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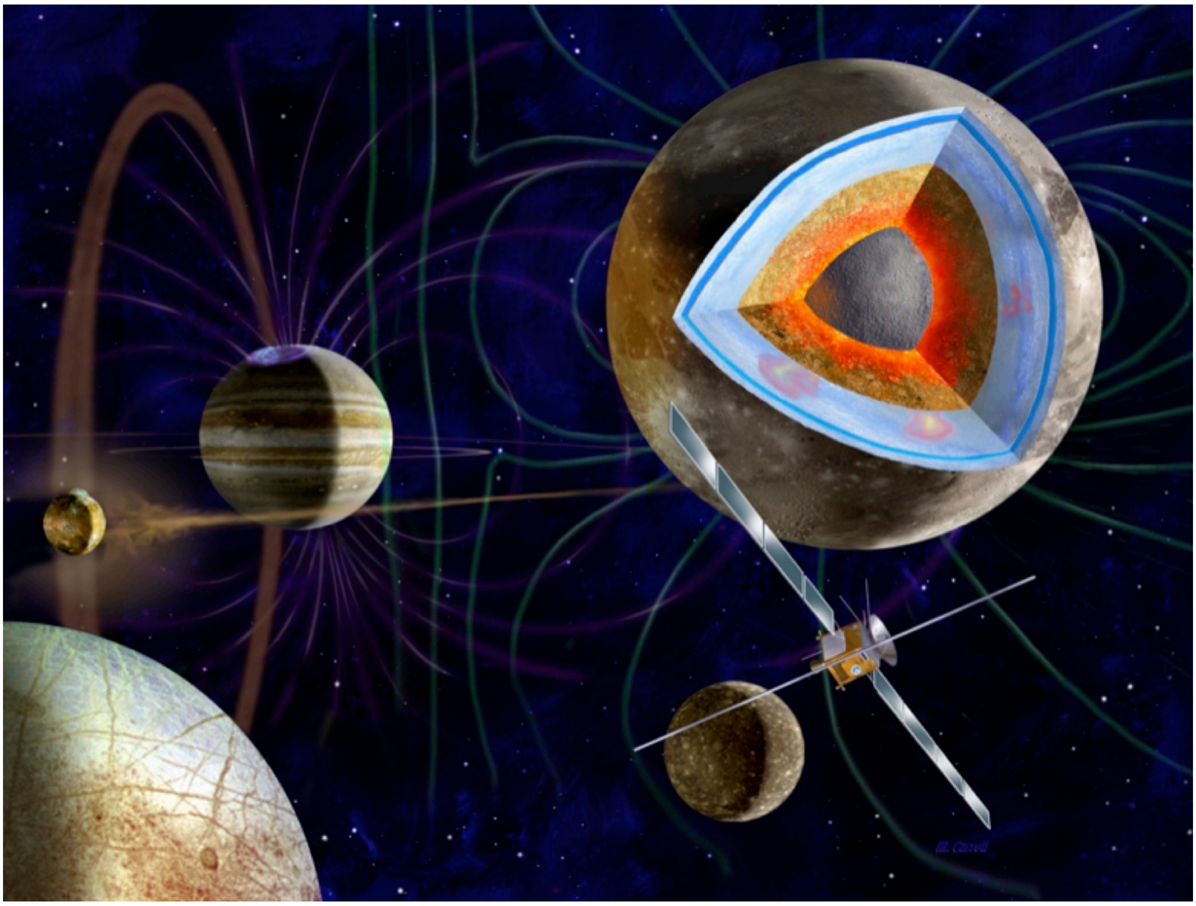
JUICE

Exploring the emergence of habitable worlds around gas giants



Assessment Study Report

European Space Agency

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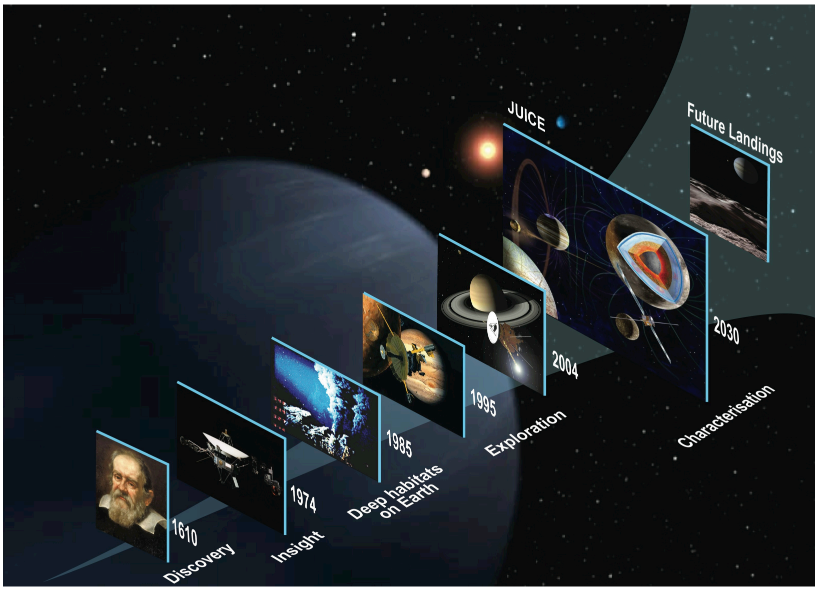
Foreword

The JUICE (JUpiter ICy moon Explorer) concept results from the reformulation of the EJSM-Laplace mission into a European-led mission. JUICE will maintain the L-Class science return from the original Jupiter Ganymede Orbiter (ESA contribution to the EJSM-Laplace mission), which is to fully characterise Ganymede as a planetary object and carry out a thorough investigation of the Jupiter system. In addition, JUICE will also resolve key Europa science goals focusing on surface composition and the first subsurface observations at an icy moon with the addition of two dedicated flybys, and enhance the spatial and temporal coverage of the Jovian atmosphere and magnetosphere by the implementation of a high-latitude phase during the Callisto flyby portion of the mission. The JUICE mission has been formulated with consultation and strong support from the international planetary science community and it will have broad appeal across a number of different disciplines including geologists, astrobiologists, magnetospheric and atmospheric scientists. The goals of JUICE have been refined over the last decade by numerous community studies and flow from the resulting priorities.



Following Galileo's discovery 400 years ago of the Galilean satellites, our knowledge of the large gas giants within our Solar System has continued to grow. The figure to the left has an artist's impression of a giant exoplanet in the background, with a timeline overlaid, revealing the growth of our knowledge of the gas giant planets through time. There have been numerous ground and space-based observations of the Jupiter and Saturn systems; flybys by the Pioneer and Voyager spacecraft; the discovery of habitable environments in deep ocean ridges on the Earth; the orbital tour by the Galileo spacecraft at Jupiter; and the ongoing orbital tour by the Cassini spacecraft at Saturn.

JUICE is the necessary step for future exploration of our outer Solar System. It is now time to characterise the potential habitable worlds Ganymede, Europa, and Callisto. JUICE will also provide a thorough investigation of the Jupiter system, which serves as a miniature Solar System in its own right, with a myriad of unique environments to explore. Jupiter serves as the archetype for exoplanetary systems, played an essential role in the development of our own habitable environment, and is the perfect destination for exploration of our origins. JUICE will address two of the key science themes of ESA's Cosmic Vision (2015-2025 call for proposals), that of "What are the conditions for planet formation and the emergence of life?" and "How does the Solar System work?".

This report 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 JUICE, and the proposed management approach. The document was written by the Science Study Team and by the ESA Technical Study Team.

We are extremely grateful to the planetary community for their support and pleased to have been given the opportunity to take part in this exciting journey.

The JUICE Science Study Team

Mission Description

Jupiter Icy Moons Explorer	
Key Science Goals	**The emergence of habitable worlds around gas giants** Characterise Ganymede, Europa and Callisto as planetary objects and potential habitats Explore the Jupiter system as an archetype for gas giants
Model payload	***11 instruments with total mass of 104 kg*** Narrow Angle Camera Wide Angle Camera Visible and Infrared Hyperspectral Imaging Spectrometer Ultraviolet Imaging Spectrometer Submillimetre Wave Instrument Laser Altimeter Ice penetrating radar Magnetometer Particle Package Radio and Plasma Wave instrument Radio Science Instrument and Ultrastable Oscillator
Overall mission profile	06/2022 - Launch by Ariane-5 ECA + EVEE-type Cruise 01/2030 - Jupiter orbit insertion Jupiter tour Transfer to Callisto (11 months) Europa phase: 2 Europa and 3 Callisto flybys (1 month) Jupiter High Latitude Phase: 9 Callisto flybys (9 months) Transfer to Ganymede (11 months) 09/2032 – Ganymede orbit insertion Ganymede tour Elliptical and high altitude circular phases (5 months) Medium altitude (500 km) circular orbit (3 months) Low altitude (200 km) circular orbit (1 month) 06/2033 – End of nominal mission
Spacecraft	3-axis stabilised Power: solar panels:636-693W(EOM) HGA: 3.2 m, body fixed X- and Ka bands Downlink ≥ 1.4 Gbit/day High delta-V capability (2700 m/s) Radiation level: 240 krad /10 mm Al solid sphere Dry mass at launch: ~1800 kg
Ground TM stations	ESTRACK network
Key mission drivers and technology challenges	Radiation Power budget Mass budget
Responsibilities	ESA: manufacturing, launch, operations of the spacecraft and data archiving PI Teams: science payload provision, operations, and data analysis.

Authorship, acknowledgements

The JUICE Science Study Team

Michele Dougherty	Imperial College	United Kingdom
Olivier Grasset	University of Nantes	France
Emma Bunce	Leicester University	United Kingdom
Athena Coustenis	Paris-Meudon Observatory	France
Michel Blanc	Ecole Polytechnique	France
Andrew Coates	University College London	United Kingdom
Angioletta Coradini*	Institute for Interplanetary Space Physics	Italy
Pierre Drossart	LESIA/Observatory of Paris	France
Leigh Fletcher	Oxford University	United Kingdom
Hauke Hussmann	German Aerospace Centre (DLR)	Germany
Ralf Jaumann	German Aerospace Centre (DLR)	Germany
Norbert Krupp	MPI for Solar System Research	Germany
Olga Prieto-Ballesteros	Centre of Astrobiology—INTA-CSIC	Spain
Paolo Tortora	University of Bologna	Italy
Federico Tosi	Institute for Interplanetary Space Physics	Italy
Tim Van Hoolst	Royal Observatory of Belgium	Belgium

* *Deceased*

The ESA study was led by: Dmitri Titov, ESA Study Scientist, Christian Erd, ESA Study Manager, Arno Wielders, ESA Payload Study Manager, Nicolas Altobelli, ESA Science Operations Study Manager with the Support of ESA's planning and coordination office: Fabio Favata, Philippe Escoubet.

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

The cover page graphical illustration was prepared by artist Mike Carroll.

It is with great sadness that we acknowledge the recent deaths of Angioletta Coradini, JUICE SST member, and Ronald Greeley, the US Co-Lead of the Joint Science Definition Team for EJSM-Laplace. It was a pleasure and a privilege to work with them both; we could not have produced the mission that we present to you now without them. They will be sorely missed.

Structure of the Assessment Study Report and table of content

This document provides a scientific, technical and management summary of the JUICE assessment study that was performed from March 2011 to October 2011. This report is structured in such a way to guide a reader through all aspects of the proposed JUICE mission from scientific themes and objectives to concrete measurements and results of industrial studies at different levels of details.

The executive summary gives general overview of the document. Section 2 describes the JUICE strategy and the steps that led to the JUICE that evolved from EJSM-Laplace. Section 3 describes the high-level science themes of JUICE and their relation to the ESA Cosmic Vision programme and important implications for planetary physics and astrophysics. Section 4 breaks the high-level science themes into concrete science objectives that will be addressed by the mission. Section 5 summarises measurement techniques and general requirements to the mission needed to achieve JUICE science goals and briefly describes the science scenario, mission phases and their science priorities. Section 6 presents the model payload complement capable of achieving the formulated science goals. This instrument complement created representative payload examples for ESA technical studies, supported by the industry teams. The results including mission analysis, spacecraft design, payload accommodation, mission resources and risks are summarised 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.

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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 the first detailed exploration of the Jovian system in the footsteps of the Pioneer 10 – 11, Voyager 1-2, and Ulysses missions. Galileo made new discoveries in the Jovian system, especially as concerns the four Galilean satellites, which were revealed as unique worlds worthy of further in depth exploration. The Galileo discoveries included strong evidence of subsurface oceans hidden beneath icy crusts within Europa, Ganymede and Callisto. The discovery of subsurface oceans on these moons led to the emergence of a new habitability paradigm which considers the icy satellites as potential habitats. If extrasolar planetary systems are analogous to our own, then icy satellites, having a subsurface 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 that permit surface oceans. The Galileo spacecraft 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 planetary environments represented by the four satellites should reveal the physical and chemical mechanisms driving the evolution of the Jovian system. The Juno mission, launched on 5 August 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.

JUICE science goals The overarching theme for JUICE is: The emergence of habitable worlds around gas giants. Within our Solar System, we know of one body that 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. JUICE will address the question: Are there current habitats elsewhere in the Solar System with the necessary conditions (water, biological essential elements, energy and stability) 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.

The focus of JUICE 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 three ocean-bearing worlds, Ganymede, Europa, and Callisto. Ganymede is identified for detailed investigation since it provides a natural laboratory for analysis of the nature, evolution and potential habitability of icy worlds in general, but also because of the role it plays within the system of Galilean satellites, and its unique magnetic and plasma interactions with the surrounding Jovian environment. JUICE will determine the characteristics of liquid-water oceans below the icy surfaces of the moons. This will lead to an understanding of the possible sources and cycling of chemical and thermal energy, allow investigation of the evolution and chemical composition of the surfaces and of the subsurface oceans, and enable an evaluation of the processes that have affected the satellites and their environments through time. The study of the diversity of the satellite system will be enhanced with additional information gathered remotely on Io and smaller moons. 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, Europa and Callisto on geologic time scales, including gravitational coupling between the Galilean satellites and their long term tidal influence 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 enhance our understanding of the evolution and dynamics of the Jovian system.

In conclusion, 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, JUICE 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?

JUICE mission scenario. On arrival in the Jupiter system following orbit insertion, JUICE will perform a tour of the Jupiter system using gravity assists of the Galilean satellites to shape its trajectory. This tour will include continuous monitoring of Jupiter's magnetosphere and atmosphere, two targeted Europa flybys, a Callisto flyby phase reaching Jupiter latitudes of 30°, culminating with the dedicated Ganymede orbital phase. The current end of mission scenario involves spacecraft impact on Ganymede. The spacecraft would be an orbital flight system using conventional bi-propellant propulsion systems. The basic design for the spacecraft 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 the current mission concept, although new developments are planned focusing on lower mass instruments and radiation designs. Planned to be launched in 2022, JUICE would use chemical propulsion and an Earth-Venus-Earth-Earth gravity assist to arrive at Jupiter 8 years later. JUICE's trajectory will remain outside of the inner radiation belts at Jupiter and it uses solar arrays for its power source.

JUICE Model Payload The JUICE spacecraft will carry a highly capable state-of-the-art scientific payload consisting of up to a dozen instruments. The model payload was compiled by the ESA Science Study Team (SST) as representative instruments that address the JUICE science goals. The SST is aware that new or additional science measurements could be included in order to enhance, offer alternatives to, or complement the present measurements and therefore further enhance the science return from JUICE. Different techniques and measurements may be proposed by the scientific community in response to a future Announcement of Opportunity.

The model remote sensing package would include spectro-imaging capabilities from the ultraviolet to the near-infrared, wide angle and narrow angle cameras and a submillimetre wave instrument. The model geophysical package would include laser altimetry and radar sounding for exploring the surface and subsurface of the moons. The radio science instruments would complement the remote sensing package (to enable probing of the Jovian/satellite atmospheres) and the geophysics package (enabling estimation of gravity fields). The model *in situ* package would include a magnetometer, radio and plasma wave instrument including electric fields sensors and a Langmuir probe as well as a particle package. A thorough effort has been made by the SST to ensure that 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) could be achieved with the Model Payload. JUICE science objectives are summarised in **Table 1-1**.

Goals	Science objectives		Go to pages
Exploration of the habitable zone: Ganymede, Europa, and Callisto (*Section 3.1*)	**Characterise Ganymede as a planetary object and possible habitat** (*Sections 4.1 & 5.1.1*)	Characterise the extent of the ocean and its relation to the deeper interior	20; 53
		Characterise the ice shell	20; 53
		Determine global composition, distribution and evolution of surface materials	28; 54
		Understand the formation of surface features and search for past and present activity	25; 54
		Characterise the local environment and its interaction with the jovian magnetosphere	31; 55
	Explore Europa's recently active zones (*Sections 4.1 & 5.1.2*)	Determine the composition of the non-ice material, especially as related to habitability	28; 55
		Look for liquid water under the most active sites	21; 56
		Study the recently active processes	26; 56
	Study Callisto as a remnant of the early jovian system (*Sections 4.1 & 5.1.3*)	Characterise the outer shells, including the ocean	21; 57
		Determine the composition of the non-ice material	28; 57
		Study the past activity	26; 57
Explore the Jupiter system as an archetype for gas giants (*Section 3.2*)	**Characterise the Jovian atmosphere** (*Sections 4.2 & 5.2.1*)	Characterise the atmospheric dynamics and circulation	37; 59
		Characterise the atmospheric composition and chemistry	38; 59
		Characterise the atmospheric vertical structure	38; 59
	Explore the Jovian magnetosphere (*Sections 4.3 & 5.2.2*)	Characterise the magnetosphere as a fast magnetic rotator	40; 60
		Characterise the magnetosphere as a giant accelerator	42; 60
		Understand the moons as sources and sinks of magnetospheric plasma	31; 60
	Study the Jovian satellite and ring systems (*Sections 4.4 & 5.2.3*)	Study Io's activity and surface composition	43; 60
		Study the main characteristics of rings and small satellites	44; 60

Table 1-1*: Science goals and objectives of JUICE*

JUICE industrial studies The implementation of the JUICE flight element was studied by three separate industrial contractors. The respective solutions and configurations are based on that of JGO/EJSM-Laplace. It has very robust heritage in previous flight systems (flown or in development) such as Rosetta, BepiColombo, Exomars/TGO but also telecom satellites for radiation issues. The industrial studies have proven that the specified science goals are well within current European industrial and technological capabilities and can be achieved by JUICE.

International co-operation JUICE is an ESA-led mission arising from the reformulation of the EJSM-Laplace mission. This has been carried out in consultation with the international science community and has broad appeal and strong support from planetary scientists.

<u>In summary</u> 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. The JUICE mission will thoroughly investigate Ganymede, and the entire Jupiter system including the planet itself, its magnetosphere, Europa, Callisto, as well as other satellites and rings. The addition of JUICE, the first spacecraft orbiting around a planetary moon, will offer numerous opportunities for public outreach activities to the ESA science programme. JUICE will build on scientific and technological heritage from previous large ambitious space missions and will pave the way for future extensive *in situ* endeavours to be conducted.

2 JUICE Strategy

2.1 Reformulation of the mission

Following the ESA announcement in April 2011 of a new approach to the L-Class missions, a new Science Study Team (SST) was formed whose task was to reformulate the science case for EJSM-Laplace into a new mission, called JUICE for “JUpiter ICy moons Explorer” restructured to “study if and which of the original science goals of the EJSM-Laplace mission concept can be achieved by a European-led mission”. The goal of this activity therefore, was to examine to what extent it would be possible to preserve essential parts of the science goals of the original mission EJSM-Laplace within the framework of a European-led mission with a budget for Europe still compatible with a L-Class mission within ESA's Cosmic Vision programme.

The original EJSM-Laplace mission, as presented to the science community in Paris in February 2011, consisted of two sister spacecraft: the ESA-led Jupiter Ganymede Orbiter (JGO) and the NASA-led Jupiter Europa Orbiter (JEO). They would have explored the Jupiter system to study the processes that led to the diversity of its associated components and their interactions. Both spacecraft were designed to fly independently and to achieve top-class science on their own, focusing on their primary goals. Although the two spacecraft were also capable of providing synergistic observations that would add to the individual scientific goals, it was already shown at that stage that JGO alone clearly achieved high-class science in the spirit of Cosmic Vision.

On the face of it, the implication of removing the NASA-led Europa-focused orbiter resulted in a reduced science return in the following areas: Europa, synergistic Jupiter atmosphere and magnetospheric science, and Io flyby science; but it did not endanger the feasibility of the ESA-led JGO mission, which still preserves the overarching themes of the original mission. Ganymede, the largest satellite of the Solar System, possesses a unique place which justifies the continued focus with JUICE. Understanding Ganymede as a water-rich world is crucial for assessing its own potential habitability as well as for assessing the potential emergence of habitable zones both within our Solar System and beyond. The focus of the JUICE mission on Ganymede is based not only on this critical aspect, but on the role it plays within the system of Galilean satellites, and on its unique magnetic and plasma interactions with the surrounding Jovian environment.

Early on during the JUICE study, the SST came to the conclusion that in order to fully recover the original Europa orbiter science return, 50-100 flybys of Europa would be necessary. Following such an approach with JUICE would have entailed sacrificing all of the Ganymede, Callisto, and Jupiter system science objectives. Furthermore, the technical feasibility of an extensive Europa exploration (mainly due to the radiation environment) within ESA's CV L-class cost envelope appeared very uncertain. The JUICE SST, in consultation with the relevant science community, unanimously agreed that this was not the right approach to follow in order to reformulate the mission in such a way so as to address most of the EJSM-Laplace science objectives with only one spacecraft. Instead, as the following sections will show, a reformulated mission is proposed which not only maintains the L-Class science return guaranteed with JGO, but in addition addresses key Europa-focused science with the implementation of two dedicated flybys. Similarly, the spatial and temporal coverage of the Jovian atmosphere and magnetosphere will be enhanced by the modification of the previous Callisto flyby phase into a new one which adds the investigations of unexplored high-latitudes both in the magnetosphere and around Jupiter. The new JUICE mission has been formulated with consultation and strong support from the international science community and it has a broad appeal to different communities including astrophysicists and planetary scientists. The goals of JUICE result from the work and mission studies carried out by the international science community and flow from the priorities which resulted from such studies.

JUICE is the next necessary step for future exploration of our outer Solar System and is, in addition, affordable by Europe within an ESA Cosmic Vision L-Class mission budget. JUICE is ready to go in the early 2020's.

2.2 The JUICE "formula"

The JUICE mission will provide a thorough investigation of the Jupiter system in all its complexity with emphasis on the three ocean-bearing Galilean satellites, and their potential habitability. JUICE has been tailored to observe all the main components of the Jupiter system and untangle their complex interactions. Central to this system, the Galilean satellites span a broad range of possible internal structures, from pure silicate/metal bodies to dominantly icy ones. 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 Ganymede, Europa and Callisto into the right context, and to better understand the Galilean satellites as a system, our observation strategy with JUICE can be described in three steps:

- Conduct a comparative study of Ganymede, Callisto and Europa, with a special focus on Ganymede, which JUICE will characterise in great detail.
- Provide a complete spatio-temporal characterisation of the giant, rotating magnetosphere, and of the meteorology, chemistry and structure of Jupiter's gaseous atmosphere.
- 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.

2.3 JUICE Strategy

The JUICE mission is nominally planned to be launched in mid-2022 and would use an 8-year Earth-Venus-Earth-Earth gravity assist trajectory. On approach to Jupiter, long term monitoring of Jupiter's atmosphere and magnetospheric processes and dynamics utilising the powerful remote sensing capability of JUICE will be performed. Following orbit insertion a multi-year tour of the Jovian system is planned beginning with an initial Jupiter tour focusing on continuous magnetosphere observations and regular monitoring of Jupiter's atmosphere. This will be followed by two targeted Europa flybys focused on composition of the non water-ice material, and the first subsurface observations of an icy moon. A Callisto flyby phase reaching Jupiter latitudes of 30°, will then enable not only unique Callisto science but in addition mid- to high- latitude Jupiter atmosphere and magnetosphere observations over an extended temporal and spatial baseline. The mission will culminate in dedicated Ganymede orbital phases that will fully characterise Ganymede as a planetary object and potential habitat.

2.4 Heritage and legacy

JUICE builds on the outstanding heritage of many past and current space missions to the outer planets. At Jupiter the first multi-year orbital exploration by the NASA Galileo mission made many new discoveries despite its rather severe downlink constraints, providing the first comprehensive description of Jupiter's components. As a result, Galileo discoveries have driven the identification of the next generation of key scientific questions. Many of these 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 need for orbiting spacecraft at the gas giant systems, in order to globally monitor and resolve spatial and temporal variations.

The first mission of this new generation will be NASA's Juno mission, launched in August 2011. Juno uses a specific mission profile to focus on a sub-set of the outstanding questions: for example, the focus of Juno on Jupiter itself and in particular its interior and upper atmosphere makes it entirely complementary to JUICE. 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. JUICE will complement Juno with a longer term remote sensing investigation over a more diverse wavelength range. Juno will neither focus on the low-latitude regions of the Jupiter system, where all regular satellites reside, nor investigate the Galilean satellites. That is the focus of the JUICE mission.

JUICE timeliness and importance for ESA's Cosmic Vision

JUICE is the next logical step for an in-depth exploration of the geophysical and environmental characteristics of Ganymede and exploration of Callisto and Europa, and will provide an in-depth understanding of Jupiter's atmosphere and magnetosphere. It will focus on Ganymede by flying the first orbiter around an icy moon, whilst also studying the entire system during its first mission phase on both approach to Jupiter and in Jupiter orbit. JUICE will 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. JUICE will elucidate the conditions which may led to habitable environments, take a significant step towards characterising the archetypal gas giant of our Solar System and provide a cosmic connection to exoplanetary systems. JUICE meets two of the themes of Cosmic Vision:

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

Theme 2: How does the Solar System work?

and will represent a timely major step forward in improving our perception of astrophysical objects in general. JUICE will build on and consolidate the extremely productive collaborations among the international planetary community.

3 JUICE Science Themes

The discovery of the Galilean moons changed our understanding of the Jupiter system, our local Solar System, and beyond. The detailed exploration of Jupiter's four diverse Galilean satellites, three of which are believed to harbour subsurface oceans, is central to elucidating the habitability of icy worlds in general. The study of the Jupiter system and the possible existence of habitable environments offer the best opportunity for understanding the origins and formation of the gas giants and their diverse satellite systems.

The JUICE mission will perform detailed investigations of Jupiter and its system in all their inter-relations and complexity with particular emphasis on Ganymede as a planetary body and potential habitat. The investigations of the neighbouring moons, Europa and Callisto, will complete a comparative picture of the Galilean moons.

The main science objectives of JUICE are described in detail in the following sections but are briefly summarised as follows. For Ganymede and to a lesser extent Callisto: characterisation of the ocean layers; detection of putative subsurface water reservoirs; study of the Ganymede's intrinsic magnetic field; topographical, geological and compositional mapping; physical properties of the icy crusts; characterisation of the internal mass distribution, dynamics and evolution of the interiors and investigation of the moons' exospheres. For Europa, where two targeted flybys are foreseen within the JUICE mission, the focus will be on the chemistry essential to life, including organic molecules, and on understanding the formation of surface features and the composition of the non water-ice material, leading to the identification and characterisation of candidate sites for future *in situ* exploration. Furthermore, JUICE will provide the first subsurface observations of this icy moon, including the first determination of the minimal thickness of the icy crust over the most recently active regions.

The circulation, meteorology, chemistry and structure of Jupiter will be studied from the cloud tops to the thermosphere as the paradigm for giant planet atmospheres. These observations will be attained over a sufficiently long temporal baseline to investigate evolving weather systems and the mechanisms transporting energy, momentum and material between the different layers. The focus in Jupiter's magnetosphere will include an investigation of the three dimensional properties of the magnetodisc and in-depth study of the coupling processes within the magnetosphere, ionosphere and thermosphere. Aurora and radio emissions and their response to the solar wind will be elucidated. Within Jupiter's satellite system, the moons' interactions with the magnetosphere, gravitational coupling and long-term tidal evolution of the Galilean satellites will be studied. Small satellite studies will include improved mass determination, ephemerides, surface composition definition, as well as possible new detections. Ring system studies will characterise their physical and chemical properties.

A thorough study of the various coupling processes between the different components which make up the Jupiter system will allow its evolution and development to be better understood. Environmental investigations by JUICE will shed new light on the potential for the emergence of life in our galactic neighbourhood and beyond. Thus, an overarching theme for JUICE is *the emergence of habitable worlds around gas giants.*

3.1 Emergence of habitable worlds around gas giants

3.1.1 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. It refers instead 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 requires an understanding of what life is. A unique definition of life does not yet exist and may be difficult to produce (Cleland and Chyba, 2007). However it does include properties such as consuming nutrients and producing waste, the ability to reproduce and grow, to pass on genetic information, evolve via Darwinian evolution, and to 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).

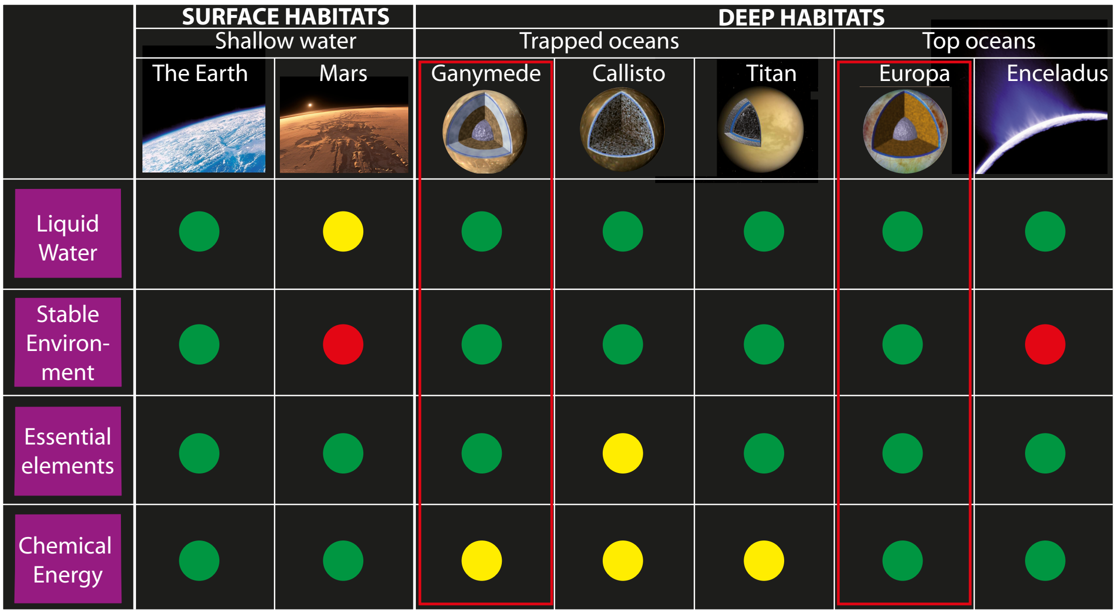


***Figure 3-1**: Present state of the existing and past habitable worlds in the Solar System. For each planet or moon, the status of the four pre-requisites for life to be sustained is ranked from red (not possible), to yellow (likely but not yet demonstrated) and to green (demonstrated or very likely).*

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 it can be 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 chemical blocks made of (C, H, O, N, P, S) to drive biochemical reactions. Habitability therefore rests on the fulfilment of four conditions: water, elements, energy, and time (**Figure 3-1**). 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 then is if the liquid water can exist for sufficient periods of time to be biologically useful.

3.1.2 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 JUICE will greatly enhance our knowledge of habitability, particularly through the investigation of several of the Jovian satellites. The JUICE 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 any of the investigated icy satellites would 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 snow-line, such as Jupiter or Saturn, can 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% in mass of water. Thus, icy layers are extremely thick, ~600 km for Ganymede, Callisto, and Titan. For Callisto, Galileo data indicate that it is probably not fully differentiated, implying a thicker icy layer 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 chemical 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.

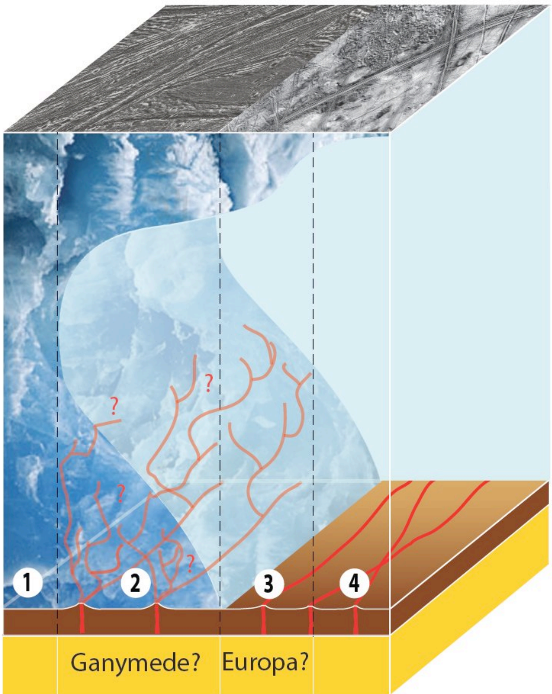


Figure 3-2*: Possible locations of liquid layers in the icy moons of Jupiter are shown here as a function of depth:1) completely frozen; 2) three-layered structures impeding any contact between the liquid layer and the silicate floor; 3) thick upper icy layer (>10 km) and a deep ocean; 4) very thin upper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

Liquid water reservoirs have been proposed on Ganymede, Europa 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 independently 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 3-2**). Case 2 in **Figure 3-2** 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 has been discovered at Enceladus (Blanc et al. 2009). This arises at Europa since the moon possesses a thinner water layer (80-180 km) (Anderson et al., 1998), with the amount of water present being estimated to be ~10 % in mass. Europa's ocean is unique 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 may enhance habitability conditions since the rock layer could release elements and energy 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. An estimation of the minimal thickness of the icy crust over the most active regions of Europa is among the measurement goals of JUICE and this will provide important constraints on the subsurface structure of the moon.

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 clear-cut as the exchanges which can be envisaged for Europa. This provides an interesting difference compared to the Europa example, the implications of which must be understood.

On Ganymede and Europa, endogenous materials may rise to the surface through fractures and cryo-magmatic processes, thereby revealing properties of the deep aqueous environment for remote observation. Volatiles, organics and minerals solidified from the aqueous cryo-magmas, 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 the moons (Kargel et al., 2000). Many other compounds such as CO_2 (Europa, Ganymede and Callisto), or CH_4 (Titan) have been observed on the surfaces and may emerge from the deep interiors of the moons. 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 the icy satellites. Since 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, 1997, 1998). The effect of radiation on the stability of surface organics and minerals at Europa is poorly understood. Therefore, JUICE instrumentation will target the environmental properties of the younger terrains in the active regions 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 astrobiology. Surface oxidants could be diffused into the interior, and provide another type of chemical energy (Hand et al., 2007).

JUICE will therefore address key areas that emerge in the study of habitable worlds around gas giants including constraints on 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 icy moons, and determine the magnitude of their transport among the moons which exchange material as a result of volcanism, sputtering, and impacts. The mission may also allow us to infer environmental properties such as the pH, salinity, and water activity of the oceans and will investigate the effects of radiation on the detectability of surface organics.

3.2 The Jupiter System as an Archetype for Gas Giants

JUICE will perform a comprehensive study of how the Jupiter system works, including in depth studies of the giant icy moons, the planet itself, and its vast rotating magnetosphere.

3.2.1 Jupiter System Components

The Jupiter system is the largest closely coupled planetary system, and has been previously referred to as a mini Solar System in its own right. This system comprises 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, their production processes and their interactions with the surrounding local environment.
- Jupiter's giant magnetosphere, the largest in the Solar System, within which all other objects are embedded including two unique components: Io, the main source of material, and Ganymede with its mini-magnetosphere embedded within Jupiter's.

