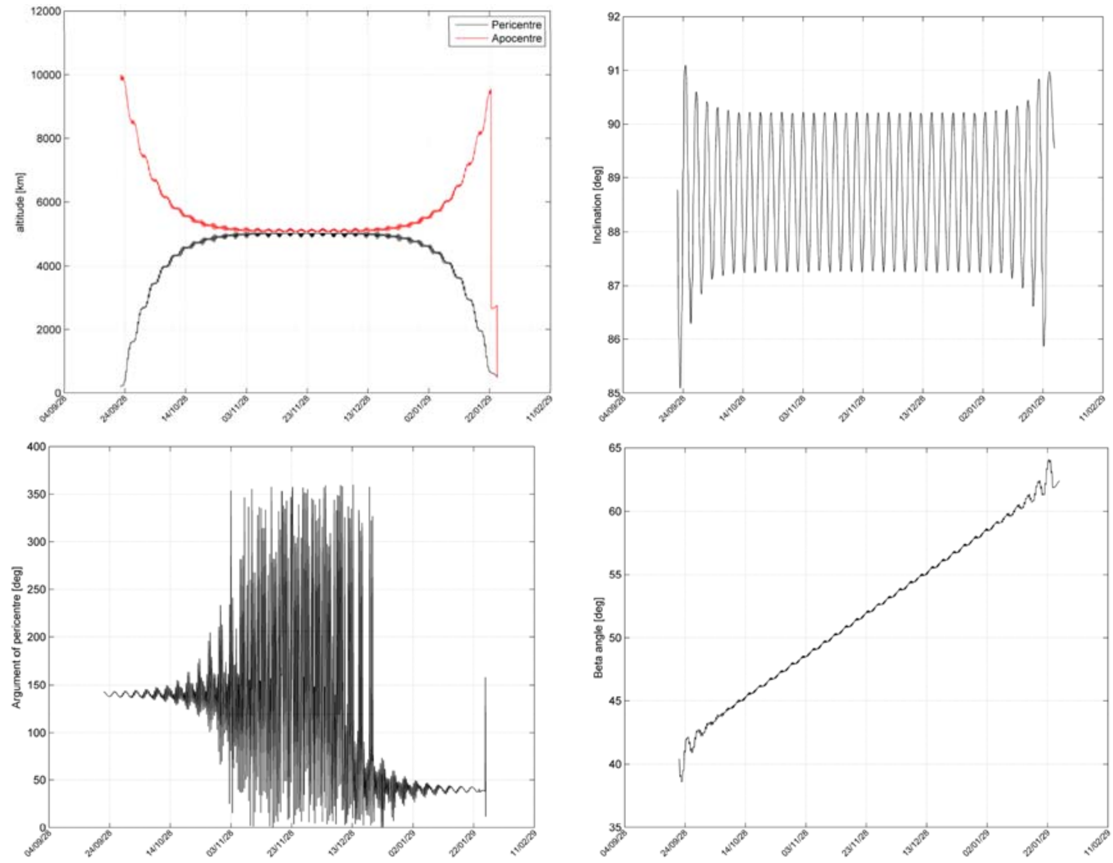


Figure 7-5. *Evolution of the orbit during the Ganymede elliptical phase: apocentre and pericentre altitudes (top left); inclination (top right); argument of pericentre (bottom left); sun declination, called β-angle (bottom right).*

When a suitable altitude is reached, a manoeuvre of 480 m/s will be applied to arrive at a circular 500 km altitude orbit, where the spacecraft would operate for 120 days, and the final orbit of 200 km altitude will be obtained after a Δv of 92 m/s. After nominal operations of at least 60 days (extension would be possible based on remaining consumables and spacecraft health), orbit maintenance will be discontinued, and the spacecraft will be left in an orbit with natural growth of eccentricity until disposition on Ganymede's surface. In this final phase the orbit will be very close to polar (deviation <1°), and its evolution of the sun declination is shown in Figure 7-6.

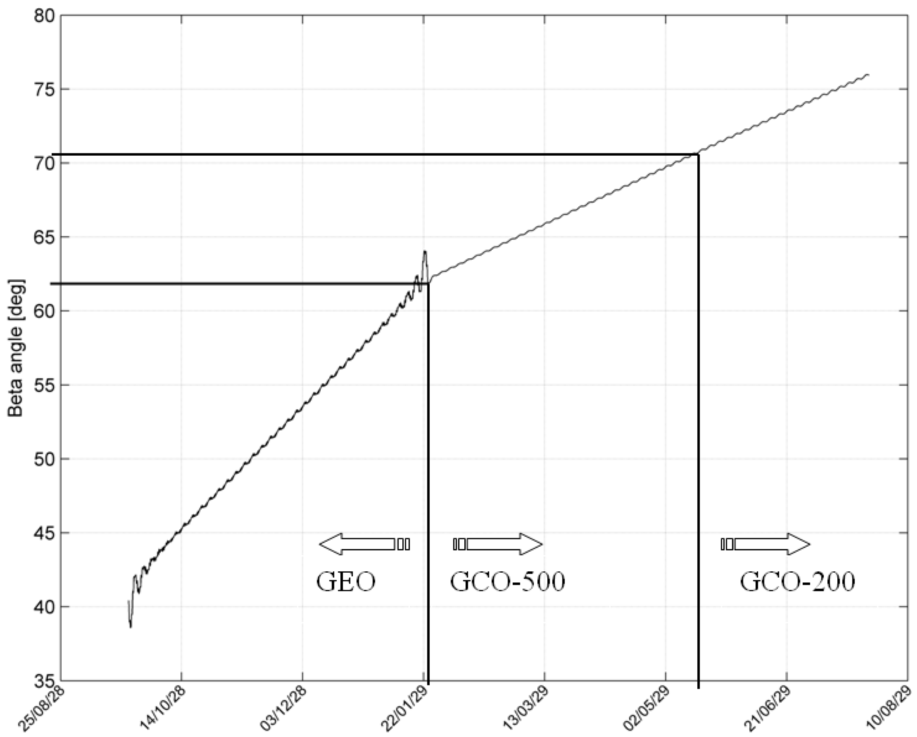


Figure 7-6. *Evolution of the sun declination (β-angle) as a function of time during the Ganymede orbit phases: GEO stands for Ganymede Elliptical Phase, and GCO stands for Ganymede Circular Phase.*

7.3 Radiation Environment

The mission radiation environment [5] is dominated by the properties of the plasma at Jupiter. Figure 7-7 summarizes the environment from ionizing radiation through the absorbed dose as a function of shielding material thickness for the total mission. The contribution during the interplanetary phase is less than 1% of the total dose, about 34% is accumulated during the tour in the Jupiter system, and about 63% are obtained during the final phases at Ganymede.

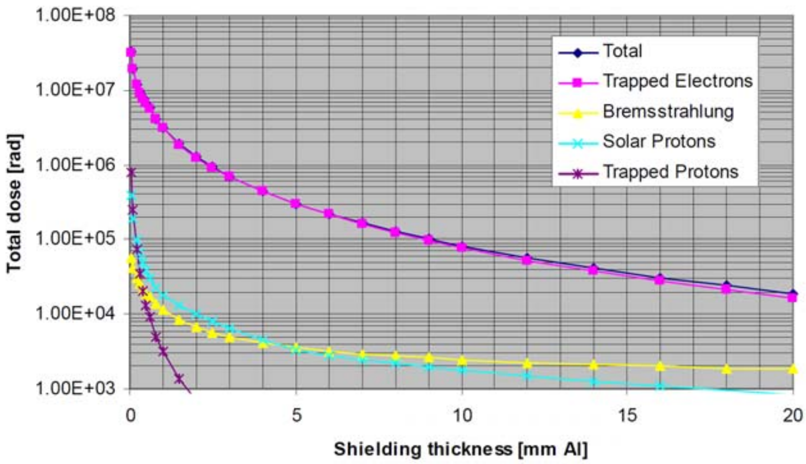


Figure 7-7. *Total dose as a function of shielding thickness. The contributions from the various particle species are also indicated.*

As can be seen, the radiation environment is dominated by electrons (purple lines), which have an energy spectrum with significant densities up to 1 GeV. Due to these high energies the penetration depth is deeper than considered for typical geostationary applications (assuming about 10 years lifetime), for instance. At lower energies, where the density is significantly higher, the interactions with the surface layers will dominate, causing local surface charging effects, if not properly mitigated, e.g. by shielding and conductive layers.

The design solutions assumed below consider the accommodation of instrument and platform equipment in reasonable close vicinity and within compartments, taking advantage of shielding by neighbouring units. In addition, the amount of extra shielding applied to the compartments (also called vault) was derived from first order radiation transport calculations.

Due to the radiation spectrum being dominated by electrons, shielding by high Z materials, such as tantalum or tungsten (or allows with e.g. copper) are very efficient. Charged particle transport simulations showed that a reduction of about 35% in shielding mass could be possible when using high Z materials, as compared to shielding by aluminium. This could be used as shielding material for the vault, and for spot shielding of specific items with lower radiation tolerance.

7.4 Spacecraft Design

7.4.1 Mission Drivers and Design Consequences

7.4.1.1 Deep Space, Solar Power, and Telemetry

The main mission drivers are related to the large distance to the Sun, the fact that the mission shall use solar power generation, and to Jupiter's specific radiation environment. The orbit insertions at Jupiter and Ganymede and the large number of flyby manoeuvres (>25 gravity assists and flybys) lead to a rather high Δv requirement, which translates into a high wet/dry mass ratio (about 2.6:1), which amplifies changes of the dry-mass. The large distance to Earth results in a signal round trip time of up to $1^{h}46^{m}$ requiring careful pre-planning and autonomous execution of operations by the spacecraft. Additionally, a high gain antenna is required for data downlink. The studies that were conducted aimed at maximizing the diameter of the high gain antenna for maximum science return. For the study purposes, a daily data volume of 1 Gb was assumed as being feasible.

