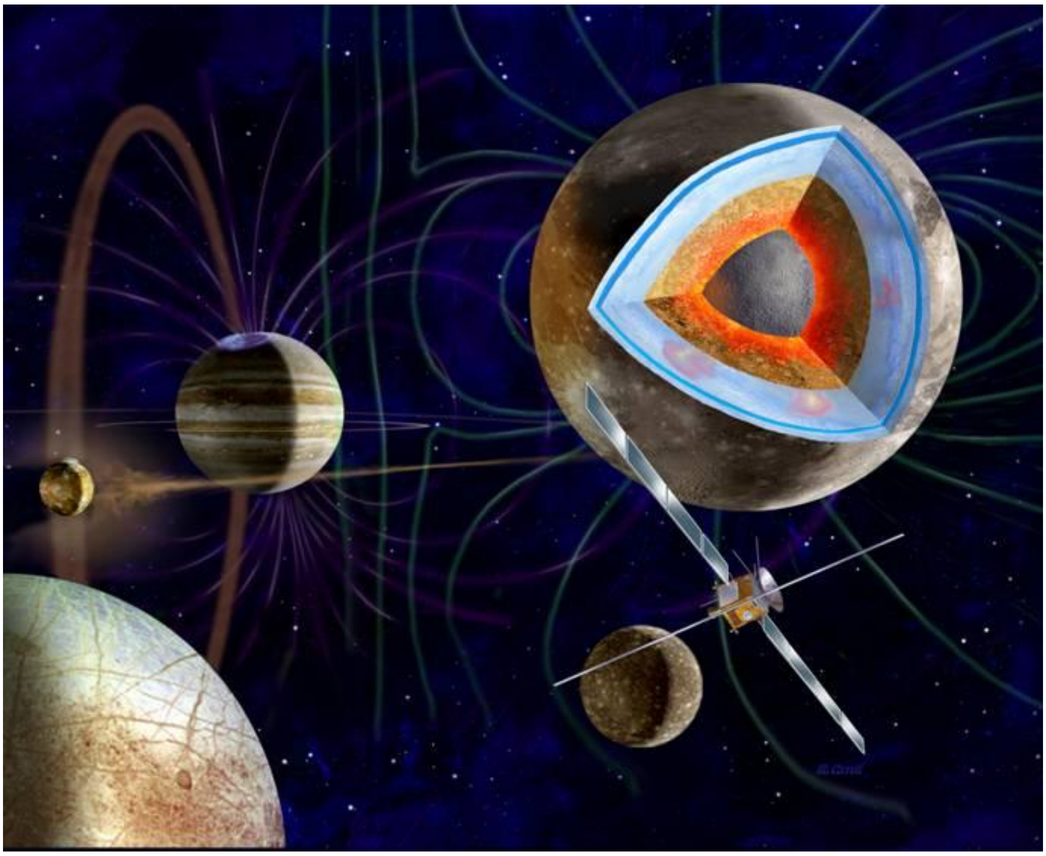
ESA/SRE(2014)1
September 2014

JUICE

JUpiter ICy moons Explorer

Exploring the emergence of habitable worlds around gas giants



Definition Study Report

European Space Agency

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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
Payload	**Ten instruments** Laser Altimeter Radio Science Experiment Ice Penetrating Radar Visible-Infrared Hyperspectral Imaging Spectrometer Ultraviolet Imaging Spectrograph Imaging System Magnetometer Particle Package Submillimetre Wave Instrument Radio and Plasma Wave Instrument
Overall mission profile	06/2022 - Launch by Ariane-5 ECA + EVEE Cruise 01/2030 - Jupiter orbit insertion <u>Jupiter tour</u> 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 <u>Ganymede tour</u> Elliptical and high altitude circular phases (5 months) Low altitude (500 km) circular orbit (4 months) 06/2033 – End of nominal mission
Spacecraft	3-axis stabilised Power: solar panels: ~900 W HGA: ~3 m, body fixed X and Ka bands Downlink $\geq$ 1.4 Gbit/day High Δv capability (2700 m/s) Radiation tolerance: 50 krad at equipment level Dry mass: ~1800 kg
Ground TM stations	ESTRAC network
Key mission drivers and technology challenges	Radiation tolerance Power budget and solar arrays Mass budget
Responsibilities	ESA: manufacturing, launch, operations of the spacecraft and data archiving PI Teams: science payload provision, operations, and data analysis

Foreword

The JUICE (JUpiter ICy moon Explorer) mission, selected by ESA in May 2012 to be the first large mission within the Cosmic Vision Program 2015–2025, will provide the most comprehensive exploration to date of the Jovian system in all its complexity, with particular emphasis on Ganymede as a planetary body and potential habitat. Investigations of the neighbouring moons, Europa and Callisto, will complete a comparative picture of the environmental conditions on the Galilean moons and their potential habitability. 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 range of different disciplines including geologists, astrobiologists, magnetospheric and atmospheric scientists. The goals of JUICE flow from the priorities of the Cosmic Vision program as defined by the science community. They have been refined during the study phases in synergy with technical studies so as to optimize mission design.

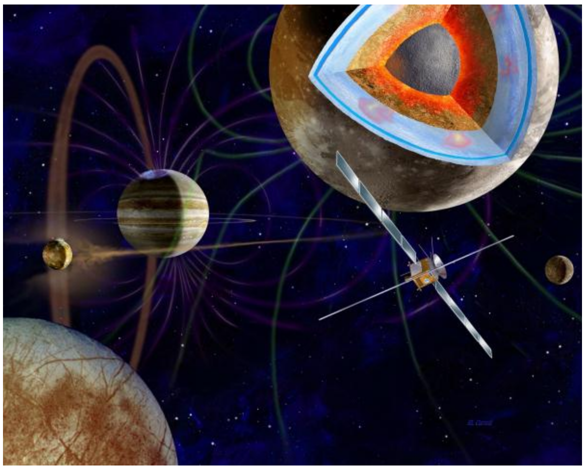

Figure 1. *Artist's impression of the JUICE spacecraft in the Jovian system. Credit: Artist M. Carroll.*

The diverse environments of the four Galilean moons have always been tantalising destinations for future exploration ever since their discovery four centuries ago. Flybys of these worlds during the space era have revealed stark differences between these four worlds, from volcanic Io, to icy Europa, giant Ganymede and ancient Callisto, and raised the exciting prospect that some of these worlds might harbour sub-surface liquid oceans and potentially habitable conditions. The comparative characterisation of the Galilean satellites' surfaces, sub-surfaces, oceans, interiors, tenuous exospheres and interactions with Jupiter's giant magnetosphere will provide a comprehensive view of habitable conditions in the Jovian system as the paradigm for giant planet systems throughout our galaxy.

JUICE is the necessary step for future exploration of our outer Solar System, extending and complementing Cassini's exploration of the Saturn system and the Galileo and Juno explorations of Jupiter and its system. It is now time to characterise the potential habitable worlds Ganymede, Europa, and Callisto. JUICE will also provide a thorough investigation of the Jovian 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. It played an essential role in the development of our own habitable environment. JUICE will therefore contribute to a better understanding of the origins of our solar system. JUICE will address two of the key science themes of ESA's Cosmic Vision (2015-2025): *"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 Definition Study (Phase B1), including a description of the mission science objectives and requirements, payload, mission scenario, science operations and expected science return, the main features of the spacecraft design, and the proposed management approach. The document was written by the JUICE Science Working Team with support from experimental teams and the ESA Technical Study Team.

The JUICE Science Working Team

September 2014

Authorship, acknowledgements

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Valuable contributions were provided by members of the JUICE experimental teams, in particular by the Co-investigators: J. Bergman, E. Bunce, G. Cimo, A. Coustenis, G. Cremonese, M. Di Bendetto, H. Hoffmann, K. Retherford, P. Tortora.

The ESA study was led by Christian Erd, ESA Study Manager with support from Dmitri Titov, ESA Study Scientist; Martin Gehler and Philip Willemsen, System Engineers; Philippe Gare, Nathalie Boudin, Ludovic Duvet, Ignacio Torralba Elipe, Torgeir Paulsen, Arno Wielders, ESA Payload Team. Support was provided by Fabio Favata and Luigi Colangeli, ESA's Planning and Coordination Office.

Support to the ESA study was provided by: A. Boutonnet, J. Schoenmaekers, G. Boscagli, M. Lanucara, D. Gherardi, L. Duvet, F. Torelli, P. Nieminen, N. Altobelli, G. Santin, F. Panin, M. Smith, R. Peyrou-Louga, C. Baur, A. Junge, A. Accomazzo, E. Montagnon, I. Tanco.

The two industrial studies were conducted by Consortia led by: Airbus DS and Thales Alenia Space.

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

Scope, structure and table of content

This document provides a scientific, technical and management summary of the JUICE definition study that was performed from February 2012 to October 2014. The report is structured in such a way so as to guide a reader through all aspects of the JUICE mission including scientific objectives and requirements, mission scenario, operations and expected science return, and payload. The executive summary provides a general overview of the document. Sections 2 and 3 describe the JUICE science objectives and requirements. Section 4 reviews the main characteristics of the payload. Section 5 presents the mission analysis and current baseline scenario. It describes also the main features of the spacecraft design, and the planetary protection approach. Due to the ongoing competition between two industrial contractors for construction of the spacecraft, this document presents only basic spacecraft features omitting the details of the industrial studies. Section 6 outlines main features of the science observation strategy at key targets within the Jupiter system and contains a preliminary analysis of the expected science return. Section 7 presents a few examples of science benefits potentially allowed by the mission flexibility, in addition to the objectives achievable by the baseline mission. In the last section, the mission management approach and schedule are described.

Contents

1 Executive Summary

Galileo Galilei's discovery of four large moons orbiting Jupiter four centuries ago spurred the Copernican Revolution and forever changed our view of the Solar System and universe. Today, Jupiter and its diverse collection of moons is seen as the archetype for giant planet systems both in our Solar System and around other stars throughout our Galaxy. A comprehensive characterisation of the Jovian system, from the churning gas giant and its enormous magnetosphere to the orbiting rock/ice worlds in all their complexity, will allow us to unravel the origins of the giant planets and their satellites and search for evidence of potentially habitable environments in the cold outer solar system. By dedicating a mission to explore the Jovian system with particular focus on Ganymede as a planetary habitat, JUICE will significantly deepen our understanding of the conditions for the emergence of life and how our Solar System works, two themes at the heart of ESA's Cosmic Vision.

Science background. In 1995, the Galileo spacecraft arrived at Jupiter to conduct the first detailed orbital exploration of the Jovian system in the footsteps of previous flyby missions (*Pioneer 10-11, Voyager 1-2,* and *Ulysses*). Despite the limitations, *Galileo* made a plethora of new discoveries, especially concerning the four Galilean satellites, each of which was revealed as a unique world and a fascinating destination for further in-depth exploration. Most importantly, *Galileo* discovered strong evidence for the existence of subsurface oceans hidden beneath the icy crusts of Europa, Ganymede and Callisto, leading to the emergence of a new habitability paradigm that considers the icy satellites as potentially habitable. The recent discovery of water geysers erupting from Europa has helped to solidify this new paradigm, and offers the tantalising prospect of direct access to the materials contained within the hidden sub-surface ocean. If extrasolar planetary systems share a common planetary architecture to our own solar system, then icy satellites of gas giants, having a subsurface liquid water ocean, could be the most common habitats in the universe, potentially 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 JUICE's 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 detailed JUICE characterisation of the wider Jovian system will extend Juno's focussed 2016-2017 study of Jupiter's interior and inner magnetosphere, and is the next logical step in our exploration of the outer solar system after Cassini's exploration of the Saturn system.

JUICE science objectives. 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 even under the most extreme of environmental conditions. Is the origin of life unique to our planet or could it occur 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 could have developed in other Solar System environments and 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 an 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 the smaller moons. The mission will also characterise the diversity of processes in the Jupiter system that 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. The advanced instrumentation carried by JUICE will also permit extensive new 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 to further enhance our understanding of the evolution and dynamics of the Jovian system. The long-term Jovian magnetospheric and atmospheric science will push significantly beyond the capabilities of previous missions like Galileo, and directly complement the results of the short-lived Juno mission. The JUICE science objectives are summarised in **Table 1-1**.

JUICE mission scenario. Following a launch with Ariane 5, JUICE will use an Earth-Venus-Earth-Earth gravity assist strategy to reach Jupiter. The nominal launch date is in September 2022, with an arrival at Jupiter in July 2030. There are back-up launch opportunities in 2023 and 2024. After insertion into Jupiter orbit, JUICE will use multiple gravity assists via flybys of the Galilean satellites to shape a comprehensive orbital tour over ~3.5 years. After reducing the orbit period with Ganymede flybys, this tour will implement two close Europa flybys, then a series of Callisto flybys so as to reach an inclination of 22° with respect to the equatorial plane of Jupiter. A dedicated series of Callisto and then Ganymede gravity assists will make it possible to approach Ganymede at a low velocity. During the tour, Jupiter's magnetosphere and atmosphere will be continuously monitored. At the end of the tour, JUICE will be set in a polar orbit around Ganymede, becoming the first spacecraft in history to enter orbit around an icy satellite in the outer solar system. This dedicated orbital phase will provide a comprehensive survey of the Solar System's largest planetary satellite. The current end of mission scenario involves spacecraft disposition on Ganymede.

The spacecraft uses 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. JUICE will be the second Jovian mission using solar arrays as the power source, following Juno. New technologies are not required to execute the current mission concept, although ongoing developments are focusing on lowering instrument mass and radiation designs. JUICE's trajectory will remain outside of Jupiter's inner radiation belts to provide a long-lived, stable and versatile platform to accomplish the broad range of science objectives.