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

3.2.2 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.

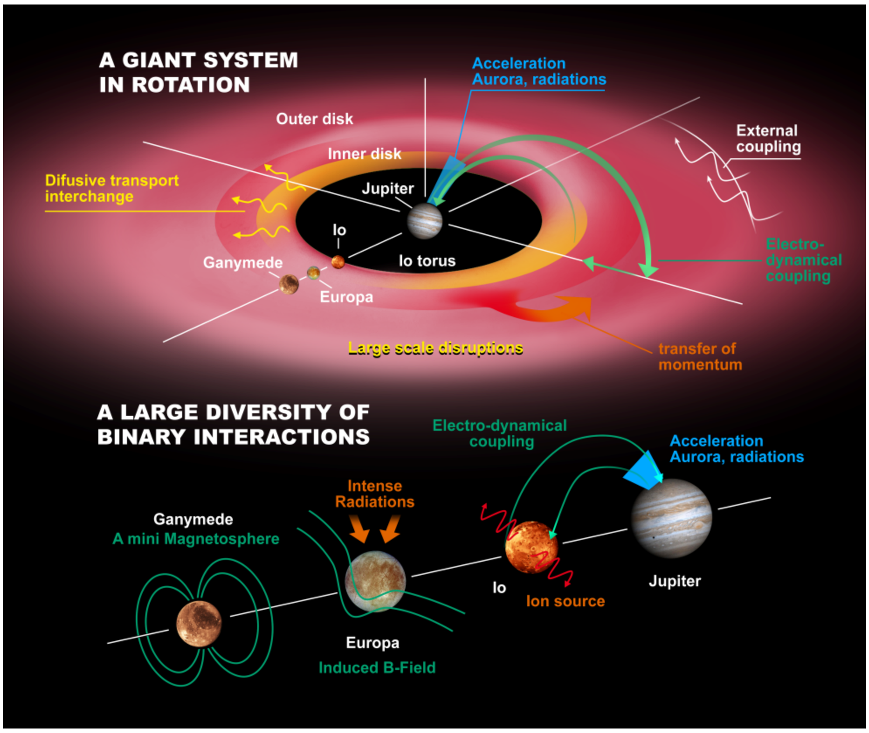


***Figure 3-3**. Electrodynamic interactions play a variety of roles in the Jupiter system: generation of plasma at the Io torus, magnetosphere / satellite interactions, dynamics of a giant plasma disc coupled to Jupiter's rotation by the auroral current system, generation of Jupiter's intense radiation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

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. Consequently, an electromagnetic torque is communicated back along magnetic field lines to the magnetosphere which forces the loaded magnetosphere into rotation but cannot bring it to full corotation. This current system, together with the associated intense particle precipitation, is an important source of momentum and heat for the upper atmosphere.

The diversity of each satellite results in characteristically different interaction signatures. The electrically conducting subsurface oceans at the Galilean satellites interact with the rotating magnetic field of Jupiter to produce induced field signatures, providing essential 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. 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 localised electric current loops extending from the satellites and closing through Jupiter's upper atmosphere (**Figure 3-3**).

3.2.3 Origin and Formation

The giant planets of the Solar System contain in their compositional make-up signatures of the proto-planetary nebula during the epoch of planetary formation, providing a window onto the earliest evolutionary stages of our Solar System. The limited composition information available, largely from the Galileo probe, favours the core accretion hypothesis for the formation of giant planets (e.g., Lunine et al., 2004), possibly with subsequent radial migration of planetary orbits (e.g., Tsiganis et al. 2005). In such a scenario, giant planets first formed a solid core of approximately 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 2.5-5.0 Ma. Conversely, the irregular Jovian satellites are 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. JUICE will use a combination of observational techniques to study the origin and evolution of the Jupiter system, with specific focus on the Galilean satellites.

The relationship between the formation of the Galilean satellites and that of Jupiter will 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 the satellites will 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. Furthermore, by investigating the composition of the small regular satellites and the irregular satellites, JUICE 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). Finally, spectroscopic observations of Jupiter's atmospheric composition will complement the deeper microwave sounding of the Juno mission (2016-2017), helping to constrain the vertical distributions of key gaseous species. By providing an in-depth study of the origins of Jupiter's diverse and extensive satellite system, JUICE will provide complementary data to Juno's investigation of Jupiter and reveal the complex formational mechanisms at work within this miniature Solar System.

3.3 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 in general. 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.

Here, we will describe how JUICE 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?

JUICE will address Cosmic Vision sub-theme ***1.3 Life and habitability in the Solar System*** by exploring the surface and subsurface of Ganymede (through flybys and orbital tour) and to a lesser extent Callisto (through flybys), including their subsurface water oceans and their environment in the Jupiter system. Measurements towards these science aims shall also be made for Europa, albeit to a lesser extent, during the two planned flybys. Comparisons of these three very different objects will provide new light on conditions for habitability in the outer Solar System, and around gas giants in the Universe.

JUICE 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 in order 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?

JUICE 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 regarded as "a mini Solar System" with a comparable degree of complexity, and 2) Jupiter itself 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 JUICE 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. JUICE will study the complex coupling processes in the Jovian environment that are key to understanding the evolution of the satellites.

3.4 Implications for Astrophysics and Planetary Physics

3.4.1 Extrasolar Planetary Systems

Our understanding of the formation, evolution and fundamental physical processes at work within the Jovian system provides the perfect template for our interpretation of newly discovered planetary systems around other stars. Over the coming 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 develop a strong statistical knowledge of a wide variety of exosystems. In some favourable cases, characterisation of the atmospheres of giant exoplanets in close-in orbits is already possible, via on-off transit transmission or emission spectroscopy (e.g. Tinetti et al. 2010; Swain et al. 2010). Detailed analysis of the transit shapes, or transit timing techniques, will also allow us to look for signatures of large satellites around these giant planets, some of which may exhibit similar characteristics to the large water-rich moons observed in our own Solar System. Furthermore, by the time of the JUICE mission, advances in space- and ground-based transit experiments will give us the opportunity to study terrestrial-sized 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.

Among the detected exoplanetary systems, we may find a significant number similar to that of Jupiter, both in terms of planet and satellite distribution, and in terms of the prevailing physical conditions. The in-depth investigation of the Jovian system by JUICE, from the gas giant itself to the collection of icy moons, provides our best possible opportunities for understanding the physical conditions on giant and terrestrial-sized planets within these exoplanetary systems. These exosystems will provide an extreme test of our understanding of how Solar Systems work, placing the scientific goals of JUICE into a broader astrophysical context. Furthermore, the JUICE assessment of the habitability of the Jovian moons could have far reaching implications for the prevalence of live throughout our cosmos.

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

3.4.2 The 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* spacecraft 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 a very 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 JUICE 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, JUICE 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 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, and by crossing directly some of its source regions, JUICE 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 recognise planetary signatures in radio emissions from distant stars, and will contribute to giant exoplanets search and detection.

3.4.3 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 unravelling 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 broader context. JUICE'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. In many ways, giant planets are simpler systems than terrestrial planets, lacking the complex atmosphere-surface interface. Jupiter is therefore viewed as the ideal 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, but will be studied as part of the JUICE science goals: 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 vertical 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 in-depth investigation of the Jovian atmospheric circulation, and the mechanisms transporting energy, momentum and material vertically and horizontally, will ultimately allow us to develop predictive numerical models of giant planet atmospheres.

The advanced instrumentation, broad wavelength coverage and long temporal baseline offered by JUICE 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 modelling, permit predictions of variability and allow us to study the mechanisms driving atmospheric variability on giant planets both in our Solar System and beyond.

Finally, Jupiter's atmospheric composition (atomic and molecular abundances, isotopic ratios etc) can be compared to that on other planets in our Solar System and beyond 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 conditions within the primordial planetary nebula from which the planets formed. As a constraint on the formational history of our Solar System, chemical studies of the atmospheres of planets and their moons, provide a window onto the past and help us to understand the expanding range of planetary systems around other stars.

4 Science 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 large satellites –the Galilean Satellites (Io, Europa, Ganymede, and Callisto), (2) a ring system, (3) four small inner satellites (Metis, Adrastea, Amalthea, and Thebe), that are located in the equatorial plane of Jupiter inside Io's orbit, 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 JUICE mission. The icy moons, and especially Ganymede the primary target 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 satellites from remote observations. Broader studies of Jupiter's atmosphere and magnetosphere will complete the investigation of the Jovian system.

4.1. Exploration of the habitable zone : Ganymede, Europa, and Callisto

The Galilean satellites Io, Europa, Ganymede and Callisto show an increase in geologic activity with decreasing distance to Jupiter (McEwen et al., 2004; Greeley et al., 2004; Pappalardo et al., 2004; Moore et al., 2004). Io, nearest to Jupiter, is volcanically active. Europa could still be tectonically and volcanically active today, while Callisto, the outermost Galilean satellite, is geologically "dead". In the Jovian satellite system Ganymede holds a key position in terms of geologic evolution because it features old, densely-cratered terrain, like most of Callisto, but also widespread tectonically resurfaced regions, similar to most of the surface of Europa. Furthermore, Ganymede is the only satellite and - besides Mercury and the Earth- one of only three solid bodies in the Solar System that generate a magnetic dipole field at present. Investigating Ganymede, the largest satellite in the Solar System, from an orbiter is essential because (1) of its wide range of surface ages which reveals a geologic record of several billions of years, (2) its great variety in geologic and geomorphic units, (3) its active magnetic dynamo and (4) the possible presence of a subsurface ocean (Schubert et al., 2004, and references therein).

4.1.1 Subsurface oceans, icy crusts, and interior

4.1.1.1 Overview: the oceans below the icy crusts

Voyager and Galileo data indicate that Europa and Ganymede, and possibly Callisto 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 Ganymede, Europa, and Callisto. However, the depth and composition of the oceans, as well as the dynamics and exchange processes 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. On Europa, recent modeling relates chaotic terrains with shallow lenses of liquid water (Schmidt et al., 2011).

From liquid layers to deep interior: outstanding questions

<u>*Ganymede*</u>

- Is there liquid water on Ganymede? If so, what is its spatial distribution? How thick is the ice layer and what are the properties of the liquid? What is the relationship between the surficial geologic units and the history of the liquid water?
- What are the chemical and biological potentials of Ganymede's ocean?

- 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 moon? Is Ganymede in hydrostatic equilibrium? How are mass-anomalies distributed, and what is their relation to geologic features and evolution.
- What is the role of tidal heating in the evolution of Ganymede?

Europa

- What is the minimal thickness of the icy crust over the most active regions?
- Is there liquid water in the shallow icy crust of Europa?
- What is the nature of dynamical processes going on in the icy crust? How is this related to subsurface features and geological processes?
- What is the role of tidal heating in the evolution of Europa?

Callisto

- Is Callisto in hydrostatic equilibrium? What is the state of differentiation? How is the incomplete separation of ice and rock related to the formation of a subsurface ocean?
- Is there any liquid water embedded in Callisto's icy crust?
- Is the dark and non-icy surface material restricted to the upper several km?

4.1.1.2 Science objectives

A. Oceans

Electrical currents in oceans that contain salts –and hence provide excellent electrical conductivity– can generate secondary magnetic fields in response to the external rotating Jovian magnetic field. Such 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 JUICE at Ganymede at multiple frequencies will constrain the electrical conductivity and extent of Ganymede's ocean (**Figure 4-1**).

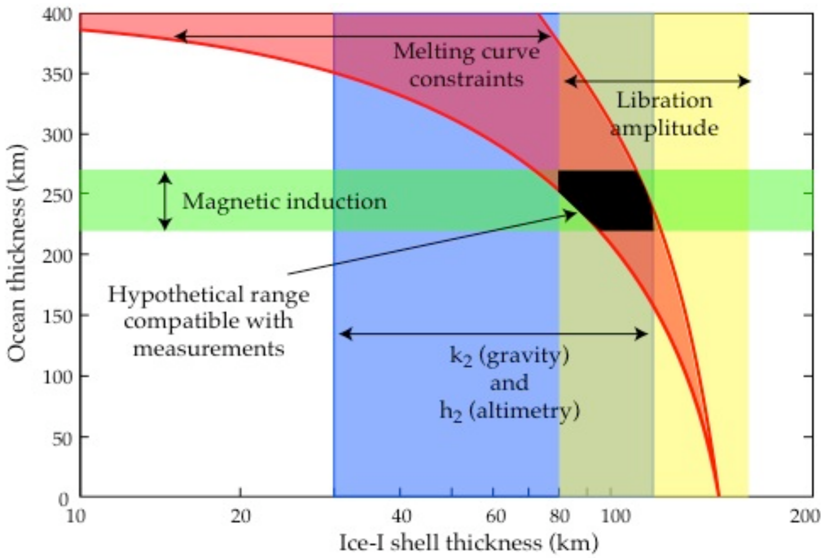


***Figure 4-1** Schematic view of the strategy to characterise Ganymede's icy crust and liquid layer by using combined techniques. The parameter space (ice-I shell thickness and ocean thickness) is bounded by the domain of stability of ices (red curves), but not fully constrained due to our poor knowledge of the temperature profile and the volatile content. JUICE 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.*

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 one 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 can be 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 one 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 can 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 JUICE (Figure 4-1).

The Galilean moons are locked in a stable 1:1 spin-orbit resonance. However, slight periodic variations in the rotation rate (physical librations) and the amplitudes associated with these librations can provide further evidence for subsurface oceans. JUICE will measure precisely the rotation rate, pole-position, obliquity, and libration amplitude of Ganymede. This will further constrain the dynamical history of the satellite, e.g., despinning, resonance capture, non-synchronous rotation of the icy shell, besides yielding information on the subsurface ocean and deeper interior.

JUICE will also determine the minimal thickness of the icy crust below the most active regions on Europa. Using the subsurface radar sounding at closest approach, it will probe the crust possibly down to the ice-ocean interface if the ice shell is only a few km thick as expected in a few models (Greenberg and Geissler, 2002). With its two flybys, JUICE will help solving the controversy about the depth of the ocean below the active regions, and will determine whether or not the liquid material can ascend through cracks up to the surface, an active process which is possible only if the icy crust is very thin (Pappalardo et al., 1999).

At Callisto JUICE will provide evidence for a subsurface ocean by measuring the induced magnetic field during the flyby campaign. Past and ongoing activity inside the shallow subsurface including the presence of liquid water will be investigated by subsurface sounding.

B. The icy crust

Subsurface radar sounding will be used to locate liquid water in the ice shells, to identify the stratigraphic and structural patterns, and in the case of Europa to provide a minimal depth for the ice-ocean interface. By using subsurface sounding we also seek to test hypotheses related to the origin (marine, convective, tectonic, or impact) of structures at the surface and in the shallow subsurface. Whereas the main focus at Ganymede will be to understand the tectonic features that are widely distributed on the surface and their relation to the shallow subsurface, Callisto will be the ideal ‘laboratory’ to study all possible kinds of impact features. Relaxation processes in the icy lithosphere will constrain the thermal state of the satellite at formation of the impact. The scientific objectives 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. JUICE will characterise the structure of the icy shell including its properties and the distribution of any shallow subsurface water on Ganymede, Europa, and Callisto. It will also correlate surface features and subsurface structure in order to investigate near-surface and interaction processes.

C. Internal structures

Galileo data suggest that Callisto is partially differentiated while the other satellites, especially Ganymede, are highly condensed objects (Schubert et al., 2004). Interior structure models are currently based on degree-2 measurements of the gravity fields using an a priori hydrostatic assumption (Schubert et al., 2004). Using polar flybys at Callisto and/or the orbit phases at Ganymede, JUICE will improve the degree-2 fields without relying on the assumption of hydrostatic equilibrium. For Ganymede, the accuracy on the degree-2 gravitational coefficients J_2 and C_{22} will be three orders of magnitude smaller than the current accuracy. 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 Ganymede. Finally, for Ganymede, JUICE will determine time-dependent variations of J_2 and C_{22}, and thus the satellite’s response to tidal forcing for the first time, with an absolute accuracy on the Love number k_2 better than 0.01. Tides strongly depend on the existence of liquid layers in the interior and their determination will constrain basic physical characteristics of Ganymede's ocean and icy crust. JUICE will verify on Ganymede and Callisto whether hydrostatic states are actually obtained by measuring the low-degree gravity fields in different orbital geometries. These measurements will also improve our understanding of the degree of differentiation of the satellites and determine on Callisto whether the ice and rock components are separated in the outer part of the icy crust. Measuring the high-order fields, JUICE will also quantify mass anomalies, asymmetries in the mass distribution and other non-hydrostatic contributions to the satellites' gravity fields.

On Ganymede, offsets between centre of mass and centre of volume will be determined by combining gravity data with shape measurements. The finite strength of planetary material and dynamic processes in the interior cause deviations of the surface from the equilibrium surface. JUICE will perform global high precision topographic measurements 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 the interior structure of Ganymede, thus providing important constraints for evolution models.

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). JUICE 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.

In summary, JUICE will:

- Provide a broad understanding of the present state and evolution of the hydrosphere of Ganymede in comparison to the ones of Europa and Callisto
- Characterise the structure of the icy shells including the possible detection of shallow subsurface water on Ganymede, Europa, and Callisto
- Determine the extent of Ganymede's ocean and its main physico-chemical properties
- Determine the minimal thickness of the icy crust below the most active regions on Europa
- Characterise the magnetic field of Ganymede and resolve what conditions are required for generating and maintaining the dynamo activity
- Verify on Ganymede and Callisto whether hydrostatic states are actually obtained and improve our understanding of their degree of differentiation

4.1.2 Geology

4.1.2.1 Overview: the diversity of geological features

The icy Galilean satellites Callisto, Ganymede and Europa show a tremendous diversity of surface features and differ significantly in their specific evolutionary paths. Each of these moons exhibits its own fascinating geologic history – formed by the competition of external and internal processes. Their origins and evolutions are influenced by factors such as density, temperature, composition (volatile compounds), stage of differentiation, volcanism, tectonism, the rheological reaction of ice and salts to stress, tidal effects, and interactions with the Jovian magnetosphere and space. These interactions are still recorded in the present surface geology. The record of geological processes spans from possible cryovolcanism through widespread tectonism to surface degradation and impact cratering.

Ganymede: With its mix of old and young terrains, ancient impact basins and fresh craters, and landscapes dominated by tectonism, possible icy volcanism, or slow-rate degradation by space weathering (**Figure 4-2**), Ganymede serves as an archetype body for understanding many icy satellite processes throughout the outer Solar System and how this entire class of worlds evolved differently from the terrestrial planets (e.g., Pappalardo et al., 2004, Prockter et al., 2010, Stephan et al., 2011). Ganymede's surface is subdivided into (1) 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 (2) bright, less densely cratered, heavily tectonised, grooved terrain. In addition to craters, dark terrain also displays hemispheric-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 non-water ice contaminants that appear to be concentrated at the surface by a variety of processes including sublimation, sputtering and mass wasting (Prockter et al., 1998). Bright terrain subdivides the dark units into 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, generally characterised by extensional rifting, causing the partial or total transformation of dark terrain into bright terrain by tectonism (e.g. Pappalardo et al., 1998, 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 viscous cryovolcanic flows (Head et al., 1998).

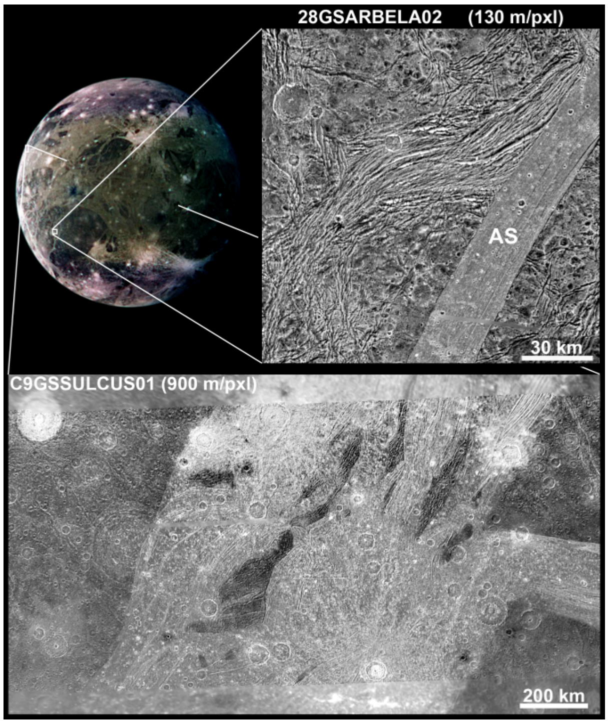


Figure 4-2*. Ganymede's surface is characterised by old, dark densely cratered plains, and by younger, bright and more ice-rich, tectonically resurfaced terrain. Bright terrain formed at the expense of dark terrain, mostly through extensional tectonism, (lower panel; Galileo SSI target area C9GSSULCUS, 900 m/px). Bright, smooth bands (upper right panel; Galileo SSI target area 28GSARBELA02, 130 m/px) 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 are thought (a) either to represent cryovolcanic flows, extruded as icy slushes (Pappalardo et al., 2004), or (b) to be issued from mass wasting processes along slopes (Prockter et al., 1998, 2010). Viewed at high resolution, even the smoothest bright units also exhibit some degree of tectonics, implying that cryovolcanism and tectonic deformation are closely linked (Head et al., 2002). Although the ultimate driving mechanism for the formation of bright grooved and smooth terrain is uncertain, there are many intriguing possibilities that it may be tied to the internal evolution of Ganymede and to the history of orbital evolution of the Galilean satellite system, involving tidal interactions (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. Passey and Shoemaker, 1982; Schenk et al., 2004). The subdued character of Ganymede's oldest impact craters implies a steep thermal gradient in Ganymede's early history, with more recent impact structures reflecting a thicker and stiffer elastic lithosphere (e.g. Shoemaker et al., 1982). Such an interpretation indicates a much warmer shallow subsurface ocean early in Ganymede's history than at present. The size-frequency distribution of impact craters also provides an important tool to derive relative and absolute ages of Ganymede's geologic units (e.g., Neukum et al., 1998; Zahnle et al., 1998, 2003; Burger et al., 2010).

***Europa**:* Europa's surface (**Figure 4-3**) can be subdivided into bright (in colour bluish) plains, featuring numerous parallel ridges in a wide range of orientations, and darker, brownish mottled terrain (Lucchitta and Soderblom, 1982; Greeley et al., 2004; Prockter et al., 2010, Stephan et al., 2011). Linear ridges are the most widespread landforms on Europa; the most common type of ridges are double ridges, consisting of a pair of ridges with a medial trough. They are thought to have originated through a variety of mechanisms, including, e.g., tectonism, cryovolcanism, intrusion, or diapirism, and require either the presence of liquid water in the shallow subsurface, or warm mobile ice underlain by an ocean at depth (Greeley et al., 2004, and references therein, Schmidt et al., 2011).

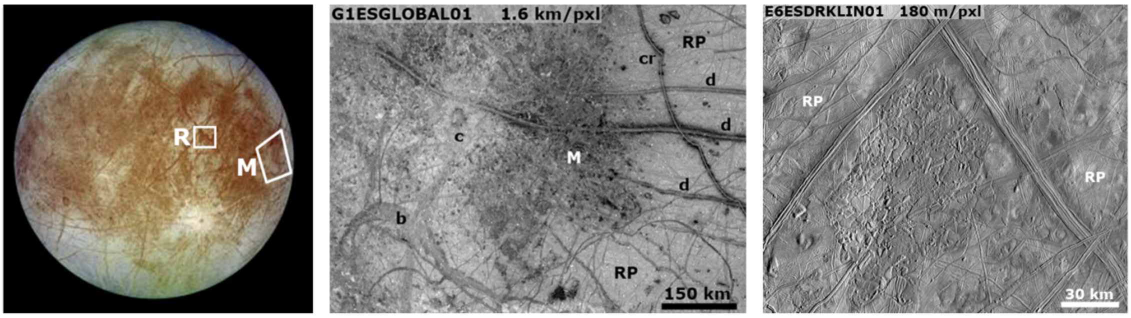


***Figure 4-3**. Europa's surface shows the widest range in colours of the three icy Galilean satellites (left) and exhibits two major surface units: bright, bluish plains, and dark, brown, mottled terrain. Bright plains consist of numerous parallel ridges and troughs (RP) superposed by mottled terrain (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.*

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; Prockter et al., 2010). Chaos regions are characterised 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 of, or has altered, pre-existing terrain (e.g. Greeley et al., 2004, Prockter et al., 2010). Widespread abundance of erosional or degradation features are absent.

Craters, especially those larger than 10 km, are rare on Europa inferring the youth of its surface (e.g., Schenk et al., 2004).

***Callisto**:* Callisto is characterised by globally abundant dark, densely cratered plains (**Figure 4-4**). It is the geologically least evolved Galilean satellite and therefore represents an end-member body (e.g., Moore et al., 2004, Prockter et al., 2010). Its surface is dominated by various impact features, similar to those which occur on Ganymede, and by landforms

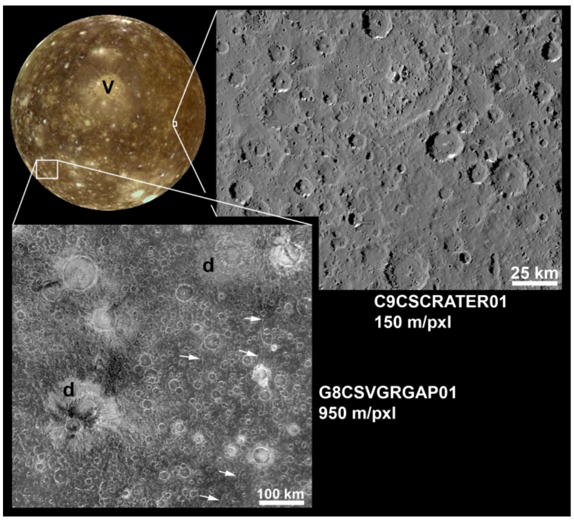


***Figure 4-4**. Galileo images of Callisto. Upper left: old densely cratered surface of Callisto with large multi-ring structures, such as Valhalla (V). Lower panel: SSI medium resolution image of a cratered plain including dome craters (d) and ring arcs of old, degraded multi-ring structures (arrows).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

indicative of intense surface erosion and degradation. Callisto and its cratered landscape, including crater size-frequency distributions, hold a specific place as a window into the early history of the Jovian system. Similar crater forms on Callisto and Ganymede indicate similar rheologic properties and subsurface layering but degradation states and ages of craters with a specific morphology, e.g. palimpsests, infer different rates of change of these properties with time. A process called sublimation degradation, triggered by the presence of CO_2, caused the degradation of bright high-standing terrain (e.g., crater rims) and the formation of a globally abundant dark, smooth blanket but the time-scale of this dark lag formation is not known (Moore et al., 1999, 2004). Unlike Ganymede or Europa, tectonism on Callisto is not widespread but systems of furrows and albedo lineaments do occur. Some of these features are caused by impacts, others could originate from not impact-related stresses active at early times (e.g., Moore et al., 2004, Prockter et al., 2010, Burger et al., 2010).

Geology of the icy moons: outstanding questions

Ganymede

- What are the relative roles of tectonism and cryovolcanism in shaping the dark and bright terrains?
- What does the distribution of craters tell us about the evolution of the impactor population through time?
- How is the geological evolution related to the impact, tectonic and cryovolcanic history and how is it correlated with differentiation processes and stages?
- What are the ages of specific geological units and how will these findings contribute to our understanding of the origin and evolution of the Jupiter system and the geological activity with time?
- To what extent are surfaces altered by cosmic weathering and what are the major exogenic surface alteration processes (micrometeorites, radiation, charged particles)?

Europa

- How is the geological evolution related to the impact, tectonic and cryovolcanic history and how is it correlated with differentiation processes and stages?
- What is 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)?

Callisto

- What does the distribution of craters tell us about the evolution of the impactor population through time?
- How is the geological evolution related to the impact, and tectonic history and how is it correlated with differentiation processes and stages?
- To what extent are surfaces altered by cosmic weathering and what are the major exogenic surface alteration processes (micrometeorites, radiation, charged particles)?
- What are the specific fine-scale characteristics of non water-ice materials ?
- By which intriguing mechanisms is the unique CO_2-replenishment taking place?

4.1.2.2 Science objectives

Formation and characteristics of landforms on the icy Galilean satellites. Galileo SSI data have allowed us to describe the global geology of the icy Galilean moons for the first time. However, it was not possible, except for a few cases, to study regional and local geology in extent, most of the Galileo SSI data being at low or medium resolution. On Ganymede, less than 1% of the surface was studied at resolutions better than 100 m/px. In order to improve our understanding of geological processes on the Galilean icy satellites, coverage of higher resolved data such as the Cassini mission is currently providing for the Saturnian satellites (Jaumann et al., 2009) are required. Combined with spectral mapping, these observations of the three icy satellites will contribute to a comprehensive picture of their geological evolution, constrain the role of cryovolcanism and tectonics in their geological evolution, and help us to understand the origin of these bodies. Detailed topographic profiles of tectonic features, grooved terrain (Ganymede), impact forms and cryovolcanic features will be acquired by laser altimetry which, combined with imaging stereo data, will enable the identification of dynamical processes that cause internal evolution and near-surface tectonics.

JUICE will provide a breakthrough in the geology of Ganymede and investigate its surface from orbit by global imaging with regional spatial resolution (<400 m/px) and high-resolution imaging (<5 m/px) of selected targets. In addition, two close flybys at Europa at regional (500 – 1000 m/px) and locally at high (< 50 m/px) resolutions will provide context for the understanding of geological processes such as tectonics, cryovolcanism, surface erosion and contamination in the Jovian System. Finally, Callisto will be imaged during several flybys at envisaged resolutions of 300 – 800 m/px in order to complete coverage of its densely cratered plains, and at high resolution << 100 m/px of selected target areas in order to perform detailed studies of its unique erosion and degradation processes.

Global and regional surface ages. The morphology and distribution of craters on the icy Galilean surfaces is significantly different from those on the terrestrial planets. Both Ganymede and Callisto have old, densely cratered surfaces with a record of large impact features, including multi-ring structures which imply old surfaces (Moore et al., 2004; Pappalardo et al., 2004; Schenk et al., 2004; Burger et al., 2010). On Ganymede, the widest range in crater morphology on any body with a solid surface is found (e.g., Pappalardo et al., 2004; Schenk et al., 2004). Callisto displays similar crater forms as Ganymede, but most of them shows a higher state of degradation (Moore et al., 2004; Schenk et al., 2004). Europa's surface is characterised by a very low density in impact craters (only 16 craters with diameters of 3 – 27 km could be identified) which suggests a relatively young surface age (e.g., Greeley et al., 2004; Schenk et al., 2004).

JUICE will significantly improve the current estimates of Ganymede, Europa and Callisto surface ages by measuring crater distributions from nearly global image coverage at 200-1000 m/px resolutions on all three satellites, plus sufficient high-resolution target areas (5-50 m/px), and by monitoring Ganymede's surface on a time-scale of the order of hundreds of days up to years to identify potentially newly formed craters. This will allow to establish a comprehensive stratigraphy of the icy moons and a history of geological activities in the Jovian system.

In summary, JUICE will:

- Investigate Ganymede's entire surface and subsurface from orbit and describe the geological processes that have shaped this moon
- Study Europa at regional scale and with high resolution for understanding its young surface and recently active processes
- Investigate the unique erosion and degradation processes on Callisto's densely cratered plains
- Improve our understanding of the geologic evolution of Ganymede, Europa and Callisto by constraining their surface ages

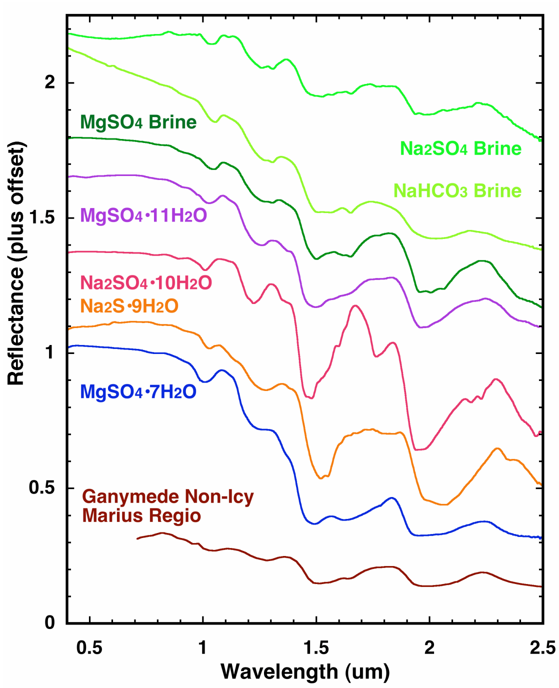
4.1.3 Surface composition and the search for biosignatures

4.1.3.1 Overview: the complex chemistry of the icy Galilean moons

As revealed by the Galileo mission, there are substantial amounts of non water-ice components present at the H2O-ice dominated surfaces of Ganymede, Europa and Callisto. 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 (C, H, O, N, P, S) and other major elements (Cl, K, Na, Ca, Mg, Se, Zn, Fe, Mn, Cu, Co, Ni, Mo) is critical in assessing habitability (Wackett et al., 2004). But the composition and the small-scale distribution of non water-ice materials on the Galilean moons is still very poorly known, due to the limited spectral and spatial resolution of the Galileo spectro-imagers, and the limited coverage provided by the small number of flybys

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 sulphuric acid ($H_2SO_4{\cdot}nH_2O$), formed by the radiolysis of water and of a 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 water-ice spectra would be actually best matched by mixtures of sulphuric acid hydrates together with hydrated salts, so both these chemical classes may be present on the surface with variable concentrations. Other non water-ice species, like CO_2 and H_2O_2, were also found in the leading hemisphere at equatorial to mid-latitudes.

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 sulphate 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 (co-product of radiolysis is O_2 gas, Hall et al., 1998). So the detection of O_2 at mid-latitudes due to exogenic material falling onto Ganymede's surface (Calvin et al., 1996; Spencer et al., 1995) is the signature of the probable presence of organic material.



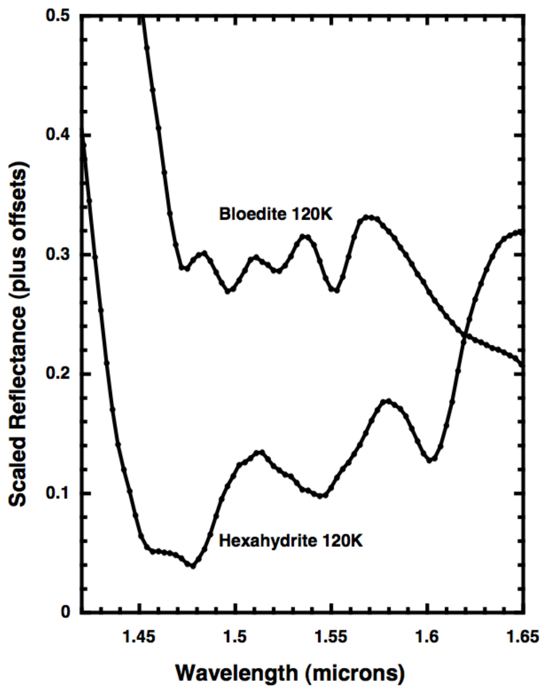


Figure 4-5. Left: *Spectra of several hydrates and brines, measured at 100 K in the range from 0.4 to 2.5 μm, compared with a NIMS spectrum of non-icy material of Ganymede (Dalton et al., 2005).* ***Right:*** *Close-up of the spectra of hydrated minerals bloedite ($Na_2Mg(SO_4)_2{\cdot}4H_2O$) and hexahydrite ($MgSO_4{\cdot}6H_2O$) in the range from 1.42 to 1.65 μm, measured at 120 K. The narrowest feature here exhibits a FWHM of 7 nm. (Dalton, 2003).*

Callisto: its 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 Europa, and with an extreme heterogeneity at the small scale (1-10 km). Superficial CO_2 is concentrated on the trailing hemisphere (Hibbitts et al. 2000), leading to a slightly larger atmosphere on that side of the satellite (Johnson et al., 2004), consistent with a slightly more robust ionosphere (Kliore et al. 2002). Therefore, surface alteration due to radiolysis and photolysis of many organic molecules that may be intrinsic or delivered by comets and meteoroids to the surface (Bernstein et al., 1995; Johnson, 2001; Ehrenfreund et al., 2001) are likely important also on Callisto.