The requirement of using solar array power generation in combination with the large distance from the Sun, providing a worst case solar constant of 46 W/m^2, results in large area solar arrays, of typically about 60 – 75 m^2. This is a constraining item, which is also correlating the maximum available power with the allowed launch mass.

From the detailed analysis of the mission phases, the Ganymede circular phase was identified as the most challenging phase, which was therefore used as the reference for system sizing.

During this phase, the largest amount of scientific data will be generated. For the baseline, it was assumed that data downlink would occur every time the spacecraft is visible from the single ground station, and would last for the entire pass, possibly only interrupted, by Jupiter or Ganymede occultations. To maximise the data return, more power will be provided to the telemetry system, and very limited instrument operations would be performed during downlink periods. Consequently the need for a steerable high gain antenna was ruled out, allowing for mass optimization and avoiding losses by the radio-frequency chain due to flexible joints. Furthermore, for orbits, during which the spacecraft would be in eclipse, an increase of the required solar array area (and therefore mass) was found as a function of eclipse duration, already requiring significantly more area even for short eclipse durations (Figure 7-4). It was therefore decided to avoid orbits around Ganymede, which would cause the spacecraft flying through regular Sun eclipses.

The power generation was further optimized by keeping the solar arrays close to normal to the Sun direction. This will be achieved by a combination of the rotation of the solar arrays around their mounting axis and a spacecraft rotation around the nadir direction. Such a rotation of the spacecraft (yaw steering) will be performed during baseline operations. It is however foreseen to be able to halt this yaw steering for a limited period of time, e.g. for high resolution imaging. This case was however not considered as a design driver, and would therefore only be allowed in combination with power saving measures. This will not affect plasma measurements since the spacecraft attitude will be performed by reaction wheels.

7.4.1.2 Radiation and Low Temperature Environments

To optimize the required shielding, and to benefit from units shielding each other, all studied spacecraft designs found the accommodation of critical electronic and instrument hardware in a common compartment the most efficient solution. Preliminary analysis of the required shielding was performed. In addition, spot shielding of components with lower radiation tolerance is assumed.

Particular attention needs to be paid to the effects of the ionizing radiation on insulation of cables and connectors. The proposed accommodation within a shielded compartment is helpful for mitigation of this effect as well.

The foreseen accommodation of instrument and platform units within compartments, favours the thermal balancing, in that non-operating units are being heated by operating units within the same compartment. This concept optimizes the heating power required.

7.4.1.3 Payload Operations Scenarios

To arrive at a realistic sizing of the spacecraft power subsystem, the mass memory and the telemetry subsystem, a generic baseline operations scenario of the model instruments was compiled. Instruments that would likely be operated together were combined in one scenario, and a schedule of a generic operations sequence was compiled. The Ganymede orbit phase was considered as the reference for this specification, as it is generating the highest volume of science data. The grouping of instruments that would operate in a combined manner on a per orbit basis is summarized in Table 7-3.

Table 7-3. *Definition of five generic model instrument observation scenarios; observing scenarios Obs1 to Obs5 were grouped such that one scenario would operate for an entire orbit.*

Obs1 Remote Sensing	**Obs2 *In situ*, WAC, LA**	**Obs3 Radar + *in situ***	**Obs4 Radio Science & downlink**	**Obs5 Jupiter obs., others**
VIRHIS NAC UVIS MAG LA	WAC LA MAG RPWI PP	SSR RPWI MAG PP	JSRT USO	SWI VIRHIS NAC WAC UVIS

Observation scenarios Obs1 and Obs2 would mainly be used during flights over the dayside of Ganymede. In the baseline assumption, these modes would be used alternating and all instruments listed in these groups would be operational. Observation mode Obs3 would be the baseline operation mode during night side observations. The mode Obs4 would either be used in parallel to the data downlink, or for the radio-link to the JEO spacecraft for radio-occultation sounding of Jupiter's atmosphere. The mode Obs5 is intended for remote observations of Jupiter and the other Galilean moons. All these scenarios would not be limited to the Ganymede phase, but would also be used in the other mission phases. It is emphasised that these are example scenarios designed for sizing of the spacecraft resources. Detailed science operations will be developed in future, in collaboration with the instrument PI's. The mission operations, including the proposed MOC and SOC approaches and key elements of the science management are described in sections 9 and 10.

7.4.1.4 Model Payload Accommodation Considerations

Several instrument accommodation requirements appear to be competing for similar locations, which makes the configuration complex. The model instruments include a large number of sensors that need to be mounted on booms, and which have specific requirements on their orientation on the spacecraft and relative to the spacecraft's velocity vector. In addition there is a set of remote sensing instruments, which require unobstructed fields of view. And also some particle instruments require as close as possible to 4 π unobstructed field of view. This becomes even more challenging, due to a number of surfaces of the spacecraft already being occupied by platform subsystems, such as: solar panels (2 surfaces), high gain antenna (1 surface), main engine and launcher interface (1 surface). Therefore a compromise in sharing the surfaces had to be found for the accommodation of instruments with specific orientation requirements, such as facing nadir, anti-nadir, velocity, and anti-velocity. A set of different configurations derived as consequences of these constraints are being presented in the following sections.

To reduce the number of booms and antennae, thereby simplifying the accommodation and reducing the complexity for deployment, sharing of booms and antennae by more than one instrument is recommended. The magnetometer boom and the radar antenna may lend itself as obvious examples for accommodation of additional sensors, provided the interface requirements are compatible, e.g. on electromagnetic fields.

Due to the large number of plasma measurements to be performed, strict limits on the electromagnetic compatibility of the spacecraft subsystems was included as goals, which need more analysis during the next study phase. The electric charging of the surface of the spacecraft shall remain within a few volts in general, and a design goal of better than 1V in the vicinity of the electric field sensors and low energy particle spectrometers; the DC magnetic field shall remain <2 nT, with a stability of <0.1 nT over the range 0 to 64 Hz (at least during magnetometer measurements), and the electric stray field shall remain <50 dB μV/m within the frequency range below 45 MHz.

7.4.2 Spacecraft Design – Solution 1

7.4.2.1 Configuration

The configuration of this solution is dominated by the accommodation of the tanks of the bi-propellant system being stacked on top of each other within a central tube (derived from Spacebus; see Figure 7-8). All platform and instrument equipment would be accommodated on panels around this central tube, including a vault-type structure serving as radiation shield in the middle that would contain the majority of the units. The large solar arrays (2×32 m^2) would be attached to the side of the spacecraft structure, and consist of four panels each, two of which would be deployed sideways so as to reduce the total length and moment of inertia. The solar arrays would include one drive mechanism each for rotating the solar panels around the spacecraft Y-axis. The high gain antenna would be fixed and mounted to the side of the main tube, where it would be recessed in the main structure so as to maximize its diameter (3.2 m), while still respecting the limits of the launcher fairing. Most of the booms would be extended parallel to the Z axis so as to reduce frequency coupling during thrusting. The size of the spacecraft body (x×y×z) would be 2.25 m × 1.70 m × 3.13 m, and the extent of the unfolded solar arrays, from the edge of the spacecraft's body is 9.214 m, with a maximum of 7.038 m across.

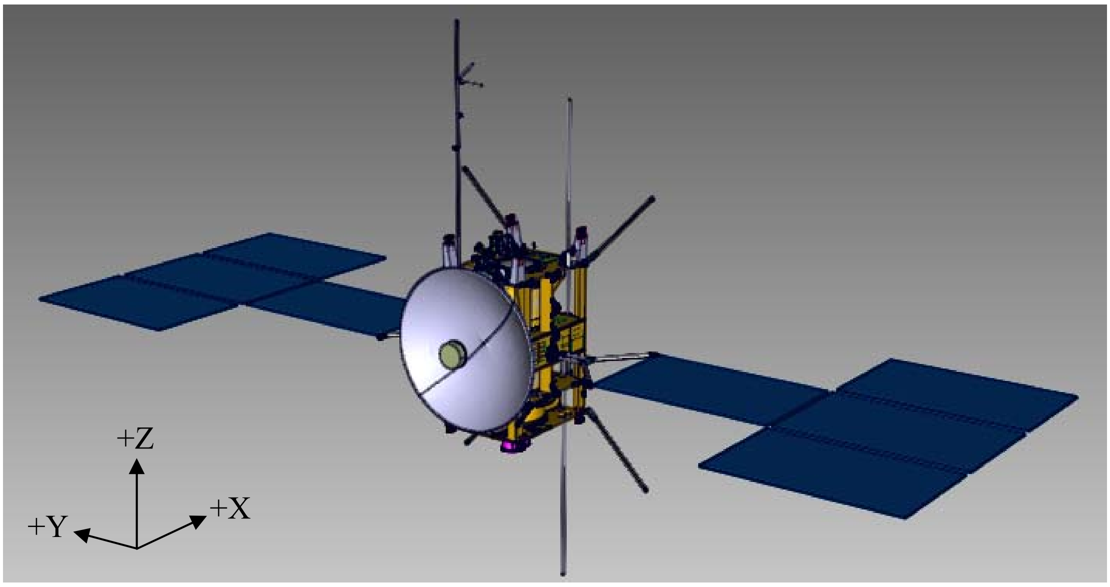


Figure 7-8. *Spacecraft configuration of solution 1 shown with the side panels removed. The main engines and the launcher interface would be at the bottom (–Z), the remote sensing and in situ instruments, which required access to the velocity direction would be located the back of this view (+X). The cold plate would be at the top (+Z).*

The main remote sensing and *in situ* instruments are mounted on the +X panel (see Figure 7-8). The spacecraft orientation with respect to the nadir and velocity directions would be changed per observation scenario. During remote sensing operations, the +X panel would be oriented to the target and the main component of the velocity vector would be parallel to the spacecraft Y axis. During the Ganymede phase, the spacecraft would perform a rotation manoeuvre around the X-axis (yaw steering) with amplitude depending on the latitude, so as to allow for optimum illumination of the solar panels by the Sun. For *in situ* measurements, the spacecraft would be turned such that the +X direction is parallel to the main component of the velocity, and thus the instruments mounted on the +X panel could be exposed to the incoming plasma particles. In this configuration the Y-axis would be towards the nadir direction, and the spacecraft would perform a roll operation around the X-axis for optimization of solar panel illumination. During data downlink and radio-science measurements, the spacecraft would be inertial pointing with its high gain antenna oriented to the Earth.