This robust scenario provides an outstanding science return fulfilling the science goals and measurement objectives of JUICE as described in Sections 2 and 3. Existing flexibility in the tour design would potentially allow the options with an increased inclination of the orbit around Jupiter and/or a lower orbit at Ganymede that require modest additional Δv resources which are consistent with the spacecraft design and are in line with the science strategies examined at earlier stages of the JUICE study.

Table 1-1. *Science objectives of JUICE.*

Explore the habitable zone: Ganymede, Europa, and Callisto	
Ganymede as a planetary object and possible habitat	Characterise the extent of the ocean and its relation to the deeper interior
	Characterise the ice shell
	Determine global composition, distribution and evolution of surface materials
	Understand the formation of surface features and search for past and present activity
	Characterise the local environment and its interaction with the Jovian magnetosphere
Europa's recently active zones	Determine the composition of the non-ice material, especially as related to habitability
	Search for liquid water under the most active sites
	Study the recently active processes
Callisto as a remnant of the early Jovian system	Characterise the outer shells, including the ocean
	Determine the composition of the non-ice material
	Study the past activity
Explore the Jupiter system as an archetype for gas giants	
The Jovian atmosphere	Characterise the atmospheric dynamics and circulation
	Characterise the atmospheric composition and chemistry
	Characterise the atmospheric vertical structure
The Jovian magnetosphere	Characterise the magnetosphere as a fast magnetic rotator
	Characterise the magnetosphere as a giant accelerator
	Understand the moons as sources and sinks of magnetospheric plasma
The Jovian satellite and ring systems	Study Io's activity and surface composition
	Study the main characteristics of rings and small satellites

JUICE payload. The JUICE spacecraft will carry a highly capable suite of ten state-of-the-art scientific instruments. The remote sensing package includes spectro-imaging capabilities from the ultraviolet to the near-infrared, an imaging system and a submillimetre wave instrument. The geophysical package includes laser altimetry and radar sounding for exploring the surface and subsurface of the moons. The radio science instruments complement the remote sensing package (to enable probing of the Jovian/satellite atmospheres) and the geophysics package (enabling estimation of gravity fields). The *in situ* package includes a magnetometer, a radio and plasma wave instrument as well as a particle package. This payload suite will be supported by an experiment, PRIDE (Planetary Radio Interferometry and Doppler Experiment), using ground-based Very-Long-

Baseline Interferometry, to improve the ephemerides of the Galilean satellites and characterise the physical parameters and morphology of their surfaces. Since the selection of the payload in 2013 a thorough effort has been made to ensure that the numerous scientific 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) can be achieved with the selected payload, with important benefits of synergies between individual measurements (**Table 1-2**).

Table 1-2. *JUICE payload.*

Instrument	Acronym	Science Contribution
Radio Science Experiment	3GM	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.
Laser Altimeter	GALA	Topography and tidal deformation of Ganymede
Imaging System	JANUS	Local-scale geologic processes on Ganymede, Europa, and Callisto; Io Torus imaging, Jupiter cloud dynamics & structure Global morphology of the Ganymede surface. Global to regional scale morphology of the Callisto and Europa surface Physical and dynamical properties of minor moons and rings
Magnetometer	J-MAG	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.
Visible-Infrared Hyperspectral Imaging Spectrometer	MAJIS	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.
Particle Package	PEP	Complete plasma composition and distribution in the Jovian magnetosphere. Interaction between Jovian magnetosphere and Ganymede, Europa and Callisto. Energetic Neutral Atom imaging of neutral and plasma tori of Europa and Io, and magnetospheric energetic particle injections. Composition and structure of exospheres and ionospheres of the moons, and response to plasma precipitation.
Ice Penetrating Radar	RIME	Structure of the Ganymede, Europa and Callisto subsurface; identify warm ice water "pockets" and structure within the ice shell; search for ice/water interface.
Radio and Plasma Wave Instrument	RPWI	Ganymede: Exosphere and magnetosphere; Callisto & Europa: Induced magnetic field and plasma environment; Jovian magnetosphere and satellite interactions
Submillimetre Wave Instrument	SWI	Dynamics of Jupiter's stratosphere; Vertical profiles of wind speed and temperature Composition and structure of exospheres of Ganymede, Europa and Callisto.
Ultraviolet Imaging Spectrograph	UVS	Composition, structure & dynamics of the atmospheres of Ganymede, Europa, Callisto and Jupiter and their interactions with the Jovian magnetosphere and plasma tori; search for water vapour plumes/geysers.

JUICE industrial studies. Since JUICE was selected in May 2012, two separate industrial studies of the JUICE flight system have been conducted during Phase A/B1. The respective solutions and configurations are based on that of JGO/EJSM-Laplace. They have a 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 objectives are well within current European industrial and technological capabilities and can be achieved by JUICE.

International cooperation. JUICE is an ESA-led mission possessing broad appeal and strong support from planetary scientists. The ten scientific instruments have diverse science teams from across the planetary science community, including co-investigators from many nations to demonstrate the international support for this next step in the exploration of the outer solar system. NASA foresees to contribute with one PI instrument (the UV imaging spectrograph, UVS) and hardware for two European-provided instruments: the ice-penetrating radar RIME, and the plasma package PEP. JAXA foresees to contribute with hardware for various European-provided instruments.

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, the Rosetta cometary rendezvous, the upcoming BepiColombo mission to Mercury, a mission to the Jupiter system that addresses a broad spectrum of fundamental planetary science questions is a natural step in European exploration of our Solar System. The JUICE mission will provide the first orbiter of a Galilean satellite and a comprehensive investigation of the Solar System's largest moon Ganymede. This will be complemented by an integrated comparative study of the entire Jupiter system including the planet itself, its magnetosphere, Europa, Callisto, as well as other satellites and rings. As the first spacecraft orbiting around a planetary moon, JUICE will offer numerous opportunities for education and public outreach activities within 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* explorations of the diverse extreme environments in the distant outer solar system.

2 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 59 moons 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 objectives 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.

2.1 Explore 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 (Roth et al., 2014), 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 are known to generate a magnetic dipole field. Investigating Ganymede, the largest satellite in the Solar System, from an orbiter is essential because of (1) 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 (Gurnett et al., 1996), (4) the possible presence of a subsurface ocean (Schubert et al., 2004, and references therein) and (5) complex couplings between Ganymede, including the subsurface ocean, and the Jovian space environment.

2.1.1 ***Ganymede as a planetary object and potential habitat***

2.1.1.1 *Ocean and its relation to the deep interior*

Observational evidence for the presence of a global subsurface ocean 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). Depth, composition, and conductivity of the ocean, as well as the dynamics and exchange processes between the ocean and the deep interior and the upper ice shell, remain unclear (Vance et al., 2014). On Ganymede the investigation of the icy shell, subsurface ocean and deep interior is one of the main objectives of the mission.

Electrical currents in oceans that contain salts –and hence provide excellent electrical conductivity– can generate secondary magnetic and electric fields in response to the external rotating Jovian magnetic field. Measurements by JUICE at Ganymede at multiple frequencies will constrain the electrical conductivity and extent of Ganymede's ocean. (**Figure 2-1**).

The tidal response of the satellites' icy shells strongly depends on the presence of oceans. The amplitudes of periodic surface deformation on Ganymede are 7-8 m in case of the ocean and a few tens of cm (no ocean). They are large enough to be measured and are indicative of a sub-surface ocean (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 2-1**).

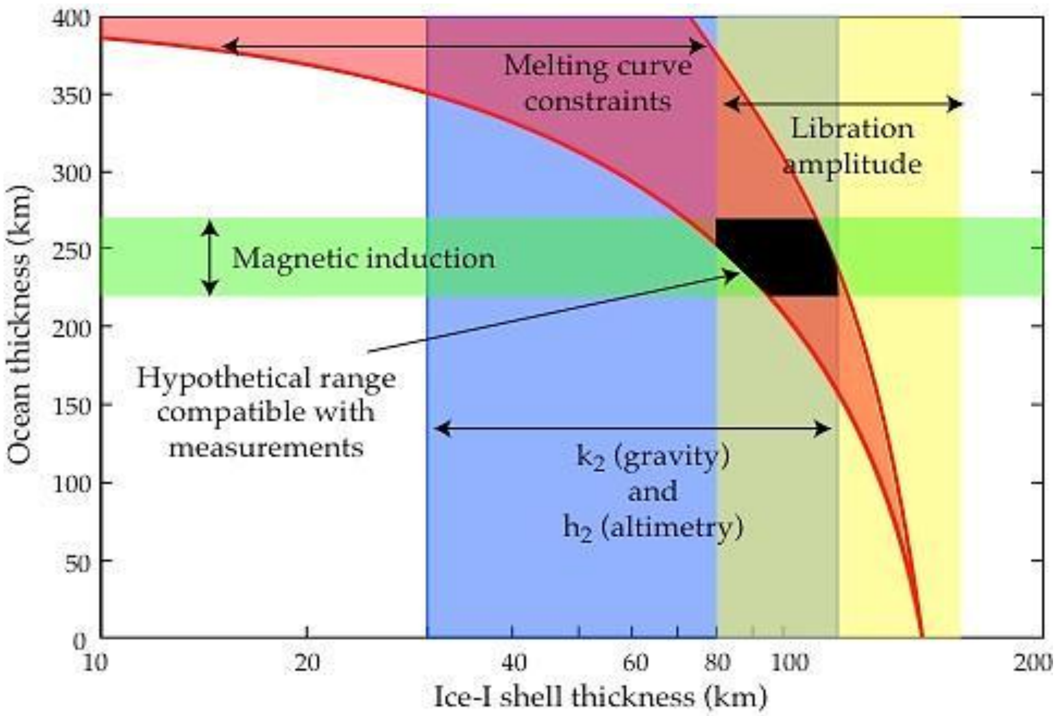


Figure 2-1. *Schematic view of the strategy to characterise Ganymede's icy crust and liquid layer by using combined techniques. The parameter space (ice-shell thickness and ocean thickness) is bounded by the domain of stability of ices (red curves), but not fully constrained due to our poor knowledge 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 error bars have been exaggerated.*

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.

Ganymede has a high level of internal differentiation. Interior structure models are currently based on degree-2 measurements of the gravity fields adopting the a priori assumption of hydrostatic equilibrium (Schubert et al., 2004). An important objective of JUICE at Ganymede is to improve the degree-2 gravity field (without relying on the assumption of hydrostatic equilibrium) and study its temporal variations related to the tidal forces. 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 0.001. 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. High-order fields and deviations from hydrostatic equilibrium will also be detected. These measurements will improve our understanding of the degree of internal differentiation of the satellite. They will also quantify mass anomalies, asymmetries in the mass distribution and other non-hydrostatic contributions to the gravity field as well as gravity field response to the tidal forcing.

On Ganymede, offsets between centre of mass and centre of figure 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 mainly 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 those of Europa and Callisto
- Determine the extent of Ganymede's ocean and its main physico-chemical properties
- Characterise the magnetic field of Ganymede and resolve the conditions required to generate and maintain the dynamo activity
- Verify whether hydrostatic states are reached at Ganymede and improve our understanding of their degree of differentiation

2.1.1.2 *Ice shell*

Investigation of the icy shell of Ganymede represents an entirely new science endeavour. This JUICE objective is to provide a broad understanding of the present state and evolution of the hydrosphere of Ganymede (in comparison to those of Europa and Callisto) and to characterise the icy shell structure including the possible detection of shallow subsurface liquid water.

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. 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. It will also correlate surface features and subsurface structure to investigate near-surface and interaction processes.

All these objectives require mapping of the moon by a radar sounder. This has the ability to penetrate the surface and to perform a subsurface analysis with penetration down to 9 kilometres with a vertical resolution of some meters. Composition mapping of the surface by imaging spectroscopy in UV to IR range as well as measurements of large-scale and regional topography 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, this will be investigated with the submillimetre sounding instrument using multiple wavelengths with polarization capabilities.

In summary, JUICE will:

- Characterise the structure of the icy shell of Ganymede
- Determine the minimal thickness of the icy crust on Ganymede
- Correlate dynamics in the ice shell with the surface structure and topography

2.1.1.3 *Local environment and its interaction with the Jovian magnetosphere*

Ganymede has earned a unique place within the Solar System: it possesses an internally generated magnetic field and hence a miniature magnetosphere is formed within the larger Jovian magnetosphere (Gurnett et al., 1996). This mini-magnetosphere constantly interacts with the plasma flow and electromagnetic fields of the rapidly rotating Jovian magnetosphere, producing a dynamic interaction region. Ganymede also has induced magnetic field signatures that are much weaker than the internal magnetic field of Ganymede and the background Jovian field. The important objective of the mission is to separate the effects of these electrodynamic interactions to characterise the subsurface ocean. Ganymede possesses a tenuous atmosphere, and ionosphere, while exhibiting strong auroral emissions. The auroras provide a visual representation of the electrodynamic interactions between Jupiter's magnetosphere and Ganymede's magnetosphere, through processes that are not yet understood in detail. JUICE will aim at detailed characterisation of the magnetic and electric fields and particle populations at Ganymede and their interaction with Jupiter's magnetosphere, including the moon footprint aurora in Jupiter's atmosphere.

The magnetic field at Ganymede is a result of complex interaction of the induced field, Ganymede's intrinsic field, Jupiter's magnetosphere and the plasma environment (Kivelson et al., 2002, 2004; **Figure 2-2**).