Composition of the icy moons: outstanding questions

Ganymede

- What is the chemical composition of visually dark, non water-ice materials?
- How do these materials correlate with the surface geology, in a wide range of spatial scales?
- Where is the non water-ice material linked to the subsurface?
- What is the degree of contamination by exogenic material? Where does it come from (Io and / or the outer Jovian system)?
- What is the temporal cycle of the oxygen species?

Europa

- What is the chemical composition of visually dark, non water-ice materials over targeted sites of very high interest?
- Are chemical building blocks of life and other elements essential for habitability present?
- How do such materials correlate with local geology and the subsurface?
- To what extent is the composition and physical state altered by radiation weathering effects?

Callisto

- What is the chemical composition of visually dark, non water-ice materials?
- How do these materials correlate with geology (in a wide range of spatial scales) and the sub-surface at local scale?
- What is the mechanism that allows CO2 to be continuously replenished at the surface?
- What is the composition and structure of Callisto's exosphere?

4.1.3.2 Science objectives

Characterise surface organic and inorganic chemistry. A reliable identification of all non water-ice compounds is still missing on Ganymede, Europa and Callisto, due to the lack of high spatial resolution data with good signal-to-noise ratio (**Figure 4-6**), and to low spectral resolution. At Ganymede, main target of JUICE, hyperspectral imaging in a wide spectral range from UV to IR will be achieved at regional scale with spatial resolution between 2 and 3 km/px over more than 50% of the surface, while very detailed compositional mapping (at spatial resolution of at least 100 m/px) will be obtained on a few tens of selected sites of interest. On Europa, the ability to perform two close flybys will eventually allow a thorough characterisation of some sites that are currently ranked at very high priority for both astrobiology and geology. By using the highest possible spectral and spatial resolution of the onboard spectrometers, it will be possible to detect biologically essential and major elements, as well as organics, oxidants and reductants on the surface of the three icy moons. In Callisto flybys and even with only two Europa flybys, the spectral coverage at the small-to-medium scale (1-30 km) will be significantly improved. In all cases, the spectral resolution will be at least 4 times better than the Galileo data in the near infrared range.

JUICE will provide regional spectral mapping over more than 50% of Ganymede's surface and over significant portions of Europa and Callisto. High spatial resolution spectral imaging of selected targets will allow reliable identification of non water-ice materials for the three icy moons.

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 an INMS-type instrument or a Submillimetre wave 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. JUICE particle instruments should be capable of achieving enough sensitivity to detect sputtered H_2O molecules (**Figure 4-7**), resultant products of H_2O and other minority species (O, O_2, OH, H, H_2) with mixing ratios of 1 ppm.

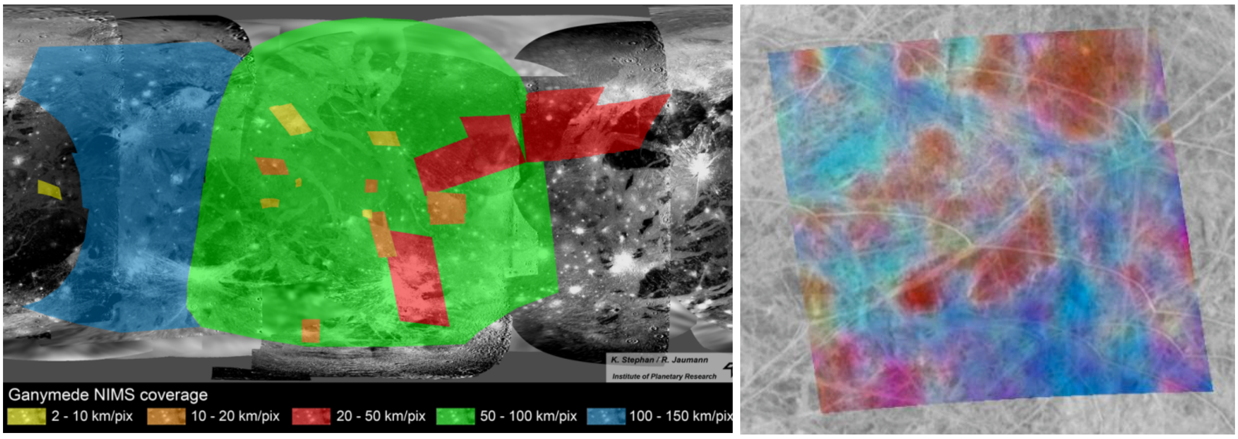


Figure 4-6. Left: *Spatial coverage of Galileo/NIMS on Ganymede superimposed on the mosaic obtained from the Galileo/SSI optical images. The low spatial resolution (>20 km/px) of Galileo data did not allow proper investigation of composition and spatial distribution of non water-ice compounds on the surfaces of the moons. (Credit: K. Stephan, R. Jaumann, DLR)* ***Right:*** *False-colour image of Europa obtained by Galileo/NIMS and superimposed to an optical Galileo/SSI image. The area imaged in colour is about 400 by 400 kilometres. Colours reveal the presence of materials with differing compositions. Blue areas represent the cleanest, brightest icy surfaces, while the reddest areas have the highest concentrations of darker, non water-ice materials. (Credit: NASA/JPL).*

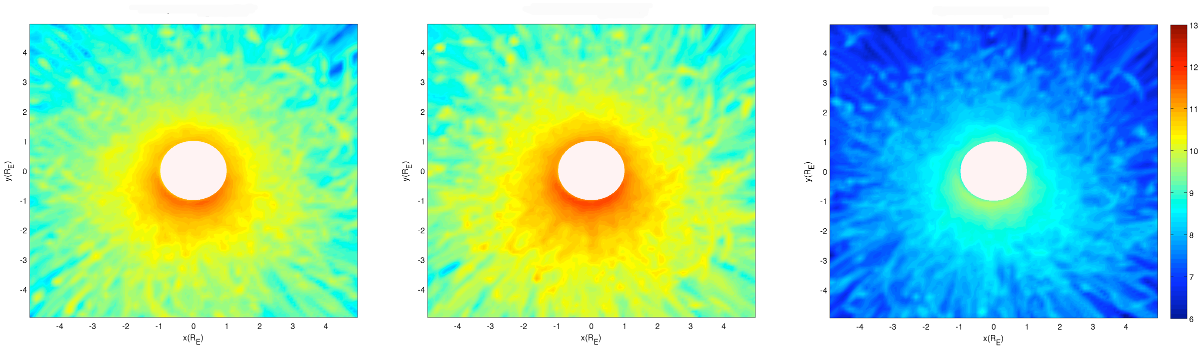


Figure 4-7 *Simulated sputtered-water density spatial distribution due to diverse species of magnetospheric ions impacting the surface of Europa (left panel corresponds to S+, middle panel to O+, right panel to H+). The unit of the logarithmic colour-bar scale is m^{-3}. The Sun is on the top, trailing hemisphere is at the bottom. (Credit: Plainaki, et al., 2011).*

On Ganymede, JUICE will 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 will sample the noble gases Ar, Kr, and Xe. The same kind of measurements at closest approaches of Europa and Callisto flybys, even though much more limited in space and time, would be also unique and would constrain the origin and evolution of the volatile inventories of the three icy moons.

Relate surface composition to geology. The relationship of ice and non water-ice materials and their distribution is crucial for understanding the origin and evolution of the surfaces of Ganymede, Europa and Callisto. 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).

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 neither leading/trailing hemispheric asymmetry in the distribution of CO_2 exists nor the impact craters tend to be CO_2-rich (Hibbitts et al., 2002). It is also occasionally enriched in terrain containing larger-grained ice in comparison with adjacent terrain of similar morphology and ice abundance. Combined with geological mapping, multi-wavelength spectral mapping and *in situ* measurements, JUICE will lead to a consistent picture of the surface chemistry of Ganymede and separate the relative contributions of endogenic subsurface chemistry and exogenic magnetosphere-driven radiolysis, and assess the role of processes that exchange material between the surface and subsurface.

On Europa, hydrated compounds are concentrated at the lineaments and chaotic terrains. Some young cryovolcanic flow and deposit units exhibit high proportions of hydrated salts and low abundance of sulphuric 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 sulphate salts into sulphuric acid hydrate by exogenically-driven radiolysis (Dalton et al., 2010). The presence of large quantities of brine and sulphate salts in certain deposits may reflect the composition of subsurface liquid source reservoirs (Dalton et al., 2010). JUICE will correlate distribution of non water-ice material with geologic units in a wide range of spatial scales, up to very high spatial resolution (~1 km and possibly less) over regions of very high interest targeted at closest approach. The combination of high spatial and spectral resolutions data with unprecedented ice-penetrating radar exploration will be the key to unveil the exchange processes occurring between surface and subsurface.

On Callisto, 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 at the temperatures typical of the satellite's equator at noon, trapping structures (e.g., ice clathrates, physisorption) that can form a stable underground reservoir of CO_2 are envisaged. The SO_2 distribution appears generally mottled, with some areas of high concentrations correlated with ice-rich impact craters (Hibbitts et al., 2000). Large-scale patterns include the depletion of SO_2 in the polar regions; and a depletion of SO_2 on the trailing side relative to the leading side is observed. JUICE will correlate distribution of non water-ice material with geologic units in a wide range of spatial scales and will combine imagery, spectral mapping and subsurface sounding to study the exchange processes. Moreover, JUICE will investigate the intriguing mechanism of replenishment of CO_2.

<u>*Investigate the effects of radiation on surface composition and structure*</u>. Ganymede shows evidences of the presence of oxygen species. In particular, solid O_2 and O_3 (Noll et al., 1996; Hendrix et al., 1999) have been detected in the trailing hemisphere of Ganymede, 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 polymerised 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. JUICE 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 surface. Moreover, it will closely explore the physical processes involved in the cycling of oxygen species and the availability of oxidants for biological processes.

The spectra of non water-ice, visually dark and reddish materials on Europa could be matched by mixtures of sulphuric 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 sulphuric acid. Thus sulphuric 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 equilibrium between creation and destruction that varies based on sulphur content and radiation flux. O_3 is not as obvious in Europa as in Ganymede, but signatures of O_2 and H_2O_2 are evident (Hall et al., 1995; Fanale et al., 1999; Carlson et al. 1999; Johnson et al., 2003; Hand et al., 2007). If oxidants can be delivered to the internal liquid water reservoirs, they can be a source of free energy available for biology. JUICE will provide information on the contamination processes acting on the surface of Europa, enhancing the mapping of leading/trailing asymmetries due to implantation of exogenic material and revealing interactions with the subsurface material.

At Callisto, sublimation may be more significant than charged particle sputtering. However, the interaction with plasma environment must be evaluated and compared to different surface release processes. Current knowledge of the atmosphere is based on isolated observations, derived largely from observations of spectral emission features that are reliant on the local plasma environment, which provide little information on minor species chemistry and temporal variations. Therefore, combining spectroscopy and atmospheric/exospheric measurements, JUICE will enable the identification of the asymmetries of Callisto's surface release. JUICE measurements, including limb scans and stellar occultations, identification of major and minor constituents of Callisto's neutral atmosphere and mapping of low energetic neutral released from the surface, would reveal information about the sources and sinks of the atmosphere/exosphere.

In summary, JUICE will:

- Characterise the surface composition and chemistry of the icy Galilean moons; identify biologically essential elements; search for biosignatures at Ganymede and Europa
- Unveil places where the exchange processes between surface and subsurface liquid reservoirs have been more intense
- Provide a consistent picture of the surface chemistry of Ganymede and separate the relative contributions of endogenic subsurface chemistry and exogenic magnetosphere-driven radiolysis and sputtering
- Constrain the origin and evolution of the volatile inventories of the three icy moons, and reveal information about the sources and sinks of their thin atmospheres
- Investigate the intriguing mechanism of replenishment of CO_2 on Callisto

4.1.4 Galilean moons and their interaction with Jovian magnetosphere

4.1.4.1 Overview: the complexity of the moon's environments

Ganymede, the largest of the Galilean moons, has earned a unique place within the Solar System: it possesses an internally generated magnetic field and hence a miniature magnetosphere is formed (about the same size as Mercury's) within the larger Jovian magnetosphere. This mini-magnetosphere constantly interacts with the plasma flow and electromagnetic fields of the rapidly rotating Jovian magnetosphere, producing a dynamic interaction region which has some parallels with the Earth's magnetosphere (e.g. driving of the system through magnetic reconnection). The "opening" of Ganymede's magnetic field lines (in a similar way that the Sun's magnetic field "opens" the Earth's magnetic field lines following reconnection on the dayside) allows direct access of the Jovian plasma onto the surface of Ganymede near the poles in the open field region, which may result in a subsequent alteration of the surface properties and brightening of the polar caps (Khurana et al., 2007). Ganymede (and Europa) also have induced magnetic field signatures which are much weaker than the internally driven magnetic field (at Ganymede), and also weaker than the background Jovian field. Therefore it is complicated but crucial to separate the effects of these electromagnetic interactions in order to characterise the subsurface oceans. The optimum way to understand this complex scenario, and to characterise the interaction region both close to Ganymede and at the boundaries of the magnetosphere, is to observe the system over multiple frequencies (e.g. hours, days, and weeks) both from elliptical (magnetosphere) and circular orbits (internal and induced field). Callisto also exhibits evidence for induced magnetic field signatures, and these will be studied during the Callisto flybys, along with the plasma environment there.

Europa, Ganymede and Callisto possess 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 also produce an exosphere at Callisto. The exospheric properties are thus indicative of such sputtering and sublimation processes and will also provide information on the surface composition and surface aging (erosion).

Local environments of the icy moons: outstanding questions

Ganymede

- What are the characteristics of Ganymede's various magnetic field components (dynamo, induced) and mini-magnetosphere?
- What factors control the interaction with Jupiter's magnetosphere and atmosphere?
- How does the local plasma environment affect the surface, and exosphere/ atmosphere?
- What is the nature and controlling factors of the Ganymede aurora?

Callisto

- What is the nature of Callisto's induced magnetic field signature?
- How does the local plasma environment effect the surface, and exosphere/ atmosphere?

Europa

- How does the local plasma environment affect the surface, and exosphere/ atmosphere?

4.1.4.2 Science objectives

A. 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 known in the Solar System to possess its own intrinsic mini-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 4-9**).

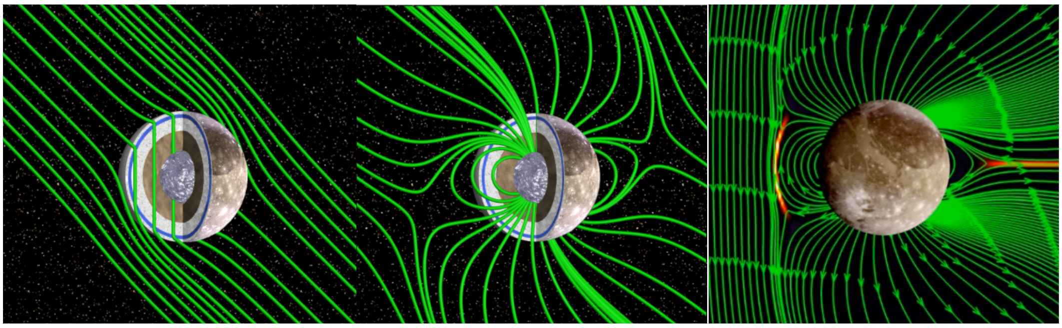


Figure 4-8 *Ganymede's induced field (left), internally generated magnetic field (middle), and resulting miniature magnetosphere (right). Credits: X.Jia (Univ. Michigan) and M. Kivelson (UCLA)*

JUICE will investigate Ganymede's intrinsic magnetic field in detail and characterise 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 will determine the regions of open and closed Ganymede magnetic field where particles are either trapped, transported, or field-aligned. JUICE will identify particle precipitation along the open field lines at the poles through auroral observations at multiple wavelengths and through detection of sputtered and radiolytically-produced ENAs. JUICE will take measurements in the regions between the atmosphere/exosphere of Jupiter and Ganymede (where the particles are mainly produced through sputtering and radiolysis) - along the flux tube connecting both bodies. JUICE will uncover the nature of the time-varying interaction of Ganymede's magnetic field and plasma environment with the surrounding Jovian magnetosphere – separating the various sources of magnetic fields. It is thought that variations in the magnetic field signals occur according to: 1) the dipole phase of Jupiter's field which is tilted with Jupiter's rotation axis (~11 hour timescale); 2) the location of Ganymede in its orbit about Jupiter (~1 week); and 3) with solar wind activity (~ 26 day solar rotation). The ocean-related currents will be measured using the observed induced magnetic signals varying over such time-scales. Long-term changes in the internal and induced magnetic field may also be detected by comparison with the Galileo data.

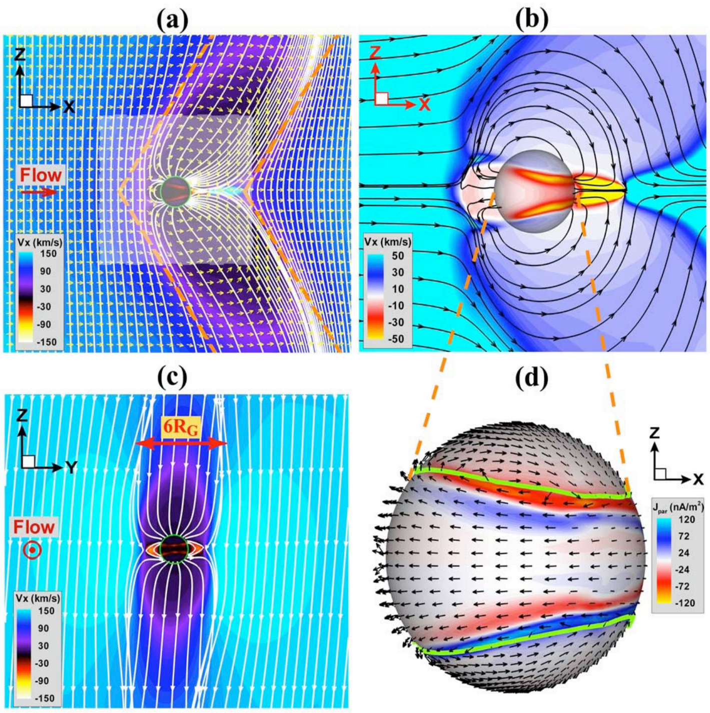


Figure 4-9. *Magnetic field of Ganymede immersed within that of Jupiter. (a) Flows and the projection of field lines (white solid lines) in the XZ plane at Y = 0. The colour scale on the LHS indicates the value of the Vx flow in km/s, and unit flow vectors in yellow show the flow direction. A theoretical prediction of the Alfvèn characteristics (orange dashed lines) is shown for reference. The projection of the ionospheric flow is also shown as colour contours on a circular disk of r = 1.08 RG in the centre. (b) A zoomed-in view of the light area in (a). Flow streamlines are superimposed on colour contours of Vx. Note that the colour 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 RG. (taken from Jia et al., 2008)*

B. Particle populations and their interaction with Jupiter's magnetosphere.

Many crucial parameters of the satellite/magnetosphere coupling have not yet 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 the intense bombardment 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 from 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 significance of these effects depends on the magnetic environment. Ganymede, as an example, possesses an internal dipolar magnetic field which interacts with the Jovian magnetic field, thus permitting the plasma to impact the surface at specific regions possibly resulting in the specific albedo distribution observed, with the polar regions being brighter than the equatorial belt (Khurana et al., 2007), see **Figure 4-10** below.

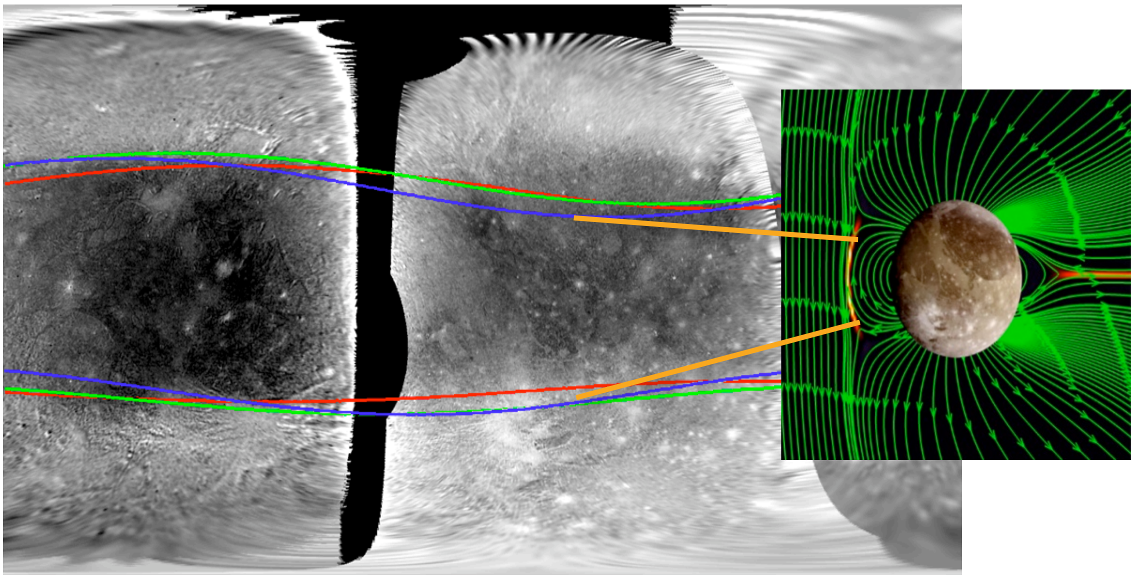


Figure 4-10 *Surface alteration associated with magnetosphere-surface interactions at Ganymede (Khurana et al., 2007)*

JUICE will identify the particle populations near the moons (Ganymede and Callisto) 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 from eV to keV of the impacting plasma and ejected material.

C. The aurora

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 conducting bodies. As they move through the Jovian magnetic field, they create a specific current system (the unipolar dynamo). This electro-dynamical coupling is not stationary and it generates Alfvèn wave structures, known as 'Alfvèn wings', which 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.

Europa, Ganymede and Callisto are in similar situations. The magnetosphere interaction at Io is the most powerful, and in many ways the best understood moon-magnetosphere interaction. The coupling with Europa is thought to be less powerful, but it appears to generate intense waves and a weak auroral footprint in the atmosphere of Jupiter. As discussed above the Ganymede situation is unique. The details of how this mini-magnetosphere interacts with the giant magnetosphere of Jupiter are not well understood. In terms of auroral emission, we do know that this interaction is powerful enough to create an auroral footprint in Jupiter's atmosphere, which varies on a number of time-scales which may be related to magnetospheric dynamics (Grodent et al., 2009) and aurora in the exosphere of Ganymede itself (see Feldman et al., 2000).

JUICE will study the aurora in Ganymede's exosphere, and will measure the location and intensity of the footprint aurora from Io, Europa and Ganymede in Jupiter's atmosphere remotely, where possible in combination with *in situ* measurements of particles and fields in the field–aligned current systems flowing between the moon and the planet.

D. Sources and sinks of the ionosphere and exosphere

The Galilean satellites are known to have thin atmospheres / exospheres (McGrath et al., 2004), produced by sputtering processes and sublimation of the surface materials. 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 from limbscan measurements.

JUICE 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.

In summary, JUICE will:

- Investigate Ganymede's internal, induced, and magnetospheric field components, and how they are modulated by the Jovian magnetosphere
- Identify the magnetic field and particle populations near the moons and their interaction with Jupiter's magnetosphere, including the moon footprint aurora in Jupiter's atmosphere
- Study the particle interaction with the surface of Ganymede
- Contribute to our understanding of the atmospheres of the icy satellites, their origin and evolution

4.2 Jupiter

4.2.1 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 characterisation 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 essential insights to the interior structure, bulk composition, and formation history of our Solar System.

Jupiter is the end product of energetic accretion processes, thermochemistry, photochemistry, condensation processes, planetary-scale turbulence and gravitational differentiation. Its atmosphere is characterised 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 that 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.

JUICE provides a significant potential for Jupiter atmospheric science from its broad spectral coverage from advanced instrumentation; robust orbital tour with access to a wide range of latitudes and phase angles (including a high-inclination phase to study the polar atmosphere); large data volume capacity; long approach phase and 2+ year baseline of tour-phase observations (**Figure 5-2**). By combining the gas giant exploration of JUICE with the knowledge acquired from previous missions (e.g., Juno, New Horizons, Cassini, Galileo and Voyager), this mission will revolutionise 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. JUICE 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.

The atmosphere of Jupiter: outstanding questions

Atmospheric dynamics and circulation

- What dynamical processes are involved in the redistribution of deposited solar energy, internal potential energy and material tracers within the Jovian atmosphere and between the different layers?
- What mechanisms determine the origins, variability and periodicity of localised processes (lightning, discrete vortices, upheavals of the belt/zone structure) in Jupiter's atmosphere?
- What drives the time-variable three-dimensional flow field from the troposphere to the thermosphere, and how is it maintained?
- How important is wave activity in the global circulation of Jupiter and the transport of energy to the upper atmosphere?

Composition and chemistry

- How is the spatial variation of condensable species and disequilibrium gases related to the meteorology of Jupiter's weather layer?
- What is the origin and flux of material entering Jupiter's upper atmosphere?
- What is the spatial variation of stratospheric composition and how is it related to atmospheric circulation, photochemistry and the unique environment of the poles?

Vertical structure and interior

- What is the nature of coupling processes between Jupiter's deep interior, the upper layers and the external planetary environment?
- What are the optical properties, vertical distributions and composition of the clouds, hazes and coloured chromophores in the atmosphere of Jupiter?
- What processes govern the production of haze within the polar vortices, and what what drives the hemispheric asymmetry?

4.2.2 Science Objectives

The atmospheric science objectives of JUICE fall into three categories designed to address the unresolved mysteries raised by previous missions to the outer Solar System. With advances in instrument sensitivity and resolution, as well as the long temporal baseline to permit the study of the dynamic, evolving atmosphere, JUICE will enable new discoveries and address the fundamental physical and chemical processes at work on giant planets (**Figure 4-11**).

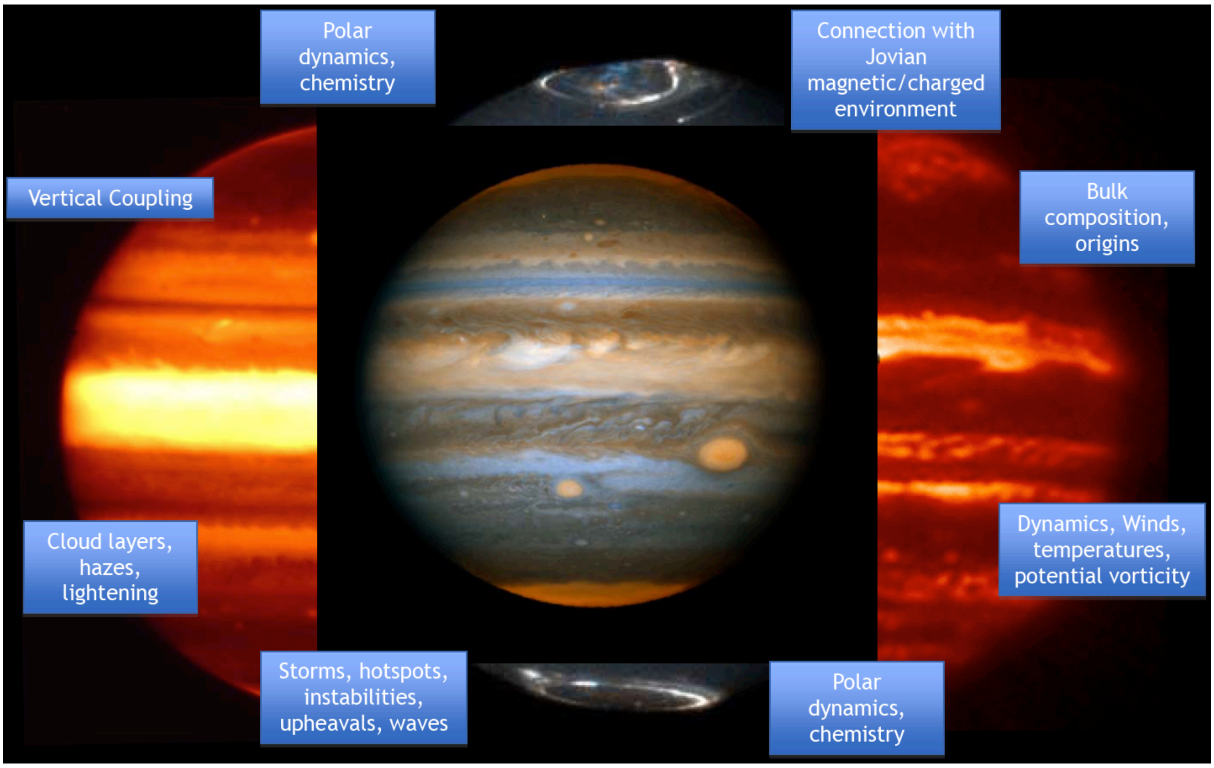


Figure 4-11. *Examples of the Jupiter science objectives of JUICE. Each image shows Jupiter's appearance at a range of different wavelengths, from visible colouration and wind tracking (centre, HST, credit: NASA/ESA/A. Simon-Miller/I/ de Pater) to cloud properties in the near-IR (left, Gemini/NIRI image, 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).*

A. 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, JUICE 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 (e.g., the recent fade and revival of Jupiter's South Equatorial Belt). For example, JUICE will study wave activity 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. Submillimetre spectroscopy will provide our first direct measurements of wind velocities in Jupiter's stratosphere. Regular cloud-tracking at a range of tropospheric altitudes will be used to assess the stability and energy sources driving zonal jets and giant vortices (e.g., the Great Red Spot). Night side imaging will catalogue the distribution and energetics of Jovian lightning, a powerful tracer for atmospheric circulation. High-latitude observations will provide a unique survey of the dynamics of Jupiter's polar vortices for the first time. Crucially, JUICE's broad spectral coverage will allow us to determine the environmental changes (composition, cloud characteristics) associated with variations in albedo and circulation (e.g., colour changes, wind speed variations). Meteorological investigations of these phenomena will benefit from the long temporal baseline and broad spectral range offered by JUICE, permitting global mapping at frequent intervals to identify the underlying dynamical causes for Jupiter's atmospheric variability. JUICE 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.

B. Composition and Chemistry

Jupiter's atmospheric composition 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. Spectroscopic mapping from the UV to the submillimetre will allow JUICE to study (a) the 3D spatial distribution and variability of stratospheric hydrocarbons and exogenic oxygen-bearing species; (b) localised and non-equilibrium composition (e.g., PH_3, AsH_3, GeH_4) 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. Submillimetre spectroscopy will search for previously undetected trace species in Jupiter's stratosphere, and near-IR mapping of ammonia and water humidity within and above the condensation clouds will directly complement the deeper atmospheric studies of Juno. Finally, spectroscopy of Jupiter's polar regions will be used to study the unique chemistry and cloud formation mechanisms at high latitudes, the apex of Jupiter's planet-wide circulation and the location of a unique connection with the external environment. JUICE's survey of Jupiter's atmospheric composition will significantly advance our understanding of chemical processes and transport in giant planet atmospheres.

C. Vertical Structure of the Atmosphere and Interior

JUICE's broad wavelength coverage from the radio to the far-UV will be used to characterise 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). JUICE will use occultations at a wide range of latitudes to 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 Jupiter's unique polar environment, which exhibits unusual composition, circumpolar waves and vortices, and a poorly-understood north/south asymmetry in haze properties, will be studied from JUICE's high inclination phase. Finally, although not currently envisaged in the model payload, the detection of internal oscillation models connecting the troposphere to the deep interior via Jovian seismology would complete JUICE's characterisation of the atmospheric structure and provide valuable complementary information to Juno. JUICE 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.

In summary, JUICE will :

- Study Jupiter's atmosphere as a complex, coupled system from the dynamic weather layer to the upper thermosphere
- Study the variability of Jovian climatology, dynamics, winds, gaseous composition and cloud structure
- Include a varied and extensive orbital tour with access to high latitudes to provide a comprehensive study of the unique environmental conditions at Jupiter's poles
- Provide first direct measurements of atmospheric circulation in the middle atmosphere
- Investigate the processes responsible for shaping the environmental conditions in gas giant atmospheres

4.3 The magnetosphere

If it were visible, the Jovian magnetosphere would be the largest object in the sky. Its stellar-like transfer of angular momentum from the fast rotating planetary magnetic field to the space plasma environment is the engine that drives the Jovian magnetosphere, and it is the biggest planetary particle accelerator within the Solar System. Dense plasma originating principally from Io and Europa loads the fast rotating planetary magnetic field, stretching it into a magnetodisc until a multi-step process involving magnetic field ruptures ("reconnection") and plasma instabilities, accelerates ions and electrons up to very high energies. The energetic particles in turn impact the moons, releasing surface material back out in to space to form their tenuous atmospheres and tori.

With its suite of global imaging and *in situ* measurements, JUICE will for the first time unveil the global machinery of an astrophysical object within our own Solar System. JUICE will investigate the high-latitude middle magnetosphere up to 30 degrees above the equatorial plane, enabling exploration of the three dimensional structure of the Jovian magnetodisc, including *in situ* measurements outside the magnetodisc to determine plasma heating and acceleration processes, and will provide remote sensing measurements of Jupiter's ring current and aurora. JUICE will study the magnetospheric parameters in the vicinity of Europa, Ganymede (and its magnetosphere), and Callisto in detail.

4.3.1 Overview: the outstanding properties of the Jovian magnetosphere

The strong internal magnetic field of Jupiter (equatorial surface strength 50 times that of the Earth) 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 (tilted by 9.7 degrees relative to the dipole axis). It is driven by the fast rotation of its central spinning object, Jupiter.

Its major plasma source is the moon Io, which orbits deep inside the magnetosphere, and releases about 1 tonne/s of oxygen and sulphur through volcanic eruptions which feeds an equatorial magnetodisc extending to hundreds of planetary radii.

The Jovian magnetosphere is the most accessible environment for direct *in situ* investigations of processes regarding:

- the stability and dynamics of magnetodiscs, and more generally, angular momentum exchange and dissipation of rotational energy (the 'fast rotator' theme),
- 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 ionised media.

Jupiter is also a powerful particle accelerator, its inner magnetosphere being the most severe radiation environment in the Solar System and therefore can be seen as an accessible template for similar acceleration processes in the environment of exoplanetary gas giants.

The jovian magnetosphere: outstanding questions

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?

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?

4.3.2 Science Objectives

JUICE will study the dynamics of the Jovian magnetosphere in and out of the magnetodisc (with angular momentum exchange and dissipation of rotational energy), determine the electrodynamic coupling between the planet and the satellites, and assess global and continuous acceleration of particles.

A. The magnetosphere as a fast rotator.

The magnetosphere of Jupiter has been traditionally divided into inner ($<10\ R_J$), more dipolar-like configuration, and a middle ($10\text{-}40\ R_J$) to outer ($>40R_J$) magnetosphere with highly stretched, more radial magnetic field configuration.

The inner region contains the synchrotron radiation belt of Jupiter ($1.1 < r < 3\ R_J$) formed by energetic electrons gyrating in the strong magnetic field and having energies up to tens of MeV. The inner region is also the location of the main plasma source of the magnetosphere, namely Io, as well as the significant source Europa. It is believed that cold 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). In addition hot plasma is being injected from the middle and outer magnetosphere into the inner magnetosphere and exchanged with cold plasma (Mauk et al, 1997).