7.4.2.2 Attitude and Orbit Control System

A careful trade-off optimizing the effective total mass required for reaction wheels (including solar array mass for producing the required power) resulted in three large momentum wheels (plus one backup) with maximum capacity 68 N·m·s, rotating at low speed. The system is designed to support the necessary yaw-steering in the Ganymede orbit (up to 28 N·m·s), and nadir tracking during Callisto flybys (200 km altitude, $v_\infty = 2.1$ km/s) in the worst configuration (solar panels along track) requiring a capacity of 26 N·m·s. The thruster configuration would be pure torque for support of wheels unloading without parasitic Δv. AOCS sensors include a mini-IMU, a three-head star tracker (Hydra), and Sun sensor. The IMU includes ring laser gyro and an accelerometer with sub-mg precision, sufficient for monitoring the Δv changes due to the impulse firing.

7.4.2.3 Propulsion

The propellant system would be based on MON/MMH bi-propellant with a total available mass of 2861 kg (driven by the backup launch Δv requirements). Major manoeuvres will be performed with a 424 N main engine ($I_{sp} = 321$ s), and a backup main engine would be implemented for redundancy.

Eight 22 N thrusters would be included in redundant configuration for the support of the AOCS. The AOCS thrusters support the momentum wheel off-loading and the attitude control during main engine thrusting periods. Additionally four of these thrusters will be used for executing low amplitude Δv

manoeuvres. The manoeuvres by the main engine would be performed in pressurized mode (two Helium tanks) to optimize the Δv performance, while the AOCS thrusters would be used in blow-down mode.

7.4.2.4 Power and Solar Array

The power conditioning and the data handling would be combined into the power conditioning and distribution unit (PCDU). The PCDU would provide a regulated power bus at 28 V. The battery is sized for the longest eclipse of 8.3 h, which would be due to Jupiter, and which would require 4750 Wh stored energy.

The solar cells would be arranged on 8 panels of equal size, which would be mounted on either side of the spacecraft with a total area of 64 m^2. The cells would be covered by 75 µm cover glass for protection against electron dominated environment, and by ITO for protection against electrostatic charging. The cells are assumed to be triple-junction GaAs based optimized for Low-Intensity-Low-Temperature (LILT), which is an ongoing development by ESA with Azur, having shown promising results. As a backup cells of existing technology could be used after careful selection of their performance under LILT conditions. Assuming a worst case 46 W/m^2 illumination, a total of 636 W would be generated at end-of-life.

7.4.2.5 Command and Data Handling

This functionality would be integrated with the power conditioning and distribution unit. The command and data handling processor would be based on the Leon 2 type, and would include spacecraft management functions, mass memory management and remote terminals. The mass memory would be internal and based on flash memory with a total of 60 Gb at end of life (including a margin of a factor of two), which is driven by the generic instrument operations scenario (see section 7.4.1.3), being the highest science data volume accumulate during a Callisto flyby (27 Gb). The interface to instruments and sensors would be by MIL-STD-1553 and SpaceWire for the higher data rate instruments (VIRHIS, cameras).

7.4.2.6 Communications

Data downlink would be provided by a fixed 3.2 m high gain antenna (HGA), which is capable for X and Ka-band transmission. The antenna geometry and feeds are optimized for interplanetary Ka-band. According to the baseline assumption, housekeeping data would be transmitted in X-band during the early parts and during the late parts of the pass above the single ground-station, when the ground station antenna elevation is low. The science data would be transmitted in Ka-band at higher ground-station antenna elevations. Transmission from the spacecraft would take place with 100 W_{RF}. In addition, to optimize the total downloaded data volume, the downlink data rate would be adjusted as a function of elevation from the ground station. A single ground station was assumed, with a data link being established during each pass (once per day). Initial estimates confirm that the assumed data volume of 1 Gb per day could be met with margin. Command uplink would be performed in X-band. Provisions for the integration of the radio-science experiment and the link to JEO would also be included in the telemetry subsystem.

A two-axis steerable medium gain antenna (MGA) would be provided to allow for communications during the path of the inner solar system (when the HGA is being used as a thermal shield). Furthermore, for distances >2 AU during the interplanetary phase, and during the Jupiter phase, the MGA would be used for Earth search during safe mode recovery.

7.4.2.7 Thermal Design

The entire spacecraft will be optimized for the cold environment and will be covered with black Kapton MLI (20 layers). The requirements of the thermal design are simplified by the fact that the high gain antenna would be used as sunshield during the Venus gravity assist, keeping the remainder of the spacecraft structure in shadow. During the Venus gravity assist the solar panels will be tilted (30° incidence angle) so as to reduce the irradiation, resulting in a temperature of the solar array of

100°C maximum. During the Ganymede phase the solar constant would only be at maximum 55 W/m^2, with the albedo from Ganymede being negligible (the albedo was however included in the thermal model). The solar array temperature would be at the minimum –90°C. Radiators are assumed on the sides of the solar panels (±Y, see Figure 7-8) with a total area of 0.78 m^2. Furthermore the +Z panel could be held in shadow at all times and would provide a heat sink with a temperature of –143°C. The lowest dissipation would occur during survival mode and is the sizing case for the heater power, which would be 217 W (mainly for heating of battery and tanks).

7.4.2.8 Payload Accommodation

The majority of the scientific equipment would be accommodated within a main and a smaller secondary compartment (see Figure 7-9). These compartments provide the possibility of additional wall shielding. The main compartment would be located at the centre of the spacecraft providing accommodation volumes at the inside of the ±Y panels, and the +X panel (nadir direction). The sensor heads would be accommodated in the +X panel, and electronic units on the ±Y panels, which also allow for additional radiator surfaces. The second instrument compartment would be located on the corner of the +X and the +Z panels, close to the coldest radiator. Instruments requiring high cooling power, and/or high stability mounting would be included, such as the high resolution camera and the visible near infra-red hyperspectral imager. *In situ* particle and plasma sensors would be accommodated on the +X panel, the +Z panel for access to the anti-nadir/anti-velocity directions, or on booms, as required.

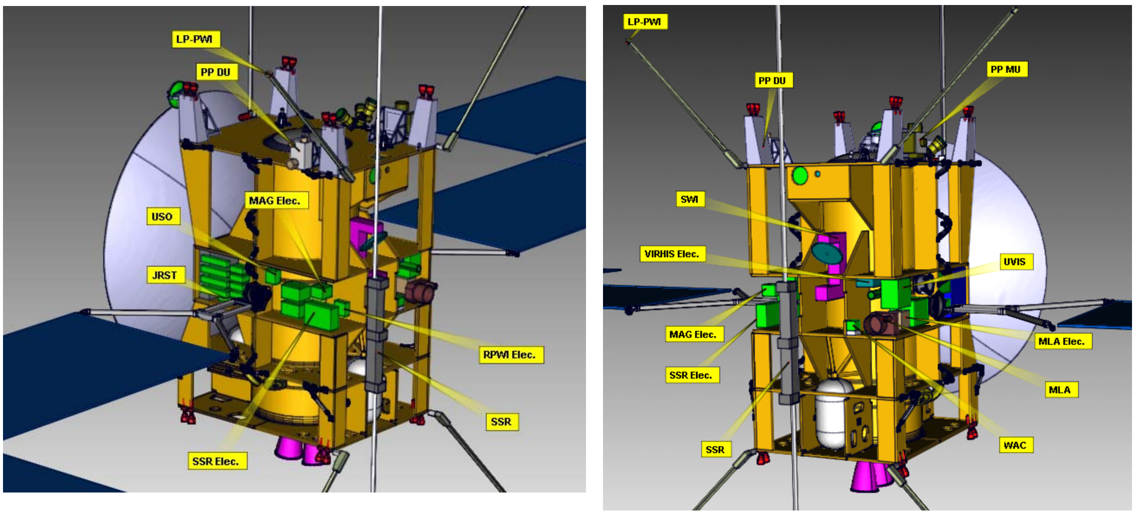


Figure 7-9. *Accommodation of the model instruments in spacecraft solution 1.*

7.4.2.9 Mechanisms

The solar array deployment for achieving the configuration with side-panels is being used on telecommunications satellites, and is therefore not considered new. One axis solar array drive mechanisms will be needed. The main force will occur during the periods of the main engine thrusting. For stability the solar arrays would be rotated such that they are aligned with the plane of the thrust vector. All other booms and appendices are accommodated such that they are extending parallel to the thrust vector so as to reduce vibration loads.