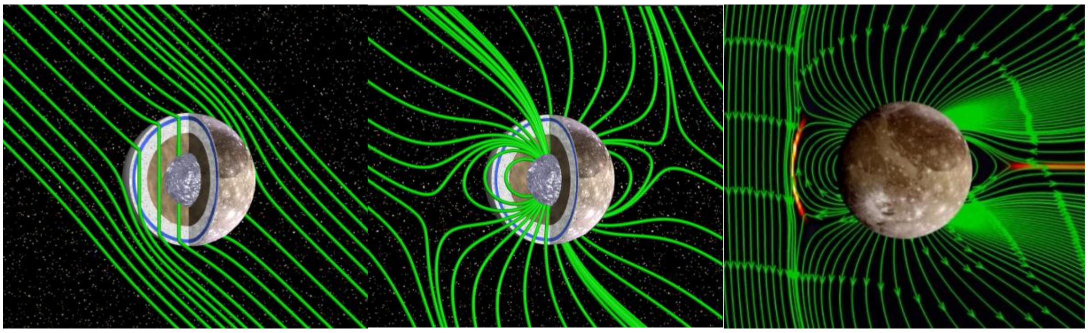


Figure 2-2. *Schematics to show Ganymede's induced magnetic field perturbation added to Jupiter's background field (left), the background/induced magnetic field is then added to Ganymede's internally generated magnetic field (middle), and finally the resulting miniature magnetosphere is shown (right). In the left hand and middle images, Jupiter's background field is oriented from the top left to bottom right, whilst in the right hand image the Jovian background field is aligned from the top to the bottom of the figure. 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 electromagnetic 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 plasma is either trapped, transported across or along the magnetic field. JUICE will identify in-situ particle precipitation and related electric acceleration potentials and waves along the open field lines at the poles, along with auroral observations at multiple wavelengths and through detection of sputtered and radiolytically-produced ENAs. JUICE will monitor and map (charged) dust, and infer its effect on the surface of Ganymede. JUICE will take measurements in the regions between Jupiter and Ganymede along the magnetic flux tubes connecting both bodies (so called Alfven wings), where accelerated plasma and magnetically field-aligned electric currents exist, consequently producing "auroral" footprints in Jupiter's atmosphere. JUICE will uncover the nature of the time-varying interaction of Ganymede's electromagnetic fields and plasma environment with the surrounding Jovian magnetosphere – making it possible to separate the various sources of the electromagnetic fields. Thus far, our knowledge of this complex system is based upon Galileo flyby data, and subsequent MHD models. It is thought that variations in the magnetic and electric 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 and electric signals expected to vary over such time scales. JUICE will measure the plasma flows (convection) and electric currents as part of the global electrodynamic current system in Ganymede's ionosphere and magnetosphere.

Many crucial parameters of the coupling of the satellite with the magnetosphere have yet to be measured. At Ganymede, plasma and dust interacting with the surface are key processes to be investigated. The main processes are sputtering of surfaces by plasma ion impact promoting material into the exospheres and radiolysis in the near surface volume due to the intense bombardment by penetrating radiation. Given the complex composition of the plasma environment of Jupiter, including sulphur ions, the understanding of plasma interaction with the surface is necessary for the interpretation of the spectral signatures from the surfaces. The role played by charged particles (including charged dust) 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 2-3**).

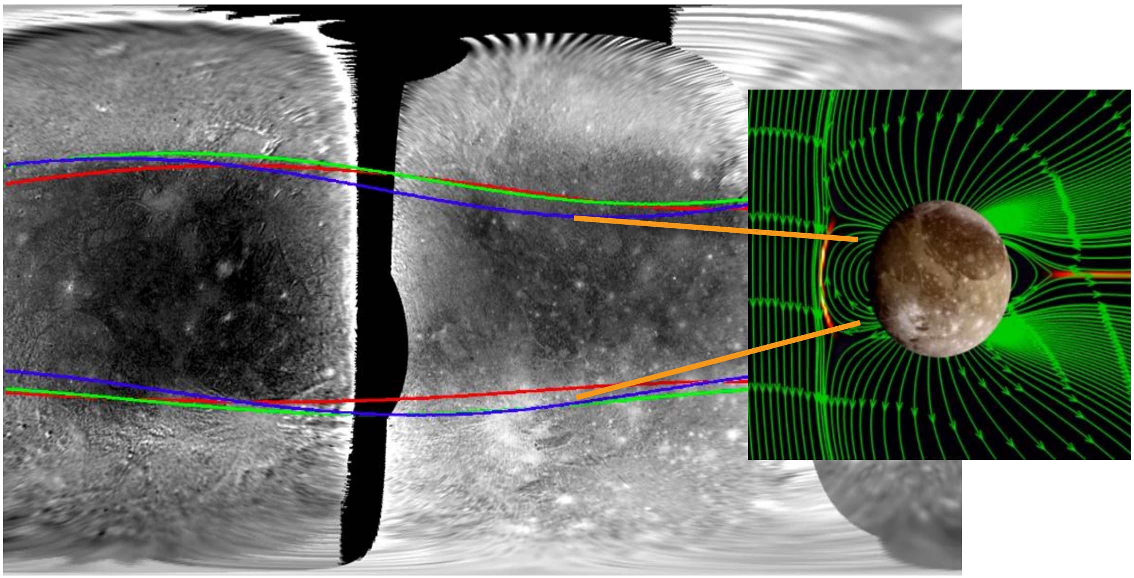


Figure 2-3. *Green/violet ratio composite image of Galileo colour data from orbits E14 (west, 10.4 km/pixel), G1 (central, 13.1 km/pixel), and C10 (east, 7.3 km/pixel green and 14.7 km/pixel violet). Superimposed are the open/closed field line boundaries for three different model configurations, shown in: red when Ganymede is farthest above Jupiter's plasma sheet, green when Ganymede is located in the middle of the plasma sheet, and blue when Ganymede is located farthest below the plasma sheet. The equatorial dark band on the surface is then proposed to correspond to the closed magnetic field region on Ganymede (inset to the right), while the lighter surface poleward of the coloured lines maps to where Ganymede's magnetic field lines are "open", i.e. connected to the Jovian magnetospheric field. Adapted from 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 0.01 eV to MeV, plasma and radio waves, and neutral imaging from eV to keV of the impacting plasma and ejected material.

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 and 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.

The Ganymede situation is unique due to the presence of the internal magnetic field. 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.

The Galilean satellites are known to have thin atmospheres, technically exospheres (McGrath et al., 2004), produced by ion-induced sputtering 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, and similar evidence for local H_2O plume sources now await confirmation; Na and K have also been measured at Europa, in ground-based observations. Callisto's atmosphere, with CO_2 first detected by Galileo NIMS from limb scans, is surprisingly dense in O_2. Ganymede also has a thin O_2 atmosphere, inferred from Hubble measurements of UV emissions, and a hydrogen exosphere, measured by the Galileo UVS from limb scans.

JUICE will significantly contribute to our understanding of the atmospheres of the icy satellites, their origin and evolution, as well as the chemical composition of their surfaces, by observing the exospheres of Europa, Callisto and Ganymede through remote monitoring, imaging of the aurora, multi-wavelength limb scans and stellar occultation, and directly by *in situ* measurements by sensors of the particle packages from low orbits and fly-bys.

In summary, JUICE will:

- Investigate Ganymede's internal, induced, and magnetospheric magnetic field components
- 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 particle interaction with the surface of Ganymede
- Contribute to our understanding of the atmospheres of the icy satellites, their origin and evolution

2.1.1.4 *Formation of surface features and search for past and present activity*

With its mix of old and young terrains, ancient impact basins and fresh craters, and landscapes dominated by tectonism, possible icy volcanism, and slow-rate degradation by space weathering (**Figure 2-4**), Ganymede serves as an archetype body for understanding many icy satellite processes throughout the outer Solar System and provides clues on 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).

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. 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.

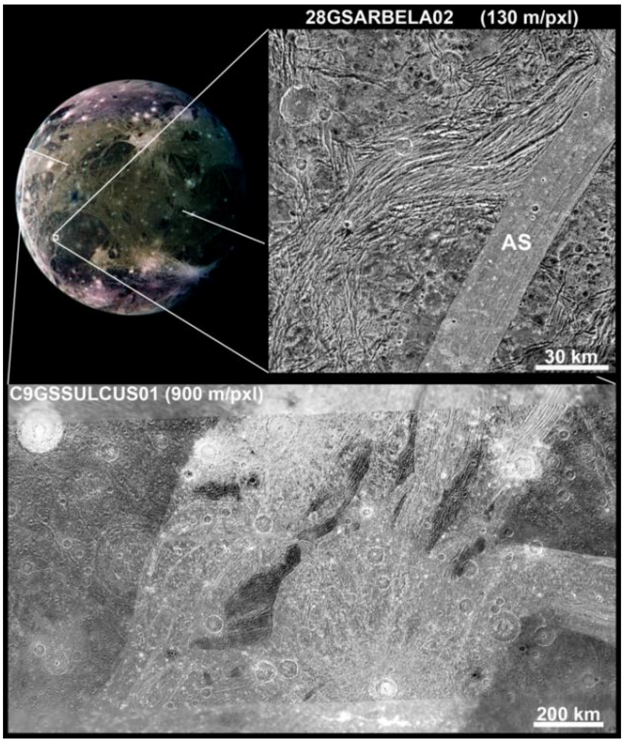


***Figure 2-4**. Ganymede's surface is characterised by old, dark densely cratered plains, and by younger, bright and more ice-rich, tectonically resurfaced terrain. Bright terrain formed at the expense of dark terrain, mostly through extensional tectonism, (lower panel; Galileo SSI target area C9GSSULCUS, 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).(Credit: NASA.)*

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 study of geology of Ganymede and investigate its surface from orbit by global imaging with regional spatial resolution (<400 m/px) and high-resolution imaging (<10 m/px) of selected targets. By combining stereo imaging and laser altimetry data digital terrain models on regional and local scales will be provided for analysis of surface structures and processes.

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).

JUICE will significantly improve the current estimates of Ganymede surface age 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 (10-50 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 an establishment of 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 selected targets on Ganymede's surface with high resolution for understanding its local geological processes
- Improve our understanding of the geologic evolution of Ganymede by constraining its surface ages

2.1.1.5 *Global composition, distribution and evolution of surface materials*

One objective of JUICE will be to understand the surface chemistry and its evolution and to characterise the role of various processes (endogenic, exogenic, exchange with subsurface). As revealed by the Galileo mission, there are substantial amounts of non-water ice components within the water ice dominated regions of 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. The nature and origin of these species, which may be exogenic or derived from a subsurface briny layer, are widely debated. Various non-water ice materials have been identified on the Ganymede surface 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 2-5**). However a reliable identification of all non-water ice compounds and their small-scale distribution is still missing on Ganymede, due to the lack of high spatial resolution data with good signal-to-noise ratio.

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.

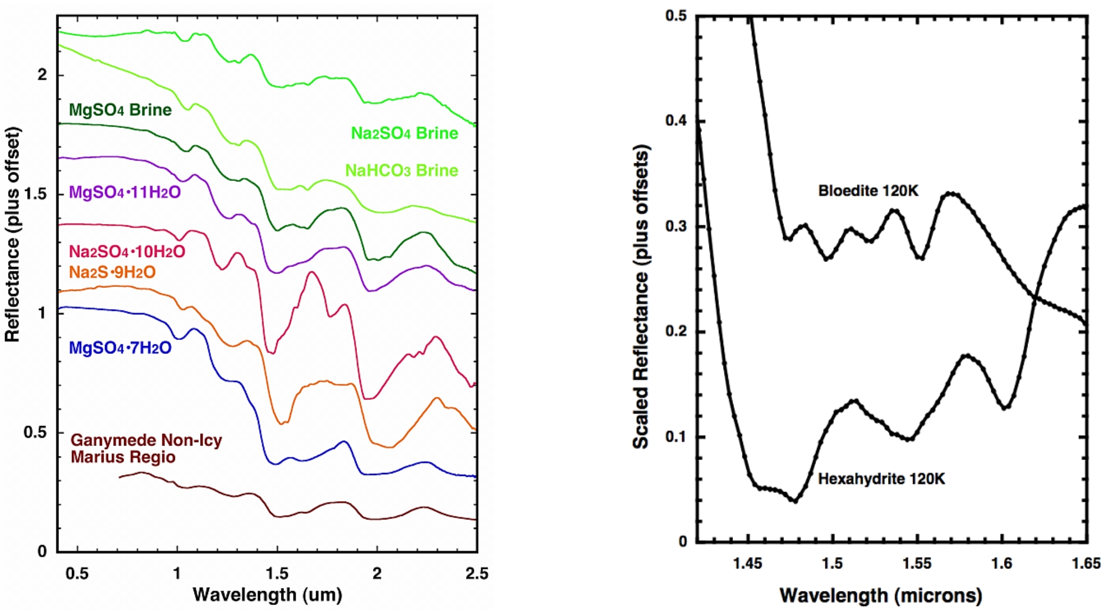


***Figure 2-5. Left:** Infrared spectra of several hydrates and brines, measured at 100 K in the range from 0.4 to 2.5 µm, compared with a NIMS spectrum of non-icy material of Ganymede (Dalton et al., 2005). **Right:** Close-up of the spectra of hydrated minerals bloedite ($Na_2Mg(SO_4)_2{\cdot}4H_2O$) 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).*

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 1 km/px and 5 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. 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 Ganymede surface.
The relationship of ice and non-water-ice materials and their distribution is crucial for understanding the origin and evolution of Ganymede's surface. Surface material distribution can be linked to the internal activity of the moons but also to external processes (e.g. the shielding effect that Ganymede's intrinsic field provides from high-energetic particles at equatorial to mid-latitudes) and sublimation processes. Ganymede also shows evidence of embedded 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 this being upstream side of the satellite facing Jupiter's magnetospheric plasma. Thus ion bombardment is thought to have created O_3 in the ice matrix, while photodissociation destroys it, on a continual basis. Constraints on the distribution of biologically essential (H, C, N, O, S, P) and other major elements (Na, Mg, Cl, K, Ca, Fe) can be obtained from the distribution of ices and non-ice materials on the surface of Ganymede. Capabilities of in-situ measurements of these species sputtered from the surface strongly depend on their densities, and in turn on altitude. Such constraints are important for assessing habitability (Wackett et al., 2004).