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 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 variable in size. 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 night side 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 all the way to the orbit of Saturn.

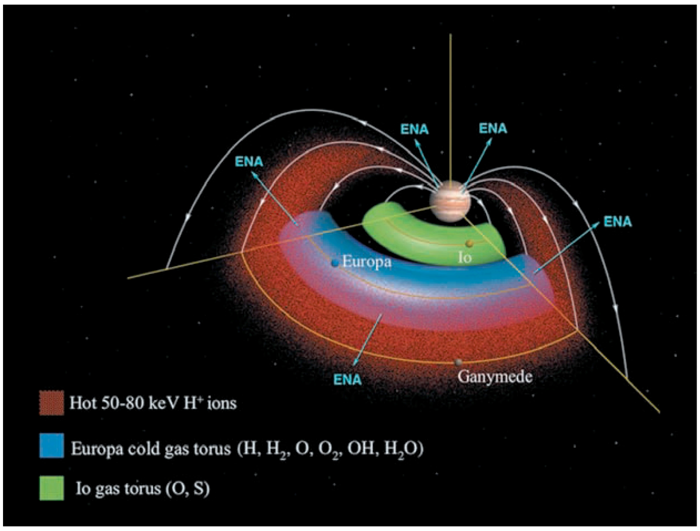


***Figure 4-12**: Artist's conception of the Io- and Europa torus (from Mauk et al. 2004), illustrating the neutral and charged particle distributions in the region between Ganymede and Io, one of the key regions of the Jovian magnetosphere.*

The fast rotation of the planet, combined with the continuous supply of ion populations principally from Io's volcanism, lead to the formation of a neutral and plasma torus, and further out, of a magnetodisc (**Figure 4-12**). In the inner magnetosphere, the warm and cold plasma of the Io-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. In addition to the Io torus there is also a neutral gas torus along Europa's orbit, inferred from energetic particle signatures measured onboard Galileo (Lagg et al, 2003) and imaged in energetic neutral atom (ENA) emissions onboard the Cassini spacecraft during its Jupiter flyby (Mauk et al., 2004). The uniqueness of JUICE measurements will be that the torus region will be studied *in situ* during the Europa flyby times as well as remotely e.g. with ENA measurements during the high latitude Callisto phase of the mission. Different from Galileo, the global imaging instrumentation of JUICE is dedicated to capturing the global dynamics of Jupiter as a space plasma system, rather than just focused on parts of it. JUICE will investigate the magnetosphere between the orbits of Ganymede and Europa where the neutral tori are and where the magnetodisc starts to form, at the transition between the inner and the middle magnetosphere.

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. 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, mesoscale interchanges, global sporadic disruptions and reconfigurations of the disk, magnetic reconnection. The chain of processes involved in these phenomena, most likely common to any magnetised 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 characterise the dynamical processes at work and guide any theoretical or simulation analysis.

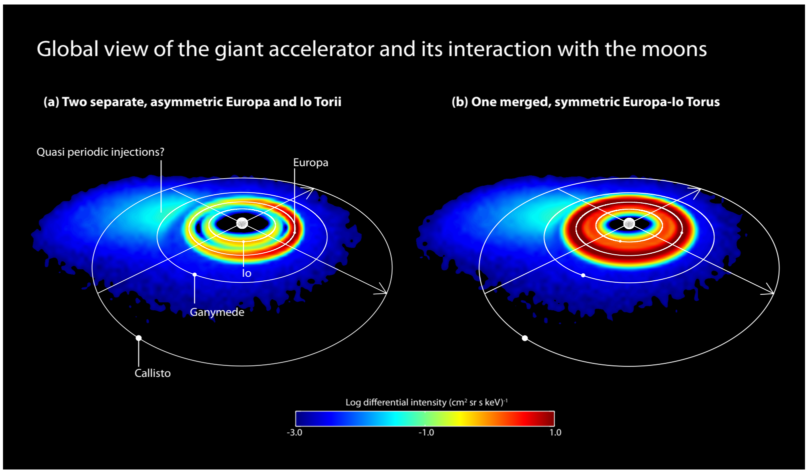


***Figure 4-13**: JUICE will be equipped to discover the global 3D dynamics of the Jovian plasma-neutral environment that are currently one of the outstanding open questions. Simulations of two hypothetical scenarios based on our limited knowledge from Galileo data showing global ENA images of dramatic appearance of heated plasma in the magnetotail and its subsequent interaction with the moons and neutral gas. (a) The Europa and Io tori are two separate distributions; (b) The Europa and Io tori are merged and symmetric.*

JUICE will investigate the global configuration and dynamical behaviour of Jupiter‘s magnetodisc along its trajectory inside the system including high latitudes and the magnetospheric region between Ganymede and Europa.

B. The magnetosphere as a giant accelerator.

The global dynamics of Jupiter‘s magnetosphere is one of the most compelling mysteries of our Solar System that will provide detailed insights into astrophysical phenomena. The huge dimensions of the magnetosphere and the wealth of processes in the different regions make 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 close to the equatorial plane 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 rigid plasma corotation 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.

JUICE will significantly enhance our knowledge of the processes occurring in the magnetosphere in the equatorial plane and at higher latitudes with better time resolution and better directional information as for previous missions.

In summary, JUICE will
- Investigate the global configuration and dynamics of Jupiter's magnetodisc
- Study the electrodynamic coupling between Jupiter's magnetosphere and the satellites
- Assess the global and local acceleration of particles within the giant magnetosphere
- Investigate the magnetospheric region between the orbits of Ganymede and Europa

4.4 Study the Jovian satellite and ring systems

4.4.1 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. In addition to the thorough studies of the three icy moons described in the previous sections, JUICE will also remotely explore Io, small moons, and the ring system of Jupiter. 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.

4.4.2 Science objectives

A. Study Io's active dynamic processes

Despite its relatively small size, Io is the most volcanically active body in the Solar System. 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 sulphur-rich edifices.

Io's colourful appearance is the result of various materials produced by 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 sulphide minerals. JUICE will monitor the volcanic activity of Io, and determine the composition of different materials on the surface at regional scale (50-200 km/px) through remote multi-wavelength imaging spectroscopy.

B. Study the rings and small satellites

Jupiter's ring system is faint and consists mainly of micron-sized dust. It has four main components: a thick inner torus of particles known as the "halo ring", extending from 1.29 to 1.71 R_J; a relatively bright, exceptionally thin (< ~30 km) "main ring" between 1.71 and 1.80 R_J, showing a rich fine structure; and two wide, thick and faint outer "gossamer rings" extending up to 3.16 R_J, one bound by the orbit of Amalthea and the other mostly within Thebe's orbit (Esposito, 2002, Ockert-Bell et al., 1999). Total mass of the ring system (including unresolved parent bodies, with size < 0.5 km) is poorly known, but it probably lies in the range 10^{11}-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 be the last remnant of a past population of small bodies near Jupiter. Various processes in Jupiter's fierce environment readily destroy small particles, thus faint rings must be continually replenished from a population of parent bodies if they are long-lived features.

JUICE will characterise the physical and chemical properties of Jupiter's rings, constraining the processes that define the origin and dynamics of the ring dust in all of the main components and characterising their fine structure. To achieve this goal, imaging of the ring system in 3D and in a wide range of 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 radial and vertical structure of the main ring will also be determined through radio occultations at X- and Ka-bands.

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). 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 a 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. JUICE will shed light on the physical shape and bulk composition of these small moons. At least for the largest objects Thebe and Amalthea, JUICE will investigate their individual relationships with the ring system. JUICE will also improve their orbital elements, ultimately constraining their origin.

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

In summary, JUICE will

- Monitor the volcanic activity of Io in space and time
- Determine the composition and different widespread materials on Io at regional scales
- Explore the physical and chemical properties of Jupiter's rings, constraining the processes that define the origin and dynamics of the ring dust in all of the main components and characterising their fine structure
- Shed light on the physical shape and bulk composition and origin of Jupiter's small inner moons and irregular satellites

4.5 Transverse Themes

4.5.1 Comparative planetology

4.5.1.1 Atmospheres of Giant planets

The poles of the giant planets can be considered as the apex of a planet-wide circulation pattern, surrounded by circumpolar vortices that separate the polar atmosphere from the lower latitudes. On Saturn, the poles were discovered to be the site of unique wave activity (Saturn's polar hexagon), dynamic convective cloud activity, and warm hurricane-like polar vortices. As the poles have similar temperatures to the equator, despite the contrast in solar energy input from equator to pole, some form of efficient transport of energy towards higher latitudes must be occurring, making the poles a vital component of the planetary circulation. Jupiter's polar regions are the least-studied areas of the planet, having been observed only once by Pioneer 11. Galileo remained in a largely-equatorial orbit, and Jupiter's low orbital obliquity (3 degrees) means that we cannot investigate the atmospheric dynamics, chemistry and energy balance at polar latitudes from Earth-based observatories. JUICE's broad-wavelength capabilities and long temporal baseline during the high-inclination phase will complement the high-resolution localised imaging of Juno. These unique polar observations will permit direct comparisons between the circulation of polar atmospheres of both Jupiter and Saturn (observed from Cassini's high-inclination orbits) to identify the common physical and chemical processes at work.

Cassini's long-term study of Saturn's atmosphere and its seasonal variability can be contrasted with Jupiter's atmospheric evolution, where seasonal effects are thought to be less important (due to the smaller orbital obliquity) and the dynamic weather layer is not obscured by layers of upper tropospheric hazes as they are on Saturn. Indeed, with its extreme contrasts in cloud colouration, temperatures and composition, Jupiter's atmosphere is a paradise for atmospheric scientists. The atmospheres of Jupiter and Saturn are very similar, so the differences in dynamics, chemistry and vertical structure can reveal the subtle ways in which a giant planet atmosphere responds to differences in solar insolation. The atmospheric dynamics and chemistry that will be studied by JUICE (particularly the importance of moist convection, the role of wave activity in atmospheric circulation, and the unique conditions of Jupiter's high latitudes) will have far reaching implications for our understanding of the atmospheric processes at work on the other giant planets, both in our Solar System and around other stars.

4.5.1.2 Magnetospheres

Planetary magnetospheres provide a natural laboratory for the study of plasma interactions and electrodynamic phenomena. Our understanding of the terrestrial magnetosphere is well developed. Cassini's extended observations of Saturn's magnetosphere show us that the properties of the extra-terrestrial magnetospheres can be best elucidated if we draw on our knowledge of the Earth. It shows that much is to be learnt from a comparative approach to magnetospheric physics in general terms, and

JUICE will contribute significantly to the advancement of this topic in two major ways, as outlined below.

Outer planet magnetospheres – Jupiter and Saturn. A fundamental property of planetary magnetospheres is the dynamical influence either of the solar wind and its embedded interplanetary magnetic field (IMF) or of the rotation of the planet. At the Earth we understand well that it is the former which plays a dominant role. The magnetospheres of the outer planets are much larger and they rotate faster. At Jupiter we have a system dominated by planetary rotation effects, though the IMF may be important in the outer regions and in the tail – issue that JUICE will address. In addition, the spinning Jovian magnetodisc forms the dominant field and particle signature of the middle magnetosphere, which JUICE will study in detail in three dimensions. The fundamental physics of this disc (and other aspects of this magnetosphere) is relevant to many astrophysical objects, including extrasolar planetary space environments, and JUICE will contribute to advancing our knowledge of extrasolar magnetospheres. Another major difference between the Earth and Jupiter is that the main auroral emissions at Jupiter are formed by the inability of the magnetodisc to corotate at the rapid Jovian rotation rate, and also show footprint displays associated to the moon-magnetosphere interaction. Observations from JUICE will study these unique electrodynamic interactions. At Saturn, Cassini observations have revealed a magnetosphere unlike any other we have experienced – highlighting the need for comparative planetology.

Miniature magnetospheres – Ganymede and Mercury. After a nearly 30 year hiatus, MESSENGER has recently returned new data from the miniature magnetosphere of Mercury, and begun the first orbital tour of the planet. The new results indicate a highly dynamic magnetosphere, constantly buffeted by the solar wind whose effects are stronger at ~0.3 AU. Due to the weaker magnetic moment of Mercury's internally generated field, the magnetosphere finds it hard to "hold off" the super-Alfvénic flow of the solar wind and it is frequently eroded almost to the surface of the planet itself. Given the lack of an appreciable atmosphere or ionosphere, one of the outstanding questions regarding Mercury's magnetosphere is the question of electric current closure. Interestingly, some parallels may be drawn between Mercury's magnetosphere and the magnetosphere of Ganymede. Both magnetospheres are so small that radiation belts, familiar from studies of Earth, cannot form. Both systems have exospheres and hence the question of current closure will be important at Ganymede too. However, at Ganymede the Jovian plasma confining the magnetosphere is flowing at sub-Alfvénic speed which means that no bow-shock forms in the upstream flow. JUICE will have a unique opportunity to uncover the properties of Ganymede's magnetosphere, but also to complement and extend the studies of miniature magnetospheres that will have come before with MESSENGER and BepiColombo.

4.5.1.3 Habitability

JUICE will give the opportunity to study a variety of ocean worlds at the Jupiter system. The particular characteristics of Europa, Ganymede and Callisto, such as the internal structure, geological activity and global composition, determine the liquid layers context and the final fate of habitability of these environments. Comparisons among these ocean worlds have implications for astrobiology. While Europa's ocean is probably in contact with the rocky layer, which may be a direct source of biologically important elements, Ganymede and Callisto's oceans are sandwiched between layers of different water ice phases. However, rise of deep silicate-rich melts has been argued to contaminate the Ganymede's ocean (Barr et al. 2001). Another example of intriguing implications is concerning the effects of the radiation environment, which is less intense at the surface of Ganymede than at Europa, thus alteration of analogous materials will be different and particularly interesting to explore in the case of organics and potential biosignatures.

Since Enceladus and Titan are both objects of the outer Solar System that also show evidences of a subsurface water ocean (Waite et al. 2009, Postberg et al. 2011, Tobie et al. 2005), they should also be considered in comparison with the Galilean icy moons during the JUICE investigation of *the emergence of the habitable worlds around gas giants.* On Enceladus, the discovery of water vapor plumes, the sources of which are fractures in the southern hemisphere, suggests the presence of a liquid water ocean (or pockets) in the interior. On Titan, there are several hints from Cassini-Huygens measurements that it has a liquid water ocean in the interior. Whereas the surface of Enceladus is mostly water ice, the composition measurements of the geyser by INMS showed a more complex composition of the endogenous reservoir, which includes mixtures of organics, salts and ammonia. Thus, all requirements for habitability are probably present at Enceladus but most likely not the stable environment. On the other hand, Titan is organic-rich in its atmosphere and at its surface but whether biologically interesting compounds may also occur in the internal water ocean is unknown but they could be created from the hydrolysis of organics in the chondritic matter accreted during the formation of Titan. JUICE, combined with Cassini-Huygens measurements, will bring strong constraints on the possible presence of liquid water at regions further away from the Sun than previously supposed by the standard habitability zone models in the Solar System, and would provide essential new constraints for the search for habitable worlds outside our Solar system, in exoplanetary systems.

4.5.2 Coupling processes in the Jupiter system

4.5.2.1 Gravitational coupling – the Laplace resonance

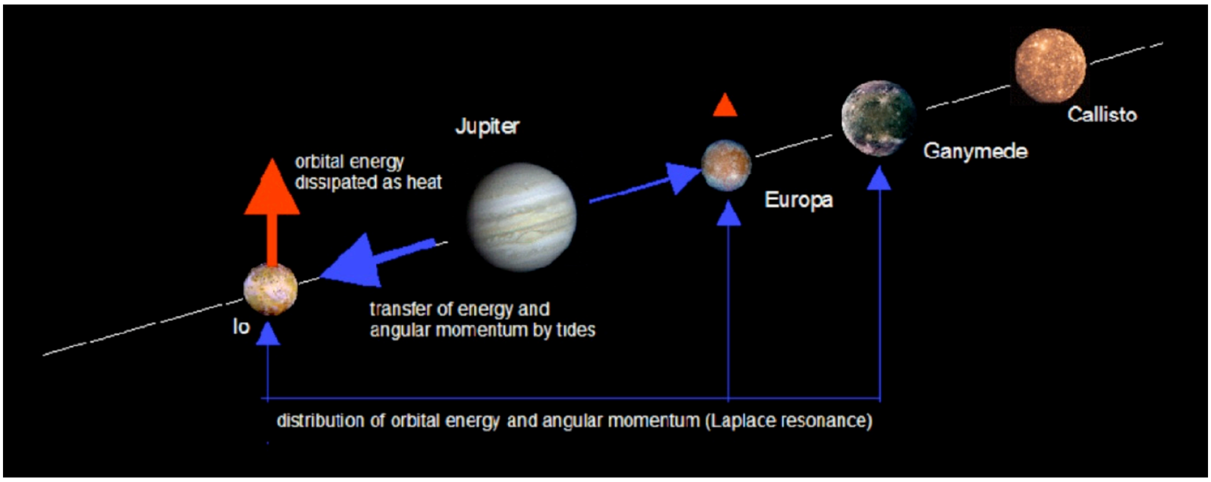


Figure 4-14*. The rotational energy of Jupiter is a huge reservoir of energy for the three inner Galilean satellites. Orbital energy gained by Io due to tidal torques exerted by Jupiter is distributed among Io, Europa, and Ganymede, due to the Laplace resonance.*

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 4-14**). It is still unclear how and when the resonance formed. It might be of primordial origin (Greenberg 1987, Peale and Lee 2002) or formed by orbital expansion of the satellites due to tides and subsequent capture into resonance as a result of the decreasing speed of orbital expansion with increasing distance from Jupiter (Yoder 1979, Yoder and Peale 1981). The Laplace resonance plays an essential role in the redistribution of rotational and orbital energy between the Galilean moons and Jupiter and also determines the amount of 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 aspects of Jupiter system science, including habitability. In particular, the evolution of the Laplace resonance may be important for the subsurface oceans of

Europa and Ganymede and for the future of volcanism on Io. 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 out of the exact Laplace resonance.

JUICE will study the tidal response of Ganymede and complement the ground-based astrometric observations to quantify tidal energy dissipation in the satellites and Jupiter, and provide new constraints on the evolution of the system.

4.5.2.2 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.

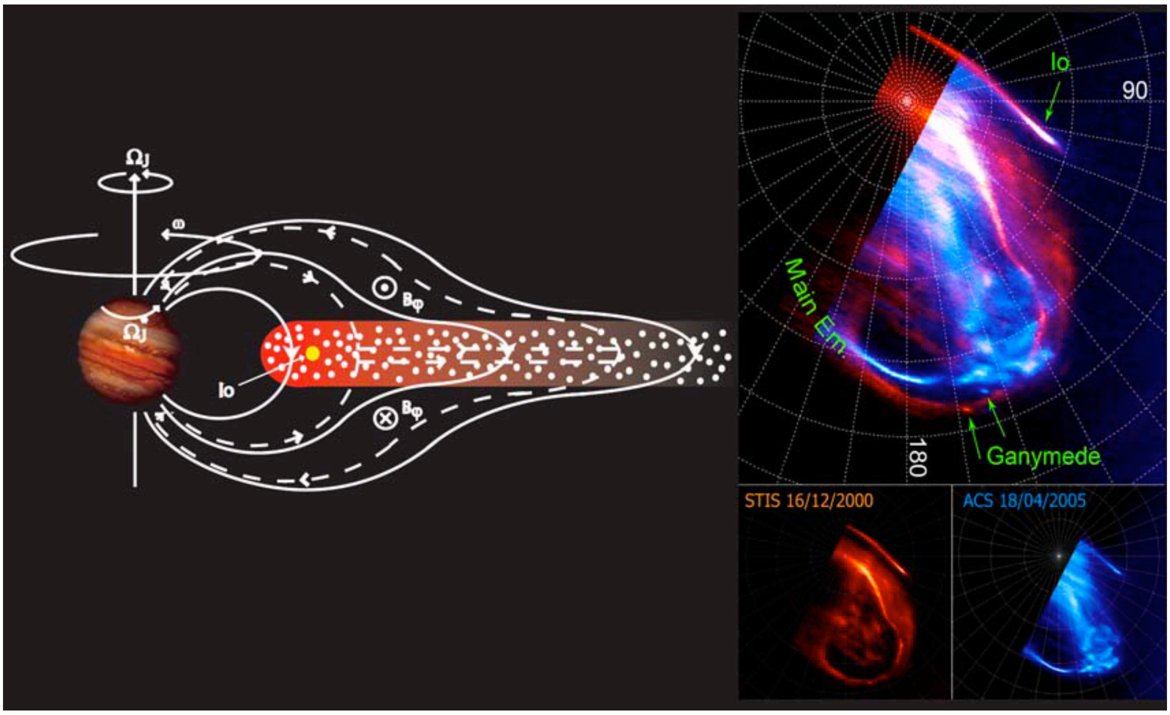


Figure 4-15 Left*: The magnetosphere - ionosphere coupling current system (After Cowley and Bunce, 2001).* ***Right****: The main auroral emissions, including the magnetically mapped moon footprints (Grodent et al. 2008).*

In the 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.

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 4-15**) 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.

JUICE will provide systematic and long term investigations of the coupling processes in the Jupiter magnetosphere by measuring the properties of the magnetic field, plasma and waves and through monitoring of the aurora, particularly during the high-inclination phase.

4.5.3 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. JUICE will supply new crucial information to address this topic by providing an unprecedented understanding of the surface properties and internal structure of the icy Galilean satellites (especially Ganymede). JUICE 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 atmospheric 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 studied by JUICE.

From internal structures to models of evolution. Gravity and laser altimeter investigations from the quasi-polar, low circular orbits of JUICE will strongly improve our knowledge of the internal structure of Ganymede. Moreover, the limited dataset supplied by Galileo on Callisto will be significantly complemented by non-equatorial JUICE fly-bys of the moon. The internal structures of these 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 JUICE, this will provide huge constraints on the processes and timescales of formation of the satellites and of the Jovian system as a whole. JUICE 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 (Pollack et al., 1996; Boss, 2000; Coradini et al., 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. JUICE will not improve the determination of these gravitational moments compared to Juno, but one possible alternative – the use of a seismological approach – may prove to be a new method for probing the interior density structure of Jupiter in regions inaccessible to conventional remote sensing (e.g. Gaulme et al., 2011). The detection of internal oscillatory modes could provide significant advances in our search for evidence of a core within Jupiter (Blanc et al., 2009; Coradini et al., 2010).

Composition constraints on the formation of the Jovian system The physics and chemistry of the Galilean satellites can be directly related to the processes that led to the formation of the planets (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 formed. JUICE 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 (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 up to the limits in the sensitivity and the mass resolution.

The formation and survival processes of the small satellites (both inner and outer) are still unanswered questions. Some of the inner satellites 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 (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 from remote, and possibly the other small inner satellites, JUICE 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 the JUICE mission, for two reasons. First, this population of captured objects represents a sample of the planetesimals that 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 (Tosi et al., 2010; Coradini et al. 2010). Depending on the mission profile, JUICE 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.

In summary, JUICE will

Comparative planetology

- Characterise the Jovian system for direct comparisons to the other giant planets of our Solar System and beyond
- Contrast the properties of icy satellites, with potential subsurface oceans, to provide insights onto the existence of habitable environments in our Solar System and beyond
- Investigate solar wind versus planetary rotation effects in Jupiter's magnetosphere, and compare to other systems (Mercury, Earth, Saturn)
- Uncover the properties of Ganymede’s miniature magnetosphere, thus complementing and extending analogous studies of Mercury's miniature magnetosphere

Coupling processes

- Quantify tidal energy dissipation in satellites and Jupiter, and provide new constraints on the evolution of the system
- Provide systematic and long term investigations of the coupling processes in the Jupiter magnetosphere

Origins

- Explore the physical and chemical processes responsible for shaping Jupiter and its diverse satellite system, to place constraints on the formation and evolution of giant planet systems.
- Infer the bombardment history on the Galilean satellites
- Provide new constraints on the composition, internal structure, and evolution of the moons

5 Science Requirements and Mission Scenario

The JUICE spacecraft will carry the most powerful remote sensing, geophysical, and *in situ* payload complement ever flown to the Outer Solar System. Following the formulation of the mission goals, this section identifies experimental techniques required to address the science objectives and translates science objectives into payload requirements in term of resolution, coverage, sampling rate, spectral properties etc. It describes the measurement techniques outlined by the SST which addresses all the science objectives for the JUICE mission. In this reformulation phase, the SST has reconsidered the model payload previously defined for the JGO of EJSM-Laplace. It was concluded that the model payload inherited from the JGO mission is fully capable of achieving the JUICE objectives, because the priority science for the ESA mission has not changed. The SST is aware that new or additional science measurements could be included in order to enhance, offer alternatives to, or complement the present measurements and therefore further enhance the science return from JUICE. Additional techniques and measurements may be proposed by the scientific community in response to an Announcement of Opportunity. These proposals will need to demonstrate that such techniques and measurements answer the science objectives of JUICE, are technically feasible and can be accommodated.

5.1 Exploration of the habitable zone: Ganymede, Europa and Callisto

5.1.1 Ganymede

5.1.1.1 Subsurface ocean, ice shell, and interior

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

Proposed experimental techniques. JUICE will exploit several methods to investigate the icy crust, the subsurface ocean, and the deep interior of Ganymede. Oceans will be characterised 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 interior. 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 moon's 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 moon's 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 tracking will be required to build an altimetry corrected network on Ganymede's surfaces to characterise its dynamical rotation state (forced libration, obliquity and nutation). Finally, the magnetic induction response from the ocean will be characterised by measuring the magnetic field vector continuously between 8 and 32Hz with an accuracy of 0.1nT. These measurements must be supported by plasma and wave observations to constrain contribution from currents not related to the subsurface ocean.

JUICE will study the icy shell of Ganymede. It will investigate its structure and physical properties, interaction with the ocean, and the correlation between the surface features and the subsurface. All these objectives require global mapping of the moon by a radar sounder. This has the ability to penetrate the surface and to perform a subsurface 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 surface by imaging spectroscopy in UV to IR range will complement subsurface sounding to correlate near-surface and interior processes. As for the thermo-physical properties of the surface down to a few centimetres, it will be investigated with the Submillimetre sounding instrument using multiple wavelengths with polarization capabilities.

5.1.1.2 Geology

JUICE investigations. For Ganymede the mission 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 cameras covering a broad range of parameters (field of view, spatial resolution) is required. Wide-angle imaging will provide context coverage of the entire surface of Ganymede at 400 m/px. 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 of selected areas. The cameras should have both panchromatic and narrow band channels in the visible and near-IR range to reconstruct colour images of the surface. The ice penetrating radar will provide the third dimension to the geology investigations. Both UV and IR imaging spectroscopy with high spatial resolution (better than 100 m/px 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.

5.1.1.3 Surface Composition

JUICE investigations. The mission will characterise 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 moon to constrain its origin and evolution.

Proposed experimental techniques. Imaging spectroscopy in the broad spectral range from UV to infrared will be the main remote sensing technique of JUICE to study the surface composition. 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. Remote sensing will be complemented by ion and neutral mass-spectrometry and particle/ plasma analysis of the moon's exosphere that originates from sputtering and sublimation of surface material. This technique should allow measuring 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 over a mass range better than 300 Daltons and with mass resolution better than 500. To achieve exospheric profiling during fly-bys a sensitivity of 10^{-14} mbar would be sufficient. ***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. Submillimetre sounding will support spectro-imaging investigations of the physical and thermo-physical 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.

5.1.1.4 Local Environment and Interaction with the Jovian Magnetosphere

JUICE investigations. JUICE will characterise Ganymede's intrinsic and induced magnetic fields 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 characterisation 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 utilised.

The study of tenuous atmospheres requires imaging spectroscopy from UV to IR (0.1 to >5 μm). 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 occultation. This investigation also needs submillimetre observations to characterise the vertical temperature profile from ground up 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.

5.1.2 Europa

5.1.2.1 Surface Composition

JUICE investigations. With two flybys, JUICE will perform high-resolution multi-wavelength 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.

Proposed experimental techniques. Imaging spectroscopy in the broad spectral range from UV to IR will be the main remote sensing technique to study the surface composition. The mission goals require spectral mapping of selected sites with spatial resolution of at least 1 km/px and spectral resolution high enough to resolve characteristic features of non water-ice materials. The imaging spectroscopy will emphasize compositional differences between geologic features (bands, chaos, domes, or ridges) and the surrounding areas. At medium spatial resolution in the range 5-10 km/pixel, it will also map on large areas leading/trailing asymmetries due to contamination by exogenic material. Submillimetre sounding will sound composition of the exosphere and physical and thermo-physical 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. Variations of the (low altitude) exospheric ENA flux around the body can be indices for regions of diverse surface compositions or/and major weathering. Combining ENA detection and imaging spectroscopy in the broad spectral range from UV to IR should provide a more detailed picture of the moon's surface.

5.1.2.2 Subsurface exploration

JUICE investigations. One of the main objectives is to explore for the first time the subsurface in the most recent active regions of Europa to understand the exchange processes from the subsurface to the surface and also to constrain the minimal thickness of the ice shell.

Proposed experimental techniques. Exploration of the icy shell of Europa requires an ***ice penetrating radar sounder*** that could investigate the subsurface down to a few kilometres depth (for an averaged frequency ranging within 5 and 50 MHz) with a vertical resolution of several meters. Proper interpretation of radar sounding data requires high signal-to-noise ratio (SNR) and a very good knowledge of the topography over the explored areas. At closest approaches (below 1000 km), laser altimetry will be used in order to create precise topographic profiles along-tracks with at least 10 m vertical and better than 1 km horizontal resolution. Stereo imaging will be added by using narrow angle imaging targeted over the area of interest during approach and departure phases.

5.1.2.3 Geology

JUICE investigations. The Europa flybys will enable high resolution (few m/px) observations of selected high priority targets and will put them in the global context of distant imaging. These observations will provide a geological context to the high priority composition mapping. They will also 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. Wide-angle imaging will provide context observations of the moons' surfaces at 1 km/px at approach and departure. 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. The cameras should have both panchromatic and narrow band channels in the visible and near-IR range to reconstruct colour images of the surface. The subsurface radar sounding will deliver third dimension to the geology investigations.

5.1.2.4 Local Environment and Interaction with the Jovian Magnetosphere

JUICE investigations. JUICE will detect and characterise the induced magnetic field of Europa and its interaction with the Jovian magnetosphere, and investigate particle population.

Proposed experimental techniques. Characterisation of the magnetic field requires precise measurements of 3 axis magnetic and electric field vectors with high sampling frequency, combined with plasma and wave observations in a broad range of distances to the moon. Measurements of thermal plasma and energetic particles, including neutral imaging of impacting and ejected plasma will also 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. Multi-wavelength spectral imaging of aurorae in the range from 0.1 to at least 5 μm at ~1min temporal resolution and maximum spatial resolution will be utilised. This technique will be also used to study column densities of exospheric species at about 1 km spatial resolution, and will constrain the amount of some specific compounds from limb scans and stellar occultation. Submillimetre observations will characterise the vertical profiles of temperature and water molecules from ground to 300 to 400 km altitude with about 5 km vertical resolution by observations of water lines in the 500-600 μm and 230-270 μm ranges.

5.1.3 Callisto

5.1.3.1 Geology

JUICE investigations. JUICE flybys of Callisto will enable near to global mapping at regional scale, and high resolution [up to a few m/px] observations of selected high priority targets that will be put in the global geological context. These observations will constrain global and regional surface ages, and enable investigation of the processes of erosion and deposition.

Proposed Experimental techniques. Similarly to Europa, a suite of imaging instruments covering a broad range of parameters (field of view, spatial resolution) is required. Wide-angle imaging will provide context observations from a few km/px down to 400 m/px at closest approach. 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 below 1000 km altitude. The cameras should have both panchromatic and narrow band channels in the visible and near-IR range to reconstruct colour images of the surface. The subsurface radar sounding will deliver third dimension to the geology investigations.

5.1.3.2 Surface Composition

JUICE investigations. The mission will characterise the surface composition of Callisto and relate it to geology. The composition observations will have important synergy with surface imaging and subsurface investigations that would provide geological and morphological context.

Proposed experimental techniques. Imaging spectroscopy in the broad spectral range from UV to IR will be the main remote sensing technique to study the surface composition. The Callisto phase being not optimal from the point of view of remote sensing because of the similarity of the flybys (**Figure 7-6**), it will be necessary to achieve off-nadir observations with cameras and spectrometers in the approach/departure phases. JUICE will also allow for very precise determination of the exospheric composition if *in situ* instruments can be used while nadir pointing, because all flybys will be at a 200 km low altitude.

5.1.3.3 Subsurface and interior

JUICE investigations At Callisto, several strategies will be used to investigate the surface and shallow subsurface of the icy crust, the ocean, and also the deep interior. JUICE will perform spectral imaging investigations at regional scale with spatial resolution of 1-30 km/px and study selected targets by means of spectral imaging and *in situ* observations in the closest approach phase. Combining complementary datasets and measurements for the same targeted regions, knowledge will be gained on how internal, subsurface and surface processes are acting together. It will be possible to verify whether Callisto is in a hydrostatic state by measuring the low-order static gravity field, J_2 and C_{22}, independently from each other. JUICE will also improve the determination of the low-order gravity field and the moment of inertia and thus, constrain further the deep interior structure of the moon.

Proposed experimental techniques. Determination of the hydrostatic state of the moon, and study of the deep structure, will require Doppler tracking at an equatorial and a highly inclined flyby. The latter was not possible with Galileo. This will be done by 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.

Subsurface exploration will permit to look for water reservoirs, to study the dynamical processes leading to the crater morphologies, and to investigate the relaxation processes. It requires an ice penetrating radar sounder that could investigate the subsurface down to a few kilometres depth (for an averaged frequency ranging within 5 and 50 MHz) coupled with laser altimetry and stereo imaging to measure the topography (see section 5.1.2.2).

The magnetic induction response from the ocean will be characterised by precise measurements of 3 axis magnetic and electric field vectors with high sampling frequency, combined with plasma and wave observations in a broad range of distances to the moon.

The global shape of Callisto will be studied from limb imaging and laser altimeter profiles.

5.1.4 Requirements to the Mission

On Ganymede, JUICE objectives described in section 5.1.1 will be fulfilled during the dedicated phases around the moon (Table **5-1**). The objectives indicated in section 5.1.2 and 5.1.3 will be achieved during the 2 flybys of Europa and 12 flybys of Callisto, respectively. The observation techniques impose certain requirements, which are discussed below. These constraints have been taken into account for defining the best observation strategies.

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

Pointing accuracy: High-resolution imaging is incompatible with yaw steering and would require suspending of yaw-steering above selected targets when JUICE is in medium (500 km) and low (200 km) circular orbits around Ganymede.

Orbits: Laser altimetry and subsurface radar investigations can effectively sound the moons' surfaces from an altitude ≤ 1000 km. In addition, the study of tidal deformation of Ganymede 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 the spacecraft should be able to perform stellar occultation measurements.