The medium gain antenna would include two rotation mechanisms, the elevation with a stroke of 100°, and the azimuth with a stroke of 360°. Such mechanism will be employed on the *BepiColombo* mission.

In support of the instruments, a 5 m boom is baselined for the magnetometer, four 3 m booms for

RPWI probes, and two 5 m sub-surface radar booms.

7.4.3 Spacecraft Design – Solution 2

7.4.3.1 Configuration

The spacecraft is based on a cube structure, which would include four main propulsion tanks and the propulsion system. The platform electronic units and the instruments would be accommodated outside of this structure in separate compartments on the +X and –X panels (see Figure 7-10). The size of the main structure (*x*×*y*×*z*), without solar arrays and high gain antenna, would be 1.56 m × 1.56 m × 2.68 m. A 3.5 m diameter high gain antenna would be fixed to the body of the spacecraft on the +Z panel and could be accommodated inside the launcher fairing with margin. The diameter of the high gain antenna was derived from a combination of mass optimization, data transmission capability and pointing performance. Large solar arrays consisting of seven panels each would be mounted on either side of the spacecraft body yielding a total area of 72 m^2. The solar arrays can only be rotated about the Y-axis of the spacecraft. The instrument booms would be extended in the ±X directions, avoiding conflicts with the solar panels and with the high gain antenna.

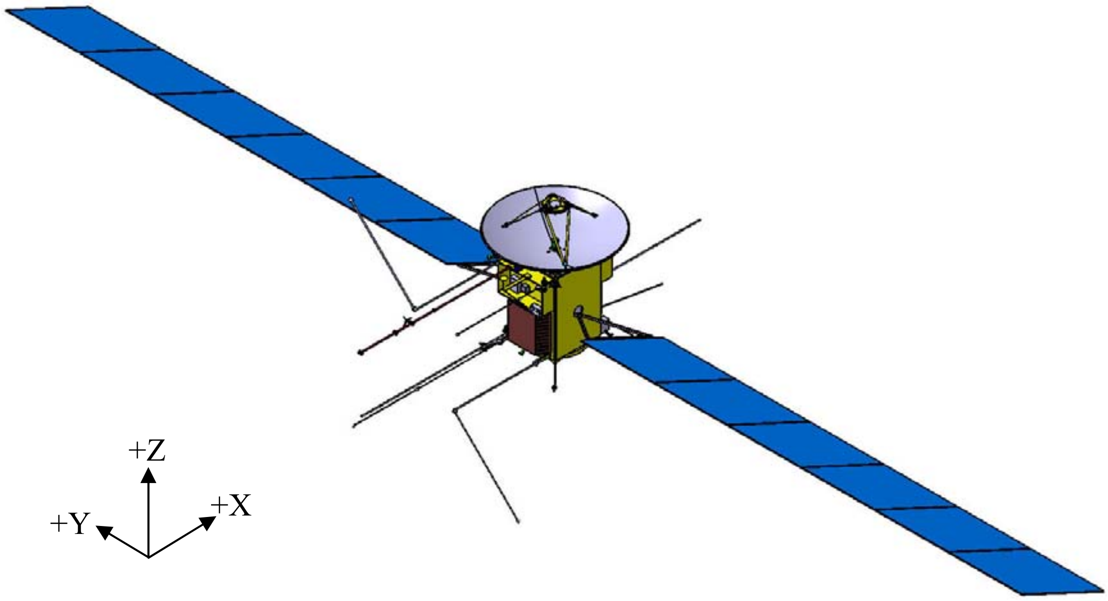


Figure 7-10. *Spacecraft configuration of solution 2. The main engine and the launcher interface is at the bottom (–Z), the remote sensing instruments are located the back of this view (+X), and the in situ instruments, which require access to the velocity direction are mounted on the –X panel. The high gain antenna is at the top (+Z).*

The remote sensing and the *in situ* instruments would be mounted on opposing faces of the spacecraft and consequently the *in situ* measurements and the remote sensing measurements would be performed using different orientations of the spacecraft with respect to nadir and to the flight direction. During remote sensing the +X panel would be facing the surface, and the main component of the velocity vector would be parallel to the spacecraft Y-axis. In the baseline, during the Ganymede phase, the spacecraft would perform a rotation around the nadir direction (yaw steering) optimising the illumination of the solar panels. During *in situ* observations, the spacecraft would be oriented such that the solar arrays (Y axis) are aligned with the nadir/anti-nadir direction, pointing the –X panel to the anti-velocity direction. In this orientation illumination of the solar arrays would be optimized by rotations around the velocity vector (roll). During both modes the rotations could be stopped for limited duration, so as to allow for observations with a stable instrument platform. Radio science measurements would be performed in parallel to science data download, when the spacecraft would be held using inertial pointing with the high gain antenna pointing to the Earth.

7.4.3.2 Attitude and Orbit Control System

The sizing of the reaction wheels for the required momentum storage was based on careful mass optimizations taking the mass of the wheels and their required power including solar generator mass into account. A baseline with three wheels plus one redundant was selected, with a slightly asymmetric configuration accounting for different angular momentum needs. The maximum required capacity of 50 N·m·s was driven by the Callisto flyby scenario, allowing full flexibility of the orientation of the spacecraft during the flyby. The required yaw rotation around Ganymede was not considered as a driver during the study, as it was calculated that the reduction of the power generation due to a minor off-pointing of the solar arrays during the short period of peak rotation (around the equator) would be negligible (0.5% power loss). The thruster configuration is enabling pure torque and pure force in all directions, resulting in 12 thrusters being mounted on three corners of the spacecraft. Two additional thrusters are foreseen for control of the main engine torques. The star tracker would utilize a three head system (Hydra). The sensors would also include a redundant inertial measurement unit and two redundant Sun sensors.

A redundant navigation camera with a field of view of 1.5° and optimized for extended object recognition would be provided in support of navigation at the Jupiter system. To reduce the risk of failure due to the extended required operational lifetime of the reaction wheels and gyros, a hibernation mode for transfer to Jupiter would be implemented, which would be similar to the near Sun hibernation mode of Rosetta.

7.4.3.3 Propulsion

The propulsion system would be based on a helium pressurized bi-propellant system using MMH and MON. Four 650 l propellant tanks and four helium pressurant tanks would be installed at the centre of the spacecraft and could accommodate 2915 kg (driven by the backup launch Δv requirements). The propulsion system is designed to operate in a constant pressure mode during the main engine firings using a regulated helium supply. Following completion of the orbital injection manoeuvres the main engine or pressurant tank would not be isolated and the system would remain in a regulated helium supply mode. However the hardware and feed system technology enables the switching to the blow-down mode to protect the regulator and valves from propellant vapour migration, or regulated mode providing the main engine with full efficiency. A 445 N main engine was selected with an I_{sp} = 317 s. 14 AOCS thrusters of 10 N would be provided in total duplicate redundancy (total of 28) and would be mounted such that pure thrust could also be provided for navigations corrections independent on the orientation of the spacecraft.

7.4.3.4 Power and Solar Array

The power conditioning and distribution unit would provide a 50 V regulated bus to the spacecraft equipment. Although 50 V is being used less frequently, it has been used on past mission as the bus voltage, and off-the shelf radiation tolerant space qualified components are available. The battery would be sized for the longest eclipse and would provide 4650 Wh.

The solar cells would be using the Low-Intensity-Low-Temperature (LILT) optimized technology, and would be arranged on seven segments each on either side of the spacecraft with a total area of 72 m^2, providing 693 W at end of life. The cover glass was optimized by trading-off mass due to increased shielding and reduced transparency, with the necessary solar generator area and mass for required radiation tolerance of the solar array. A thickness of 76 µm was found as the optimum value. Electrostatic discharge protection would be achieved by current limitation on each string and by limiting the differential voltage between adjacent cells, and possibly by the application of conductive surfaces (e.g. ITO coating). The thermal model yielded temperatures within the solar cell qualification range (up to 120°C) for the Venus gravity assist. In addition the control of the angle of incidence (e.g. by rotating the solar array away from the sun) may be performed.

7.4.3.5 Command and Data Handling

The processor would either be based on an ERC32 or on a type from Leon family. Either processor type was considered of sufficient processing power. The processor, the interface unit and the payload data handling units would be combined into the data handling unit. The data interface would be based on SpaceWire for all interfaces. The memory would be based on flash memory, and could be met by using memory boards as on Sentinel 2, guaranteeing 1 Tb at end of life. This size was driven by the generic instrument operations scenario (see section 7.4.1.3) during a Callisto flyby, and is available using standard components.

7.4.3.6 Communications

The spacecraft would provide a 3.5 m HGA which is fixed to the body, and which would provide 60 W_{RF} output power in either X- or Ka band. The initial comparison on the maximum of the achievable downlink data volume per telemetry band indicated a critical dependency on the spacecraft pointing performance (assumed between 0.1° and 0.05°). Therefore the studied design of the telecommunications system is compatible with either band for data downlink, which will be revisited during later study phases when a more accurate assessment of the pointing performance would be available. In either case, would the specified data volume of 1 Gb per day be obtainable with margin.

A one-axis steerable medium gain antenna would be provided for communications during the Venus gravity assist, and when the omni-directional low gain antenna is out of reach from the ground station.

7.4.3.7 Thermal Design

On the inside of the structure a high emissivity finish would be used so as to homogenise the temperatures. All external surfaces would be covered with 23 layers MLI, which would be coated with ITO on the outside for providing the necessary conductivity for avoiding electrostatic discharge. The propellant tanks, helium tanks and the necessary pipes are located at the inside of the structure to provide good isulation from the external environment and to reduce the amount of required heating. The high gain antenna would be used as Sun shield during the Venus gravity assist.