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, maybe 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, resultant products of H_2O and other minority species (O, O_2, OH, H, H_2) with mixing ratios of 1 ppm.

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, will be unique and will constrain the origin and evolution of the volatile inventories of the three icy moons.

The surface structure and composition is also affected by the bombardment of particles and dust from the space environment. It is most evident from the difference in Ganymede surface characteristics at high latitudes, on open magnetic field lines, compared to low latitudes, on closed magnetic field lines (Khurana et al., 2007). JUICE will investigate the acceleration processes of the charged particles, through measurements of the time variable electric and magnetic fields and plasma waves, the particles' energy and pitch angle distributions, as well as monitor the charged dust environment around the icy moons.

In summary, JUICE will:

- Characterise the composition and chemistry of Ganymede's surface
- Identify biologically essential elements and search for biosignatures
- 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 inventory, and reveal information about the sources and sinks of the atmosphere

2.1.2 *Europa's recently active zones*

2.1.2.1 *Composition of the non-ice material, especially as related to habitability*

Galileo spectra of Europa show distortions in several water ice absorption bands in the 1-3 μm range, indicating the presence of hydrated compounds concentrated in the visually dark and reddish regions. Orlando et al., (2005) and Dalton (2007) reported that the Europa non water-ice spectra are 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, are claimed but not confirmed in the leading hemisphere at equatorial to mid-latitudes. A reliable identification of all non-water-ice compounds on Europa is still missing, due to the lack of high spatial resolution data with good signal-to-noise ratio.

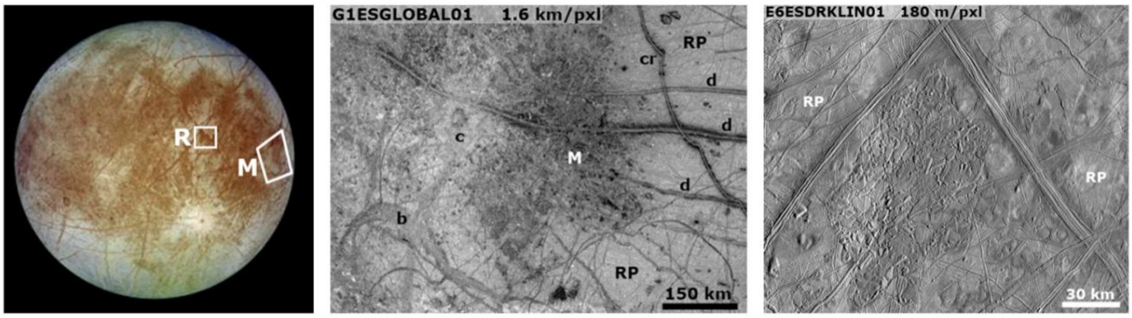


Figure 2-6*. Europa's surface shows the widest range in colours of the three icy Galilean satellites (left) and exhibits two major surface units: bright, bluish plains, and dark, brown, mottled terrain. Bright plains consist of numerous parallel ridges and troughs (RP) superposed by mottled terrain (M) 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. (Credit: NASA.)*

On Europa, hydrated compounds are concentrated at lineaments and in chaotic terrains (**Figure 2-6**). 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 hydrates 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).

Over the broad range from UV to IR, JUICE will provide spectral imaging of selected sites that are currently ranked at very high priority for both astrobiology and geology, with spectral resolutions high enough to map the spectroscopic signatures of non-water ice materials. 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. The spectral mapping will be supported by high resolution imaging to correlate the distribution of surface materials with geology. 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.

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.

The mission will also map leading/trailing hemispheres asymmetries due to contamination by exogenic material. Combining in-situ detection and imaging spectroscopy, JUICE shall provide a detailed understanding of the composition of the moon's surface.

In summary, JUICE will:

- Characterise the composition and chemistry of Europa’s surface
- Identify biologically essential elements and search for biosignatures
- Provide a consistent picture of the surface chemistry 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, and reveal information about the sources and sinks of their thin atmospheres

2.1.2.2 *Search for liquid water under the most active sites*

Voyager and Galileo data indicate that Europa possesses important prerequisites for habitability. Galileo’s detection of induced magnetic fields (Kivelson, 2000; 2002) combined with imaged surface characteristics (Pappalardo, 1999) and thermal modelling of the moons' evolution (Spohn and Schubert, 2003), indicate the presence of a liquid water ocean below the icy crust. However, the depth and composition of the ocean, as well as the dynamics and exchange processes between the ocean and the deep interior or the upper ice shell, 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 modelling relates chaotic terrains with shallow lenses of liquid water (Schmidt et al., 2011).

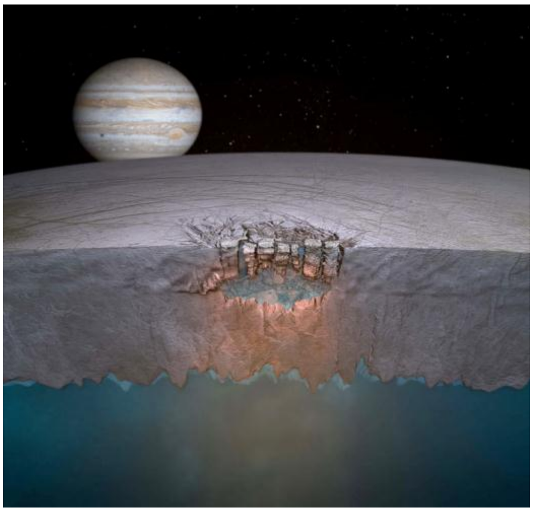


Figure 2-7. *Artist impression of a water pocket in the shallow sub-surface of Europa. (Credit: Britney Schmidt/Dead Pixel VFX/Univ. of Texas at Austin.)*

One of the objectives of JUICE is to explore for the first time the subsurface in the most recent active regions to understand the exchange processes from the subsurface to the surface and also to constrain the minimal thickness of the ice shell in the most active regions (**Figure 2-7**). At closest approach, JUICE will probe the Europan crust possibly down to the ice-ocean interface, if the ice shell is only a few km thick as expected in some models (Greenberg and Geissler, 2002). JUICE will help to solve the controversy concerning the depth of the ocean over liquid water reservoirs with the ice shell, and will determine whether or not liquid water can ascend through the ice shell from a subsurface ocean to the surface (e.g. Pappalardo et al., 1999).

In summary, JUICE will:
- Search for pockets of liquid water in the shallow sub-surface of Europa
- Unveil places where the exchange processes between surface and subsurface liquid reservoirs have been more intense

2.1.2.3 *Study the active processes*

Europa's surface is notable for its very low density of impact craters (only 16 craters with diameters of 3 – 27 km could be identified), suggesting a young surface age (e.g., Greeley et al., 2004; Schenk et al., 2004). Europa's surface can be subdivided into bright (bluish colour) 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., 2012). Linear ridges are the most widespread landforms on Europa; the most common of which 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, 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).

Europa also has a tenuous mainly O_2 atmosphere (Hall et al., 1995) produced by intense radiation bombardment (though occasional venting cannot be ruled out). Na and K have also been measured from ground-based observations (Coustenis et al., 2010 and references therein). O_2 is seen on Europa's surface (Hand et al., 2006). The evidence for trapped O_2 indicates that the radiolytically-produced O_2 may be supplied to the subsurface ocean, where it could be a source of energy for life (Chyba, 2000). An important objective at Europa will be to search for and study present and/or recently active processes. Their manifestation can be found both on the moon's surface and in its atmosphere (plumes, geysers) and related ionosphere.

The recent evidence for a large (~200-km high) plume of water vapour provided by Hubble Space Telescope (HST) imaging of far-UV emissions from excited H and O water dissociation products (Roth et al., 2014) indicates active processes at Europa and may allow accessibility to a subsurface liquid reservoir. The existence of such water vapor plumes, if confirmed in future observations, has far-reaching implications for the future exploration of Europa's potentially habitable environment, similar to those discussed for Enceladus and its plumes (Spencer and Nimmo, 2013). The source processes that control the variability and strength of plume activity on Europa are currently unclear, but rely on the geophysical mechanisms for activity that JUICE is already tailored to investigate thoroughly.

In summary, JUICE will:
- Study of at least two of the most active sites with high spatial resolution to unveil their geology and composition
- Study remotely and in-situ current activity on Europa (geysers, plumes etc.)

2.1.3 *Callisto as a remnant of the early Jovian system*

2.1.3.1 *The outer shell, including the ocean*

Galileo data suggest that Callisto is a partially differentiated body. The very old surface of Callisto indicates that it has not been active for some billion years, which may imply a total lack of dynamics in its deep interior. But, Galileo detected an induced magnetic field that could possibly be due to the presence of a large liquid reservoir below the outer icy shell, or an induced magnetosphere due to the presence of a substantial and conducting ionosphere. Thus, the key questions to be addressed by future missions to this moon are: what is the structure of the icy shell and what is the scale of the sub-surface ocean, and what is the role of the conducting ionosphere in producing the measured induced magnetic field?

JUICE will provide the first exploration of the surface of this moon down to a few kilometres and will reconnect the surface features to the subsurface characteristics of the icy shell. It will also improve the determination of the low-order gravity field and the moments of inertia and thus, constrain the deep interior structure of the moon, especially regarding the possible separation of ice and rock components in the outer part of the icy crust. In addition, JUICE will add new constraints on the evidence for a subsurface ocean by measuring the induced magnetic field due to the sub-surface ocean and/or the space environment during the flyby campaign and the time variation of the 2nd degree gravity field.

In summary, JUICE will:

- Characterise the structure of the icy shell including the possible detection of shallow subsurface water
- Determine the extent of the ocean and its main physico-chemical properties

2.1.3.2 *Composition of the non-ice material*

A reliable identification of all non-water-ice compounds is still missing on Callisto. The 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). 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). Surface alteration due to radiolysis and photolysis of many organic molecules that may be intrinsic or delivered by comets and meteoroids to the surface is also likely to be important on Callisto. 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 region, and also on the trailing side relative to the leading side (Dalton et al., 2010a).

JUICE will characterise the surface composition of Callisto and relate it to geology. Moreover, JUICE will investigate the intriguing problem of the replenishment of CO_2. In addition, by combining spectroscopy and in situ atmospheric/exospheric measurements, JUICE will enable the identification of the asymmetries of Callisto's surface release.

In summary, JUICE will:

- Characterise the composition and chemistry of Callisto's surface with emphasis on non-water-ice compounds
- Provide a consistent picture of the surface chemistry and separate the relative contributions of endogenic subsurface chemistry and exogenic magnetosphere-driven radiolysis and sputtering
- Constrain the origin and evolution of the volatile inventory, and reveal information about the sources and sinks of the atmosphere

2.1.3.3 *Study of the past activity*

Callisto is characterised by globally abundant dark, densely cratered plains (**Figure 2-8**). 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 seen on Ganymede, and by landforms 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.

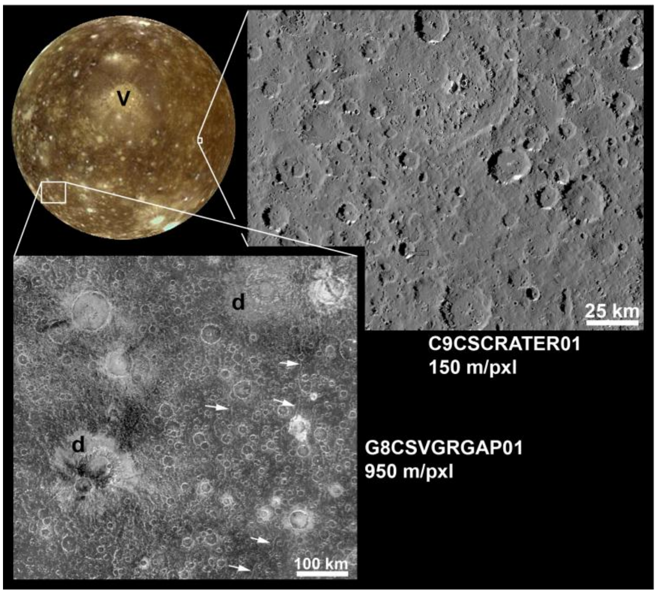


Figure 2-8. *Galileo images of Callisto. Upper left: old densely cratered surface of Callisto with large multi-ring structures, such as Valhalla (V). Lower panel: SSI medium resolution image of a cratered plain including dome craters (d) and ring arcs of old, degraded multi-ring structures (arrows). Right panel: SSI high resolution image revealing the high state of surface degradation driven by sublimation.(Credit: NASA.)*

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).

JUICE observations will constrain global and regional surface ages, and enable the investigation of the processes of erosion and deposition. Callisto will also be imaged at a regional scale (400s m/px) in order to complete the imaging coverage of its densely cratered plains, and at high resolution (<<100 m/px), on selected target areas to perform detailed studies of its unique erosion and degradation processes. Finally, the dynamical evolution is also constrained by the global structure of the moon. That is why JUICE will verify whether hydrostatic states are obtained, and shall improve our understanding of Callisto's degree of differentiation.