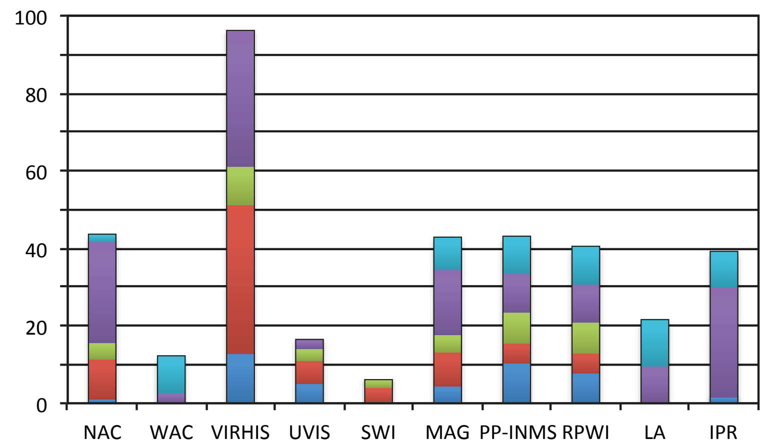


Figure 5-1. *Example of data volume production (in Gb) by the model instruments [D-1] during the baseline Ganymede mission, and assuming D/L capabilities of 1.4 Gb/day. On each bar, the colours indicate the data volume per phase from bottom (phase 6) to top (phase 10). Circular phases at 5000, 500, and 200 km altitude are shown in red, purple, and light blue at the top of each bar, respectively.*

Downlink capabilities: The JUICE baseline scenario uses a conservative approach with a minimum averaged downlink of 1.4 Gb/day. This would be the absolute minimum to fulfil the science goals at Ganymede as long as a shortening of the Ganymede phase is not required to cope with resource constraints (**Figure 5-1**). The SST has demonstrated that this conservative approach will fulfil the science objectives, but the team strongly recommends further studies for ensuring that higher downlink capabilities could be provided.

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 which require a spacecraft field level at the outer magnetometer sensor of DC <0.2 nT, and AC <0.1 nT for <64 Hz.

5.2 The Jupiter System

5.2.1 The Jovian Atmosphere

JUICE investigations. JUICE will characterise the atmospheric dynamics and circulation of Jupiter, study the chemistry of the atmosphere, and explore the atmospheric vertical structure of the giant planet. JUICE will benefit from a broad spectral coverage from advanced instrumentation, a robust orbital tour with access to a wide range of latitudes and phase angles, and large data volume capacity.

Baseline experimental techniques. JUICE will address these scientific questions using a combination of remote sensing techniques traditionally used in planetary physics: imaging, spectroscopy, and radio-occultations. Jupiter science will benefit from the unique combination of advanced instrumentation covering a broad spectral range (from the UV to the radio) with the long temporal baseline and orbital geometries offered by the proposed Jupiter tour. In particular, the high latitude phase will permit the first detailed characterisation of Jupiter's poles, providing the capabilities for broad spatial, spectral and temporal coverage. JUICE will give a different and complementary approach to Juno because of its broad spectral range, its emphasis on global mapping, the long temporal baseline offering the opportunity to study spatial/temporal variability, and the even dayside and nightside coverage.

The study of the cloud morphology and atmospheric dynamics requires systematic and regular imaging of Jupiter in the UV, visible, and near-infrared range with few tens of km spatial resolution and repetition time from days to years in order to characterise variable phenomena like storms, waves, eddies etc. and reconstruct wind field (both horizontally and vertically) from the tracking of cloud features. Spectral imaging from the UV to the near-IR with a 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 tracers of Jupiter's circulation. Reflected sunlight observations at a wide range of phase angles will be used to reconstruct the vertical distribution, optical properties and composition of Jupiter's condensation clouds. Observations in the ultraviolet will be used to study auroral emissions and upper atmospheric hazes. Submillimetre spectroscopy thanks to very high resolution ($\lambda/\delta\lambda \sim 10^6$) will provide vertical profiling and spatial mapping 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 for the first time. Radio-occultation – an ideal technique to sound the tropospheric and stratospheric temperature structure – will be used to study wave activity in the neutral atmosphere and the electron/ion density structure of the upper atmosphere. Stellar occultations will complement these studies by sounding stratospheric composition and the distribution of high altitude hazes, particularly at high Jovian latitudes.

5.2.2 The Jovian Magnetosphere

JUICE investigations. JUICE 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 characterise the global and continuous acceleration of particles (particle characterisation, study of the loss processes, dynamics of electron synchrotron emissions).

Baseline experimental techniques. The experimental techniques required to achieve the task are quite similar to those proposed for the study of the magnetosphere of Ganymede (sections 5.1.1.1 and 5.1.1.4). The goal requires measurements of 3 axis magnetic and electric field vectors with moderate sampling frequency. Measurements of thermal plasma and energetic particles will characterise 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. Jupiter is an enormous source of electromagnetic radiation located in the Io-torus and in the auroral high latitude regions. Some of those emissions are generated by file-aligned particles originating and accelerated deep in the magnetotail, travelling along field lines into the polar regions close to the planet. Especially during the high-latitude Callisto phase JUICE will be able to "image" the auroral region remotely and measure directly the source region of the decametric radiation where a spacecraft orbit inclination of about 30 degrees is required.

5.2.3 Satellites and Ring Systems

JUICE will explore remotely Io, the rings, and small satellites. The study of these other bodies of the Jovian system will strongly complement the investigations of Ganymede, Europa and Callisto and will complete the survey of the Jovian system. Experimental techniques for the other moons and rings are similar to those described in section 5.1 with the difference that they will be applied remotely, resulting in that their investigations will not be as detailed as surveys of Ganymede, Europa, and Callisto.

5.2.4 Requirements to the Mission

The most stringent requirements imposed by the measurements have been identified during the phases dedicated to the observations of the moons (section 5.1.4). No additional requirements have been identified for the exploration of the system.

5.3 Baseline Science Scenario

In this section, a high level description of the JUICE science activities is provided. It is focused on the science targets and priorities of each of the mission phases. The JUICE science scenario is divided in 10 phases summarised in **Table 5-1**. They are also described in section 7 from the point of view of mission analysis.

	Phase	**Start**	**End**	**Duration**	**Science priorities**
1	Cruise/ Interplanetary transfer	06.2022	01.2030	7.6 years	
	Jupiter Tour				
2	Jupiter equatorial phase #1/ Transfer to Callisto	01.2030	12.2030	11 mon	Jovian atmosphere structure, composition, and dynamics. Jovian magnetosphere as a fast magnetic rotator and giant accelerator. Remote observations of the inner Jovian system.
3	Europa flybys	12.2030	01.2031	36 days	Composition of selected targets with emphasis on non-ice components Geology and subsurface of the most active areas Local plasma environment
4	Reduction of V_{inf} /	01.2031	10.2031	260 d	Jupiter atmosphere at high latitudes

	Jupiter high latitude phase with Callisto				Plasma and fields out off equatorial plane Callisto internal structure, surface and exosphere. Remote observations of Ganymede, Europa, Io, and small moons.
5	Jupiter equatorial phase #2/ Transfer to Ganymede	10.2031	09.2032	11 mon	Interactions of the Ganymede magnetic field with that of Jupiter. Jovian atmosphere and magnetosphere as in phase #2
	Ganymede Tour				
6	Elliptic #1	09.2032	10.2032	30 d	Global geological mapping Search for past and present activity Global compositional mapping Local plasma environment and its interactions with Jovian magnetosphere
7	High altitude (5000 km) circular	10.2032	01.2033	90 d	
8	Elliptic #2	01.2033	02.2033	30 d	
9	Medium altitude (500 km) circular orbit	02.2033	05.2033	102 d	Extent of the ocean and its relation to the deep interior Ice shell structure including distribution of subsurface water Geology, composition and evolution of selected targets with very high resolution Global topography Local plasma environment Sinks and sources of the ionosphere and exosphere Deep interior
10	Low altitude (200 km) circular orbit	05.2033	06.2033	30 d	

Table 5-1. *Science phases of the JUICE baseline mission*

5.3.1 Jupiter Tour

5.3.1.1 Description of the tour

After the Jupiter orbit insertion (JOI) in January 2030 (**Figure 5-2**) the JUICE spacecraft will stay for about one year in elliptic orbit around Jupiter outside the Ganymede orbit and thus radiation belts. The orbit will allow detailed investigations of the inner magnetosphere of the giant planet. This phase will be also focused on monitoring of the Jupiter atmosphere and coupling processes. Seven flybys of Ganymede would begin investigation of the moon and in particular interaction of the Jovian magnetosphere with that of Ganymede.

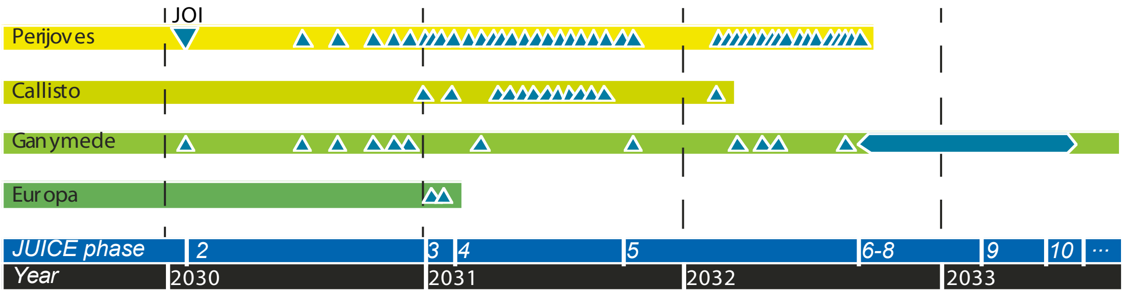


Figure 5-2. *Illustrative timeline of the JUICE baseline mission*

In December 2030 the spacecraft will arrive at Callisto and will use gravity assists at the moon to perform two flybys of Europa (**Figure 5-3**; section 7.2.3). The investigations will be focused on the composition of the non water-ice material, organic chemistry, and the first subsurface observations of an icy moon, including the first determination of the minimal thickness of the icy crust over the most active regions.

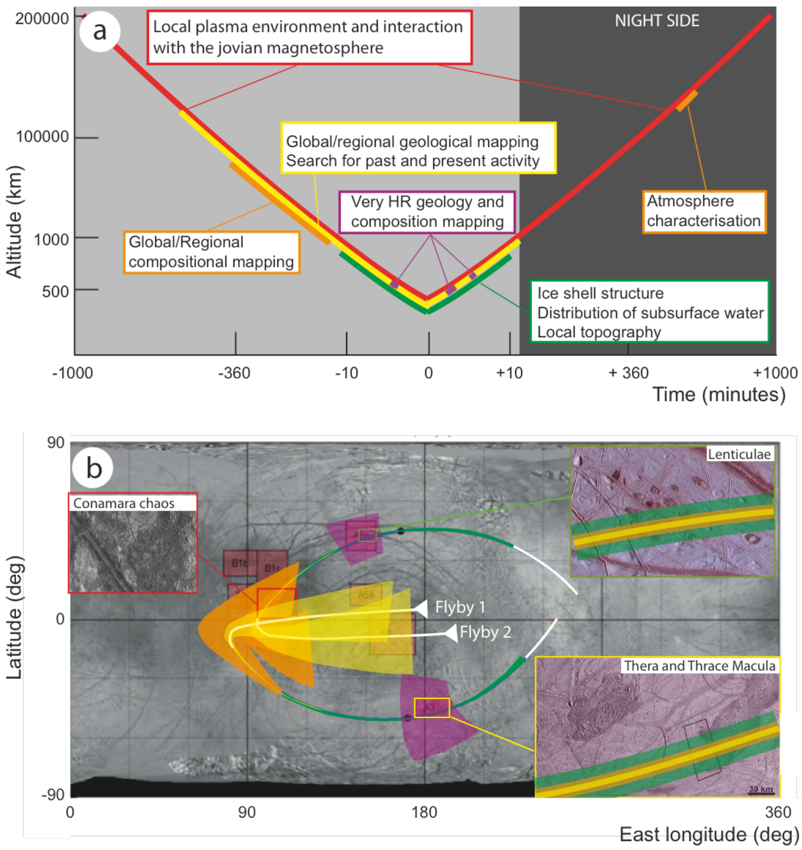


Figure 5-3. *Europa flybys. a) Possible strategy of observations during the two flybys. Timeline is constrained by the total amount of data which can be stored in the S/C, the instruments capabilities, and also the illumination conditions. Both scales are qualitative. b) Field of view of some instruments during the two flybys for mapping at regional and local scales: yellow (narrow angle camera), orange (IR spectro imager), green (ice penetrating radar), purple (wide angle camera). The field of view of the instruments for local studies close to pericentre are indicated at the bottom right. Global mapping at high altitudes during approach and departure is not shown for clarity. Red boxes indicate the location of areas with very high potential for geology, chemistry, and astrobiology.*

The subsequent 10 flybys of Callisto will be used to raise the orbit inclination to ~30 degrees and bring it back to the equatorial plane (section 7.2.4). Orbital inclinations approaching 30 degrees will enhance the investigation of the Jovian atmosphere due to an improved polar visibility (**Figure 5-4**). This will result in a better investigation of the atmospheric dynamics, chemistry and energy balance at polar latitudes, a better understanding of magnetosphere-atmosphere coupling, as well as a more detailed study of atmospheric properties in both hemispheres with radio science. Similarly, Jovian magnetosphere science will be enhanced since it will allow the first prolonged studies of this region of the magnetosphere, as well as providing a long temporal baseline study of the Jovian aurorae. In addition, it will provide detailed analysis of the

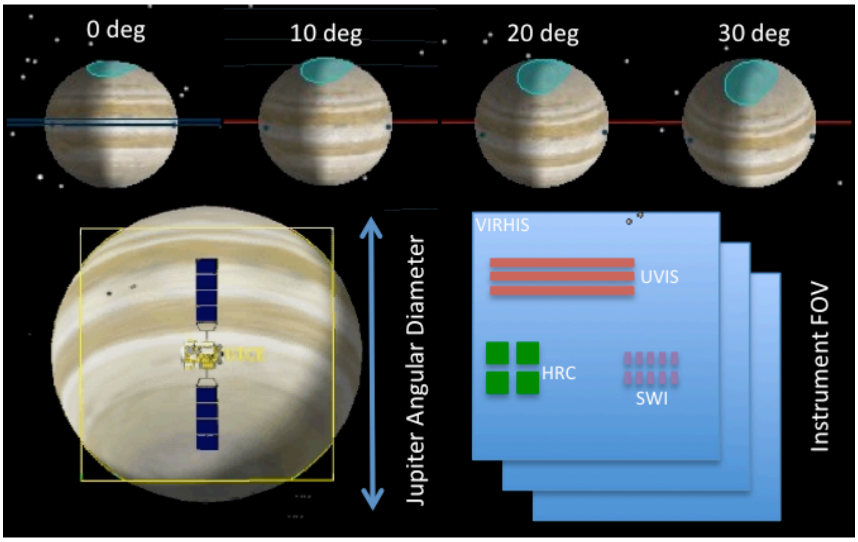


Figure 5-4*. High orbital inclinations of up to 30 degrees will allow JUICE to perform a detailed characterisation of Jupiter's polar atmosphere and aurorae, reaching vantage points that are impossible for Earth-based observers. The four figures at the top of this figure show the appearance of Jupiter at inclinations of 0, 10, 20 and 30 degrees. The images at the bottom show Jupiter at 30 degrees inclination, compared to the fields of view (FOVs) of the remote sensing instruments from a distance of 28.9 RJ, when Jupiter subtends approximately 4 degrees. VIRHIS is shown in blue, three UVIS arrays in red, four HRC FOVs in green, and 10 SWI FOVs in purple. (Credit to Nigel Bannister (University of Leicester) for STK images).*

field lines and field-aligned current systems well poleward of the main oval. And finally, it will give access to the high latitude radio sources in the Jovian magnetosphere.

JUICE will investigate the internal structure, surface and exosphere of Callisto during the flybys. 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 11 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 its icy moons.

5.3.2 Ganymede Tour

In September 2032 JUICE will be inserted in orbit around Ganymede. The mission at Ganymede consists of five phases designed to avoid eclipses, except in the beginning when short eclipses do not impose significant demand on the spacecraft power system (**Figure 5-5**). Science priorities are optimally distributed between the mission phases. At the beginning of the Ganymede mission the remote sensing instruments will perform global mapping and spectral-imaging of the surface at optimal illumination conditions. In the medium and low circular phases the priority will be given to the geophysical, exospheric and plasma investigations, that require to be as close to the moon as possible.

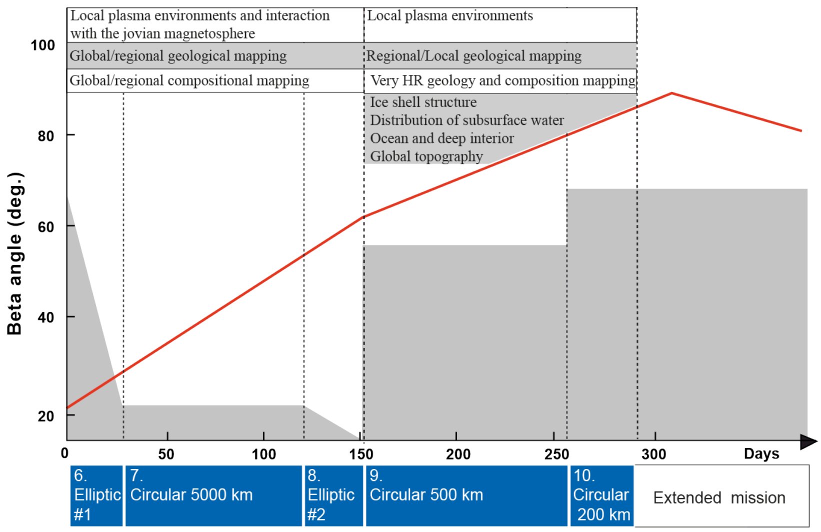


Figure 5-5. *Sketch of the baseline scenario of the Ganymede mission. Red line shows the evolution of the β-angle with mission time. Coloured rectangles display the top priority investigations on each phase. Grey areas mark solar eclipses.*

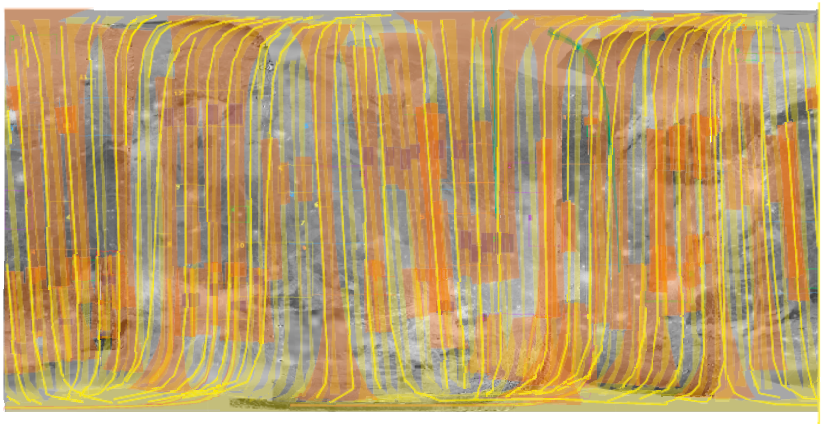


Figure 5-6*. MAPPS simulation of JUICE surface coverage in the IR (orange), visible (yellow), UV (purple), and the penetrating radar (Green) after phase 8 (before circularisation at 500 km). Hyperspectral imaging at 2-3 km/px will obtained over more than 50 % of Ganymede's surface. Imaging of the entire surface at 20, and 10 km/px will be achieved with the wide angle camera (not shown), together with several hundreds of very high resolution panchromatic images.*

The Ganymede mission will start with a highly elliptical orbit around the moon with period of ~12 hours, inclination of ~86°, and Sun declination (β-angle) of ~25° (**Figure 5-5**). (β is defined as the angle between the JUICE orbital plane and Ganymede-Sun vector.) The two elliptic and high (5000 km) circular phases will provide global imaging and spectro-imaging to study geology and surface composition taking advantage of good illumination conditions (low β-angle in **Figure 5-5**). **Figure 5-6** shows an example of surface coverage by remote sensing instruments in this period. During the high-altitude and the two elliptic phases JUICE will complete the surface imaging at 10 km/px resolution, and will perform high-resolution panchromatic and colour imaging of 16% of the surface at few hundred m/px resolution. More than 50% of the surface will be investigated by spectral-imaging at a spatial resolution comprised between 2 and 3 km/px (**Figure 5-7**).

Highly elliptic orbits (200x10000 km) in the beginning and the end of this period would enable investigation of the Ganymede plasma environment and its interaction with the Jovian magnetosphere. Closest approaches to the moon (few hundred kilometres) at pericentre would be used to test subsurface radar sounding.

In February 2033 the spacecraft will be transferred to the medium altitude (500 km) circular orbit at β ~ 62° that would still keep the spacecraft out of eclipses (**Figures 5-5 and 7-7**). JUICE will perform full mapping of the moon at 1 km/px using wide angle imaging, together with high-resolution imaging (<10 m/px) and spectro-imaging (~100 m/px) of selected targets. Routine topography study by laser altimeter and subsurface sounding by radar will begin in this phase. Plasma and fields investigations close to the moon will also be conducted in order to decipher the complex combination of the fields (Jovian, intrinsic, induced fields).

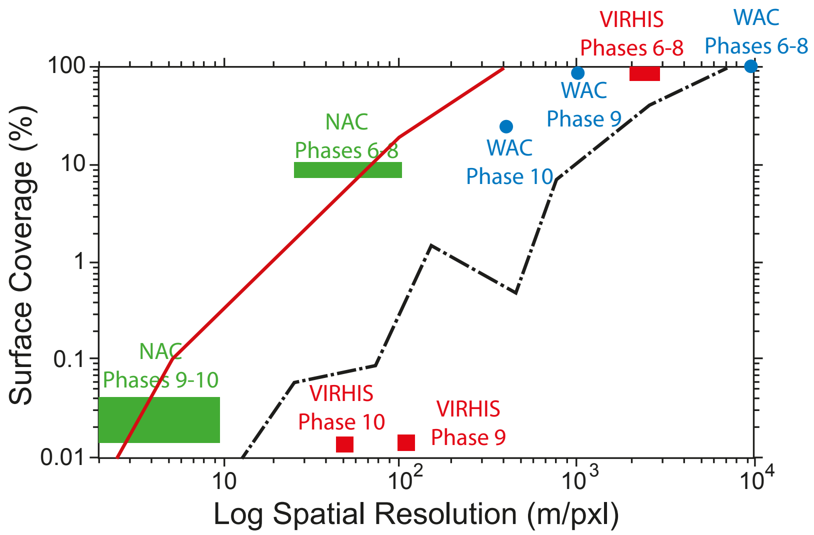


Figure 5-7. *Imaging coverage as a function of resolution as expected for JUICE (red) in comparison to the Galileo SSI results (black) for Ganymede. Green rectangles show the NAC resolution and coverage, blue dots indicate WAC and red squares indicate VIRHIS for different phases (see table 5-1).*

In May 2033 the JUICE spacecraft will be transferred to the 200 km orbit. In this phase the orbit is close to terminator (β ~80º) that allows avoiding eclipses at low altitude (**Figure 5-5**). The remainder of the nominal mission will be mainly devoted to the geophysical observations (laser altimetry, gravity, subsurface radar). The surface will be covered with density of 1 orbit per 10 km. This phase is also essential for exospheric and plasma and fields investigations. Despite of marginal illumination conditions the low orbit would allow the best resolution imaging: full surface coverage with 400 m/px and selected targets with few m/px resolution.

The nominal mission of JUICE will end in June 2033. If the spacecraft health and resources allow, there is a possibility of extending the mission by keeping the 200 km circular orbit. After reaching the terminator, the β-angle will start decreasing (**Figure 5-5**). The investigations started in the 200 km circular phase can be continued in the extended mission. About 480 days after the Ganymede orbit insertion (~200 days after passing the terminator orbit) the β-angle decreases to ~67º so that the spacecraft will start entering eclipses. Progressing further in the extended mission would enable plasma and fields investigations in eclipse and resume imaging and spectro-imaging on the day side, although the spacecraft power budget is expected to be rather limited during eclipse periods. At the end of the mission there may be an opportunity for JUICE to probe lower altitudes after orbit maintenance is stopped and the spacecraft will spiral down to impact on the surface of Ganymede.

6 JUICE Model Payload

In the re-formulation phase the Science Study Team (SST) confirmed that the model payload selected for original JGO/EJSM-Laplace mission satisfies the JUICE goals. Therefore the JUICE model payload is identical to the one of its predecessor except for the radio science receiver for inter-spacecraft communication that was removed. The model payload was chosen by the SST to address the mission science objectives (section 4) and to fulfil measurement requirements (section 5). It was used to identify key drivers 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 this is a nominal payload. The model instruments were used to show proof of concept only, and should not be considered as final selections.

The performance under the harsh Jovian radiation environment and particularly that at Europa is a challenge for the JUICE instruments. The instantaneous background flux due to the particle radiation environment is at a detector of the order of up to 10^6 cm^{-2} sr^{-1} s^{-1} (cf. **Figure 7-13**) behind a typical shielding of about 10 – 15 mm. This background needs to be taken into account for sensitivity estimates. This higher background may have a significant impact on SNR of certain detectors including micro-channel plates (MCP), CCDs and particle detectors. Furthermore, the sensitive parts and electronics need to be shielded to reduce the effects of the total ionizing dose (TID), which is equivalent to 240 krad inside a 10 mm Al sphere (cf. **Figure 7-12**). Detailed radiation transport simulations need to be performed and the shielding is optimised for reducing the TID in a mass efficient way. A number of mitigation measures in instrument designs, shielding of critical elements, and using radiation hardened parts, which are especially important for those proposed instruments directly exposed to space, are possible. Particular measures together with possible changes in the instruments performance will be discussed in relevant sub-sections below.

To enable the instruments being defined at the same level as the other mission elements (platform, launch services, etc.), assessment-level studies for the instrumentation have been carried out by Instrument Study Teams (DOI, or Declaration of Interest, studies). During the reformulation phase the Instrument Study Teams studied the impacts of the Europa environment on their instrument design and performance.

The overall conclusion regarding recent inclusion of the Europa phase in the mission is that the current model payload will be able to fulfil the science requirements with some increase in shielding mass, its optimization and use of radiation hardened components to cope with the harsher radiation environment.

The instrumental studies ran in parallel with the mission industrial studies. Feedback on the model payload related issues was provided by the 3 contractors (section 7), and allowed the improvement of the model payload definition, to define preliminary instrument-to-spacecraft interfaces, and to identify the resources requirements for the payload.

6.1 Model Payload Definition

The model payload consists of 11 instruments with total mass of ~104 kg excluding 20% system margin and shielding, for which mass was estimated separately. **Table 6-1** summarises the principal science goals and characteristics of the model payload.

Model instrument	Science Contribution	Characteristics
Laser Altimeter	Tidal deformation of Ganymede; Morphology of moons surface features	Single Beam @ 1064 nm 20 m spot @ 200 km 20 to 90 Hz pulse rate
Radio Science Experiment	Interior state of Ganymede, presence of a deep ocean and other gravity anomalies. Ganymede and Callisto surface properties. Atmospheric science at Jupiter, Ganymede, Europa and Callisto, and Jupiter rings.	2-way Doppler and ranging with Ka-band transponder 1-way Doppler at X-and Ka-band with Ultra-stable Oscillator
Ice Penetrating Radar	Structure of the Ganymede, Europa and Callisto subsurface; identify warm ice water "pockets" and structure within the ice shell; search for ice/water interface.	Single frequency: 20-50 MHz Dipole antenna: 10 m
Visible-IR Hyperspectral Imaging Spectrometer	Composition of non water-ice components on Ganymede, Europa and Callisto; State & crystalinity of water ice. On Jupiter: tracking of tropospheric cloud features, characterisation of minor species, aerosol properties, 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°
UltraViolet Imaging Spectrometer	Composition & dynamics of the atmospheres of Ganymede, Europa, and Callisto	EUV and FUV+MUV grating spectrometers λ= 50-320 nm IFOV: 0.01 mrad FOV: 2°
Narrow Angle Camera	Local-scale geologic processes on Ganymede, Europa, and Callisto; Io Torus imaging, Jupiter cloud dynamics & structure	Pushbroom imaging in orbit around Ganymede; framing imager for distant targets. Colour and multispectral imaging capability with filter wheels (12 colours); 1024 *1024 sensor FOV: 0.30°. Pixel IFOV: 0.005 mrad
Wide Angle Camera	Global morphology of the Ganymede surface. Global to regional scale morphology of the Callisto and Europa surface	12 filters Framing, 1024 *1024 sensor IFOV: 2 mrad FOV: 117 deg
Magnetometer	Ganymede's intrinsic magnetic field and its interaction with the Jovian field. Induced magnetic field as evidence for subsurface ocean on Ganymede, Europa and Callisto.	Dual tri-axial fluxgate sensors; boom length to meet magnetic cleanliness 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.
Particle Package	Jovian magnetosphere. Interaction between Jovian magnetosphere and Ganymede, Europa and Callisto. Exospheres and ionospheres of the moons.	***Plasma Analyser*** Electrons: 1 eV– 20 keV Ions: 1 eV – 20 keV ***Energetic Particle Analyser*** Electrons: 15keV-1MeV; Ions: 3 keV - 5 MeV, ENA: 10 eV – 10 keV ***Ion Neutral Mass Spectrometer*** Mass range: 1-300 amu M/dM >1000 Sensitivity: 10^{-14} mbar @ 5s measurement
Submillimetre Wave Instrument	Dynamics of Jupiter's stratosphere; Vertical profiles of wind speed and temperature Composition and structure of exospheres of Ganymede, Europa and Callisto.	2 channels λ= 550-230 μm FoV: 0.15° – 0.065°
Radio and Plasma Wave Instrument	Ganymede: Exosphere and magnetosphere; Callisto & Europa: Induced magnetic field and plasma environment; 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

***Table 6-1**. Main characteristics of the JUICE model payload*

6.2 Model Instruments

The definition of the model instruments was done by the SST and put forward prior to the start of the JGO/ EJSM-Laplace industrial study phase. The JUICE model payload consists of 11 instruments which characteristics are summarised in **Table 6-1**. Instrumental DoI studies that ran in parallel with industrial activities demonstrated sufficient maturity of this model payload.

6.2.1 Narrow Angle Camera (NAC)

Science goals and measurements. The Narrow Angle Camera (NAC) 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 altitude at Ganymede will make a breakthrough in our understanding of the 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:

- Detailed characterisation 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 rings

***Table 6-2**. Baseline NAC properties*

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

NAC will provide context imaging which is vitally important for the other experiments. Several goals will be achieved in synergy with other JUICE model instruments 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 medium and low circular phases 9, 10 (**Table 5-1**) 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 summarised in **Table 6-2**.

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 currently baselined for the NAC. An alternative solution could be a CCD detector with 2048x2048 px and smaller pixel size (Bepi Colombo heritage) or a customised detector for JUICE. 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 motorised 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 is a representative instrument, providing heritage for NAC (Credit: MPS, DLR)*

Orbit, operations, pointing and other mission requirements. The NAC will operate during the Jovian tour, icy moons 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 mosaicking. 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 (time delayed integration) 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 line of sight in combination with the spatial resolution (i.e. spacecraft height above real ground, not above the reference ellipsoid). Most appropriate would be to obtain real-time information by the spacecraft concerning time, velocity and height. Alternatively 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 the Ganymede circular phases. 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 requires the scan line to be perpendicular to the flight direction that precludes using the "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 up to 400 m/px resolution; Context imaging of Europa and Callisto surfaces with up to 1 km/ 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 rings

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

Performance requirements. The WAC goals and required performance in the Ganymede circular orbital phases 9, 10 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 the baseline WAC performance requirements.

Table 6-3. *Baseline WAC properties*

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	CMOS Star1000
Lines*Arrays	1024*1024
Pixel size, µm	15
Exposure time, msec	1-2000

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. The basic concept of the instrument is very similar to that of NAC with the difference being the optics which 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 a representative instrument, providing heritage for WAC. Other heritage instruments include VMC on Venus Express, OSIRIS on Rosetta and FC on Dawn.

Orbit, operations, pointing and other mission requirements. The WAC will operate during the Jovian tour, icy moons 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 optimal signal-to-noise requires that exposure time exceeds dwell time (minimal time to avoid image smearing). The 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 phases. 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 the scan line to be perpendicular to the flight direction that precludes using of the "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.

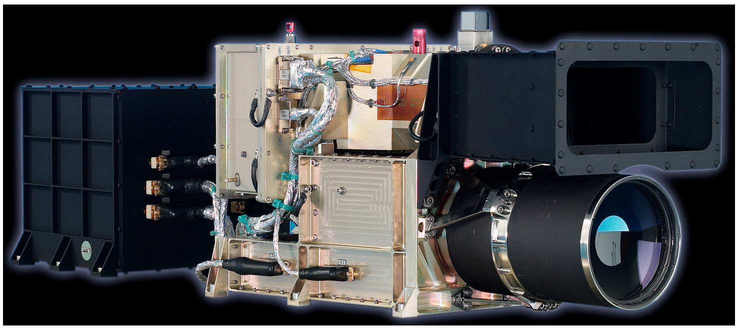


Figure 6-2*. HRSC - SRC/Mars Express camera is a representative instrument , providing heritage for WAC (Credit: DLR, INAF)*

6.2.3 Visible InfraRed Hyperspectral Imaging Spectrometer (VIRHIS)

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

- Characterisation of the composition, physical properties, geology and history of the Ganymede, Europa and Callisto surfaces with emphasis on the 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-local-thermodynamical-equilibrium emissions on Jupiter and its moons
- Composition and physical properties of the small moons and dust

Several goals will be achieved in synergy with the other model instruments, in particular with cameras, UV imaging spectrometer, ice penetrating radar sounder, Submillimetre instrument and radio science.

Table 6-4. Baseline VIRHIS properties

Parameter	**Value**
Type of instrument	Imaging spectrometer
Optics	
Spectral range, μm	0.4-5.2 (5.7 tbd)
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, ºC	< -173

Performance requirements. The VIRHIS goals and required performance at Ganymede 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 current baseline VIRHIS performance requirements are shown in **Table 6-4**.

Possible instrument concept. VIRHIS is an innovative and highly capable imaging spectrometer operating from visible to 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 optimised for Vis-NIR and IR spectral ranges. Thus, an instantaneous acquisition in each focal plane consists of a spectral image of the 1-D entrance slit. The second spatial dimension is created by a scanning mirror inside the telescope or by using the spacecraft motion (pushbroom mode). **Figure 6-3** shows the optical module of the VIRTIS / Venus Express, one of the heritage instruments for VIRHIS.

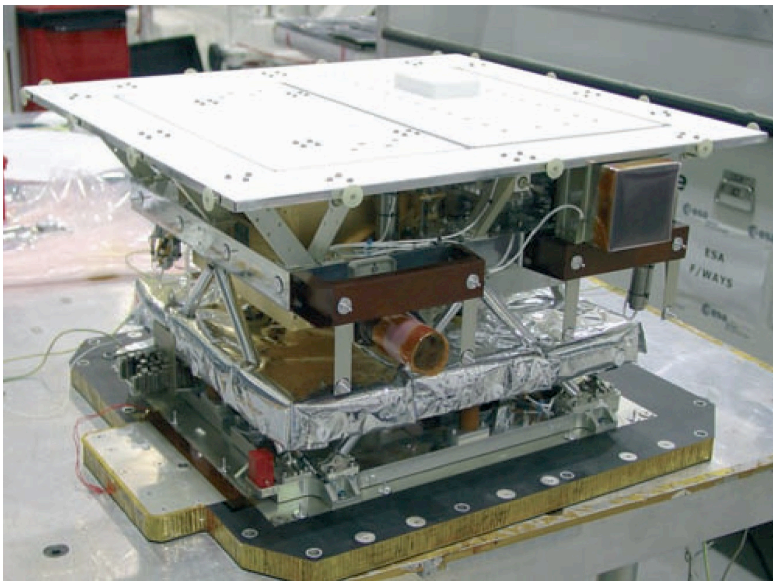


Figure 6-3. The optical module of the VIRTIS/Venus Express is a representative instrument, providing heritage for VIRHIS (Credit: INAF, LESIA)

Orbit, operations, pointing and other mission requirements. VIRHIS will operate during the Jovian tour, icy moons 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. The observation strategy will include both nearly global mapping of the Ganymede surface from the 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 the 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 (<100 K). If passive cooling by radiator is not sufficient, the use of an active cooler may be necessary with mass and power penalties of 1.3 kg and 12.6 W. This would also require extra time before the start of the observations, implying a higher complexity of 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, Europa, Callisto 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 monitoring of 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 tori. 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, Europa 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 data from 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 current baseline UVIS performance requirements are summarised in **Table 6-5**.