The service module and instrument units would be accommodated on two separate panels each, on the +X and on the –X side. Each compartment would have independent thermal control and radiators. The service module compartments would have tilted surfaces close to their sides serving as radiator areas with maximized free field of view to space. The surfaces would be covered with high emissivity white pain with a total area of 1.44 m^2. The instrument units would be mounted inside two specific compartments, with the panels connected with variable conductance loop heat pipes to radiators on both the +Y and –Y surfaces of 0.05 m^2 providing cooling power independent of the spacecraft orientation.

7.4.3.8 Payload Accommodation

The science instruments would be accommodated on the upper parts (+Z side) of the +X and –X panels (see Figure 7-11). All remote sensing instruments would be co-aligned and would be mounted on the +X platform, and *in situ* instruments and the sub-surface radar would be located on the –X platform. Electronic units, which are part of the instruments could be accommodated within either side, depending on instruments requirements and space available and could be used for balancing the thermal dissipation.

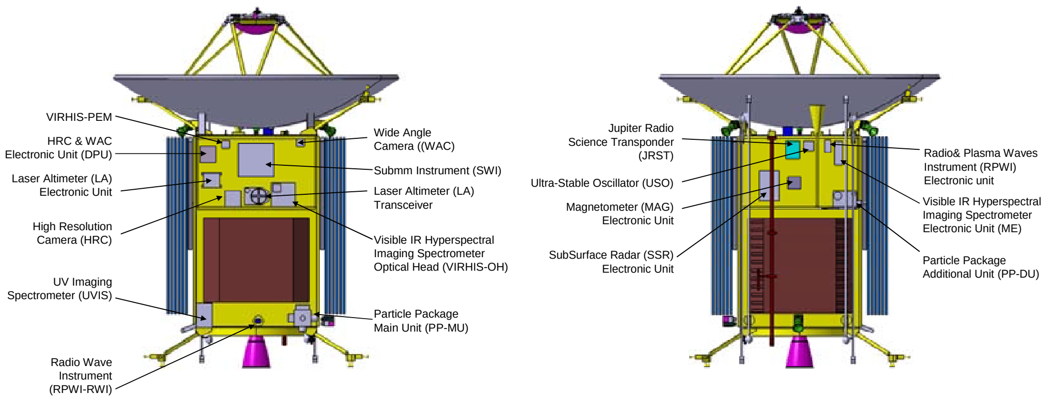


Figure 7-11. *Accommodation of the model instruments in spacecraft solution 2. Platform equipment would be accommodated within the volumes which is indicated by brown covers in this drawing.*

The instrument compartments are based on a U-shaped structure, in which variable conductance loop heat pipes would be included, which would connect the X-panels to both radiators on the +Y and –Y sides.

7.4.3.9 Mechanisms

The solar array deployment would be similar to Rosetta, which has a comparable solar array size. The solar array drive mechanisms would have one axis of rotation (around Y-axis) and would be compatible with the forces acted upon during main engine operations.

Based on a comparison of requirements with previous spacecraft, several feasible options for a magnetometer and Langmuir probe booms were identified. The booms are oriented in orthogonal direction to the major extent of the solar arrays so as to minimize interference during deployment and operations (EMC).

The medium gain antenna would be supported by a one degree of freedom pointing mechanism.

7.4.4 Spacecraft Design – Solution 3

This design solution was studied in less detail than the solutions described above, and consequently some divergent values may be derived. The solution is nevertheless presented here, discussing interesting options.

7.4.4.1 Configuration

The structure would be divided into two parts separately supporting the propellant tanks and the platform and instrument units. The single MON tank would be accommodated inside a short central tube, with the four MMH tanks around it. In addition two helium tanks would be included. The main engine would be placed on the –Z panel (see Figure 7-12). The compartment for the platform and instrument equipment would be located in a separate box-shaped structure at the +Z side. The inclusion of the majority of the equipment in a single compartment allows for a high unit density, good shielding optimization and short harness lengths. A 3.2 m fixed high gain antenna would be mounted to the side of the spacecraft body. The solar panels would be mounted on the ±Y panels and would each provide 32 m^2 with of five panels and with a single axis drive mechanism around the Y-axis. The size of the spacecraft ($x \times y \times z$) would be 3.52 m × 2.76 m × 3.47 m and the total wing span after deployed solar arrays 27.5 m.

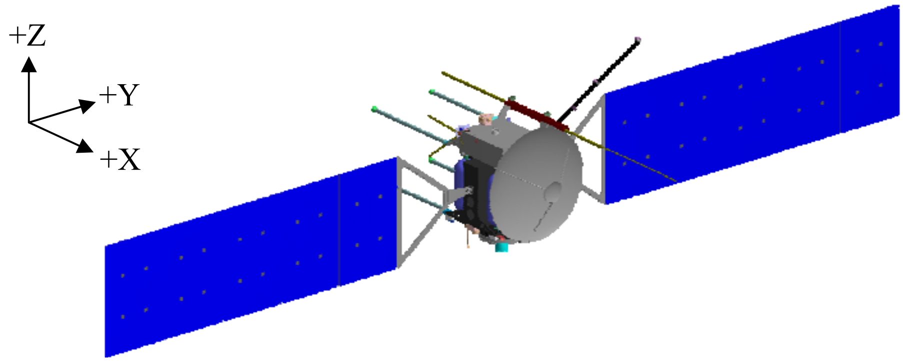


Figure 7-12. *Spacecraft configuration of solution 3. The main engine and the launcher interface is at the –Z side. The nadir direction is at the +Z side (up), and main component of the velocity remains parallel to the –X direction for all observing modes.*

With the exception of one group of sensors requiring access to the anti-nadir direction, all instruments would be included in the main compartment at the +Z panel. The remote sensing instruments would be co-aligned with the field-of-views towards nadir, and all *in situ* instruments would be accommodated at the –X panel of the main compartment. No change of orientation of the spacecraft with respect to the flight direction has to be performed for changing between remote sensing and *in situ* observations. As with the other solutions, the illumination of the solar panels would be optimized by rotation around the nadir direction (yaw). Inertial pointing would be used for data downlink to point the high gain antenna to the Earth.

7.4.4.2 Attitude and Orbit Control System

Four wheels with maximum capacity of 68 N·m·s would be used, which would allow for 16 hours continuous operations without off-loading during the Ganymede orbit phase. Two star trackers based on STAR1000 would be placed close to the high gain antenna so as to minimize pointing errors. In addition a navigation camera is foreseen for assistance in targeting the moons during the flybys with a wide field of view, which would be located at the outside of the main compartment, at its –X panel. Furthermore, a redundant set of IMU and Sun sensors would be provided.

7.4.4.3 Propulsion

The 400 N main engine and the AOCS thrusters would use a bi-propellant system based on MON/MMH with helium pressurization. The total available propellant mass would be 2817 kg (driven by the backup launch). Two times four 10 N reaction control thrusters are foreseen, which would be operated in blow-down mode with an I_{sp} of 280 s.

7.4.4.4 Power and Solar Array

The power conditioning unit would provide an unregulated 28 V power bus. The 64 m^2 solar arrays would be based on GaAs triple junction cells with a capability of 680 W at end-of-life. The solar cells would be optimized for low-temperature-low-intensity operations. The total energy provided by the battery would be 1863 Wh, supporting an eclipse duration of 4.5 hours.

7.4.4.5 Command and Data Handling

The on-board processor would be based on the Leon type. The mass memory was sized for storage of science data during a Callisto flyby and would be 48 Gb (including 20% margin). Interfaces to the instruments would be by MIL-STD-1553 and SpaceWire for high data rate instruments (VIRHIS, cameras).

7.4.4.6 Communications

The telemetry system will use redundant X and Ka transponders for telemetry reception and transmission. The amplifiers will be based on redundant 65 W_{RF} Ka travelling wave tube amplifiers for Ka-band, and 75 W_{RF} for X-band, respectively. The downlink of the science telemetry would be in either X-band, or Ka-band, or with both systems simultaneously, meeting the baseline data volume of 1 Gb per 24 hours with margin. The high gain antenna will be fixed with a diameter of 3.2 m. A medium gain antenna would be based on a horn antenna with an opening angle of the 20°, which covers the maximum angular distance of the Earth when seen from Jupiter, and would therefore allow the MGA to be Sun-pointed during safe mode.

7.4.4.7 Thermal Design

The spacecraft will be covered by 20 MLI layers with black Kapton as the outer layer. Surfaces that are exposed to the Sun during the Venus gravity assist will be protected by Beta cloth as the outer layer. High temperature MLI will be applied at areas close to the main engine. The inside of the compartments will be black painted so as to optimize the thermal coupling. The high gain antenna will be used as sunshield during the Venus gravity assist. The solar arrays will be tilted during the Venus gravity assist such that the angle of incidence will be about 10°, yielding a temperature of –26°C. The lowest temperatures of the solar arrays would occur during the Jupiter phase, and are expected to be at –172°C.

Radiators would be installed on the ±Y panels of the main compartment with in total 0.74 m^2 and would be protected by optical solar reflectors (OSR's). In addition louvers would be used for better balancing the thermal emissivity between the inner solar system cases and the Jupiter case. The units with the highest dissipations would be mounted close to the radiators, with direct access. Units with lower dissipation would be accommodated at the centre of the compartment, and their dissipation would contribute to the heating.

The power consumption of the thermal control during the science operations would be 247 W.