In summary, JUICE will:

- Investigate the unique erosion and degradation processes on Callisto's densely cratered plains
- Improve our understanding of the geologic evolution of Callisto by constraining its surface ages
- Verify whether hydrostatic state is actually obtained and improve our understanding of the degree of differentiation

2.2 Explore the Jupiter system as archetype of gas giants

2.2.1 *Jovian atmosphere*

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; Grodent 2014; Badman et al., 2014), and the local Jovian environment of the rings and icy satellites.

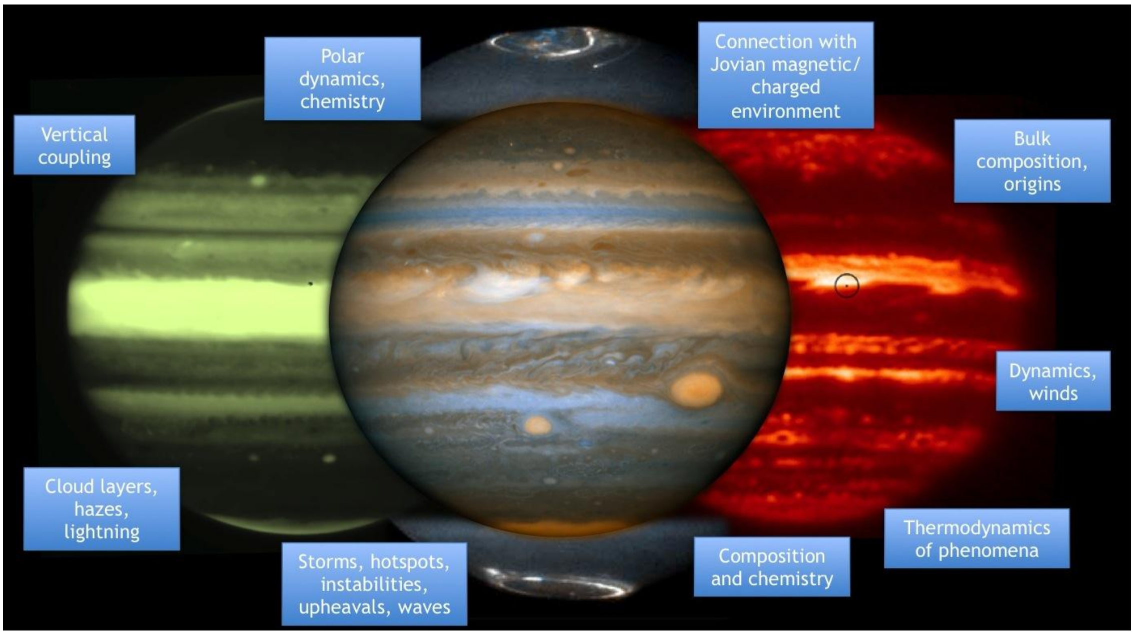


Figure 2-9. *Examples of the Jupiter science objectives of JUICE. Each image shows Jupiter's appearance at a range of different wavelengths, from visible colouration and wind tracking (centre, HST, credit: NASA/ESA/A. Simon-Miller/I. de Pater) to cloud properties in the near-IR (left, Gemini/NIRI image, 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.)*

JUICE provides a significant potential for Jupiter atmospheric science from its broad spectral coverage and 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 . 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 the forces shaping Jupiter's atmospheric structure and climate. 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 Jupiter's atmosphere and the connectivity between the different layers.

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 2-9**).

2.2.1.1 *Atmospheric dynamics and circulation*

Jupiter's atmosphere provides our most accessible example of a giant gaseous planet; an archetype for astrophysical objects that appear to be commonplace beyond our solar system. It also provides a planetary-scale laboratory for the investigation of the fluid-dynamic processes governing planetary atmospheres and oceans. The plethora of dynamical phenomena in Jupiter's 'visible' atmosphere (the "weather layer") are thought to be governed by a balance between solar and chemical 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 both horizontally and vertically. Jupiter's zonal jets serve as barriers to latitudinal mixing (strong gradients in potential vorticity) and exhibit a range of instabilities, meanders and convective outbursts (Vasavada and Showman, 2005). Jupiter's lower atmosphere also exhibits a wealth of time-variable phenomena, ranging from short-lived thunderstorms and lightning, formation and interaction of giant vortices(such as the reddening of Oval BA, Simon-Miller et al., 2006), episodic plumes and outbursts, waves and turbulence to quasi-periodic variations in the banded cloud patterns ("upheavals") and storms (such as the recent fade and revival cycle described by Fletcher et al., 2011). By monitoring these changes and tracking features over time, JUICE will gain insights into (i) the mechanisms driving the global circulation and dynamics; (ii) how the jets, eddies and vortices are maintained, and (iii) the relation between atmospheric motions, composition and clouds.

One of the major objectives of JUICE is to investigate these time-variable phenomena with substantial coverage in latitudes and local solar time, a long temporal baseline and broad spectral range. A key objective is near-simultaneous multi-spectral observations of environmental conditions (temperatures, chemistry, winds) associated with changes in visible albedo and meteorological activity. JUICE will permit mapping from the equator to pole at frequent intervals to identify the underlying dynamical causes for Jupiter's atmospheric variability. Through imaging, spectroscopy, and occultations, JUICE will study atmospheric circulation and meteorology from the cloud-forming troposphere to the upper atmosphere and thermosphere, relating them to the deep interior and the external charged particle environment. In particular, sub-millimetre spectroscopy will permit the first direct measurements of winds in the middle atmosphere, connecting the stratosphere to the tropospheric weather layer for the first time.

2.2.1.2 *Atmospheric composition and chemistry*

Atmospheric composition determines the structures of the cloud decks; radiative energy balance influences the troposphere and middle atmosphere; and condensation processes could provide the energy required for convective dynamics. Furthermore, Jupiter's bulk composition provides a window on the formation and evolution of the gas giant. The remote sensing capabilities of the JUICE payload will allow it to study the spatial distributions of key trace species and their relation to the dynamic investigations outlined above.

JUICE will investigate (a) the 3D spatial distribution and variability of stratospheric constituents to probe circulation and photochemistry in the middle atmosphere; (b) the origins and distribution of exogenic species (H_2O, CS, CO, HCN) concentrated in the stratosphere to constrain external sources of material; (c) localised and non-equilibrium compounds (e.g., PH_3, AsH_3, GeH_4) associated with discrete atmospheric features in the troposphere; and (d) the spatial distribution of volatiles (ammonia and water humidity) to understand the importance of moist convection in cloud formation, lightning and chemistry, complementing the deeper atmospheric studies of Juno. Previously undetected trace species, in addition to isotopic ratios in known molecules, could also be detected in Jupiter's stratosphere via sub-millimeter investigations. Remote sensing of Jupiter's polar regions will be used to study the relationship between photochemistry and ion-related chemistry at the highest latitudes, searching for the unique chemical pathways and haze formation mechanisms resulting from auroral energy deposition in the upper atmosphere. Finally, the presence of an orbiting spacecraft will permit detailed scrutiny of debris clouds related to cometary and asteroidal impacts, such as Shoemaker-Levy 9 (Harrington et al., 2004) and the 2009 asteroidal impact (e.g., Orton et al., 2011), helping to constrain the influence of external impacts on Jupiter's atmosphere.

2.2.1.3 *Atmospheric vertical structure and clouds*

JUICE will aim 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 thermosphere with complete latitudinal and local time coverage. Occultation studies and sub-millimetre remote sensing will probe the middle atmosphere with good vertical resoluton to resolve 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, particularly as a dominant source of heating in the thermosphere. The long temporal baseline will allow us to understand how these processes evolve with time and respond to internal and external forcing.

JUICE will globally map the vertical structure and optical properties of the clouds and hazes from the millibar level to approximately 5 bar (West et al., 2004) to reveal the mechanisms responsible for aerosol production – photochemical production and sedimentation, condensation and uplift of NH_3 and NH_4SH ices, shock chemistry in lightning. In particular, we hope to discover the chromophores responsible for the differences in cloud coloration on Jupiter. The broad spectral observations of clouds and hazes from a range of observational geometries will be used to determine their composition, vertical structure and optical properties; relating these to the gas phase composition of condensable volatiles and hydrocarbon haze and to vertical mixing and circulation. Near-infrared investigations will search for signatures of condensed ices of ammonia, NH_4SH and water (particularly in regions of strong convective activity), in addition to photochemical hazes of hydrocarbons and hydrazine. Ultraviolet and visible studies will help to constrain the altitudes and scattering properties of the aerosols associated with the banded structure and discrete features. These will feed into dynamical models with active hydrological cycles, including precipitation as rain and snow (e.g., Palotai et al., 2014). Taken together, this will provide new insights into cloud formation processes at work on all giant planets.

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

2.2.2 *Jovian magnetosphere*

If it were visible, the Jovian magnetosphere would be the largest object in the sky. The 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 creates the biggest planetary particle accelerator within the Solar System. Dense plasma originating principally from Io loads the fast rotating planetary magnetic field, stretching it into a magnetodisc. The magnetodisc region exhibits multiple processes including magnetic reconnection and plasma loss processes, plasma instabilities, and the acceleration of ions and electrons up to very high energies. These energetic particles in turn impact the moons, releasing surface material back out in to space to form their tenuous atmospheres and tori.

The strong internal magnetic field of Jupiter (whose equatorial surface strength is approximately 10 times that of the Earth is generated deep within the rotating core of the planet. Consequently, the rotating planet and internally driven magnetic field gives rise to the largest, and fastest rotating, magnetosphere in the Solar System. The whole magnetosphere thus tries to rotate with the planet (i.e., once per 10 hours about the spin axis (which is tilted by ~9.7° relative to the magnetic axis).

The major plasma source is the moon Io, which orbits deep inside the magnetosphere, and releases about 1 tonne/s of sulphur dioxide gas through continuous volcanic eruptions. The neutral atoms are eventually ionised, picked up by the rotating magnetic field, and subsequently feed the equatorial magnetodisc, which extends 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.

As noted above, Jupiter is also a powerful particle accelerator, its inner magnetosphere represents the most severe radiation environment in the Solar System. The inner magnetosphere can also therefore be regarded as an accessible template for similar acceleration processes elsewhere in the environments of gas giant exoplanetary systems.

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 mid-to-high-latitude middle magnetosphere up to ~22° above the equatorial plane (~32° magnetic latitude), 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.

2.2.2.1 *A fast magnetic rotator*

The magnetosphere of Jupiter has been traditionally divided into inner (<10 R_J), more dipolar-like configuration, and a middle (10-40 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).

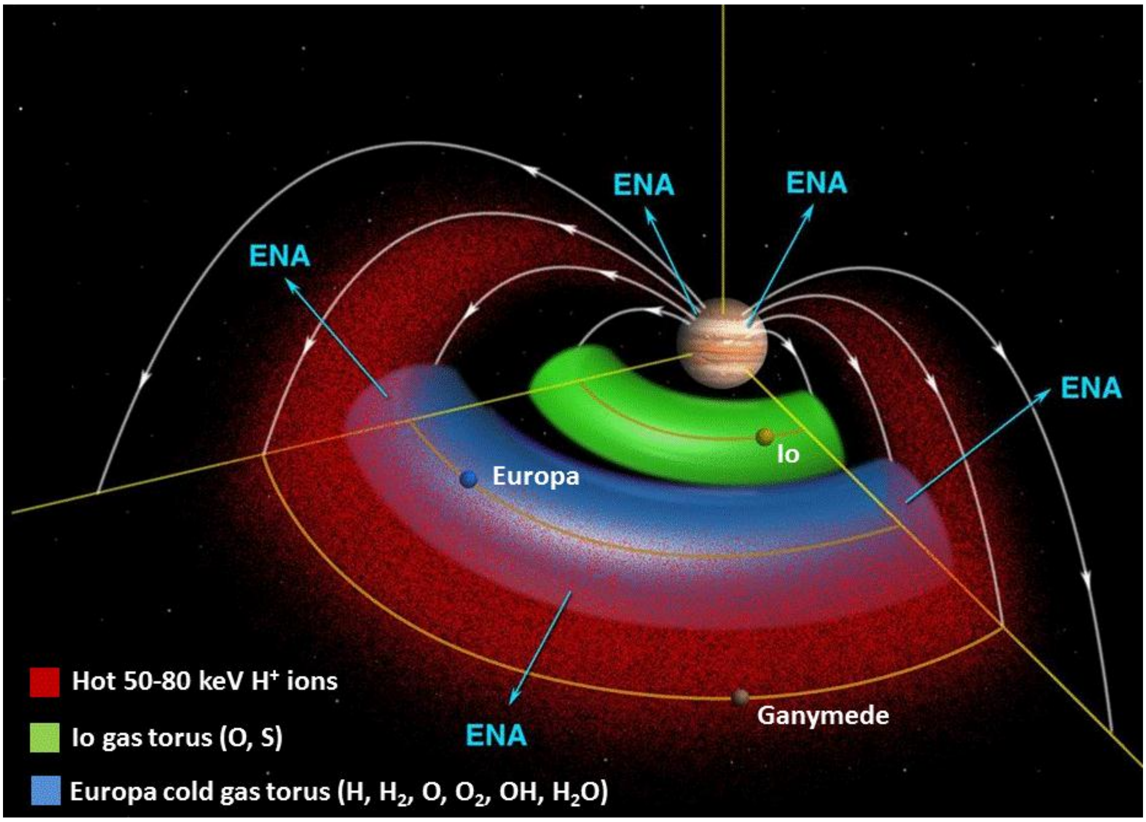


Figure 2-10. *Artist's conception of the Io and Europa torus illustrating the neutral and charged particle distributions in the region between Ganymede and Io, one of the key regions of the Jovian magnetosphere (from Mauk et al., 2004).*

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.