Table 6-5. *Baseline UVIS properties*

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 (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 spacecraft 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 an 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 spacecraft. **Figure 6-4** shows structural and thermal model of the Phebus/BepiColombo UV spectrometer as a representative heritage instrument for UVIS. To cope with the radiation environment at Europa a reflective design instead of using MCP is possible in UVIS to reduce the effect of the electron background.

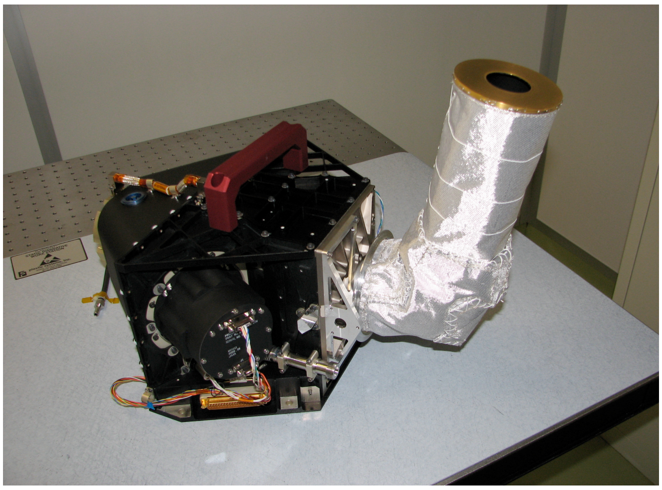


***Figure 6-4**. Structure thermal model of the Phebus/Bepi Colombo is a representative instrument, providing heritage for UVIS (Credit LATMOS)*

Orbit, operations, pointing and other mission requirements. UVIS will operate during the Jovian tour, icy moons flybys, and in orbit around Ganymede. The pointing prediction shall be sufficiently accurate to point the instrument at selected targets. The camera should ideally have a common viewing direction with 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.

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 Submillimetre Wave Instrument (SWI)

Science goals and measurements. The main objective of a submillimetre 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 in the Jupiter system will provide pioneering direct measurements of wind speeds in the middle atmosphere of the giant planet and high-sensitivity composition measurements. The main measurements expected from SWI are as follows:

***Table 6-6.** Baseline SWI properties*

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

- Characterisation 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 thermophysical properties of the surfaces of the Jovian moons

SWI will have strong synergy with VIRHIS and PP experiments.

Performance requirements. The SWI objectives on 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 the 600 and 1200 GHz bands (**Figure 6-5**). The front ends include feed horns, sub-harmonic mixers, low noise amplifiers and the submillimetre 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 an instrument specific radiator. The two electronic units are placed inside the S/C vault and are 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.

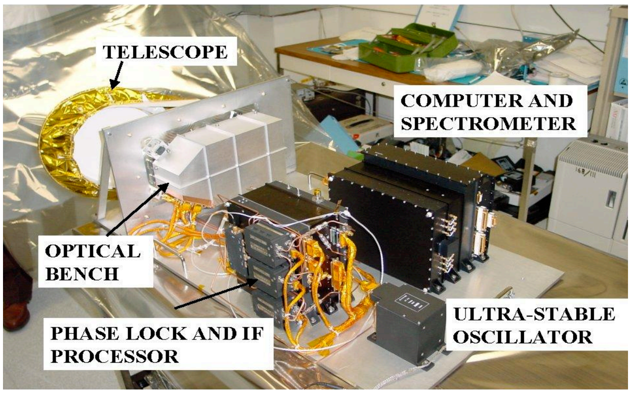


***Figure 6-5**. The flight model of the MIRO/ Rosetta is a representative instrument, providing heritage for SWI (Credit: JPL, MPS)*

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

6.2.6 Laser Altimeter (LA)

Science goals and measurements. A Laser Altimeter (LA) will contribute to the characterisation 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.

LA will provide topographic measurements which will be extremely important for the other experiments related to the geophysical and geo-morphological characterisation of the moons. Several goals will be achieved which are complementary with the other model instruments in particular with the Radio science instrument, and the two cameras WAC and NAC and the subsurface radar.

Performance requirements. The LA goals and required performance in the Ganymede medium and low circular phases 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, slopes and albedo measurements during the sequence of observation at very high resolution of the targeted areas. The baseline LA performance requirements are shown in **Table 6-7**.

Table 6-7. *Baseline LA properties*

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

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 footprint 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.

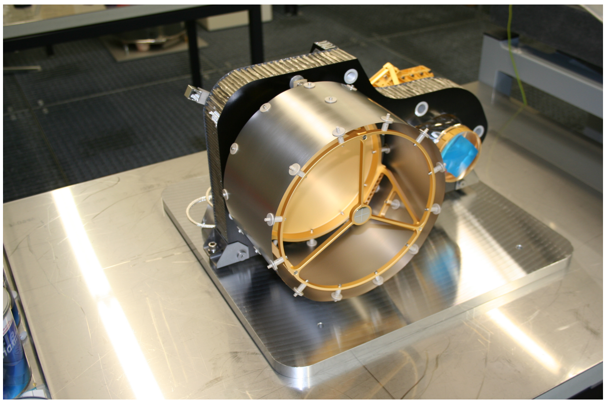


Figure 6-6 *Structural and Thermal Model (STM) of the BepiColombo laser altimeter BeLa is a representative instrument, providing heritage for the LA (Credit: BeLa Team UBE/DLR/MPS).*

- 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 the 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 particle background 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 an 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 / BepiColombo instrument provides the heritage for the LA instrument and is shown in **Figure 6-6**.

Orbit, operations, pointing and other mission requirements. The instrument will operate during the spacecraft orbital phase around Ganymede and at flybys of Ganymede, Europa and Callisto whenever the distance is small enough to detect the reflected signal (< 500 km at Ganymede and Europa, and < 300 km at Callisto because of the lower albedo). With single photon counting higher ranges could be possible. To obtain the dynamical tides (variation of the tidal deformation of the satellite along its orbit around Jupiter) measurements at the 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. Night-time 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. The global shape of the moons should be acquired at a moderate pulse repetition rate with a 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 full data rate in order to provide additional measurements of albedo, slopes, and roughness of the areas.

The instrument should also be capable of 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.

6.2.7 Ice Penetrating Radar (IPR)

Science goals and measurements. The study of the subsurface of Ganymede, Europa and Callisto with a radar sounder instrument will bring new data on 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 characterisation 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 characterise subsurface horizons by obtaining sounding profiles of subsurface down to a few kilometres at relatively high vertical resolution (in the order of 10 m in free space). Several goals will be achieved in a complementary fashion with the other model instruments, in particular with the laser altimeter.

Table 6-8. *Baseline IPR properties*

Parameter	Value
Type of instrument	Radar sounder
Transmitted central frequency	In the range 5 – 50 MHz
Transmitted bandwidth	10 MHz
Along-track resolution	1 km
Cross-track resolution	< 5 km
Penetration depth	Between 3 km to 9 km
Vertical resolution, m	From 10 m to 1 % of the target depth

Performance requirements. The Ice Penetrating Radar (IPR) is a radar sounder system at low frequency. A single frequency sounder will be appropriate for JUICE because it provides 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 of penetrating the surface and performing a subsurface analysis with a penetration ability of a few kilometers (depending on the selected central frequency of the pulse) with a vertical resolution of several 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 5 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 summarised in **Table 6-8**. The decrease of the lower frequency to 5 MHz would enable deeper penetration into the Europan ice, and will not have impact the science return at Ganymede.

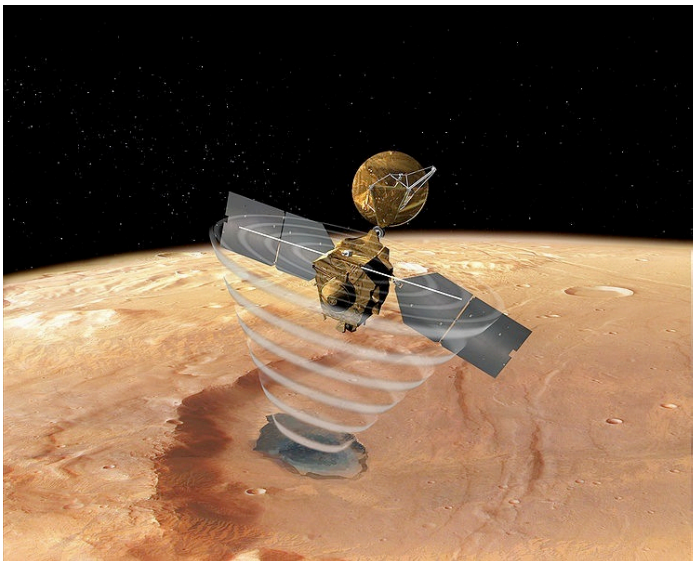


Figure 6-7. *Pictorial view of Mars Reconnaissance Orbiter using SHARAD radar at Mars (Credit: NASA/JPL)*

Possible instrument concept. The instrument has an architecture similar to the radar sounders of MARSIS/ Mars Express and SHARAD/ MRO (**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 characterisation of the Jupiter noise and by modeling of the Ganymede surface and subsurface. The length of the antenna could be reduced by increasing the central frequency (e.g. at 50 MHz the length would be ~4 m.

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.

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 the measurements. Concerning yaw, a deviation from parallel to the ground should be less than 1°. It is also important to have a small roll (<10°) in order to have the maximum antenna beam pattern size at nadir.

The IPR instrument will not operate continuously due to downlink limitations. The best option for the reduction of the clutter in radar measurements is to have the antenna in the cross-track direction (perpendicular to the flight direction). However, this might result in 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 degraded spatial resolution. 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 subsurface oceans at Ganymede, Europa 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 consist 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; characterise 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 model 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 properties*

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: ± 128 nT @ 4pT resolution ± 65536 nT @ 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.

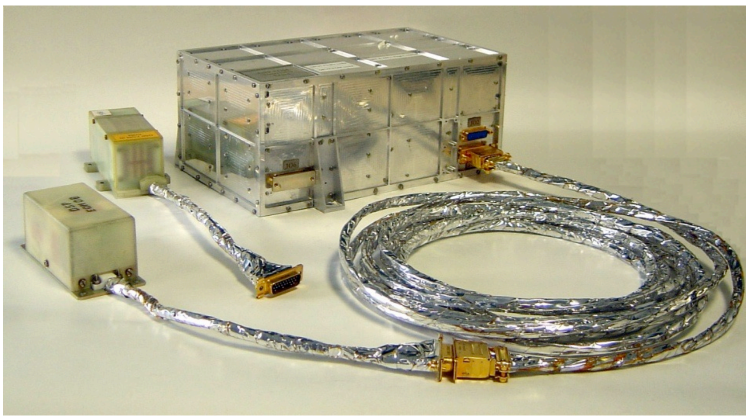


Figure 6-8*. Double Star magnetometer, with electronic box, in and outboard sensors and boom cable, as representative instrument, providing heritage for MAG (Photo courtesy Imperial College.*

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 the other 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 the 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 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), the electric component of plasma waves (E-field sensors and use of the radar antenna), magnetic field component of electromagnetic waves (Search Coil Magnetometer), radio emissions (triad of radio antennae) as well as some 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 JUICE science topics: i) the Jupiter moons - magnetosphere interaction (Ganymede, Europa and Callisto) with the objective to contribute significantly to the characterisation of the subsurface oceans; ii) the Jupiter magnetosphere, its dynamics and acceleration of particles as well as radio wave emission sources.

RPWI will contribute to a broad range of science objectives, for example:

- Determine the electrical conductivity of the ionised 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 exospheres of Europa and Callisto and interaction of the moons with Jupiter's magnetosphere, and investigate the generation mechanisms of Ganymede's aurorae
- Contribute to characterising 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 investigating subsurface outflow processes through direct *in situ* measurements of the ionised 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 cold 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 in collaboration with the PP electron spectrometer); 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** summarises the RPWI performance requirements.

Table 6-10. *Baseline RPWI properties*

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, δ**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, δ**E**(f)	10 kHz – 45 MHz
SCM	
Magnetic field vector, δ**B**(f)	0.1 Hz – 20 kHz (one coil up to 600 kHz)
RA-PWI	
Electric field, δE(f)	1 kHz – 45 MHz

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 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. The instrument has robust heritage in Europe (LAP/ Rosetta, CEFI-LP/ Swarm, EFW/ Cluster, PWI/ Bepi Colombo, F1&F4/ Freja) and on NASA missions (RPWS/ Cassini, Waves/ Stereo, and Juno.

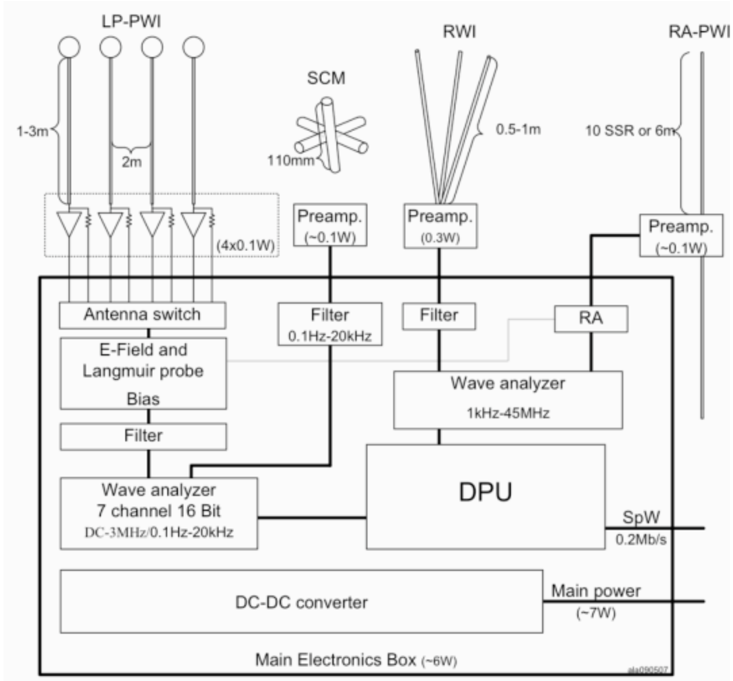


***Figure 6-9**. Block diagram of the potential RPWI instrument*

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 fulfil the science objectives during low altitude flybys of the icy moons 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 Package (PP-INMS)

Science goals and measurements. The main science objectives for the JUICE 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
- Characterisation 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
- Characterisation of the dynamics of 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. Plasma measurements are desired with a coverage of the whole sphere (4π) with specific attention to the plasma corotation and ram directions. The capability of the instrument should provide measurements from few 10's eV up to 10 keV for characterisation of exospheres around the moons. Characterisation of cold (down to a fraction of an eV) plasma is required to provide the spacecraft potential, needed to interpret 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/ΔM = 1000, however larger mass resolutions would be helpful for isotope analysis (to resolve CO and N_2 one would need M/ΔM = 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** summarises the PP-INMS performance requirements.

Table 6-11*. Baseline PP-INMS properties*

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

<u>*Possible instrument concept.*</u> 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 <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/ΔM ≈ 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/ΔM ≈ 50).
5) Energetic Plasma Spectrometer (EPS), for ion and electron distributions, from few keV to few MeV.
6) Energetic Neutral Analyzer (ENA), to characterise neutrals from a few eV to a ~10 keV.
7) An ion and neutral gas mass spectrometer (INM) with mass resolution of M/ΔM > 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 PP-INMS unit on the other side of the spacecraft. **Figure 6-10** shows an image of the PP-INMS instrument. An additional layer of anti-coincidence detection could be included into the design ensuring a proper measurement of the particles around Europa.

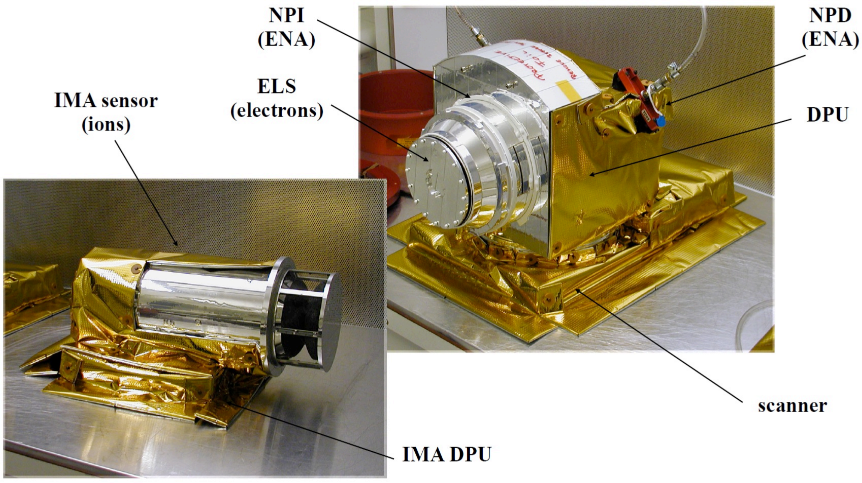


Figure 6-10. *ASPERA-4/Venus Express is a representative instrument providing heritage for PP-INMS (Credit: IRF)*

<u>*Orbit, operations, pointing and other mission requirements.*</u> Continuous operations of the plasma instruments are required to fulfil 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 (RST & USO)

<u>*Science goals and measurements.*</u> The Radio Science instrument uses parts of the spacecraft telecommunication subsystem with added hardware capability: a Radio Science Transponder at Ka-band (RST) and an Ultrastable Oscillator (USO). The radio science has the following goals:

- Characterisation of internal structure and subsurface oceans at Ganymede and Callisto and possibly at Europa by tracking the spacecraft using the RST
- Determination of the degree 2 gravity field at Callisto by tracking the spacecraft 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 the ionospheres of Jupiter, 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 JUICE using RST.

<u>*Possible instrument concept and performance requirements.*</u> The Radio Science Instrument will provide dedicated additional on board hardware interfaced with the telecommunication subsystem, namely a Radio Science Transponder (RST) at Ka-band 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 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 uplink one-way measurements carried out at X and Ka-bands. The RS instrument has a heritage in similar experiments onboard ESA's Rosetta, Venus Express and BepiColombo missions.

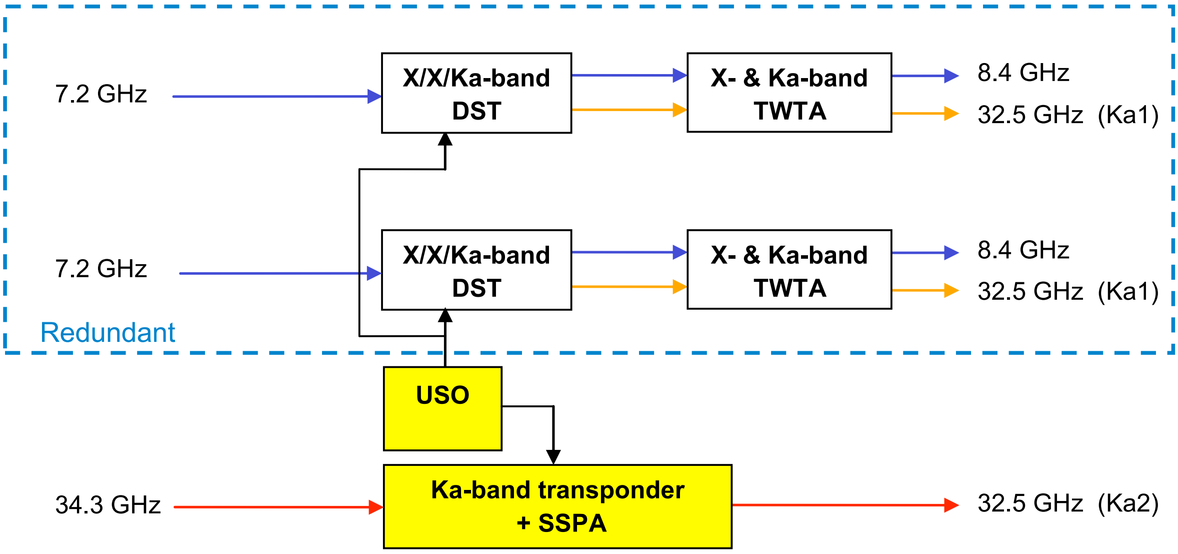


Figure 6-11. *JUICE Radio Science payload (in yellow) integrated with the TT&C system*

When used in two-way mode, both the DST and the RST do not produce any telemetry (except 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 hand, when Earth-to-spacecraft one-way 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 the ground through the telemetry channel. **Figure 6-11** shows a possible architecture for the JUICE communication system, capable of fulfilling the science goals listed above.

Orbit, operations, pointing and other mission requirements. For estimation of the gravity fields of Europa, Callisto and Ganymede, it will be required to operate the RST during the flybys and the Ganymede orbital 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**.

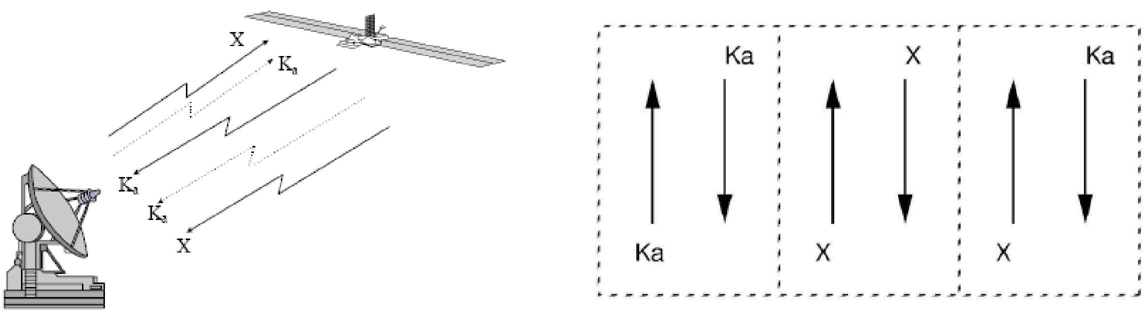


Figure 6-12. *Triple link - X/X, X/Ka (Ka1) and Ka/Ka (Ka2) - operations proposed for JUICE*

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 Ground Station as this is needed to estimate the satellite surface dielectric constant.

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 Europa flybys, when a gravity pass will require coverage using 3 consecutive ground stations.

During JUICE one- and two-way tracking from Earth the following requirements apply:

- The S/C shall be three axis stabilised, 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 spacecraft 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;
- Additional science could be performed, if continuous tracking of the spacecraft during Europa and Callisto flybys would be available such that the radio science experiment could be performed in combination with nadir observations, which could be achieved by using a dedicated steerable antenna for RS.
- The S/C angular speed around the antenna 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 Earth-spacecraft direction 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 Earth-spacecraft direction antenna, so this can be optimised for other S/C requirements.

6.2.12 JUICE Model Payload Summary

Table 6-12 summarises interface parameters of the model instruments. A more detailed description of the interfaces is included in the Payload Definition Document [D-1].

Table 6-12. *JUICE 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 + 20x18x15 cm	24	30	BeLa/ BepiColombo
Magnetometer	MAG	1.8	10 x 6 x 6 sensors; 16x16.5x12 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 Transponder	RST	2-2.5	17x19x10 (TBC)	26	very low, HK data only	Cassini, Bepi-Colombo, Juno
Ultrastable Oscillator	USO	1.5	15.2x9.0x13.0	5	low HK only	ERS, Rosetta, Venus Express, Huygens

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/ Bepi-Colombo
Visible InfraRed Hyperspectral Imaging Spec-trometer	VIRHIS	17	Optical Head: 50×40×30 ME: 30×25×20	20	5000	VIMS-V/ Cassini VIRTIS/ Rosetta/ VEX
Particle Package	PP-INMS	18.2	Main unit: 35x40x25cm Add. Unit: 25x25 x70cm (incl boom)	50	5-50	ASPERA/MEX,VEX, ROSI-NA/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 booms		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
	RA-PWI	3.7	2x6m dipole		From 50 bps to 2kbps	RPWS/Cassini PWI/BepiColombo

6.3 Conclusions and Recommendations

The model payload consisting of 11 instruments was carefully selected by the SST to prove the concept of the JUICE mission. The studies by instrumental teams, industrial contractors, SST and at ESA during the assessment and re-formulation phases demonstrated that this instrument suite can be accommodated on the spacecraft, is well within available mission resources, perfectly fits into the mission scenario and would, eventually, achieve the JUICE science goals. The model payload is based on example instruments that have flight heritage or are currently developed for ESA missions and can be built in Europe. Although the harsh radiation environment in the Jovian system is a challenge for the scientific payload, the assessment has ensured that the radiation risk can be mitigated by proper shielding and the instruments can reach the required scientific performance.

7 Mission Design

7.1 Mission Profile

The configuration of the JUICE spacecraft is driven by the long distance to Jupiter, the high Δv, the need to protect equipment from the intense radiation environment, 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 optimise the data downlink rate, a large high gain antenna is included. Due to its remote sensing and *in situ* exploration requirements, the spacecraft would be three-axis stabilised.

Savings of the propellant mass are achieved for the interplanetary trajectory by gravity assists (Earth-Venus-Earth-Earth for both baseline and backup launches), and, following the 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. After reduction of the spacecraft velocity with these gravity assists, Europa flybys would be conducted, followed by a phase where repetitive gravity assists would be performed with Callisto raising the inclination of the orbit around Jupiter up to 30°. This would allow for extended observations of Jupiter's high latitude regions and Jupiter's magnetosphere at a wide range of latitudes. Finally the spacecraft would be transferred into an elliptical orbit around Ganymede, which would be circularised and reduced in altitude, until final deposition on Ganymede's surface. A more detailed mission profile is summarised hereafter.

7.2 Mission Phases

The following phases of the mission can be identified:

1. Launch and interplanetary trajectory (7.6 years, 8.0 years for the backup launch date)
2. Jupiter orbit insertion, and energy reduction for transfer to Callisto (11 months)
3. Europa flybys (36 days)
4. Reduction of V_{inf} (2 months) / Jupiter High Latitude Phase with Callisto gravity assists (200 days)
5. Reduction of V_{inf} and transfer to Ganymede (11 months)

6-10. Ganymede science phases (282 days)

The total mission duration amounts to close to 11 years for both launch opportunities, of which 3.5 years would be spent in the Jupiter system. With the currently envisaged launch opportunities in 2022 and 2023, the mission would end in June 2033 and December 2034, respectively. The required propellant mass would be 2900 kg providing a total Δv of 2634 m/s.

7.2.1 Launch and Interplanetary Trajectory

Launch is foreseen on an Ariane 5 ECA with direct escape with an Earth-Venus-Earth-Earth gravity assist sequence. With the baseline launch date in June 2022 (backup in August 2023), a JOI, preceded by a Ganymede gravity assist manoeuvre, would be performed in January 2030, after 7.6 years (for the backup launch in August 2031 after 8 years). The mass injected into the Earth escape trajectory would be 4800 kg (without launch adapter), with a hyperbolic escape velocity of 3.15 km/s, which increases to 9.5 km/s after the last Earth swing-by. In this baseline transfer scenario the launch declination is -2°, which is optimal for launch-to-orbit mass performance within the allowed range. The fact that the first arc includes an Earth gravity assist for both launch opportunities removes the dependency of the relative declination of Venus, and therefore the baseline and backup launches have the same escape velocity, resulting in similar launch mass performance.

7.2.2 Jupiter Orbit Insertion and Transfer to Callisto

The JOI is the most critical manoeuvre of the mission. All other manoeuvres would either be 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 900 m/s.

The Jupiter orbit insertion manoeuvre will be preceded by a Ganymede gravity assist. From a purely kinetic energy point of view, it would be most efficient having a gravity assist as close as possible to Jupiter, however, with significantly increased radiation. It was therefore decided for this phase to limit the closest approach to similar distance as Ganymede's 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 into a 13x243 R_J orbit, the perijove being defined by the orbit after the Ganymede gravity assist, and the apojove being a consequence of the optimization for the following Ganymede gravity assist (this orbit is a 25:1 resonance with Ganymede). A perijove raising manoeuvre of 63 m/s will be performed at apojove to reduce the radiation exposure 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 in **Figure 7-1**, where the orbits of Callisto, Ganymede and Europa are also indicated. The first orbit will take 179 days.

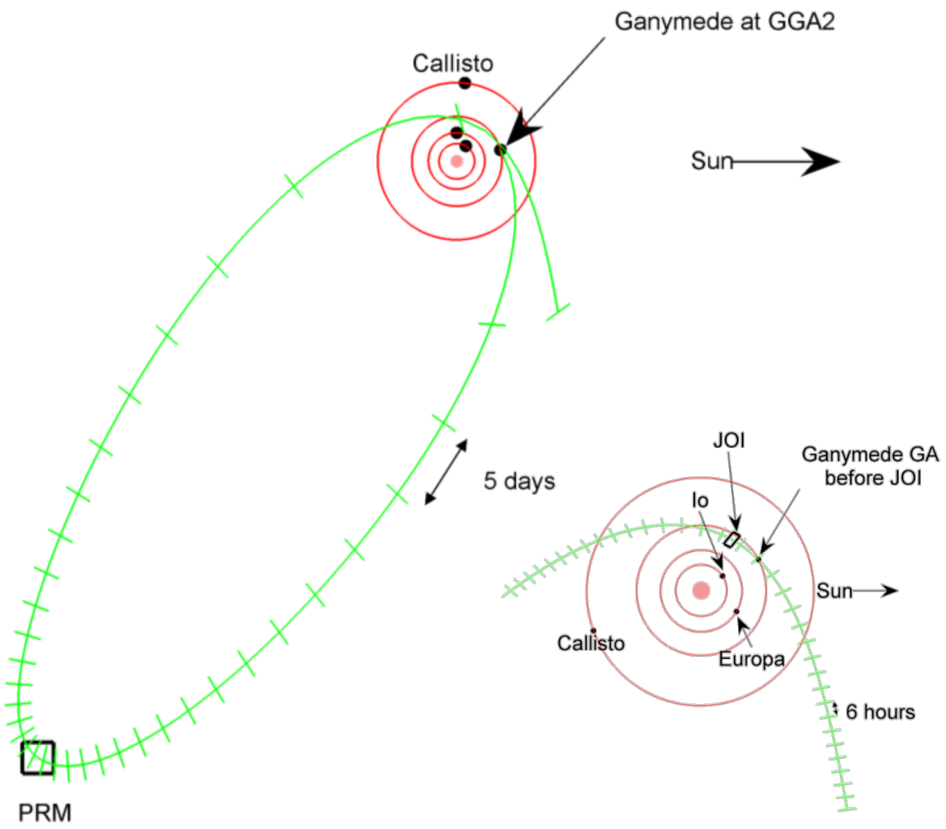


***Figure 7-1** Trajectory of the first Jupiter orbit. Also shown are the orbits of Callisto, Ganymede, Europa and Io. The inset shows the JOI together with the preceding Ganymede gravity assist.*

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 9° with respect to the Jupiter equatorial plane to equatorial inclinations. The total required deep space Δv is 23 m/s, and the final apojove and perijove are 41 R_J and 11.6 R_J, respectively (duration 170 days).

7.2.3 Europa Flybys

After having achieved sufficient velocity reduction, two Europa flybys will be performed. The flybys are planned such that the radiation exposure to the s/c is as low as possible, first by encountering Europa at perijove (i.e. the spacecraft's perijove is equal to Europa's orbital radius), and second by having only one low perijove passage per Europa fly-by. The two flybys are planned to be conducted one after the other from a 4:1 resonant orbit. This resonance is inserted in the middle of a 2:2 – negative pseudo-resonance with Callisto: to achieve the correct timing, the s/c would leave Callisto on an outbound arc of the 4:1 resonant orbit with Europa, would then conduct two successive Europa flybys and would arrive back at Callisto on an inbound arc. A gravity assist at the second Callisto encounter would bring the s/c to an orbit with a higher altitude perijove. The sequence is illustrated in **Figure 7-2** where the orbits of the moons and of the spacecraft are indicated.

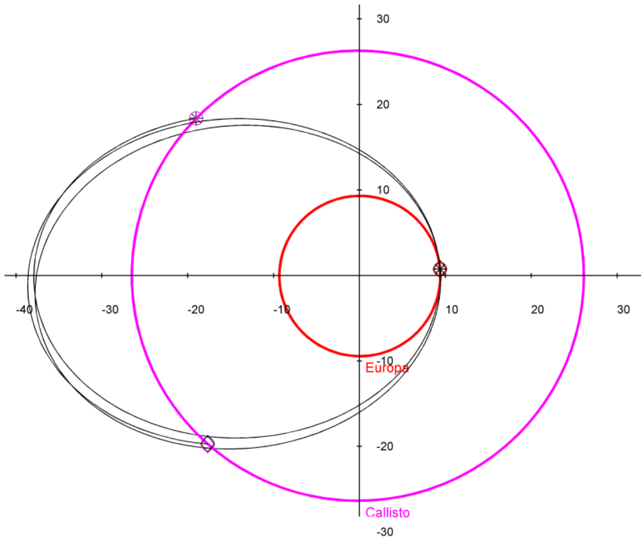


Figure 7-2 *Two Europa flybys from a 4:1 resonant orbit. The orbits of Callisto (purple), Europa (red) and the spacecraft (black) are drawn on a Jupiter Solar Orbital (JSO) coordinate frame. Symbols indicate the encounters of the spacecraft with the moons*

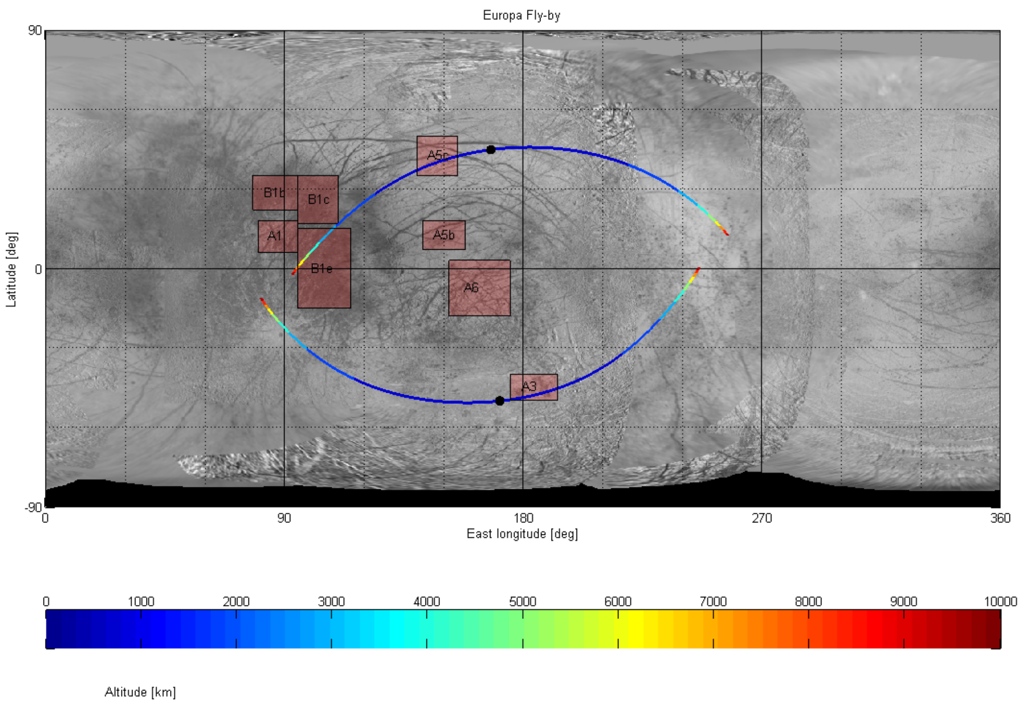


Figure 7-3 *Ground track of the spacecraft during Europa flybys. The image shows a Europa surface map with the areas of specific interest indicated by colour rectangles. The ground tracks of the two flybys are indicated in coloured lines, with the colour indicating the altitudes in 1000 km (see colour bar). The closest approaches are plotted by red dots.*

The possible surface target areas of closest approach at Europa are constrained by the fact that Europa's rotation is in a 1:1 tidal lock, and by the spacecraft being on a Jupiter bound orbit. The longitude of closest approaches is therefore limited to areas close to 0 and 180° (by standard nomenclature the 0° meridian is facing Jupiter). This is also evident from the geometry shown in **Figure 7-2**. However, there is some freedom in latitude (up to ±50°), and therefore the two flybys were designed such that the spacecraft would fly over different regions. The target altitude for closest approach is 400 km. **Figure 7-3** shows the baseline ground tracks for altitudes <50,000 km overlaid on a tentative map of Europa. Identified areas of specific interest being suspected active regions, or possibly having the thinnest ice layer are also indicated on the map by coloured rectangles (see section 5.1.2). Due to the constraints described above, passes over these areas can be achieved for altitudes ranging from 1000 up to 6000 km, depending on the target area.