7.4.4.8 Payload Accommodation

The main compartment at the +Z panel would be split into two parts, where the lower part (closer to the propulsion module) would be reserved for platform equipment, and the volume closer to the surface be reserved for instruments. The accommodation of the instruments in the main compartment is illustrated in Figure 7-13. The remote sensing instruments would have access through the +Z panel, and the *in situ* instruments would have access through the –X panel, which would be parallel to the main component of the velocity direction. The PP-DU sensor requires access to the anti-nadir direction and would therefore be accommodated outside the main compartment, close to the –Z panel.

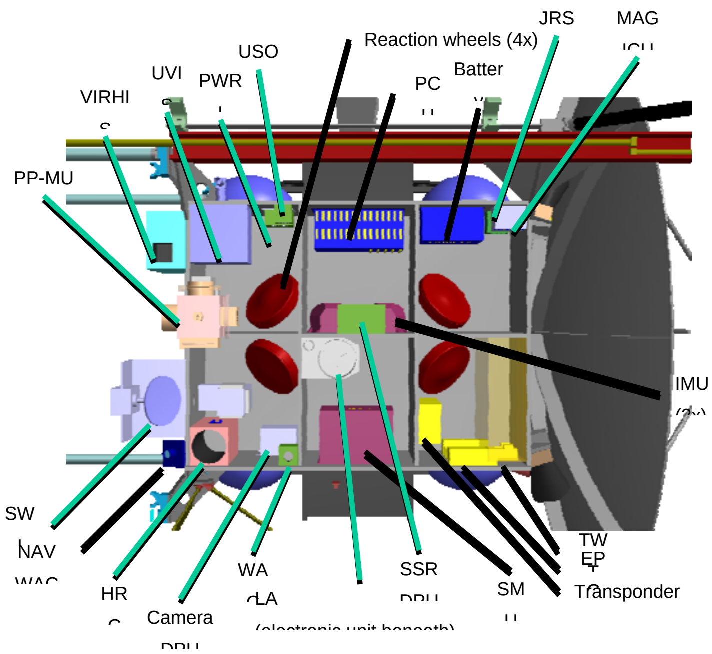


Figure 7-13.*Accommodation of platform units and model instruments in spacecraft solution 3*

7.4.4.9 Mechanisms

Standard deployment mechanisms would be used for the deployment of the solar array panels. The drive mechanisms would be single axis rotations around the spacecraft Y-axis.

All appendices are mounted on the main compartment, except the RPWI booms, which are mounted on the corners of the –X panel, such that the sensors are oriented towards the velocity direction (ahead of the spacecraft).

A 5 m magnetometer boom is foreseen and would consist of two elements, which would be deployed towards the nadir direction but pointing slightly aside such that interference with the field of view of the remote sensing instruments is avoided. The structural support for the magnetometer boom would be shared with the sub-surface radar boom The sub-surface radar boom (2×5 m) would be deployed with segments of 2.5 m length each and could be based on the MARSIS antenna design, and would be mounted asymmetrically, so as not to interfere with the accommodation requirements of he RPWI sensors (the extent of the radar boom in the –X direction would be equal to the length of he RPWI booms). The RPWI sensors would be mounted on four 3 m booms in the –X panel.

7.5 Mass Budgets

Table 7-4 summarizes the mass budget for the solutions studied. On a subsystem level, mass margins have been applied according to Technology Readiness Level (TRL) status and in addition a 20% system margin has been applied (following [6]). All solutions are compatible with the launch requirements with spare mass.

Table 7-4. *Mass budgets for the spacecraft solutions studied. All values are including margin. A system margin is also included. Differences in instrument masses are due to different accounting for antennae, etc.*

Baseline 2020 Item	Solution 1 [kg]	Solution 2 [kg]	Solution 3 [kg]
S/C			
Total Dry	1366.1	1426.4	1102.5
Structure	238.1	281.5	139.1
Shielding	88.2	156.0	54.9
Thermal CS	66.6	38.3	38.5
Mechanisms	40.2	25.4	48.4
Communications	79.8	99.7	56.3
Data Handling	22.8	26.3	40.5
Power	371.0	325.3	336.5
AOCS	52.1	50.5	48.6
Propulsion	212.0	235.4	219.9
Harness	85.0	72.0	0.0
Instruments	110.4	116.0	119.6
System Margin	273.2	285.3	220.5
Propellant	2502.9	2447.0	2367.0
Adapter	190.0	190.0	165.0
S/C wet	4332.1	4348.7	3855.0
Max launch	4362.0	4362.0	4365.0
launch margin	29.9	13.3	510.0

7.6 Electromagnetic Compatibility

For the sensitivity of the plasma and electromagnetic field measurements, strict limits on the electromagnetic compatibility of the spacecraft subsystems would be required and were included as goals in the studies: The electric charging of the surface of the spacecraft shall remain within a few volts in general, and a design goal of better than 1V in the vicinity of the electric field sensors and low energy particle spectrometers; the DC magnetic field shall remain <2 nT, with a stability of <0.1 nT over the range 0 to 64 Hz (at least during magnetometer measurements), and the electric stray field shall remain <50 dB μV/m in the frequency range below 45 MHz. Initial evaluations of these requirements indicated that some options would be available for meeting these goals. More specific measures will be discussed in the next study phase, and will also include instrument teams.

7.7 Planetary Protection

Ganymede is a Planetary Protection Category II target ("significant interest relative to the process of chemical evolution and the origin of life, but only a remote chance that contamination by spacecraft could compromise future investigations"), however the COSPAR working group on *Outer Planets and Satellites* has identified the need for additional requirements which are reflected in [7]. These requirements related to the technical mission implementation can be grouped in two categories:

1. Collateral contamination of alternative critical bodies, such as Europa shall or Mars (including any part of the launch vehicle within 50 years) shall be smaller than 10^{-4} and 10^{-2}, respectively.
2. The bio-burden brought to Ganymede shall be controlled and limited such that the likelihood of one active organism reaching the Ganymede sub-surface ocean shall be $<10^{-4}$.

Contamination avoidance of Europa can easily be demonstrated based on the fact that the energy of the spacecraft in Jupiter orbit is too high to reach Europa within a reasonable timescale (innermost orbit is Ganymede at distance to Jupiter). At the time of the planned launch of the mission Mars will not be for gravity assists, as it would be in a very unfavourable position. It can be demonstrated that neither the spacecraft nor any part of the launcher will impact Mars within a reasonable timescale.

For the calculation of the likelihood of bringing a surviving organism to the Ganymede sub-surface ocean the recommendation in [8] is followed, and it is largely reduced by the assumption of the low probability of the burial mechanism (10^{-4}) and by the low likelihood of landing in an active region (2×10^{-3}). Further factors, such as the estimated cruise survival fraction (10^{-1}), sterilization through radiation (10^{-1}), and probability of survival during transport on the surface (10^{-2}), bring the total likelihood to 2×10^{-11}. Assuming a typical bioburden at launch around 10^{6} based on the assumption of equipment exposure to a standard clean room environment the requirement of 10^{-4} would be met by a factor of 5.

Consequently apportionment and monitoring of the bioburden will be required during the mission implementation, by break down and allocation of allowed budgets to each hardware supplier, including payload. Monitoring will be achieved through essays taken at regular intervals.

7.8 Critical Elements and Drivers

Significant heritage exists from planetary missions with high radiation environments such as *BepiColombo*, or a deep space mission such as *Rosetta*.

The main JGO mission challenge is due to the high intensity radiation environment. This requires careful modelling and increasing level of detail of transport simulations, such that the spacecraft configuration can efficiently be optimized early in the design. The expected total mission low energy electron fluence is actually lower than a typical exposure for 10-year geostationary mission. At such energies electrons are predominantly being absorbed at the surface, and therefore heritage is available on materials withstanding such doses. At high energies, the electron fluence is more enhanced for the JGO mission, causing charge deposition at deeper layers. Electrons can however very effectively be shielded, and thereby the optimization of shielding material by careful simulations and design appears feasible. Due to the lack of detailed designs being available of all units, large margins for shielding mass were considered in the spacecraft solutions. The uncertainties of the model were taken into account by assuming the worst cases of a combination of available models. In addition early estimates indicated that the shielding by Ganymede during the final mission phases would reduce the radiation fluence at Ganymede by 40 – 50%, which was not taken into account yet, due to the uncertainties of the model predictions.

Existing GaAs based triple junction solar cells showed a lower than expected efficiency at the combination of low temperature and low intensity. ESA is currently developing the technology for producing reliable high efficiency solar cells. Results from prototypes confirmed the feasibility of such cells, and an ongoing activity is focusing on increasing the yield with a larger production base. As a backup, it was assumed during the studies that a careful selection of cells at low temperature would provide cells with equivalent efficiency.

Mass is a critical parameter for any high Δv mission. Increases of equipment masses resulting in a higher dry mass will be amplified by about a factor of 2.6 for the JGO mission. Risk of mass increase comes primarily from more radiation shielding required, payload mass excursions, and higher system power requirements due to higher stand-by power of instruments, or higher equipment power consumption in general, resulting in increased size of the solar arrays. Additionally larger solar array area could also be caused by solar cell underperformance. Mitigation options of mass increases exist by using the higher performance of the launcher, as currently a more powerful launching capability is being developed than the nominal ECA version, which was assumed for this study. Alternatively the mission profile could be changed mainly resulting in a longer interplanetary transfer to Jupiter by adding an additional Earth gravity assist before the Venus gravity assist (as is the baseline for the backup launch). This increase of available dry mass could be obtained, at the cost of about 1 year longer transfer time and is similar to the difference of dry-mass between the baseline and backup launches considered during this study phase. Furthermore the reduction of the total consumed power would directly result in a reduced solar array size. As a last resort the power reduction could be achieved by reductions of the telemetry downlink durations, which are one of the drivers of the power consumption.