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 2-10**). 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 as well as remotely e.g. with ENA measurements during the high inclination 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 (see **Figure 2-11**).

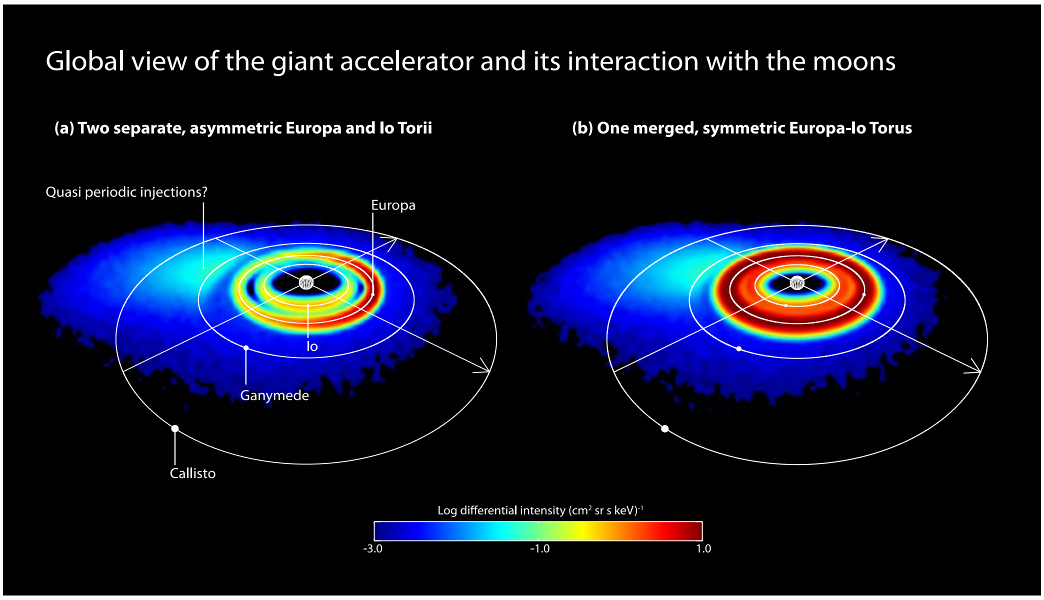


Figure 2-11. *JUICE will be equipped to discover the global 3D dynamics of the Jovian plasma-neutral environment that are currently one of the outstanding open questions. Simulations of two hypothetical scenarios based on our limited knowledge from Galileo data showing global ENA images of dramatic appearance 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.*

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. 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.

2.2.2.2 *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 (e.g., Ray et al., 2014). 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 sub-storm-like radial flow bursts have been observed that 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.

2.2.2.3 *Sources and sinks of magnetospheric plasma*

Interactions between magnetospheric plasma and the surfaces of the moons are key processes to be investigated. This includes ion-induced sputtering of surfaces and promotion of material into the exospheres and radiolysis of the near surface volume by the intense bombardment by energetic particles. Given the complex composition of the plasma environment of Jupiter, including sulphur ions, the understanding of plasma interaction with the surface is a necessity for the interpretation of the spectral signatures from the surfaces. Energetic ions and electrons are also principal sources of chemical energy in layers close to the surface of moons.

JUICE will characterise 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, plasma and radio waves, and imaging of the impacting plasma and ejected material. It will also significantly contribute to our understanding of the atmospheres of the icy satellites, especially their origin and evolution. Particular attention will be given to Io. On Io, silicate volcanism is probably dominant at thermal emission enhanced hot spots, while secondary sulphur volcanism may be important at certain places and is responsible for the dominance of SO_2 in the atmosphere. JUICE will monitor the volcanic activity of Io, and determine the composition of different materials on the surface at a regional scale.

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

2.2.3 *Jovian satellite and ring systems*

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.

2.2.3.1 *Study Io's activity and surface composition*

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 (Veeder et al., 2012; de Kleer et al., 2014). 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.

2.2.3.2 *Study the main characteristics of 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). Amalthea and Thebe may have formed by accretion from the circum-Jovian 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 sub-nebula 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
- Investigate the physical and chemical properties of Jupiter's rings
- Constrain the physical shape and bulk composition and origin of Jupiter's small inner moons and irregular satellites

3 Science, measurements and mission requirements

This section presents an overview of the requirements flow from the JUICE science objectives (Section 2) to the measurement requirements to individual instruments and mission requirements. It provides a link between the science objectives described in Section 2 and the payload performance characteristics (Section 4) and the mission design (Section 5). These objectives are presented in more detail in the Science Requirements Document and the Science Requirements Matrix [D-1].

3.1 Explore the habitable zone: Ganymede, Europa, and Callisto

3.1.1 Ganymede as a planetary object and potential habitat

3.1.1.1 Ocean and its relation to the deep interior

Physical characteristics of the deep liquid layer. Investigation of the subsurface ocean on Ganymede and its properties, as well as 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. The science requirements include determination of the thickness of the ice shell by characterization of the time dependence of the 2-d order gravity field and amplitudes of the periodic tidal surface deformation. This will be achieved by the 3GM experiment performing range-rate measurements with accuracy of ~0.01 mm/s at 60 sec integration time to determine the Ganymede-centric radial position of the spacecraft to better than 10 cm (rms) accuracy and spacecraft-surface ranging with 10 cm accuracy by the laser altimeter GALA. In addition the magnetic induction response from the subsurface conductive ocean will be determined to constrain the thickness of the ocean as well as its electrical conductivity. The mission will characterize modulation of the magnetic field by Ganymede's orbital motion (T=171 h), rotation of the Jovian magnetosphere (T~10.5 h) and solar rotation (T~27 days) to an accuracy of better than 0.1 nT. These goals will be achieved by the J-MAG magnetometer measuring three-axis magnetic field components at 32 to 128 Hz frequency. These measurements will be isolated from the contribution from magnetic fields generated by electric currents in Ganymede's ionosphere and magnetosphere. The RPWI and PEP experiments will provide supporting measurements of ionospheric currents, plasma density and velocity, electric fields and wave environment.

Internal structure of the moon. The mission will constrain the structure of the outer shell and deep interior by measuring the Ganymede gravity field up to the degree of 12, by measuring the moon's rotation state and its variability, and determine the position of the satellite's centre of mass with respect to Jupiter. Additional insights into the internal structure will be provided by measurements of the amplitude of physical longitudinal librations and the orientation of the spin pole by GALA, multiple imaging of the same surface target at varying orbital phases by the JANUS camera and range and range-rate measurements by 3GM. The sketch illustrating the method of constraining the icy crust and ocean thickness is given in Section 4.12.

3.1.1.2 Ice shell

Sub-surface structure. Exploration of the icy crust is a totally new science. The mission will characterize structure and properties of the ice shell by probing the sub-surface of Ganymede down to a depth of few kilometres. The requirement to the ice penetrating radar RIME is to obtain profiles of subsurface thermal, compositional and structural horizons down to a maximum depth from 1 to 9 km depending on the crust properties with about 50-km profile spacing and with vertical resolution ranging from 50 meters to 2% of the target depth. A need to reduce lateral surface echoes of the radar signal, called "clutter", justifies the requirement to generate the surface Digital Terrain Model (DTM) over the areas explored by RIME. The DTM with ~100 m vertical resolution and 400-600 m grid size and a swath of ~250 km will be generated on the basis of the GALA sounding and stereo imaging by the JANUS camera within available mission resources.

Correlation with the surface properties. To correlate the subsurface structure to surface features and to investigate near-surface and interior processes, the subsurface sounding will be complemented by characterization of the physical and thermo-physical properties of the surface in selected sites. The imaging visible and infrared spectrometer MAJIS will measure surface reflectance in the wavelength range from 0.4 to ≥5 microns of targeted features at better than or equal to 125 m/pixel spatial resolution. The ultraviolet spectrograph UVS will extend the spectral range to 55-210 nm. The submillimeter wave instrument SWI will perform radiometric-polarized measurements in the 600 GHz band with spatial resolution of at least 5 km to constrain the thermophysical properties of the ice, regolith and ice-regolith mixtures. And finally, the JANUS camera will provide high-resolution imaging that, combined with laser altimeter and subsurface radar sounding, should characterize surface morphology across selected targets.

3.1.1.3 *Local environment and its interaction with the Jovian magnetosphere*

The near-Ganymede environment and its interaction with the Jovian magnetosphere are strongly influenced by the nature of both intrinsic magnetic field and induced magnetic and electric fields. The major science requirements are related to characterization of the magnetic and electric fields, plasma population and neutrals, plasma wave processes, and generation of aurora.

Electromagnetic fields and interactions. The mission will characterize Ganymede's global magnetospheric fields and plasma environment to understand unique Jupiter-Ganymede magnetosphere interaction. The magnetospheric boundary crossings are often very short lived, and the boundaries often act as regions where the energy and momentum transfer is largest between particle populations. It is therefore essential that these boundary processes are studied in as much detail as possible by in-situ instrumentation. One of the science requirements is to characterise the plasma wave electric and magnetic vector and power density inside and outside of the Ganymede magnetosphere. This requires high-resolution measurements of the magnetic field by J-MAG and RPWI measurements of electric field vectors at DC to 1.6 MHz with better than <1 mV/m accuracy together with variations of the magnetic field vector at 0.1 Hz-20 kHz.

Plasma population. The mission will characterise the electron and major ion distribution function inside and outside Ganymede's magnetosphere in all plasma spatial domains. The plasma population and neutrals will be measured by the PEP instrument that should determine the distribution functions for electrons and ions with sufficient angular and energy coverage and volatile content of the exosphere, over a mass range better than 300 amu with mass resolution better than 500.

Neutral atmosphere and ionosphere. Investigation of the Ganymede neutral atmosphere and ionosphere, quantification of sources and sinks are the key objectives of the mission. Its achievement requires characterisation of the composition, structure, temperature and dynamics of the exosphere and ionosphere. Both requirements shall be met by joint exploitation of remote sensing and in-situ techniques (see examples in Section 4.12). Spectroscopy in the broad wavelength range, including observations in stellar occultation and limb geometry, performed by UVS, MAJIS and SWI will explore the outer layers from the surface up to about 400 km measuring important species including O_2, H_2O, CH_4, NH_3, CO, CO_2, SO_2 and their constituent atoms O, H, C, and S. In situ experiments will provide key information at low altitudes since the ability to resolve species and isotopic composition strongly increases with density. PEP will measure neutrals coming off Ganymede with a mass range up to 300 amu and a mass resolution of up to 500. The ionospheric studies will rely on the measurements of electron and ion density, electron temperature, ion drift speed (0.1-200 km/s), convection electric field (<0.1 mV/m), and ion composition by RPWI, 3GM and PEP.

Aurora. The mission shall investigate the Ganymede aurora and mechanisms of its generation. This requirement will be met by the synergy of (1) temporally resolved spectral mapping in IR and UV by MAJIS and UVS, complemented by observations of the boundary between op and closed magnetic field lines by J-MAG, (2) high-resolution in-situ particle and fields/radio emission measurements by PEP and RPWI.

3.1.1.4 *Formation of surface features and search for past and present activity.*

JUICE will investigate Ganymede's entire surface and subsurface from orbit to explore the geological processes that have shaped this moon, to improve our understanding of the geologic evolution by constraining the surface ages, and to characterize the processes that alter the surface (space weathering, micrometeorites, radiation, charged particles).

Surface properties and geology. To fulfil these objectives the mission shall provide global medium resolution (400 m/px) imaging at visible wavelengths. This context mapping shall be performed as early as possible after Ganymede orbit insertion to support and facilitate selection of targets for high-resolution (<10 m/px) that will be performed at later stages on the sites with high geological interest. The imaging will be performed by the JANUS camera. The required vertical dimension to this investigation will be provided by the RIME subsurface sounding and GALA topography measurements. Both GALA laser altimetry and JANUS stereo imaging will be used to build Digital Terrain Model (DTM) of the surface on both global and regional scales. This objective also requires complete compositional mapping at medium spatial resolution of 5-10 km/px – the requirement to be met by MAJIS, with supporting observations of the surface properties by UVS (UV reflectivity), SWI (thermal emission measurements) and PRIDE and 3GM (radio occultation and bi-static sounding).

3.1.1.5 *Global composition, distribution and evolution of surface materials*

This objective aims at characterising the composition of the surface and its relationships with the outer and inner layers. Firstly, the material, especially organic and inorganic species, must be accurately identified. Secondly, JUICE must determine whether the surface materials have been released from the deeper subsurface and interior. Thirdly, JUICE will focus on open versus closed magnetic field line regions that constitutes an ideal laboratory to study the influence of the space environment on the surface environment. Finally, remote sensing will be complemented by ion and neutral mass-spectrometry and particle/dust/plasma analysis of the moon's exosphere issued from sputtering and sublimation of surface material, diffusion from the interior, meteoritic and dust impact evaporation as well as sub-surface breaching of ocean material.

Surface composition and mineralogy. The mission shall enable mineralogical mapping of at least 50% of the Ganymede surface with 1-5 km/px resolution to identify non-water-ice materials and high-resolution (~100 m/px) compositional mapping of selected sites of geological interest. These requirements will be fulfilled by spectral imaging in VIS-NIR wavelength range by MAJIS supported by narrow band imaging by JANUS and far-UV observations by UVS.