Finally the spacecraft will be brought into a Callisto resonant orbit by further reducing the V_{inf} through a sequence of Callisto-Ganymede-Callisto gravity assists during 66 days.

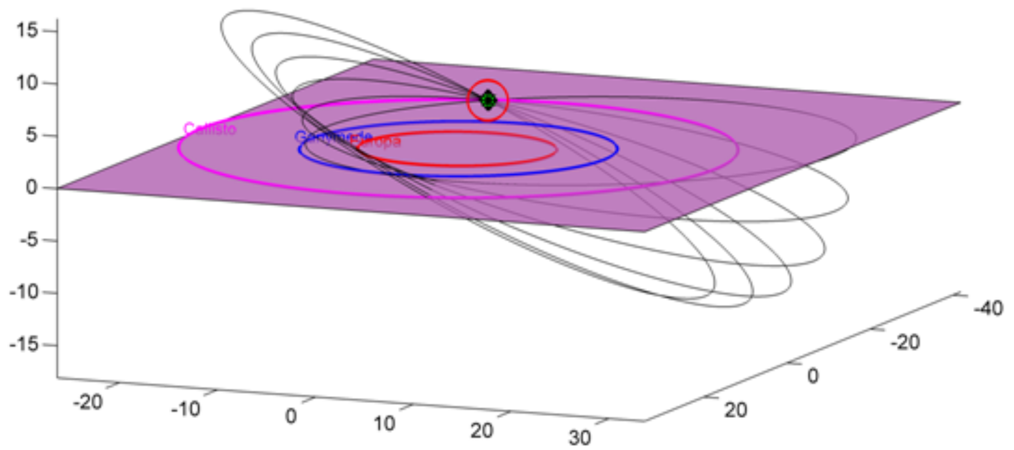


***Figure 7-4** The spacecraft trajectory (black) during the Callisto gravity assists to raise the orbit inclination. The Jupiter equatorial plane is indicated in pink, including the orbits of Callisto (purple), Ganymede (blue) and Europa (red). Jupiter is located at the centre (at coordinates [0,0,0]). Units are multiples of Jupiter's radius.*

7.2.4 Jupiter High Latitude Phase with Callisto Gravity Assists

A sequence of repetitive Callisto gravity assists will be used to increase the inclination of the orbit up to 29°. The spacecraft will be in Callisto resonance and will therefore encounter Callisto at almost the same positions. After having achieved the target inclination, the inclination will again be reduced with the same strategy. **Figure 7-4** shows the spacecraft trajectory with successive increases of inclination. The Jupiter equatorial plane is indicated by a pink plane including the orbits of Callisto, Ganymede and Europa as lines. The sequence of changes of inclination, and apojove and perijove radii per Callisto gravity assist are shown in **Figure 7-5**.

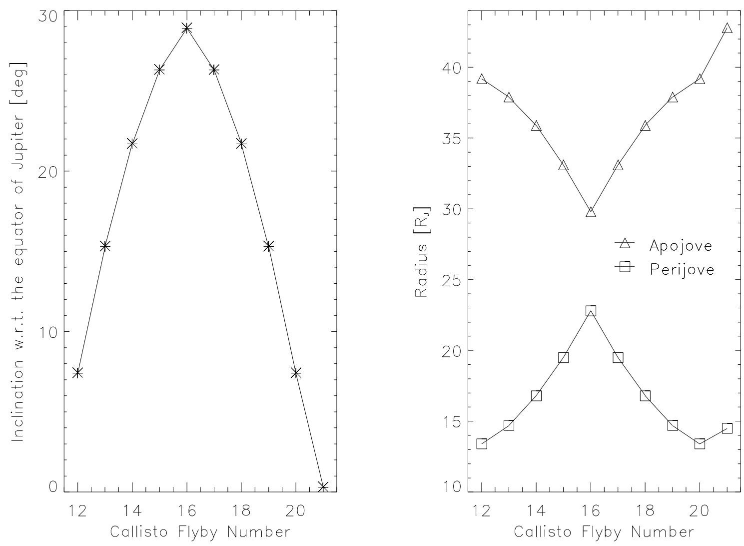


***Figure 7-5** Key properties of higher inclination orbits. The increase and decrease of inclination (left) and the apojove and perijove radii (right) are plotted as a function of the number of Callisto gravity assists.*

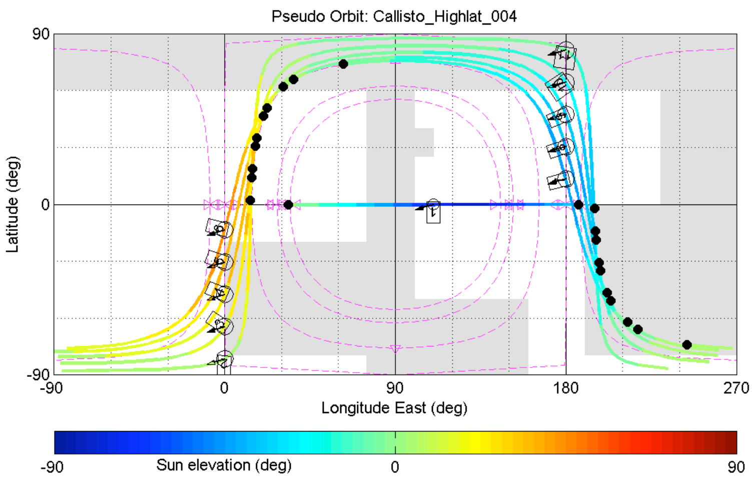


Figure 7-6 Ground track of the Callisto flybys for altitudes <5000 km. The colour scale indicates local Sun elevation of the sub-nadir point in degrees (values <0° refer to local night). Numbers indicate the sequence of the flyby. The shaded areas correspond to gaps from Galileo and Voyager data. The black circles indicate closest approach, and the small arrows indicate the direction to the Sun.

The available surface coverage during these Callisto flybys is limited, as otherwise the raise of inclination would be less efficient. The flyby ground tracks are shown in **Figure 7-6** on a cylindrical map of Callisto's surface with colours indicating the local Sun elevation angle at the sub-nadir point and closest approach locations (black dots). Due to the repetitive properties of the gravity assist manoeuvres, the ground tracks lie close to each other. All flybys are targeted at 200 km altitude. 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 apojove ranges between 48 and 30 R_J, and inclinations up to 29° would be achieved, allowing for magnetic field measurements over a wide range of magnetic field coordinates within the same orbit. Furthermore, the area of Jupiter's pole at latitudes >63° would be visible at the apocentre of the orbit with the highest inclination. The view on Jupiter from the apocentre at the highest inclination is shown in **Figure 5-4**.

For the Callisto flybys, like for all Jupiter moon 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 study phase to investigate among others, whether this Δv budget could be optimised, thereby allowing for the number of flybys being increased. No changes to the implementation of the spacecraft would be required in this case.

7.2.5 Transfer to Ganymede

Further reductions of the spacecraft's velocity will be performed with a sequence of Callisto-Ganymede-Callisto gravity assists (60 days). The transfer to Ganymede will then be performed by using the moon resonance strategy, which significantly reduces the Δv spent compared to a 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 (see section 5.1.1.4). The initial Δv reductions and the moon resonant transfer take 210 days and 100 m/s, and will be completed by the Ganymede orbit insertion manoeuvre, consuming 144 m/s.

7.2.6 Ganymede Science Phases

The Ganymede science phase will comprise four 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, as further explained below. 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. The effect of potential eclipses is shown in **Figure 7-7**, where the fraction of time spent in eclipse is plotted for polar orbits as a function of altitude and β-angle, together with the scale factor of increased solar array area needed to generate additional power during the solar illumination as compensation. As can be seen, already for short eclipses this scale factor rises steeply as a function of eclipse duration.

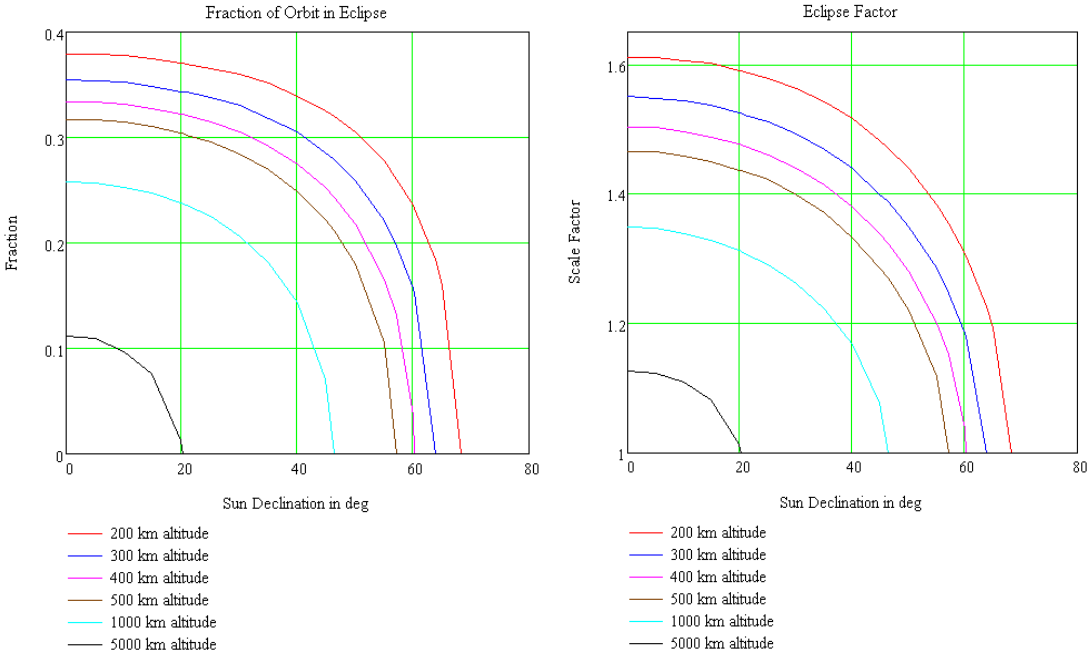


***Figure 7-7** Influences of eclipses by Ganymede on the spacecraft design. Left: the fraction of time spent in eclipse as a function of Sun declination to the orbital plane for circular polar orbits with altitudes from 200 to 5000 km. Right: the scale factor of increase of the solar panel area for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

For close to polar Ganymede orbits, the orbital plane of the spacecraft will slowly rotate around the pole, with the rotation rate being a function of inclination due to the influence of Ganymede's oblateness and Jupiter's attractive force. This was used to design the orbit such that lower altitudes could be realised later during this phase, while still avoiding sun eclipses, allowing for a sequence of orbits with decreasing altitudes as summarised in **Table 7-1**.

***Table 7-1** Parameters of the orbits around Ganymede.*

Phase	**Altitude [km]**	**Sun Declination (β-angle) at start of Phase [deg]**	**Duration of phase [days]**
Elliptical	200x10,000	20	30
Circular 5000	5000	28	90
Elliptical	200x10,000	54	30
Circular 500	500	62	102
Circular 200	200	76	30
End	200	81	n/a

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 30 days, where it will remain at an altitude of 5000 km, which will be maintained for about 90 days. 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 7-8**.

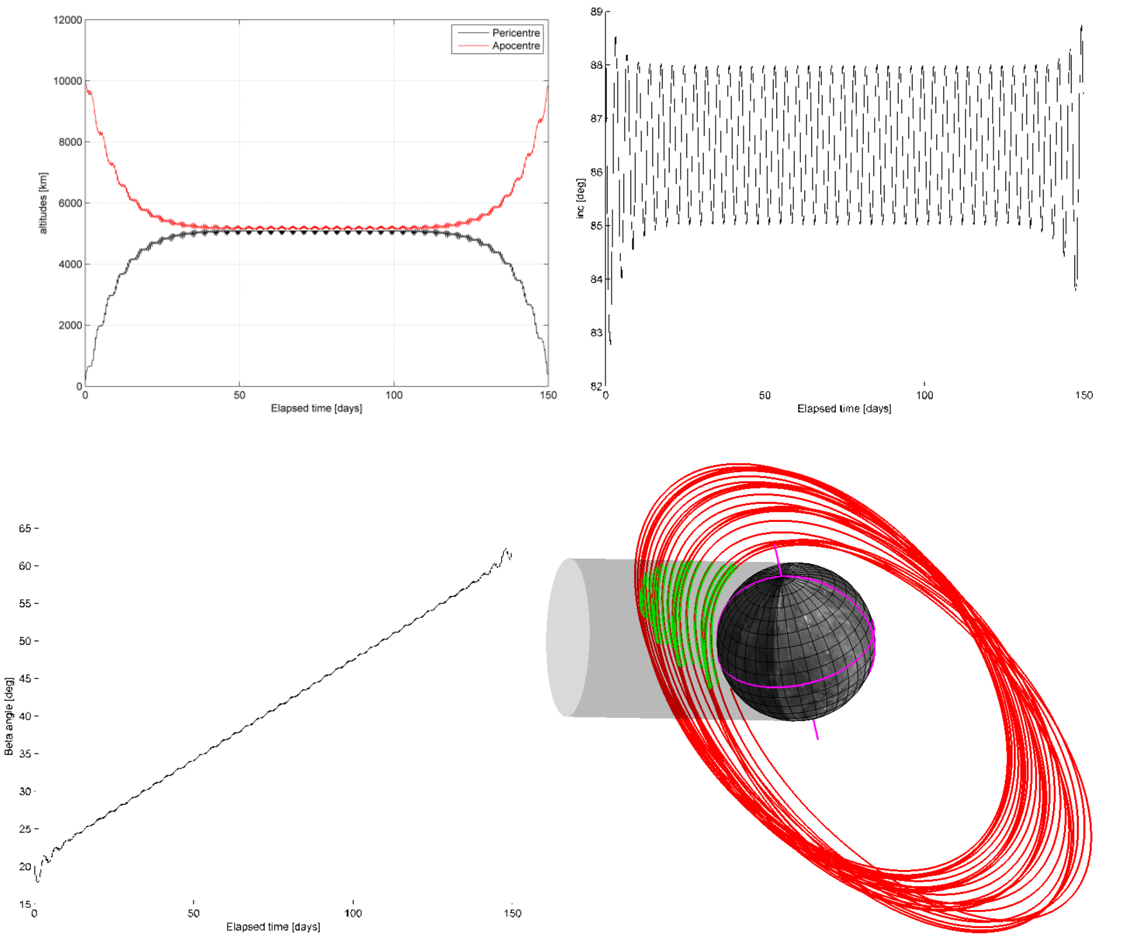


***Figure 7-8** Evolution of the orbit during the Ganymede elliptical and circular 5000 km phases: apocentre and pericentre altitudes (top left); osculating inclination (top right); sun declination, called β-angle (bottom left). On the bottom right the initial orbits following the Ganymede orbit insertion are shown together with Ganymede's shadow.*

The visible/near-infrared spectroscopy instrument requires a high altitude and high sun elevation, and therefore it was decided to place the apocentre of the initial elliptic phase above the dayside of Ganymede. At the same time this orbit satisfies a requirement by the fields and particles instruments to enable a limited number of measurements in the nightside of the exosphere. The 24 initial orbits (12 days) have low pericentre and a low Sun declination angle, and are therefore passing through eclipse, with the longest eclipse lasting for about 45 minutes. This worst case is a small fraction of the total orbit duration (12 hours), but will be compensated by reduced payload operations during these orbits. The geometry and the shadow are shown in the bottom right of **Figure 7-8**.

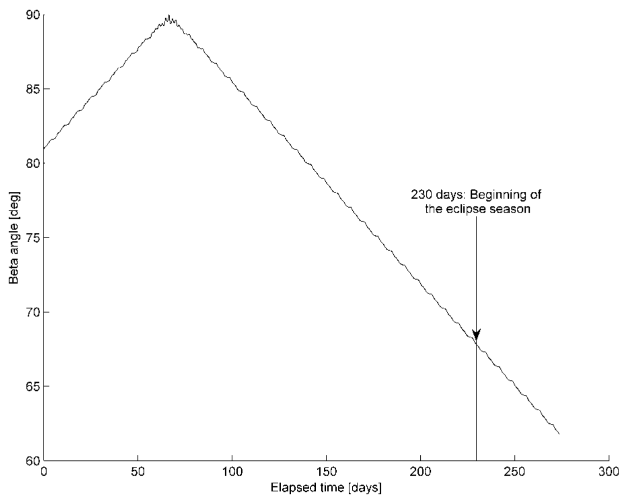


***Figure 7-9** Evolution of the sun declination (β-angle) as a function of time during the 200 km circular Ganymede orbit phase. The sun declination angle continuously changes, even after dawn-dusk orbit. The first eclipse is reached after 230 days from the start of this phase.*

At the end of this phase, 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 102 days, and then the final orbit of 200 km altitude will be obtained after applying a Δv of 92 m/s. The spacecraft would be operated in this final phase for at least 30 days. A mission extension would be possible based on remaining consumables and spacecraft health. The evolution of the sun declination angle as a function of time is shown for this final phase in **Figure 7-9**. After the nominal duration of 30 days the orbit would approach a dawn-dust orbit, and would continue to drift with continuously increasing sun elevation at the sub-nadir point. The first eclipse would occur after 230 days from the beginning of this 200 km altitude phase. In this final phase the orbit will be very close to polar (deviation <1°).

At the end of the mission, orbit maintenance would be discontinued, and the spacecraft would be left in an orbit with natural growth of eccentricity until disposition on Ganymede's surface.

7.3 Radiation Environment

The mission radiation environment [D-4] & [D-5] is dominated by the properties of the plasma at Jupiter. **Figure 7-10** shows respectively the integral fluence spectra for electrons and protons integrated over mission phases. The total electron fluence is about one order of magnitude higher than the proton fluence. The solar protons, which are mainly encountered during the interplanetary transfer, are several orders of magnitude below that. The fluence spectra show higher fluence for the phases of the mission closer to Jupiter. Specifically it can be observed that the spectrum during the Europa phase is also harder. Trapped electrons have an energy spectrum with significant densities up to several 100's MeV. In comparison, the radiation environment for geostationary applications is dominated by electrons too. The total fluence expected by the JUICE mission is for low

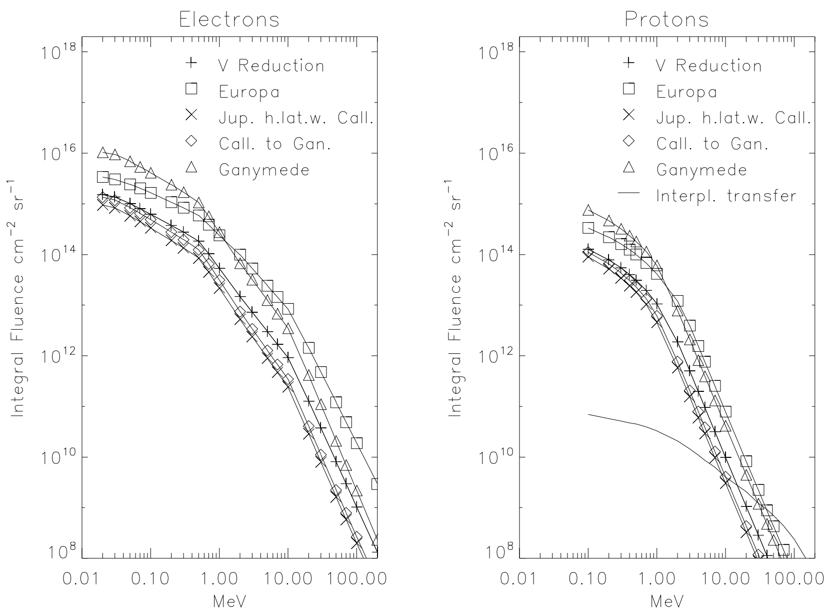


Figure 7-10 *Fluence spectra of electrons (left) and protons (right) per mission phase.*

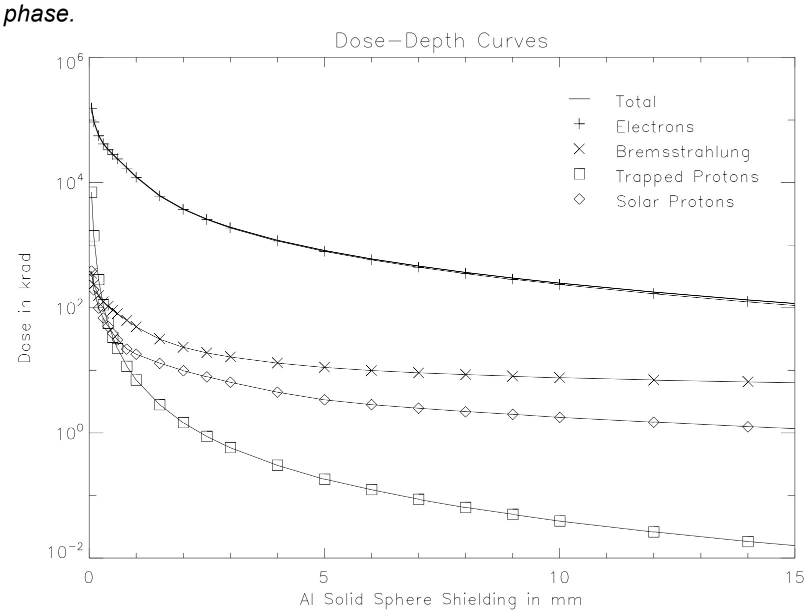


Figure 7-11 *Total dose as a function of shielding thickness. The contributions from each major particle species are also indicated.*

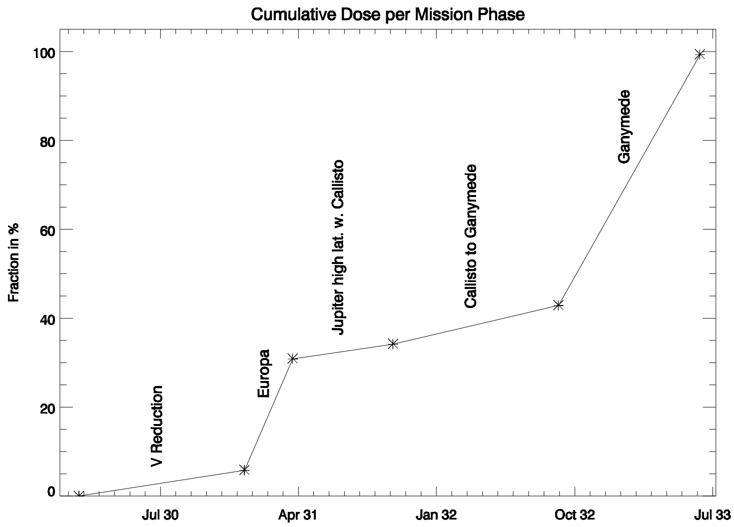


Figure 7-12 *Cumulative dose per mission phase. The figure shows the relative accumulation per mission phase as a function of time*

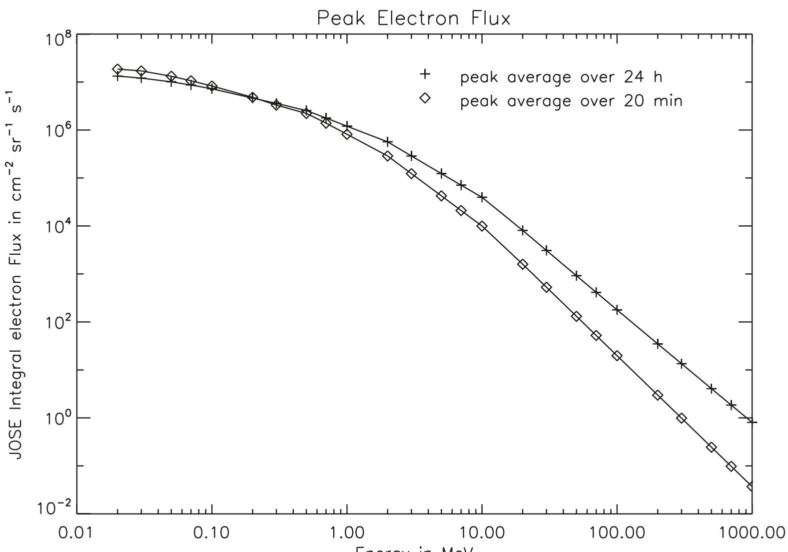


Figure 7-13 *Worst case integral electron flux spectra in cm^{-2} sr^{-1} s^{-1} during the Europa flybys, averaged over 24 h and 20 min.*

energies comparable to geostationary spacecraft after 10 – 15 years operations. At low energies, where the density is significantly higher, interactions with the surface layers will dominate, causing local surface charging effects, if not properly mitigated, e.g. by shielding and conductive layers. Similar techniques as applied for geostationary spacecraft will be used. The Jupiter electron spectrum at high energies is considerably harder than for geostationary orbits, causing deeper penetration and therefore requiring considerably more shielding than for geostationary applications.

The contribution to the total dose per particle species is plotted in **Figure 7-11** as a function of shielding material thickness for the total mission. The dose inside solid Al spheres was simulated and is equivalent of 240 krad inside a 10 mm solid Al sphere. In agreement with the discussion above, the dose is dominated by the contribution from the Jupiter electrons (electrons and bremsstrahlung). The contribution from solar protons, during the interplanetary phase is less than 1% of the total dose. Almost 60% of the total mission dose is accumulated during the Ganymede phases, and about 25% during the Europa flybys. The remaining dose is mostly accumulated during the tour in the Jupiter system (see **Figure 7-12**). These calculations include the shielding effect by Ganymede for the low altitude orbits of the spacecraft (<500 km), which was assumed for the purpose of this study to be at least 40%, and will be refined with more detailed simulations.

As the radiation spectrum is dominated by electrons, shielding by high Z materials, such as tantalum or tungsten (or alloys with e.g. copper) are more mass efficient than shielding by aluminium. 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, and will therefore be used as shielding material for equipment housing, and for spot shielding of specific components with lower radiation tolerance.

The high density of ionising radiation will also contribute to the background signal measured by detectors. In **Figure 7-13** the worst case environment flux spectrum is plotted as a function of energy. Background suppression techniques will be considered together with shielding optimizations during the following study phases, when the accommodation of the scientific instrumentation will be performed.

7.4 Spacecraft Design

There were three system studies conducted whose results will be summarised in the following sections, after a brief discussion on mission requirements and system drivers.

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 related 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 high Δv requirement, and consequently 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^h46^m requiring careful pre-planning and autonomous execution of operations by the spacecraft. Additionally, a high gain antenna is required for data downlink. The system studies aimed at maximizing the diameter of the high gain antenna for maximum science return. For the study purposes, a daily data volume of at least 1.4 Gb was assumed as being required.

The use of using solar array power generation in combination with the large distance from the Sun, with 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 with 200 km altitude 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 a single ground station, and that the downlink would last for the entire pass, possibly only interrupted, by Jupiter or Ganymede occultations. To maximise the data return, the highest possible power would be provided to the telemetry system, and reduced instrument operations would be performed during downlink periods. Consequently an articulated high gain antenna would not be needed for increasing the downlink data volume, 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) is a function of eclipse duration, requiring significant increases in solar array area even for short eclipse durations (**Figure 7-7**). It was therefore decided to avoid orbits around Ganymede with regular eclipses.

The power generation was further optimised 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 that this yaw steering could be paused for a limited period of time, e.g. in support of high resolution imaging. This specific case was however not considered as a design driver, and would therefore only be allowed in combination with power saving measures.

7.4.1.2 Radiation and Low Temperature Environments

To maximise the efficiency of the required shielding and to benefit from units shielding each other, all design solutions presented below considered accommodation of electronic and instrument hardware in a few compartments. Detailed radiation transport simulations were performed for a limited set of representative spacecraft units (e.g. such a the data processing unit, power converter and star trackers) and options for dose reductions were studied, using a three level shielding approach, including the shielding by the walls of the compartments (vault type shielding), shielding by the housing of the units, and spot shielding of particular components with low radiation tolerance. A comparison of the mass efficiency of each of these shielding options was performed, yielding the highest mass efficient shielding, when applying spot shielding. The required shielding mass was calculated per simulated unit, assuming component tolerance between 30 – 50 krad (a slightly different approach was taken in each of the studies). Then this shielding mass was scaled for all equipment, including payload, yielding for each of the design solutions total shielding masses between 155 and 172 kg including a conservative margin of 40% (see **Table 7-3**). This approach was taken because the detailed designs of all units are not available at this early phase of the study, and would be iteratively improved as the level of definition increases during future study phases. The shielding material was assumed to be a mixture of Al, which would commonly be used for housing and mounting platform, and higher Z material, such as Ta, for all additional shielding. It was also verified by simulations that the assumed shielding would sufficiently reduce the flux of the penetrating high energy electrons, such that deposited current would not cause local charging in materials, such as insulators (cables and connectors).

At low energies of the electron spectrum, the expected total mission low energy electron fluence is actually lower than a typical exposure for 10 – 15-year geostationary mission. At such energies electrons are predominantly absorbed at the surface, and therefore heritage is available of materials withstanding such doses. For the surfaces of the spacecraft, standard mitigation strategies for geostationary applications would be used, such as coating with conductive layers.

The foreseen accommodation of instrument and platform units within compartments also helps the thermal balancing, in that non-operating units would be heated by operating units within the same compartment. This concept optimises the required heating power.

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 (cf. section 0) was compiled. Instruments that would likely be operated together were combined in one scenario, and a schedule of a generic operations sequence was defined. The Ganymede orbit phase was considered as the reference for this specification, as it would be generating the highest science data volume. The grouping of instruments that would operate in parallel per scenario is summarised in **Table 7-2**.

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

Table 7-2 *Definition of five generic model instrument observation scenarios; instruments that would operate in parallel were grouped in Obs1 to Obs5 such that two scenarios would operate per orbit.*

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 for each observing scenario all the instruments listed would be operational for the entire planned duration. Observation scenario Obs3 would be the baseline operation mode during night side observations. The scenario Obs4 would either be used in parallel to the data downlink, or for radio-occultation sounding of Jupiter's atmosphere. The scenario Obs5 is intended for remote observations of Jupiter and far distance observations of the other Galilean moons and other targets. The application of these scenarios would not be limited to the Ganymede phase, but would also be used during other mission phases. It is emphasised that these are example scenarios intended 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 science and mission operations approaches and key elements of the science management are described in sections 8 and 0.

7.4.1.4 Model Payload Accommodation Considerations

The preferred accommodations of several instruments are aiming at similar locations on the spacecraft, 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. Some particle instruments require as close as possible to $4\,\pi$ 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 possible solutions 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 themselves as obvious examples for accommodation of additional sensors (magnetometer boom) or accommodation of several functions (radar antenna), provided the interface requirements are compatible, e.g. with respect to electromagnetic field environments.

Due to the highly sensitive fields and particles measurements to be performed, strict limits on the electromagnetic compatibility of the spacecraft subsystems were 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 Volt, at least in the vicinity of the electric field sensors and the low energy plasma 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 7-14**). All platform and instrument equipment would be accommodated on panels around this central tube, including a vault-type structure serving as common first level radiation shield in the middle that would contain the majority of the units. The large solar arrays ($2{\times}32\ m^2$) 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 if the spacecraft. 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 maximise 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 ($x{\times}y{\times}z$) 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 would 9.21 m, with a maximum of 7.04 m across.

The main remote sensing and *in situ* instruments would be mounted on the +X panel (see **Figure 7-14**). 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 amplitudes 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.

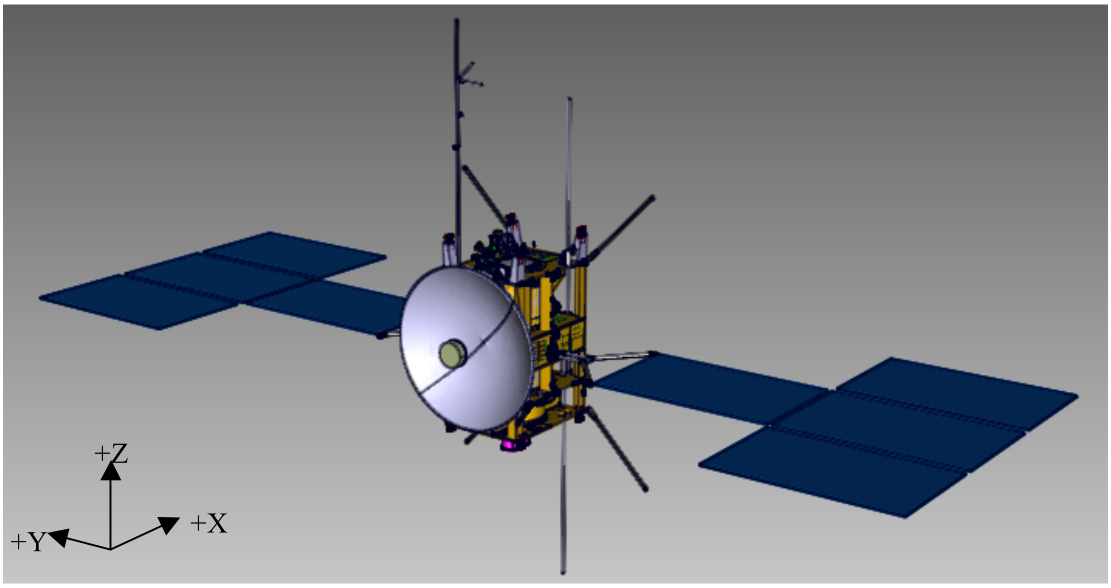


Figure 7-14 *Spacecraft configuration of solution 1 shown with the side panels removed. The main engines and the launcher interface would be at the bottom (–Z panel), the remote sensing and in situ instruments, which require access to the velocity direction would be located at the back of this view (+X panel). A cold plate would be at the top (+Z panel).*

This instrument accommodation resulted from the detailed assessment study that was carried out for repeated Callisto flybys and Ganymede orbit observations. With the addition of a few Europa flybys it became necessary to allow all instruments to operate simultaneously with optimum field of view/access to space for *in situ* instruments. Therefore the accommodation will further be optimised in the next phase.

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 at 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 spacecraft orientation (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 a 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 2887 kg. 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 momentum wheel off-loading and attitude control during main engine thrusting periods. Additionally four of these thrusters would be used for executing low amplitude Δv manoeuvres.

The manoeuvres with the main engine would be performed in pressurised mode (two Helium tanks) to optimise 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 data handling unit (PCDU). The PCDU would provide a regulated power bus at 28 V to subsystem equipments. 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 optimised 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. The solar arrays were sized for a worst case of 46 W/m^2 illumination, and for generating a total of 636 W 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 and considering the availability of standard components), which is driven by the generic instrument operations scenario (see section 7.4.1.3), being the highest science data volume accumulated during a Callisto or Europa flyby (27 Gbit). 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 of X and Ka-band transmission. The antenna geometry and feeds are optimised for the interplanetary Ka-band (32 GHz) link. According to the baseline assumption, housekeeping data would be transmitted at X-band during the early parts and during the late parts of each ground station pass, when the ground station antenna elevation is low. The science data would be transmitted at Ka-band at higher ground-station antenna elevations. Transmission from the spacecraft would take place with 100 W_{RF}. In addition, to optimise the total downloaded data volume, the downlink data rate would be adjusted as a function of ground station elevation. A single ground station was assumed, with a data link being established during each pass (i.e. once per day). Initial estimates confirm that the assumed data volume of 1.4 Gb per day could be met with margin. Command uplink would be performed at X-band. Provisions for the integration of the radio-science experiment would 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 sunshield). 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 optimised 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 the shadow. During the Venus gravity assist the solar panels will be tilted (30° incidence angle) so as to reduce the irradiation, resulting in a peak temperature of the solar arrays of 100°C. 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 same spacecraft panels as the solar panels (±Y panels, see **Figure 7-14**) 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 propulsion system).