The insertion of an additional Earth gravity assist would also provide a larger spread of launch opportunities, with at least a yearly repetition of similar launch capabilities.

7.9 Mitigation of Technical Risk

Prior to the start of the recent spacecraft Assessment Phase, ESA had initiated an effort for modelling of the Jupiter radiation environment (JOREM). This study is now being concluded and initial results were used during the Assessment Phase studies that are being reported here, albeit with conservative margins on the predicted fluences.

The availability of solar cells operating under LILT conditions and providing the assumed performance (28% at end-of-life) is critical to this mission. ESA started a development two years ago, which provided promising results. A following phase has been initiated, to determine the achievable uniformity, reliability and yield during manufacturing of the promising updated technology of triple-junction GaAs cells. This development is planned to be concluded within two years.

The majority of the remaining technical development activities are related to validation components for the high radiation environment. Investigating the limits of radiation tolerance of electronic components provides a higher accuracy of shielding calculations. The following validations are being pursued:

- Survey of critical components for power converters
- Radiation characterization of radiation tolerant optocouplers, sensors and detectors
- Characterization of radiation resistant materials
- Characterization of charging effect in materials under extreme conditions
- Latch-up protection for commercial of the shelf items
- Evaluation of star tracker performance under extreme conditions
- Demonstration of platform processor in harsh radiation environment

In addition specific components are being developed for enhancing capabilities:

- Development and qualification of analogue/mixed signal readout ASIC
- Development and qualification of front-end readout ASIC
- Low mass SpaceWire
- Development of radiation tolerant FLASH memory

It is emphasised that backup options exist for these developments by using conventional components possibly in combination with more shielding. A more detailed evaluation of the combination of radiation tolerance and shielding mass needs to be performed during the definition phase.

7.10 Conclusions

The mission trajectory was carefully optimized considering satisfying the science requirements, propellant usage and radiation exposure of the spacecraft, and showed all intended observations could be performed.

The preliminary design studies demonstrated feasible design solutions, meeting the main mission challenges (radiation dose, high Δv, solar power generation), including the accommodation of model instruments, while maintaining a positive launch mass margin.The technology investigations are focusing on the verification of tolerance of existing technology, and no show stopper was identified. Backup solutions for critical issues are available.

Therefore the mission appears to be feasible within the context and within the requirements as detailed in the studies performed.

8 Mission Operations

This chapter summarises the Mission and Science operations of the JGO element of EJSM-Laplace. It is based on information available on Mission Operations in the Mission Assumption Document (MAD) [8] and on Science Operations available in the Science Operations Assumptions Document (SOAD) [12].

8.1 EJSM-Laplace Mission Operation overview

As the baseline, JEO planning and operations would be performed for JEO by NASA, and for JGO by ESA, respectively. The mission requires strong and continuous coordination between ESA and NASA and within the international science community, in order to be best able to achieve the proposed science.

JGO Mission Operation Centre (MOC) would be located at ESA's European Spacecraft Operation Centre, ESOC, in Darmstadt, Germany, while JGO Science Ground Segment (SGS) would be located at ESA's European Science and Astronomy Operation Centre (ESAC) in Vilspa, near Madrid, Spain.

Both JEO Mission and Science operations would be conducted from JPL.

8.2 ESA and NASA Mission Planning and Science Operations Coordination

It is envisaged that appropriate coordination will be implemented between both projects, regarding mission and science operations, in order to best implement, inter-alia, the following activities:

- Design of the trajectories of each spacecraft to allow maximizing complementary and synergistic science (Approach to Jupiter, improved Jupiter and moon ephemerides, Callisto flybys, Radio science using the inter-spacecraft link, etc.._)
- Update of the environment model relevant to mission and science operations (e.g. radiation, dust, Galilean moon exosphere neutral environment) from measurements obtained by each spacecraft and eventually complemented by ground-based observations and modelling.

8.3 JGO Mission Operations Centre

ESA's European Space Operations Centre (ESA-ESOC) will provide the Mission Operations Centre (MOC) for the JGO mission element and will develop a ground segment including all facilities, hardware, software, documentation, the respective validation, and training staff, which are required to conduct the JGO mission operations. The MOC will use operational concepts proven with ESA Solar and Planetary Science missions (Rosetta, VEX, MEX, BepiColombo, SOHO) with adaptations. The concept for establishing the JGO ground segment shall be the maximum sharing and reuse of manpower, facilities and tools from the Solar and Planetary Science family of ESA missions. Sharing/reuse depends on the time of operations of this mission. All operations will be conducted by ESOC according to procedures in the long-term plan, contained in the Flight Operations Plan (FOP). The MOC will be the only interface to ground, all commands to the JGO spacecraft will be issued, and all telemetry will be received, by the MOC.

8.4 Nominal Mission Operations

JGO will be operated by an "off-line" monitoring and control approach. The spacecraft will be operated off-line by following a pre-scheduled timeline (planned sequences of operations) stored on board, and uploaded by the MOC at regular intervals. Monitoring will also be off-line, due to the non-continuous contact with the ground. In particular manned operational interfaces to other entities of the ground segment (SGS, stations) shall require nominal working hours only, with exceptions for selected operations during critical phases. JGO Flight Operations will be based upon weekly scheduled contact (with a single station) during the quiet legs of the transfer trajectory to Jupiter, and daily contacts (with a single station) between the MOC and the spacecraft during the science phase of the mission which will start TBD months before Jupiter Orbit Insertion, to upload pre-programmed autonomous operations sequences and to collect telemetry data for off-line analysis. This will be conducted by uplinking of a master schedule of commands for later execution on the spacecraft. Any spacecraft commanding will be planned under the presence of a spacecraft controller, or SPACON, with support of an on-call engineer. The ground reaction time will be within 48 hours after detection of an anomaly and any anomalies dealt with in the next scheduled coverage slot. Therefore the use of near real time reactions will be limited to exceptional cases. No required real time reaction below 12 hours is assumed during any mission phase. The need for any short-term reaction (less than 12 hours) will be clearly defined in the flight operations procedures and unambiguously identified in the spacecraft telemetry. It is assumed that any problems will be detected in the House Keeping (HK) telemetry and that flight control/contingency recovery procedures will be available.

The ESOC mission analysis team will support the mission during all phases. In particular support will be provided by trajectory analysis and navigations during the gravity assist manoeuvres at Venus and Earth, the JOI manoeuvres, the Callisto Flybys sequences, the Gravity assist manoeuvres at Callisto and Ganymede, the orbit insertion and orbit circularisation at Ganymede.

8.5 Communications

JGO Flight Operations will be supported nominally by one ESA ground station, either Cebreros or Malargüe, which are both assumed to be capable of X- and Ka-band operations at the time of JGO flight operations. Due to the evolution of the elevation of Jupiter over the ground stations during the JGO mission, Cebreros would be more favourable during the Jupiter tour and during Callisto operations, while Malargüe would be more favourable during operations in Ganymede orbit. Any ESA ground station may be used during earlier phases, including the interplanetary trajectory, and longer coverage, using additional ground stations will be provided during gravity assist manoeuvres.

8.6 Overview of JGO Science Operations

EJSM/JGO can be envisioned as a “Mapping” mission after orbit insertion around Ganymede. However, the first science phases of the mission are clearly of ‘Touring’ type. It is assumed that ESA/ESAC will play a central role in the JGO Science Ground Segment (SGS) and will coordinate the efforts to design and execute science operations throughout all mission phases. This role will be based on experience gained in ‘single target mapping’ missions, such as MEX, VEX, Smart-1 and Rosetta. Relevant ‘touring mission’ experience gained by the Cassini Science Operation team (Paczkowski and Ray, 2004) will be also taken into account.

The SGS includes all elements necessary to generate optimised science data and products as well as all required interfaces and science support. In particular, an important (and new in the history of interplanetary exploration missions) aspect of the dual-spacecraft EJSM mission design resides in the ability to coordinate joint observations between ESA’s JGO with NASA’s JEO. Therefore, the generation of appropriate interfaces should be given high priority during the development of the JGO science operations.

The particular distribution of science operation tasks in the SGS and responsibilities at all level will be detailed according to criteria of overall science return, efficiency and reliability. Major tasks to be executed by the SGS are the following:

8.6.1 Science Planning

The SGS will supervise the definition and implementation of the Science Planning Process. The SGS provides a technical interface between the JGO instrument teams and the MOC. As such, SGS will generate and pre-validate (in term of spacecraft resource check) the command sequences resulting from the instruments operation requests. SGS will also provide an interface to the instrument teams, ensuring in particular access to a centralized repository of all operationally relevant data (orbit files, spacecraft attitude, flight rules, general spacecraft resource constraints…) provided by MOC. Support during end-to-end Ground System Validation test (prior to launch), launch, and in-flight commissioning phases and regular in-flight instrument health checks, is also provided by the SGS. Tools such as a trajectory and pointing visualisation tool, and a science planning tool, will be developed by the SGS in full consultation with the PI-teams and the SWT. In addition, SGS will develop and maintain a centralized database of the detailed science objectives and measurement requirements for each instrument to fulfil those objectives as direct support to the work of the Science Working Team.

8.6.2 Data processing/handling/archiving

This technical/scientific task is also under the responsibility of dedicated SGS components. It includes, for example, i) the design and maintenance of a pipeline for raw data retrieval from the MOC and distribution including predicted and as-flown trajectory files and other information on spacecraft activity as relevant to the data analysis by the PI-teams, ii) an assessment of data products quality at engineering level, the maintenance of a 'data help/desk' to provide direct support to the PI-teams during the data proprietary period; iii) and later a 'data/help desk' for the wider science community accessing the archived data; and vi) the production of a long term archive by supporting the teams in the preparation of datasets compliant with the ESA PSA standards.