Exospheric composition. The mission shall also characterise the composition of the moon's exosphere and ionosphere, including isotopic ratios, and dust population and the study of exchange processes between the surface and space environment. These investigations will be enabled by both in-situ and remote sensing techniques. PEP will identify surface modifications due to external plasma and particle interactions by measuring (in-situ) the precipitating electrons and ions (major magnetospheric species) in the 10's eV to MeV energy range, by imaging the sputtered and backscattered neutrals from the surface in the 10's eV to few keV range, and by measuring neutral exospheric composition to identify major volatile species with mixing ratios better than 1%. RPWI will monitor micrometre sized dust and determine the total charge number density of the dust population, map the structure, convection and electron temperature of the ionosphere, as well as determine the location of electric field structures and waves that accelerates charged particles toward the surface. Independent remote sensing (including limb scans and stellar occultations) by MAJIS, UVS, SWI, and JANUS will be used to determine the vertical structure and global distribution of the primary exospheric species, O_2, and H_2O.

3.1.1.6 *Mission requirements at Ganymede*

The above described science and measurement requirements impose certain requirements that shaped the mission profile (Section 5). The remote sensing objectives require the spacecraft to be at a large range of distances to the moon from few thousand kilometres for global context imaging to few hundreds kilometres to enable both remote sensing and in-situ investigations. This objective also drives the group of pointing requirements to the spacecraft, including inertial pointing for solar and stellar occultations, nadir/off-nadir pointing, raster pointing, spot tracking and limb-tracking manoeuvre for radio occultation.

The investigation of the local plasma environment at Ganymede and its interaction with the Jovian magnetosphere by both remote sensing and in-situ techniques also requires the orbit to cover large range of distances from the moon to perform measurements on both inside and outside Ganymede's magnetosphere. This justifies the requirement for having both highly elliptical and low circular orbits at Ganymede, as well as ability of the spacecraft to perform stellar, solar and radio occultations and limb scans. Although the spacecraft will not be designed for operations of the entire payload in eclipses, remote sensing observations and in-situ measurements by some instruments on the night side atmosphere of Ganymede would be highly desirable if resources allow.

The investigation of the subsurface ocean imposes strict requirements to have circular orbits at Ganymede with altitude of about 500 km for at least 100 days.

3.1.2 *Europa's recently active zones*

The two JUICE flybys of Europa will be focused on addressing high-priority studies of this icy satellite: characterising the non-ice material, looking for liquid water beneath active sites, and the study of active processes.

3.1.2.1 *Composition of the non-ice material*

This objective aims to characterise the non-ice material (organic and inorganic) and to explore the relationships of this material with the deep ocean and also with the space environment. The objective is split into three investigations. First, the surface material must be identified accurately with an approach similar to that used for Ganymede (Section 3.1.1.5). Second, it is necessary to determine whether the material characterised on the surface originated from the deep interior. Third, sputtered and backscattered material must be identified to better constrain the exchange processes occurring on Europa. These three investigations drive the following requirements.

Non-water-ice surface materials. Characterization of the non-water ice materials requires that at least one of the selected sites of high interest for surface chemistry and subsurface exchange processes is mapped at regional (>5 km/px) and local (<500 m/px) scales with the solar incidence angle at closest approach lower than 60° to provide adequate illumination condition. This requirement will be met by MAJIS measuring the surface spectral reflectance globally at a spatial resolution between 2.5 and 10 km/px, through a spectral range from 0.4 to >5.0 µm and locally on selected sites of very high interest at a spatial resolution of better than or equal to 0.1-1 km/px and UVS measurements in 0.1-0.2 µm range. These observations, especially the global imaging, will also address the requirement to investigate asymmetry between leading and trailing hemispheres due to contamination by exogenic material. The requirement to provide geological context of recently active regions will be addressed by the JANUS colour imaging with spatial resolution of at least 500 m/px. In addition the mission shall characterize the physical and thermo-physical properties of the surface over at least one of the selected sites of recent activity.

Exospheric and ionospheric composition. Composition of the surface and its alteration by space weathering and plasma environment is an important objective of the mission. JUICE shall characterize exospheric and ionospheric composition and its variations as tracers of changes on the surface. This will be fulfilled by PEP by measuring in-situ composition of the sputtered surface products supported by spectroscopy and spectro-imaging by UVS, SWI, MAJIS and JANUS.

3.1.2.2 *Search for liquid water under the most active sites*

One of the key questions regarding the habitability of Europa is to understand whether or not material exchange between the interior and the surface occurs. To answer this question JUICE shall explore at least one of the most active sites on Europa, where these past or present exchange processes have the highest probability to be detected. Three investigations have been identified for this objective. First, JUICE must search for shallow liquid water reservoirs below young and resurfaced areas of the icy crust. Second, it will look for the ice-shell-sub-surface ocean interface. Finally, JUICE should look for evidence of current geological activity, and determine if exchange between the interior and the surface occurs.

Sub-surface sounding. To address the above listed investigations the mission shall explore subsurface of at least one of the selected sites of high interest for surface chemistry, exchange processes and geologic activity down to the depth of up to 9 km and allow determination of the minimal thickness of the icy crust.To meet these requirements, the ice penetrating radar RIME is required to identify and locally characterise the icy crust by obtaining profiles of subsurface dielectric horizons and structures down to a few kms (maximum depth from 1 to 9 km depending on the crust properties and with vertical resolution ranging from 50 meters to 2% of the target depth). This will be supported by JANUS and GALA that should provide topographic information on the selected sites. The search for liquid water in the shallow subsurface shall be complemented by the investigation of deep interior and global shape of the moon.

3.1.2.3 *Study of the active processes*

Europa interacts with other bodies of the Jovian system. Firstly, JUICE will explore the interaction between the local environment and (a) the Europa torus, (b) the effects of penetrating radiation on surface chemistry, and (c) sputtering processes. Secondly, the exchanges that may occur between the surface and the external environment should be observed in the exosphere. JUICE will explore the limb for activity. Finally, the amount of exchanges can be quantified by searching for surface changes with respect to Galileo observations at a global scale.

Composition of the exosphere, ionosphere and torus. The main requirement derived from these objectives is to characterise the Europan exospheric and ionospheric composition, fields and waves and their variations including those due to possible outgassing activity. Also active processes on Europa can be characterised by observations of the torus and its variability. The science requirement is to monitor structure and dynamics of the Europan plasma, neutral and dust tori. To meet these requirements PEP will characterise the global distribution of Europa's neutral torus and its variability, determine the particle precipitation as well as sputtered and backscattered neutrals from the surface. RPWI will determine plasma wave, electrodynamics and cold plasma characteristics with good time resolution (<10 s) supported by J-MAG monitoring of the magnetic field. Observations in limb geometry providing high sensitivity to the atmospheric minor species will be intensively used for this investigation.

Search for geologic activity and plumes. Search for recent geological activity requires mapping of selected sites with high resolution as well as high-resolution altimetry. These science requirements are translated to the measurement requirements to the JANUS camera to map the regions of interest with better than 50 m/px resolution and high-resolution altimetry (<5 m vertical and <50 m along track) by the laser altimeter GALA and conduct stellar occultations (<1 km/px profiles) over suspected plume regions with UVS. These observations should look for changes on the surface with respect to the Galileo epoch. Geologic activity should also have an impact on surface composition as observed primarily by MAJIS, complemented by investigations with UVS and JANUS, due to unaltered material being brought to the surface.

3.1.2.4 *Mission requirements at Europa*

The objective to investigate the regions of recent activity on Europa drives requirements to the mission to enable at least one Europa flyby with closest approach of <500 km above the regions with high interest for geology, chemistry and astrobiology. The spacecraft shall be capable of performing high spatial resolution imaging (<500 m/px) and spectral imaging in the broad wavelength range of selected sites on Europa, as well operating all instruments simultaneously within the distance of 150000 km from the moon at approach and departure. The flyby trajectories shall provide optimal conditions for the payload observations.

3.1.3 *Callisto as a remnant of the early Jovian system*

3.1.3.1 *Characterise the outer shell, including the ocean*

This objective has been split into two investigations. JUICE will explore the structure and properties of Callisto's icy crust and liquid shell and will also characterise the space plasma environment to determine the magnetic induction response from the ocean.

Sub-surface investigations. The subsurface of Callisto shall be explored down to a few kilometres over regions of high interest. The ice-penetrating radar RIME will measure subsurface structure in targeted regions by obtaining profiles of subsurface dielectric horizons and structures down to a few kms (maximum depth from 1 to 9 km depending on the crust properties and with vertical resolution ranging from 50 meters to 2% of the target depth). The related science requirement is to build surface Digital Terrain Model (DTM) of the sites sounder by RIME to clean the radar signal from clutter. DTM will be provided by combination of JANUS stereo imaging and GALA observations.

Ocean and interiors. The mission shall confirm the presence of a subsurface ocean and constrain the thickness of the ice shell by measuring the tidal deformations and the 4x4 gravity field. Corresponding measurement requirement is imposed on the 3GM experiment. As in the case of Ganymede (Section 3.1.1.1) the magnetic induction response from the conductive ocean shall be differentiated from plasma generated field to an accuracy of <0.1 nT that should allow to constrain thickness and conductivity of the ocean. This objective imposes measurement requirements on J-MAG. The contribution from electric currents producing magnetic fields that are not related to the ocean-induced magnetic fields will be quantified using global measurements of ionospheric currents, magnetospheric and ionospheric plasma parameters. The RPWI and PEP experiments will be responsible for fulfilling this requirement.

3.1.3.2 *Determine composition of the non-water-ice material*

To fulfil this objective, JUICE, similarly to the Ganymede investigations, will characterise surface organic and inorganic chemistry, relate material composition and distribution to geological and magnetospheric processes, and characterise the ionosphere and exosphere of the moon.

Non-water-ice surface materials. Characterisation of the non-water-ice materials requires (1) composition investigations at regional scale (~5 km/px) complemented by high-resolution (< 100 m/px) studies over representative features. This requirement will be met by MAJIS measuring the surface spectral reflectance over a wide range of spatial scales (from 5 km/px to 100 m/px or better) in the spectral range from 0.4 to >5.0 µm and UVS measurements in 0.1-0.2 µm range. In addition, the mission shall characterise the physical and thermo-physical properties of the surface over at least one of the selected sites of recent activity that should be provided by SWI.

Exospheric and ionospheric structure and composition. Composition of the surface and its alteration by space weathering and plasma environment is an important objective of the mission. JUICE shall characterise exospheric and ionospheric composition and its variations as tracers of the surface composition. This will be fulfilled by PEP measuring composition of the sputtered surface products as well as monitoring of the plasma properties by RPWI and SWI sounding of the water content. The results will be related to those obtained by MAJIS and other remote sensing instruments on the surface composition.

The mission shall characterize the ionospheric composition, structure and dynamics. This requires RPWI measurements of ion and electron density, ion temperature, and electric field, J-MAG measurements of the magnetic field, and 3GM sounding of electron density in radio occultations.

3.1.3.3 *Study of the past activity*

To study the past activity of the moon, JUICE will determine the formation and characteristics of tectonic and impact landforms, investigate the interior of Callisto with a special emphasis on its degree of differentiation, and will put some constraints on global and regional surface ages. The science requirements are to provide context medium resolution (<400 m/px) imaging of about 50% of the

Callisto surface and compositional mapping with resolution of 5-10 km/px in broad spectral range from UV to IR. These requirements will be fulfilled by the JANUS camera as well as MAJIS and UVS spectrometers.

Sub-surface and interiors. The investigation of interiors and subsurface require determination of the gravity field and sounding of the Callisto subsurface. These call for the requirements to measure the gravity field by 3GM and shape of the moon by GALA. The subsurface sounding will be provided by the RIME radar supported by the topography and/or DTM provided by JANUS and GALA.

3.1.3.4 *Mission requirements at Callisto*

The science requirements above impose the following requirements on the mission. The spacecraft shall perform at least six Callisto flybys at 1000-200 km altitude at closest approach with at least one of them having trajectory inclined by at least 50° to the moon’s equatorial plane. The Callisto flybys should enable good illumination conditions for remote sensing observations. The remote sensing instruments also impose the group of pointing requirements to the spacecraft and the requirement to perform limb scans and stellar, solar and radio occultations.

3.2 Explore the Jupiter system as archetype of gas giants

3.2.1 ***Jovian atmosphere***

To address the key mission objective of characterization of the Jovian atmosphere, the science requirements are to investigate the spatial variability of Jovian dynamics, chemistry and atmospheric structure in three dimensions, to provide long-term time-domain investigations of atmospheric processes over 2+ years, with a frequency tuned to the timescales of interest (e.g., hourly, monthly, yearly), to relate the global temperature and wind structure to visible properties (albedo, winds, clouds) and atmospheric chemistry, and to investigate the unique atmospheric properties of Jupiter’s polar regions, including the influence of auroral energy deposition and ion chemistry on the atmospheric energy budget, chemistry and cloud formation. In the following sub-sections we specify the measurement and mission requirements enabling these key science objectives.

3.2.1.1 *Atmospheric dynamics and circulation*

The characterisation of the Jovian atmospheric dynamics and circulation requires five investigations. JUICE shall study the Jupiter's weather layer, explore the thermodynamics of atmospheric meteorology, quantify the roles of wave propagation and atmospheric coupling on energy and material transport, explore the auroral structure and energy transport mechanisms at high latitudes, and investigate relationships between the ionosphere and the thermosphere.