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 7-15**). These compartments provide the possibility of additional wall shielding. The main compartment would be located at the centre of the spacecraft providing accommodation volumes on the +X panel (nadir direction), between the ±Y panels. The sensor heads would be accommodated on 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, which is available on the +Z panel. Instruments requiring high cooling power, and/or high stability mounting would be included in this compartment, 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.

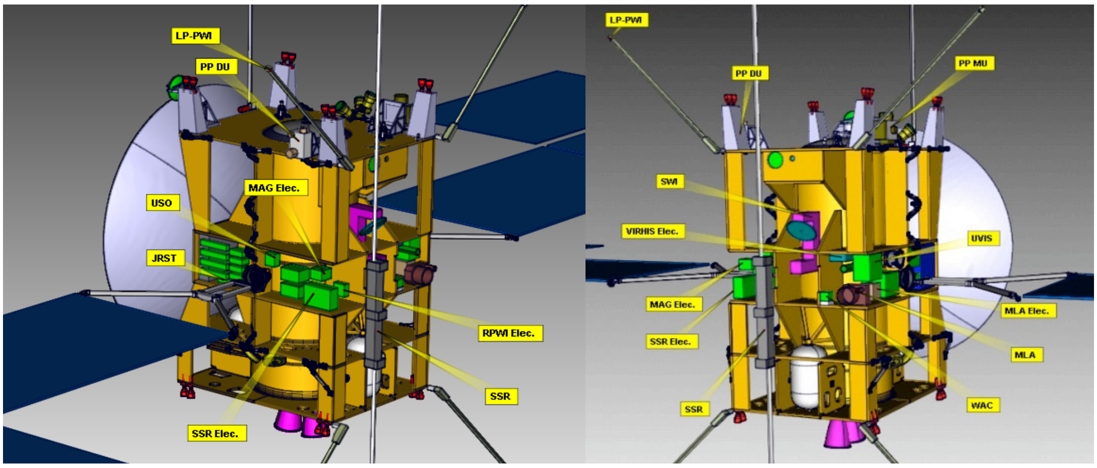


Figure 7-15 *Accommodation of the model instruments in spacecraft solution 1.*

This instrument accommodation resulted from the detailed assessment study that was carried out for repeated Callisto flybys and Ganymede orbit observations. With the addition of a few Europa flybys it became necessary to allow all instruments to operate simultaneously with optimum field of view/access to space for *in situ* instruments. Therefore the accommodation will further be optimised in the next phase.

7.4.2.9 Mechanisms

The solar array deployment for achieving the configuration with side-panels is regularly 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 would be 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 booms for the subsurface radar.

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 primary structure in separate compartments on the +X and –X panels (see **Figure 7-16**). The size of the main structure ($x \times y \times z$), 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 optimizations of mass, data transmission volume 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.

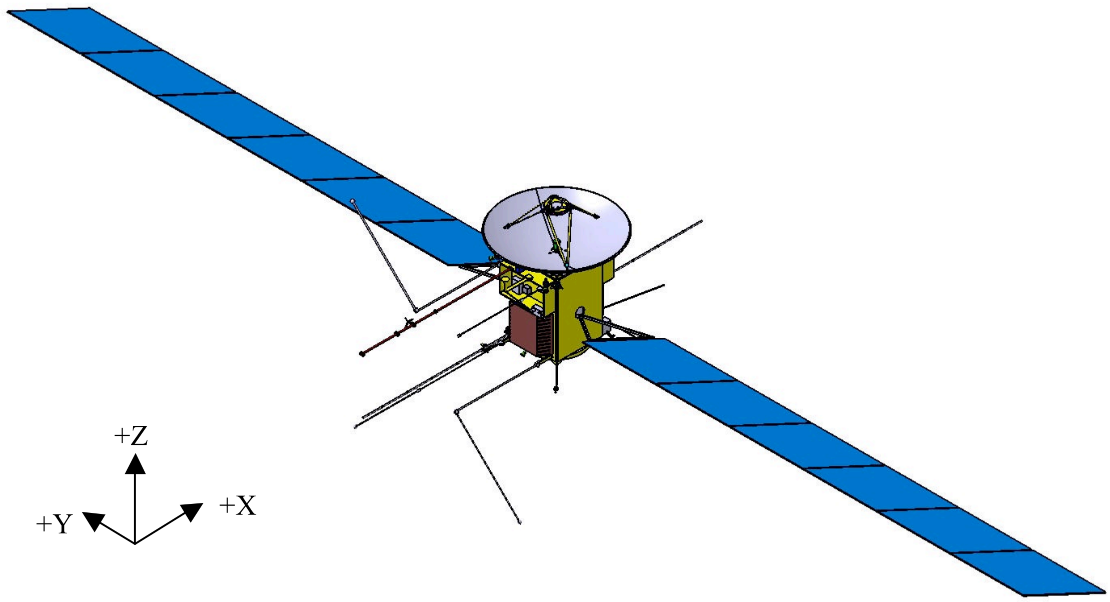


Figure 7-16 *Spacecraft configuration of solution 2. The main engine and the launcher interface is at the bottom (–Z panel), the remote sensing instruments are located at the back of this view (+X panel), and the in situ instruments, which require access to the velocity direction are mounted on the –X panel. The high gain antenna is at the top (+Z panel).*

The remote sensing and the *in situ* instruments would be mounted on opposite faces of the spacecraft and consequently *in situ* measurements and 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. During the Ganymede phase, the spacecraft would perform rotations 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 optimised 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 inertial pointing with the high gain antenna pointing to the Earth.

This instrument accommodation resulted from the detailed assessment study that was carried out for repeated Callisto flybys and Ganymede orbit observations. With the addition of a few Europa flybys it became necessary to allow all instruments to operate simultaneously with optimum field of view/access to space for *in situ* instruments. Therefore the accommodation will further be optimised in the next phase.

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 four wheels plus one redundant was selected, with a slightly asymmetric configuration accounting for different angular momentum needs. The maximum required capacity of 205 N·m·s (max. around the Z-axis) was driven by the Europa flyby scenario, allowing full flexibility of the orientation of the spacecraft during the flyby. The required yaw rotation during the Ganymede phases was not found to be 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 utilise 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 optimised for extended object recognition would be provided in support of navigation at the Jupiter system.

7.4.3.3 Propulsion

The propulsion system would be based on a helium pressurised 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 2938 kg. 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 either 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) optimised 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 optimised 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 152 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 during this phase.

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 as providing sufficient processing power. The processor, the interface unit and the payload data handling units would be combined into one data handling unit. The data interface would be based on SpaceWire for all interfaces. The memory would be based on flash technology, and the required total size could be provided by a similar memory board 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 or Europa flyby, and is available using standard components.

7.4.3.6 Communications

The spacecraft would provide a 3.5 m HGA which would be 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 accuracy of 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 future study phases when a more accurate assessment of the pointing performance would be available. In either case, would the specified data volume of 1.4 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

A high emissivity finish would be used on the inside of the equipment compartments and the structure 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 to avoid electrostatic discharge. The propellant tanks, helium tanks and the necessary pipes are located at the inside of the structure to provide good insulation 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 maximised free field of view to space. The surfaces would be covered with high emissivity white paint 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 7-17**). All remote sensing instruments would be co-aligned and would be mounted on the +X panel, and *in situ* instruments and the subsurface radar would be located on the –X panel. Electronic units, which are part of the instruments could be accommodated within either side, depending on instrument requirements and on available space, and could be used for balancing the thermal dissipation.

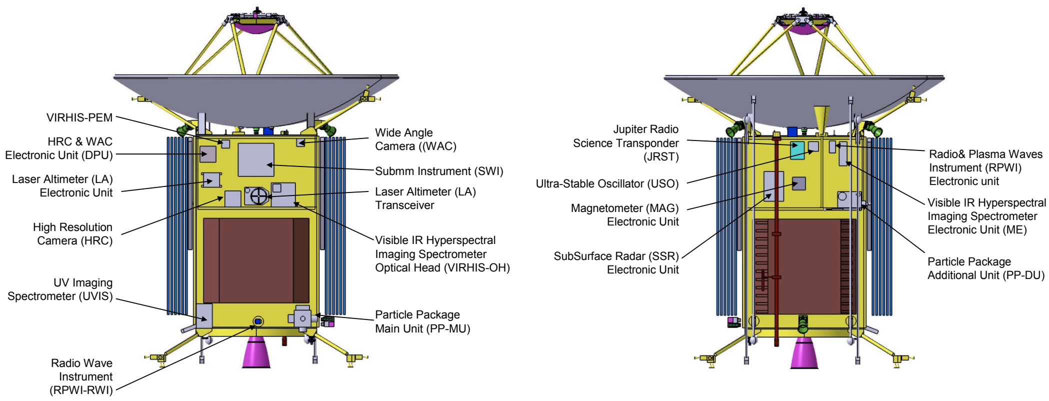


Figure 7-17 *Accommodation of the model instruments in spacecraft solution 2. Platform equipment would be accommodated within the volumes, which are indicated by brown covers in this drawing.*

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.

This instrument accommodation resulted from the detailed assessment study that was carried out for repeated Callisto flybys and Ganymede orbit observations. With the addition of a few Europa flybys it became necessary to allow all instruments to operate simultaneously with optimum field of view/access to space for *in situ* instruments. Therefore the accommodation will further be optimised in the next phase.

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 minimise 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, one part supporting the propellant tanks, the other 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 7-18**). 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 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 would be 27.5 m.

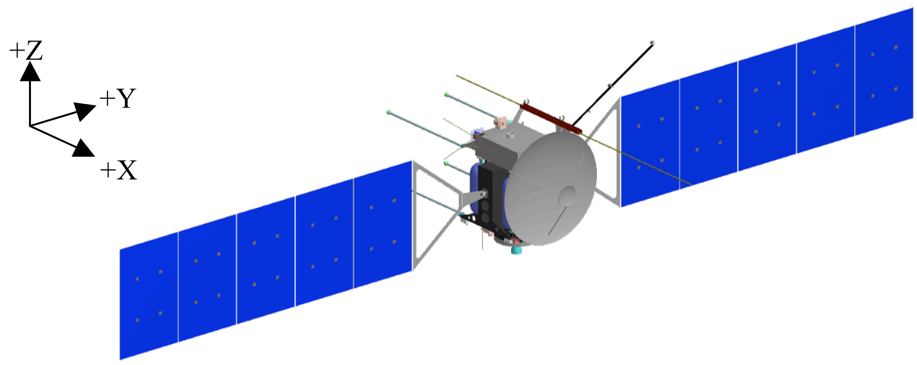


Figure 7-18 *Spacecraft configuration of solution 3. The main engine and the launcher interface are at the –Z side. The nadir direction is at the +Z side (up), and main component of the velocity remains parallel to the –X direction for all observing modes.*

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 (+Z axis), 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 between remote sensing and *in situ* observations. As with the other solutions, the illumination of the solar panels would be optimised by rotation of the spacecraft 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 minimise 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 on the outside of the main compartment, at the –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 2418 kg. 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 optimised for Low-Temperature-Low-Intensity (LILT) operations with a capability of 680 W at end-of-life. The total energy provided by the battery would be 5100 Wh, supporting an eclipse duration of 8.5 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 or Europa 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 operating simultaneously, meeting the baseline data volume of 1.4 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 from the Sun, when seen from Jupiter, and would therefore allow the MGA to be simply 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 optimise 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 area of 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 7-19**. The remote sensing instruments would have access through the +Z panel, and the *in situ* instruments would have access through the –X panel (left in **Figure 7-19**), 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.

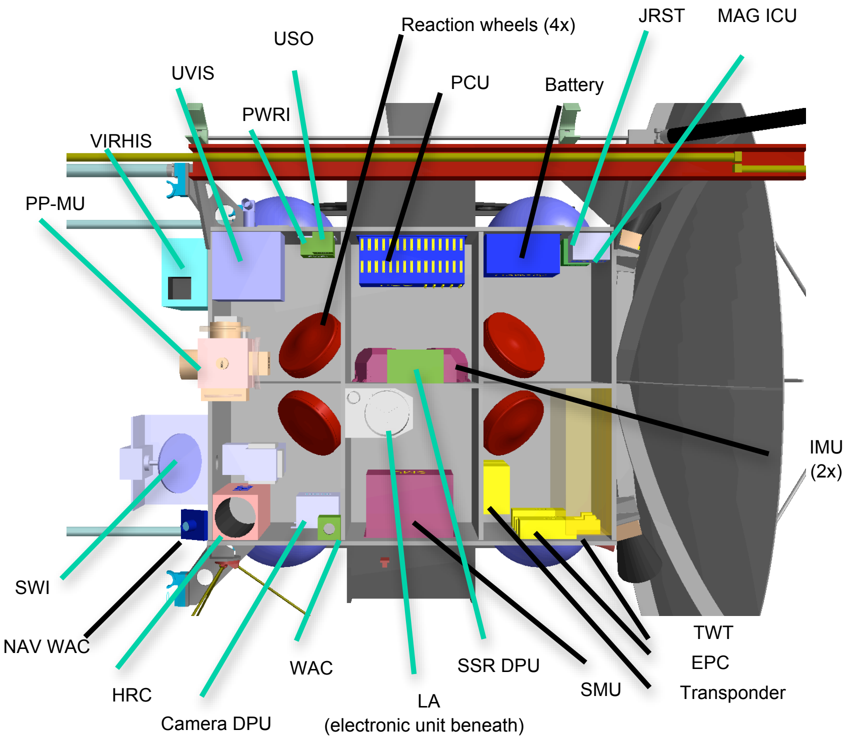


***Figure 7-19** Accommodation of the model instruments and platform units in spacecraft solution 3.*

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 would be mounted on the main compartment, except the RPWI booms, which would be 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 avoiding interference with the field of view of the remote sensing instruments. The structural support for the magnetometer boom would be shared with the subsurface radar boom The subsurface 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 the 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 on the –X panel.

7.5 Mass budgets

Table 7-3 summarises 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 [D-6]). All solutions are compatible with the launch requirements with spare mass.

7.6 *Electromagnetic Compatibility*

Baseline 2022 Item	Solution 1 [kg]	Solution 2 [kg]	Solution 3 [kg]
S/C			
Total Dry	1453.08	1493.53	1255.11
Structure	238.1	281.5	139.1
Shielding	155.4	175.2	163.5
Thermal CS	66.6	38.3	38.5
Mechanisms	40.2	25.4	48.4
Communications	93.9	99.7	56.3
Data Handling	22.8	26.3	40.5
Power	371.0	362.9	380.6
AOCS	52.1	60.8	48.6
Propulsion	221.9	235.4	219.9
Harness	85.0	72.0	0.0
Instruments	106.2	116.0	119.6
System Margin	290.6	298.7	251.0
Propellant	2887.0	2938.0	2417.8
Adapter	155.0	155.0	155.0
S/C wet	4785.7	4885.2	4078.9
Max launch	4959.0	4959.0	4959.0
launch margin	173.3	73.8	880.1

Table 7-3 *Mass budgets for the spacecraft solutions studied. All values are including margin, and a system margin is also included. Differences in instrument masses are due to different accounting for antennae, etc. The design solution 3 was studied in less detail.*

For the sensitivity of the fields and particles measurements to be achieved in full, 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 Volt, at least in the vicinity of the electric field sensors and the low energy plasma 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 these goals may be met with limited specific measures. This will be discussed in the next study phase in more detail together with the instrument teams when more detailed geometric specifications and simulations will be available.

7.7 *Planetary Protection*

The mission will include a limited number of flybys of Callisto, Ganymede and Europa, and will then finally go into orbit around Ganymede and will be disposed on Ganymede's surface. The highest Planetary Protection Category targets are Europa and Ganymede.

Europa is a Planetary Protection Category III target ("chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination which could jeopardise a future biological experiment"). The mission therefore either needs to demonstrate that the likelihood of collision with Europa is $<10^{-4}$, or undergo active bioburden reduction to meet the requirement that the probability of inadvertent contamination of the Europa ocean is $<10^{-4}$. The risk of collision with Europa is limited to the period of the Europa flybys. Before and after this 36 day period the spacecraft has a perijove higher than Europa's orbit, such that collisions are sufficiently unlikely within the timeframe of concern (several 100 years). Assuming collision likelihood with Europa of 1%, after a complete spacecraft failure and including a factor of 5 margin, the likelihood of failures of critical spacecraft subsystems has to be $<2\times10^{-3}$. This has to be demonstrated for a period of 36 days, after about 10 years of operations (worst case interplanetary transfer plus Jupiter tour until start of Europa flyby sequence), and relates to a mean rate of failure of 6.7×10^{-5} per day. The system must demonstrate failure tolerance to this level for critical subsystems (AOCS, communications, autonomy, etc) either autonomously providing failure correction or avoidance manoeuvre capability. The nominal environment to be considered includes, most importantly, ionizing radiation and micro-meteorites. A preliminary review of the spacecraft's subsystem reliability over this short period indicates that this mean failure rate appears to be feasible; however more detailed investigations need to be performed, including failure tree-analysis and associated likelihoods and consequences at system level. Also the micro-meteorite assumption will be reviewed. On approach for the Europa flyby, the targeting will be performed using an offset strategy in that the spacecraft trajectory will be corrected in steps (step-in approach) such that Europa always remains outside the 3 σ uncertainty. The project will include a reserve for active bioburden reduction, should this prove to be necessary. This is included in the project costs as a risk item.

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* identified additional requirements [D-7]. For Ganymede the bio-burden brought to it shall be controlled and limited such that the likelihood of one active organism reaching the Ganymede subsurface ocean shall be $<10^{-4}$. For the calculation of the likelihood of bringing a surviving organism to the Ganymede subsurface ocean, the recommendations in [D-8] are 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.

Furthermore, collateral probability of contamination of alternative critical bodies, such as Mars by any part of the flight segment, including any part of the launch vehicle within 50 years shall be smaller than 10^{-2}. The baseline and backup launch opportunities do not consider Mars gravity assists, and it will be demonstrated that neither the spacecraft nor any part of the launcher will impact Mars within this timescale. Early assessment confirmed this assumption.

7.8 Critical Elements and Drivers

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

The main JUICE mission challenge is due to the high intensity radiation environment. This requires careful modelling and therefore radiation transport simulations will be performed at increasing level of detail, such that the spacecraft configuration can efficiently be optimised early in the design also with respect to radiation shielding.

Existing GaAs based triple junction solar cells showed for a fraction of the cells manufactured a lower than expected efficiency when operated in 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 improvement of the reliability of cells production using a minor change in the layout. An ongoing activity is focusing on demonstrating this increased reliability with a larger sample and is showing promising results. As a backup, it was assumed during the studies that a careful selection of cells at low temperature could be performed to provide cells with adequate 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 JUICE 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 development is ongoing towards a more powerful launching capability than the nominal Ariane 5 ECA version is being developed, which was assumed for this study. Alternatively the mission profile could be changed mainly resulting in a longer interplanetary transfer to Jupiter by reducing the escape velocity. Preliminary solutions were analysed and demonstrated higher available launch mass capability. Furthermore the reduction of the total consumed power would directly result in a reduced solar array size requiring phased operations.

7.9 Mitigation of Technical Risk

Significant effort was spent on simulations of the radiation environment. The current model combines the latest interpretation of the available measurements, and uses conservative assumptions. In addition a margin of a factor of two based on the mean radiation environment model will be included for the mission implementation.

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 three 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 2012.

The majority of other preparatory technical development activities are related to component validation in a high radiation environment. Investigating the limits of radiation tolerance of electronic components provides a higher precision of the required shielding. The following validations are being pursued:

- Survey of critical components for power converters
- Radiation characterisation of radiation tolerant optocouplers, sensors and detectors
- Characterisation of radiation resistant materials
- Characterisation 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 each of 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 Conclusion

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

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.

8 Mission and Science Planning and Operations

The JUICE mission would be planned and operated by the ESA ground segment that consists of the Mission Operation Centre (MOC) and the Science Operation Centre (SOC). The Project Scientist (PS), advised by the Science Working Team (SWT), would provide science guidance and monitor all science related issues. This chapter summarises the main philosophy and structure of the mission and science planning, operations and archiving system as well as the main functionalities of the parties involved.

8.1 Mission Operations

JUICE would be operated by an "off-line" monitoring and control approach. A pre-scheduled timeline would be uploaded by the MOC at regular intervals, stored onboard and executed according to the schedule. Monitoring would also be off-line, due to the signal travel time and due to the non-continuous contact with the ground.

A single ground station is assumed for JUICE, either Cebreros or Malargüe. It is assumed they would be capable of both X- and Ka-band operations, at the time of the mission. Due to the elevation of Jupiter over the ground stations, Malargüe would be more favourable during all phases of the mission. 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.

During 7.6 years of transfer to Jupiter the spacecraft would nominally be tracked once per week (TBC), except for the planetary flybys when special operations would be carried out. Instrument health checks would be performed at regular intervals. Starting from 6 months (TBC) before the Jupiter Orbit Insertion (JOI) the spacecraft would be tracked once per day and regular science operations would commence. During Europa, Ganymede and Callisto flybys continuous tracking would be required for achieving the flyby radio-science, if it would be performed in parallel with remote sensing and *in situ* observations.

The MOC would be responsible for the mission operations and would be the only interface between the ground and the spacecraft. It would also support the mission by trajectory analysis and navigation during the gravity assist manoeuvres at Venus and Earth, JOI and GOI manoeuvres, the Callisto and Europa flyby sequences, the gravity assist manoeuvres at Callisto and Ganymede, the orbit circularisation and transfer manoeuvres at Ganymede. Five science phases in the beginning of the mission (**Table 5-1**) are of "touring" type. Relevant "touring mission" experience gained in the Cassini mission (Paczkowski and Ray, 2004) would be taken into account. After the Ganymede orbit insertion JUICE would have typical features of a "mapping" mission. The MOC would use operational concepts developed for and proven with ESA Solar and Planetary Science missions (Rosetta, VEX, MEX, BepiColombo, SOHO) adapted for particular features of JUICE. The concept of the ground segment shall be based on maximum sharing and reuse of manpower, facilities and tools from the previous ESA missions.

8.2 Science Planning and Operations

The SOC science planning and operations tasks include: (1) support of the top-level science activity planning, e.g., by analysis of observation opportunities, associated with trajectories and pointing; (2) generation and validation of the instrument command sequences (timelines); (3) monitoring of technical aspects of the instrument operations and performance with feedback to the PI teams; (4) evaluation of the science and instrument house-keeping telemetry data received from the MOC, initiation of the data processing pipeline, and quick-look data analysis in collaboration with the PS and PI Teams; (5) development and maintenance of the long-term Planetary Science Archive (PSA) including verification and ingesting of the data products, development of visualisation tools and maintaining a centralised repository of all operationally relevant data generated by MOC; (6) support of the pre-launch ground system validation tests, in-flight commissioning phases and regular in-flight instrument health checks; (7) acting as an interface between the PI teams and the MOC in close collaboration with the PS, the Science Working Team (SWT), the Science Operations Working Group (SOWG).

Science aspects of these activities are guided, monitored and advised by the Project Scientist, who chairs the Science Working Team (SWT), which would consist of instruments' Principal Investigators (PI), representatives of their teams, and Interdisciplinary Scientists (IDS). The functionalities of the PS and SWT related to the science planning and operations are defined as follows: (1) mission strategic planning and development of the long-term Science Activity Plan (SAP); (2) monitoring and advising on science aspects during the SAP implementation, data processing, archiving and distribution; (3) monitoring and advising on the science aspects of observations and tracing the science return back to the goals stated in the mission science requirements; (4) advising on science aspects of engineering models required for science and mission operations.

Figure 8-1 shows the sketch of the JUICE planning and operations concept. The PS and SWT supported by the SOC would define the SAP content based on the mission science priorities. Later, at the stage of the medium and short-term planning, the SOC would implement the SAP by planning and scheduling operations of individual instruments using inputs from the PI teams. The SOC would convert the PI observation requests into sequences of instrument telecommands and iterate them with the PI teams and PS to resolve conflicts between the requests, with flight rules and spacecraft resources. The commands would then be delivered to the Mission Operations Centre. The MOC would assemble and check the final commanding sequences and upload them to the spacecraft for execution.

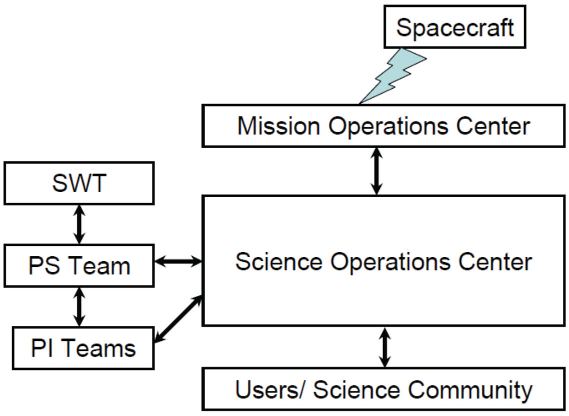


Figure 8-1. *JUICE planning and operations concept*

The MOC would receive science and housekeeping data from the spacecraft and distribute it to the SOC and the PI teams for analysis. The SOC, with inputs from the PI teams, would develop, maintain and run the data processing pipeline from raw telemetry to un-calibrated data (level 1b). The SOC would also perform quick-look analysis of the data. The generation of calibrated data (level 2/3) would be performed either by the PI teams, or by a centralised data processing pipeline at SOC, to be developed in close collaboration with the PI teams. The SOC would also ensure the long term archiving of the calibrated and un-calibrated data products. This activity would include verification and ingesting of the data products into the dedicated ESA Planetary Science Archive (PSA) and assisting the science community in using them.

9 Management

The development, launch and operations of JUICE will be led by ESA. The operations will be planned and conducted, taking into account the guidelines and priorities established by the science teams. ESA will appoint a Science Working Team (SWT) for JUICE. The SWT will be chaired by the PS and will develop strategic science activity planning. This section summarises the envisaged management approach for the Implementation and Operation Phases of JUICE and addresses the following mission management issues:

- Project Team, spacecraft and payload procurement, project schedule.
- Operations management, including mission and science operations.
- Science management, including PST, SWT, and data rights.

9.1 Overall ESA Management of JUICE

ESA will have overall responsibility for:

- The overall spacecraft definition and implementation
- Provision and integration of the spacecraft bus and payload interfaces
- Payload integration and system testing
- Spacecraft launch
- Mission operations
- Science planning and operations, data distribution and archiving

9.2 Mission Definition, Development and Implementation

Should JUICE be down-selected the mission will move into the definition phase (Phase A/B1). If the mission is adopted, a development and implementation phase will be started with one industrial prime contractor selected via competition by ESA. The prime contractor will be responsible for the design, manufacturing, integration, testing and assembly of the spacecraft. ESA will control and monitor the project.

9.3 Instrument Selection and Procurement

Instruments will be selected in the framework of the open and competitive Announcement of Opportunity (AO) process initiated and carried out by ESA. The AO will be open to European scientists as well as to scientists from other countries with which reciprocity or specific agreements exist. The payload procurement scheme is based on the concept that the instruments associated processing, data handling, and control components, will be provided by Principal Investigator teams funded by national Lead Funding Agencies (LFA). The LFAs will be responsible vis-à-vis ESA for all financial matters related to the selected investigations, namely, the instrument development and manufacturing programme, operations, data reduction and archiving. LFAs will have full responsibility for the instrument development. The instrument models will be delivered to ESA by the PI teams and will be supplied as customer furnished items to the industrial team for integration. The distribution of roles and responsibilities between ESA and LFA will be defined in a Multi-Lateral Agreement (MLA).

9.4 Payload Model Philosophy

The spacecraft assessment studies have concluded in a Proto-Flight Model development approach as the baseline, supported by a Structural Model and a functional Electric Model. All experiments will deliver instrument models of adequate detail to fully support the system tests with each model. The Structural Model will be integrated as the first model, and will be used for mechanical and thermal verification. The functional Electric Model will support tests 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 would be manufactured depending on criticality, and will range from sub-unit to spare kit level.

9.5 Schedule

A tentative schedule of the development phases is shown in **Figure 9-1**. The JUICE instrument AO would be released in the 2nd half of 2012 following a successful down-selection in the 2nd quarter of 2012. The Definition Phase (A/B1) system study is expected to start in late 2012 for a period of about 24 months, with the objective to enable final adoption of the mission mid 2014. The planned launch would be carried out in July 2022, resulting in an arrival at Jupiter in January 2030 and having about 3 years of operations at Jupiter.

The definition phase would 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 implementation 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), followed by Preliminary Design Review (PDR), Critical Design Review (CDR) and Flight Acceptance Review (FAR) (**Figure 9-1**). The implementation phase would last slightly less than 5.5 years. The schedule includes a longer than nominal contingency of more than one year, which is considered adequate for a planetary mission, having limited launch opportunity windows, which occur roughly on a yearly basis causing a delta of about one year, if missed. A launch opportunity in 2021 is available too.

The instrument development would follow the spacecraft development and implementation schedule, with an AO being issued in parallel with the ITT for the Definition Phase. The key delivery dates of instrument development models are also indicated in **Figure 9-1**.

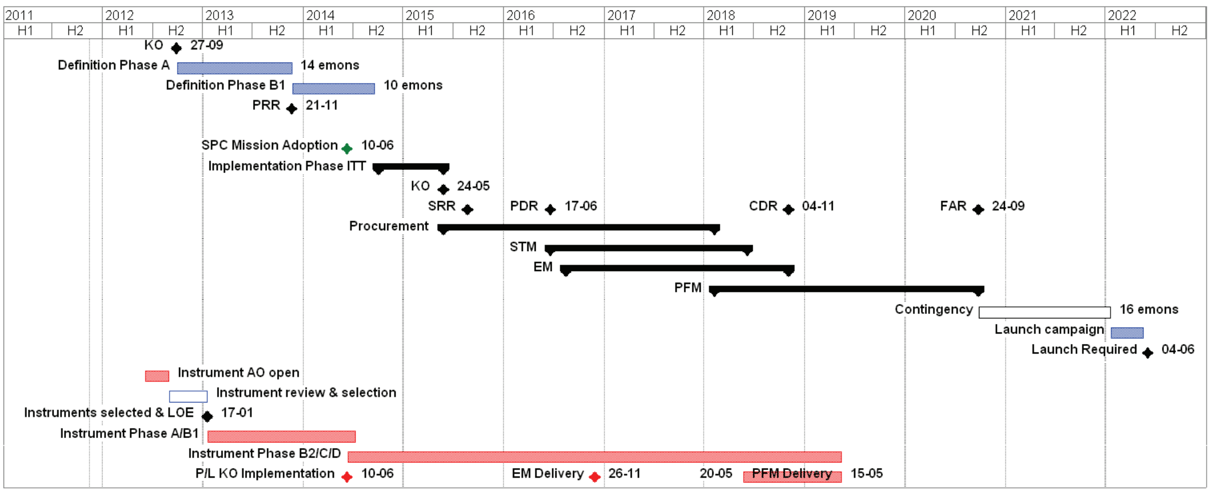


***Figure 9-1**. Preliminary outline of the JUICE schedule*

9.6 Mission and Science Planning and Operations

ESA will be responsible for all JUICE operations by implementing a Mission Operation Centre (MOC) and a Science Operations Centre. The SOC will be developed in close collaboration with the PI teams (section 8).

The MOC will be responsible for the mission operations, preparation and implement of hardware and software for all facilities, including ground station(s) and mission operations center. The MOC will include flight dynamics, commanding and health monitoring of spacecraft and instruments.

The SOC will be responsible for science operations. The Project Scientist will provide guidance to SOC on all science related issues of the operations, data processing, and archiving. The JUICE science data will be archived in the ESA's Planetary Science Archive (PSA). The data archive products delivery will be under the responsibility of the PI teams. The overall responsibility of mission operations is with a Mission Manager.

9.7 Science Management

Once the mission enters the implementation phase, ESA will nominate a PS. The PS will be the Agency's interface with PIs and advise the Project and the Ground Segment on all scientific matters of the mission. The PST will monitor the instrument developments and procurements, will provide science guidance in preparation for operations and data processing and archiving in order to ensure that the mission eventually fulfils its science goals.

Exclusive data rights will reside with the PI teams for a maximum of 6 months. After the proprietary period the PIs should make available the level L2 (uncalibrated) and L3 (calibrated) data to the scientific community at large through the ESA Planetary Science Archive (PSA). PIs will be responsible for analysis of the data from their instruments and for timely publication of the results in scientific and technical journals and at conferences. The SWT will develop the rules that regulate publication rights during the proprietary period on investigations involving several instruments. Respecting the right of the JUICE PI teams to keep the data for internal evaluation and early publications during the 6 months proprietary period, the mission data and results will be open to as broad as possible science community and public through immediate release of all quick look data in the form of plots, images, diagrams and informal regular releases of L2 data during Ganymede orbital phase and the moons flybys.

9.8 Public Outreach and Science Communication

JUICE is expected to attract broad public interest. Hence, the mission will be given adequate exposure within the communication activities of the Science Programme. ESA would have the overall responsibility for planning and would be coordinating with national agencies activities around key milestones and major achievements of the mission. Such outreach activities will be supported by the members of the SWT. Preliminary results and high level data products will, as appropriate, be published at such outreach activities.

An outreach and science communication plan will be developed early in the mission implementation phase by the Study Scientist Team in collaboration with the ESA Science Programme Communication Service. The plan will be regularly updated as the mission progresses. In coordination with the PI teams and press offices of the lead funding agencies, ESA will highlight the major milestones and achievements in the mission development and implementation, operations and data analysis through regular media events, web and press releases. During the development phase of the mission ESA will set up web pages for the general public and the media. With the progress of the mission these web pages will be enriched with more material and features related to the mission. This service will work in full coordination with the scientific individuals responsible for the mission (Project Manager, Project Scientist, Principal Investigators, Interdisciplinary Scientists etc.). Regular releases of data for Public Relations will be an important part of this activity.

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10.2 Documents

[D-1] Payload Definition Document for the Jupiter Ganymede Orbiter of the Europa Jupiter System Mission, SCI-PA/2008.029/CE, issue 2.5, 11 February 2010

[D-2] Jupiter Ganymede Observer Missions Requirements Document, SCI-PA/2008.045/ASAWCE issue 3.2, April 2009

[D-3] JGO: Consolidated Report on Mission Analysis, WP 557, 29 July 2010

[D-4] Radiation Environment Specification for the Jupiter Mission Reformulation Activities, SRE-PA/2011.050/CE, issue 1.3, 10 August 2011

[D-5] Laplace Radiation Environment, JS-10-09, issue 3.1, 18 June 2010

[D-6] Margin Philosophy for SCI-PA Studies, SCI-PA/2007-022, issue 1.0, 19 November 2007

[D-7] Preliminary Jupiter Ganymede Orbiter (JGO) Planetary Protection Categorization, TEC-Q/09-6991, 8 May 2009

[D-8] J. Rummel, F.Raulin and P. Ehrenfreund, eds. 2010, COSPAR Workshop on Planetary Protection for Titan and Ganymede, COSPAR, Paris, 29 pp

[D-9] Laplace Mission Assumptions Document, DOPS-MGT-MAD-1002-OPS-HSA, issue 1.0, 12 July 2010

[D-10] Science Operations Assumptions Document