8.6.3 Science Support

The SGS will provide a discipline-oriented support to the specific tasks of science operations such as science driven planning. Scientists with a strong science operations background and involved in the various science disciplines will interface with each of the PI science teams (and with the Science Working Team Discipline Working Groups as appropriate) to ensure that each PI-team's pointing/observation strategy and opportunity analysis is correctly understood and implemented into the centralized planning system in agreement with the priorities set by the Science Working Team upon recommendation from the Discipline Working Groups. SGS Science Support activities will help developing a balanced observation plan according to the progress being made in accomplishing the science objectives and support developing synergies between observations across disciplines and identify and solve up-front possible conflicts at measurement level. The SGS Science Support will maintain a list of the fulfilled science objectives, and make recommendations on observation strategies, as direct support to the Project Scientist, in the accomplishment of one of his/her task (monitoring and optimization of the science return).

9 Management

This section summarises the envisaged management approach for the next steps in the implementation of EJSM-Laplace. The overall EJSM-Laplace mission management and the JGO management are addressed:
i) Project Team, spacecraft and payload procurement, project schedule,
ii) Operations management, including mission and science operations, and
iii) Science management, including Project Scientist Team, Science Working Team, and data rights.

9.1 EJSM-Laplace Management

ESA and NASA would appoint a Science Team respectively for JGO and JEO. The science return of EJSM-Laplace would be coordinated by a joint Science Team. The development, launch and operations of each of the two space segments would be led independently for JGO by ESA and for JEO by NASA. The operations for each spacecraft would be planned and conducted independently, taking the guidelines and priorities into account that will be established by the science teams.

9.2 Overall ESA Management of JGO

ESA will have overall responsibility for:

- The overall spacecraft definition and implementation
- Provision and integration of the spacecraft bus and payload interfaces (through an industrial contract)
- System testing and payload integration (through an industrial contract)
- Spacecraft Launch
- Mission Operations
- Science Operations, data distribution and data archiving

9.3 JGO Mission Definition, Development and Implementation

Should EJSM-Laplace be down-selected in June 2011, JGO would move into the next study phase, Phase A/B1 mission definition phase, during which two parallel industrial studies are foreseen, which will prepare for the decision of mission adoption. If the mission is successfully adopted in late 2013, it would then move into a development and implementation phase with one industrial contractor selected in competition by ESA.

The ESA selected industrial prime contractor, with the responsibility for the design, manufacturing, integration, testing and assembly of the spacecraft, will carry out the JGO spacecraft procurement starting in phase B2. The responsibility for control and monitoring of the development will be with ESA.

9.4 JGO Instrument selection and procurement

The proposed procurement scheme is based on the concept that the payload (instruments and associated processing, data handling and control components) will be, as a baseline, provided either by Europe's national agency funded Principal Investigator teams or by NASA-funded Principal Investigator teams. The instrument models will be provided to ESA by the PI teams and will be supplied as customer furnished items to the industrial team for integration.

9.5 JGO Model Philosophy

The two assessment studies that achieved a higher level of detail, have both concluded in a proto-flight model development approach as the baseline, supported by a structural model and a functional electric model. All models will include instrument models of adequate detail to fully support the tests. The structural model will be integrated as the first model, and will be used for mechanical and thermal verification. The functional electric model would support evaluations related to verification of AOCS functionality and to modelling of EMC emissions. The proto-flight model will be exposed to the full suite of tests at acceptance level, and will be refurbished to a flight model. Spares will be manufactured depending on criticality, and will be ranging from sub-unit to spare kit level.

9.6 JGO Schedule

A tentative schedule of the development phases is shown in Figure 10-1. Following the down-selection in mid 2011, the JGO instrument AO is planned to be released. The Definition Phase (A/B1) system study is expected to start in November 2011 for a period of about 18 months, with the objective to enable final adoption of the mission mid 2013 for a planned launch in 2020 and arrival at Jupiter in early 2026 for about 3 years of operations.

The definition phase will include the Preliminary Requirements Review (PRR), to be held about the mid-term of the study. Technology activities are being initiated in parallel and are providing input to the system study. After potential mission adoption, a prime contractor for the mission will be chosen for phase B2/C/D through open competition and by taking into account geographical distribution requirements. The implementation phase would be started with a System Requirements Review (SRR).

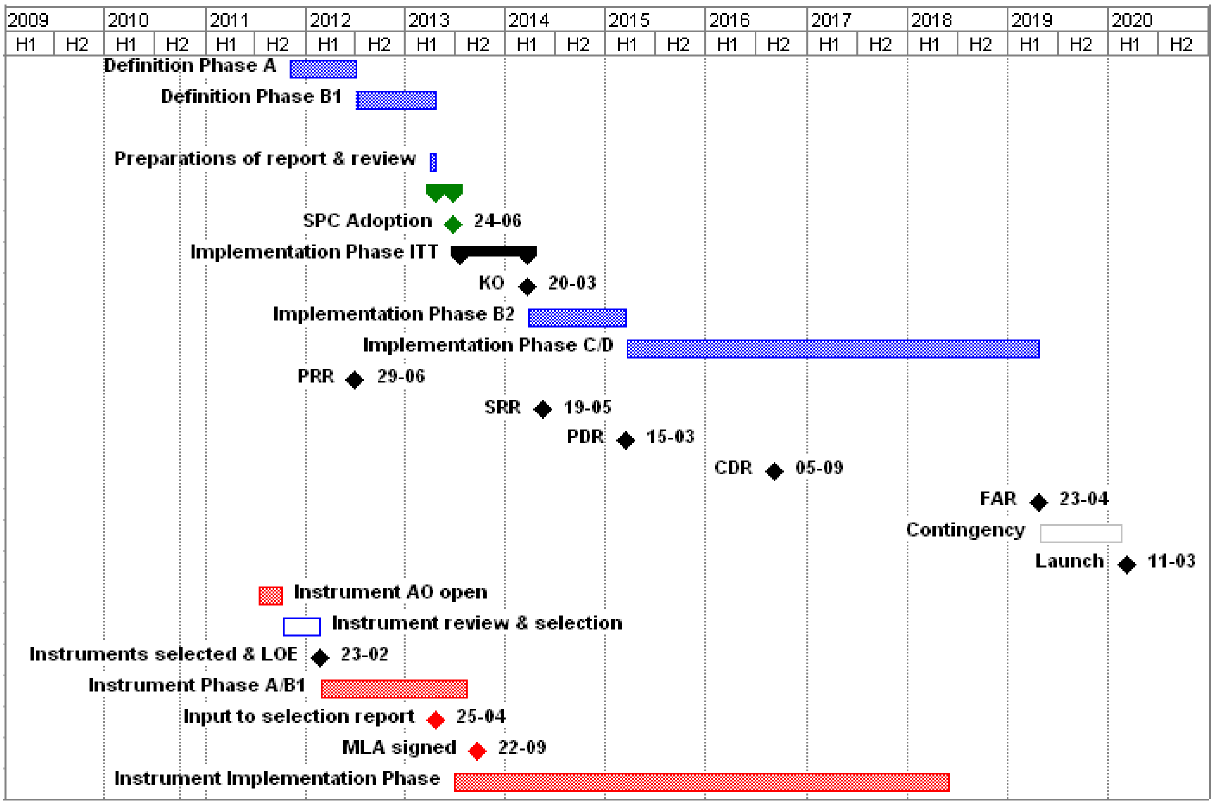


Figure 10-1. *Preliminary outline of the JGO schedule*

9.7 JGO Operations

ESA will be responsible for all JGO operations. ESA will prepare and implement an Operations Ground Segment (OGS) and a Science Ground Segment (SGS). The OGS and the SGS are foreseen to be implemented at ESOC and ESAC, respectively with input on science related requirements by the Science Teams.

JGO science data will be archived in ESA's Science PSA. It is expected that data archive products delivery would be under the responsibility of the PI teams.

9.8 JGO Science Management

Once the mission enters the implementation phase, ESA will nominate a Project Scientist (PS). The PS will be supported by an ESA Project Science Team. The PS will be the Agency's interface with all the investigators selected through the AO for scientific matters, and with his/her NASA counterpart.

During all mission phases, the PS will advise the Project for all scientific matters of the mission. The PS and his/her team will monitor and advise ESA (and the collaborating agencies) on the state of implementation of the instrument science performance, instrument science operation and data archiving.

The Project Scientist chairs the JGO Science Team and provides the formal interface between the Project Team and the Science Teams. The JGO Science Team will consist of PIs and other selected investigators. The Science Team will support the PS in maximising the overall science return of JGO and more generally of EJSM-Laplace, and advise him on all aspects of science coordination will all mission partners. The Science Team will act as the focus for the interest and involvement of the scientific community in EJSM-Laplace.

The binding agreements on all aspects of the science management will be documented in the Science Management Plan (SMP) that will be agreed by ESA's Science Programme Committee (SPC) prior to issuing the instrument Announcement of Opportunity (AO). The SMP will address all science aspects of the collaboration within EJSM, including the roles and responsibilities of the Lead Funding Agencies and PI teams, which will be selected through the JGO instrument AO. The SMP will also specify rules on data rights and data archiving.

9.9 Outreach and science communication

An outreach and science communication plan will be developed early on during the mission implementation phase. The plan will be regularly updated as the mission progresses through its different implementation phases. In coordination with the Science teams, ESA will highlight the major milestones and achievements through events and regular releases as appropriate.

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