In addition to the general requirements described above, these investigations impose the following science requirements. The vertical structure of zonal, meridional and vertical winds will be characterized globally to understand the mechanisms driving zonal jets and meteorological activity. This drives the measurement requirement to the JANUS camera and MAJIS imaging spectrometer on spectral imaging of the dayside to determine cloud-top wind speeds (zonal and meridional) and eddy momentum fluxes. SWI will directly measure Doppler shifts in atmospheric molecular lines to derive stratospheric wind speeds above the cloud tops**.**

Atmospheric features (Great Red Spot, vortices, plumes etc.) shall be observed at high spatial resolution and over sufficient period of time to determine their 3-D morphology and monitor their evolution. MAJIS will perform multispectral imaging to determine the depth and shears on the zonal wind fields, the vertical structure of vortices and plumes, and the vertical structure of horizontally propagating waves. JANUS will acquire multiple high-resolution images of mesoscale waves and cloud structure on a timescale of hours, days, months, and years. UVS will perform observations at regular intervals of evolving discrete features (e.g., plumes, vortices, Great Red Spot Wake) at 160- to 200-nm wavelengths to determine the PH_3 distribution at altitudes higher than 400 mbar level. A specific emphasis shall be placed on the study of moist convection and distribution of lightning as tracer of the convective activity. This will be done by JANUS imaging at visible wavelengths and RPWI monitoring of radio emissions (80 kHz-45MHz) originating from lightning activity.

3.2.1.2 *Characterization of the atmospheric composition and chemistry*

This objective requires four kinds of investigations. JUICE must explore the bulk elemental composition, investigate the upper atmosphere chemistry with a special focus on exogenic inputs, characterise the spatial distribution of molecular species at all depths, and study the effect of moist convection in meteorology, cloud formation, and chemistry. This objective is translated into the following science and measurement requirements.

The mission must support global and regional spectroscopic mapping of the key atmospheric species with spatial resolution of <200 km/px in the VIS-NIR range, <1000 km in UV and with about a scale height in altitude and 2000-4000 km horizontal resolution in the sub-millimeter range. These measurements will be repeated over a range of timescales from days to years. This requirement translates into specific measurement requirements for MAJIS, UVS and SWI. The mission will also provide estimates of elemental abundances and isotopic ratios in the upper atmosphere using SWI to constrain the composition of the deep troposphere and the origin of external material.

3.2.1.3 *Characterization of the atmospheric vertical structure and clouds*

The atmospheric vertical structure will be characterised from two investigations. First, JUICE will determine the 3D temperature, cloud and aerosols structure from the cloud tops to the thermosphere. Second, the coupling processes due to waves, eddy mixing, and global circulation will be studied. This objective is translated into the following science and measurement requirements.

The mission shall enable investigation of the temperature structure, aerosols from the condensation clouds to the upper tropospheric and stratospheric hazes and classify wave activity in both the horizontal and vertical dimensions. These science requirements are translated into measurement requirements on the sounding of the temperature structure by radio occultations by 3GM, SWI remote sensing, and UVS limb sounding and stellar occultations (see Section 4.12 for examples of the payload synergy). The aerosol/cloud 3-D structure and morphology will be investigated in solar/stellar occultation geometry by UVS, MAJIS and JANUS.

3.2.1.4 *Mission requirements related to the study of the Jupiter atmosphere*

These top-level science requirements in the Jovian atmosphere drive important general requirements to the mission. Firstly, the duration of the Jovian tour shall be at least 2.5 years to enable sufficient temporal coverage. To extend this continuous monitoring of the atmosphere the observations will start 6 months before the Jupiter Orbit Insertion and continue during the Ganymede phase. Secondly, investigation of the polar regions require an orbit with inclination of at least 22° with respect to the Jupiter equatorial plane. And finally, the objectives also drive the group of pointing requirements to the spacecraft.

The mission shall provide repeated observations of the same latitudes and cloud features with frequencies tuned to the timescales of interest (hours to months), capabilities for global mosaics/scans of Jupiter repeated once every 2.5 hours and repetitive imaging of discrete cloud features region with hourly frequency, and be reactive on about 1 week timescale to new and unexpected events in the Jovian atmosphere. The mission shall enable complete latitudinal, phase angle and local solar time coverage of Jupiter by remote sensing instruments and provide at least two opportunities for remote sensing of Jupiter during the Europa phase when the distance to Jupiter is at a minimum.

3.2.2 ***Jovian magnetosphere***

To address the key mission objective of characterization of the Jovian magnetosphere, the general science requirements are to explore the three main regions of the Jovian magnetosphere over a broad range of local times: the inner magnetosphere where the planetary magnetic field dominates, the middle magnetosphere where the effects of the magnetodisc controls the large-scale magnetic field and plasma populations, and the outer magnetosphere where the solar-wind effects are likely to be the largest, to explore the variability of the large scale magnetospheric processes over short periods (seconds/minutes/hours) and long periods (months/years) and to characterize the plasma environment including particles and fields and coupling processes between them. Examples of synergies between the JUICE experiments in the study of the Jovian magnetosphere are given in Section 4.12.

3.2.2.1 *A fast magnetic rotator*

This objective has been split into four investigations. The structure itself, as well as the stress balance of the magnetosphere needs to be better understood. Second, it is necessary to investigate the plasma processes, sources, sinks, composition and transport and to characterise their variability in time and space. The third investigations will characterise the large scale coupling processes between magnetosphere, ionosphere, and thermosphere. Finally, investigation is devoted to the study of the magnetic response to solar wind variability and planetary rotation effects. The following specific science requirements should be added to those described in the beginning of Section 3.2.2 above.

The mission shall investigate the magnetosphere of Jupiter in and out of magnetodisc up to 32° magnetic latitude. J-MAG, PEP and RPWI experiments will provide key measurements to characterize fields and particles in the Jovian magnetosphere. The large scale distribution and evolution of hot plasma shall be mapped in the magnetodisc and Io and Europa tori. These measurements will be performed in the broad wavelength range by MAJIS, UVS and JANUS as well as by ENA (Energetic Neutral Atoms) imaging by PEP. These investigations will be complemented by monitoring of the dust mass and size distributions by RPWI. RPWI investigations of plasma waves and particles will address the science requirement on investigation of the energy and momentum transfer.

The mission shall explore large scale coupling processes between the Jovian magnetosphere, ionosphere and thermosphere and Galilean satellites and tori**.** These requirements will be met using plasma investigations by RPWI, J-MAG and PEP and imaging of the aurora footprints of the Galilean satellites by MAJIS and UVS.

The mission shall explore magnetospheric response to internal (planetary rotation effects) and external (solar wind variability) effects. This again requires combination of in-situ plasma and fields measurements and remote sensing observations of the aurora patterns.

3.2.2.2 *A giant accelerator*

To fulfil this objective, JUICE will detail the particle acceleration processes, study the loss processes of charged energetic particles, and also measure the time evolving electron synchrotron emissions. The mission shall investigate the Jovian aurora and mechanisms of its generation, and characterise acceleration regions and underlying processes for particle acceleration and losses. This requires combination of in-situ plasma and fields measurements by RPWI, J-MAG, PEP and UVS monitoring of the aurora patterns. Study of processes of losses of charged and energetic particles also requires joint observations by plasma and waves instruments and remote sensing payload MAJIS, UVS, JANUS. And finally acceleration processes should be investigated by J-MAG, PEP, RPWI and 3GM) measuring electron and synchrotron emissions.

3.2.2.3 *Sources and sinks of magnetospheric plasma*

For this objective, JUICE needs to study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori, to explore the interactions of the magnetosphere and the four Galilean moons, and also the interactions of the magnetosphere with small satellites. The latter investigation is of a strong importance with respect to its science return, but should not be considered as a driver for the mission requirements.

To quantify the outflow from the moons surfaces and exospheres into the Jovian system, the mission shall characterise density structures of the major species in moon's exospheres and ionospheres. The relevant measurement requirements were discussed in the sections devoted to the atmospheres of Galilean satellites.

The mission shall determine the structure, particle distributions and dynamics of the plasma in Jupiter's magnetosphere in the orbits of the icy moons to estimate the escape rates of volatiles from these moons, the electrodynamic coupling between the icy moons and the Jovian magnetosphere and energy and momentum transfer. This drives measurement requirements for the imaging instruments UVS, MAJIS and JANUS to observe the moons' tori and auroral footprints and plasma suite (PEP, J-MAG and RPWI) to determine distribution functions of the electrons and ions an measure radio wave emissions from the footprints and characterize signatures of electromagnetic coupling.

3.2.2.4 *Mission requirements related to the study of the Jupiter magnetosphere*

These top-level science objectives in the Jovian magnetosphere drive important general requirements to the spacecraft capabilities and trajectory which are similar to those imposed by the atmospheric investigations. Firstly, duration of the Jovian tour shall be at least 2.5 years to enable sufficient temporal coverage. Secondly, investigation of the aurora in the polar regions and magnetosphere in and out the magnetodisc require an orbit with inclination of at least 32° magnetic latitude. And finally, the objectives also drive the group of pointing requirements to the spacecraft. Also the spacecraft shall visit equatorial regions between the orbits of Callisto and Europa.

The mission shall ensure continuous in situ observations covering all regions of the Jovian equatorial magnetosphere out to at least 100 R_J, and remote observations of Europa and Io tori. To investigate in-situ local plasma environments of the Galilean satellites and their interaction with the Jovian magnetosphere, the mission shall allow close (<500 km) approaches to the surfaces of the three icy moons (Ganymede, Europa and Callisto).

3.2.3 *Jovian satellite and ring system*

3.2.3.1 *Io activity and surface composition*

Io is the most active volcanic object in the Solar System. The key science objective relevant to this moon will be to monitor the volcanic activity of Io and determine the composition of different materials on the surface at regional scale through remote multi-wavelength imaging spectroscopy.

JUICE shall characterise composition of the Io surface and monitor Io's surface, volcanic and plasma activity including Io plasma torus at time scales from hours to months and make local scale observations of Io and its torus with spatial resolution better than 200 km and 2000 km, respectively. The JANUS camera will perform repeated imaging of selected active volcanic sites with spatial resolution of ~10 km/px. During observations of the Io dayside, MAJIS will monitor thermal hot spots linked to volcanic activities during all close encounters. It will obtain spectral mapping of the far side of Io at a scale of 50 km/px during flybys on the dayside of the satellite. The UVS spectrograph will search for SO_2 plume activity and SWI will map gas abundances and temperatures in the Io exosphere.

The mission shall also monitor radio emissions from 1 kHz to 45 MHz from the Io environment including the Io torus and auroral radio emissions linked to the Io-Jupiter interaction – the requirement to be fulfilled by RPWI.

3.2.3.2 *Characteristics of rings and small satellites*

Jupiter's ring system is faint and consists mainly of micron-sized dust. JUICE objective is to study the physical and chemical properties of Jupiter's rings. 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. JUICE aims at shedding 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.

To fulfil the science objectives mission will characterize the in-plane structure, physical and chemical properties of Jupiter's rings. Remote sensing instruments will be responsible for that. JANUS will determine the phase function and color of the entire ring system with a resolution of finer than ~100 km/px and a sensitivity to reflectivity of 10^{-8}. MAJIS and UVS will focus on the study the rings composition performing spectral imaging of the rings in wavelength range from UV to IR. To determine the composition, properties and dynamical groupings of the small moons, JANUS will determine 3-D structure of the rings, monitor time-variable phenomena, and refine orbits of the small moons. 3GM will determine the structure of the main ring on scales of ~100 km. JANUS will also perform disc-resolved characterisation of at least one irregular moon, with disk-integrated spectral characterisation by MAJIS. And finally, the mission shall improve ephemeris of the bodies in the Jovian system by astrometric observations of the outer irregular moons against the star background.

3.2.3.3 *Mission requirements related to the study of small satellites and rings*

The science requirements specified in Sections 3.2.3.1 and 3.2.3.2 impose the requirements on the mission to enable repetitive remote observations of the inner Jovian system and on the trajectory to have orbits with inclination of at least 22° with respect to the Jovian equator.

4 Payload

This section contains a brief description of the experiments comprising the JUICE payload as listed in Table 1-2, including a summary of their main science objectives, instrument performance, basic measurement principles, design features and operation concepts. Examples of payload synergies in achieving mission objectives are given in Section 4.12.

4.1 Imaging System (JANUS)

JANUS will conduct an in-depth comparative study of Ganymede, Callisto and Europa, and explore the Jovian system and Jupiter itself using panchromatic, broad- and narrow-band imaging of these targets. The science objectives addressed by JANUS are:

- Characterise Ganymede, Callisto, and Europa as planetary bodies, including their potential habitability, with special focus on Ganymede; this implies an in-depth geological study including tectonics, mass wasting, cryovolcanism, impact structures, crater relaxation history and surface ages, orbit, rotation status and interior, color characteristics, potential water plumes sources;
- Characterise and study the physical properties of other satellites in the Jupiter system, including Io, the irregular and inner satellites;
- Study Jupiter's troposphere, imaging of the active dynamical processes, cloud systems, waves, vortices, and other instabilities, determining the vertical cloud structure within discrete features, and detecting lightning;
- Observe Jupiter's stratospheric aerosol variability due to vigorous water meteorology and disturbances from large vortices, such as the Great Red Spot;
- Investigate Jupiter's upper atmosphere by imaging auroral activity and particle precipitation in the form of polar hazes.
- Contribute to the study of the interaction between the Jovian magnetosphere and the bodies embedded within it.
- Perform a physical characterisation of the ring system;

The main expected JANUS science products will be geo-referenced color maps of the icy satellites, including DTMs, at different scales (from global/regional at few km/pixel or hundred m/pixel or till local at few tens or few m/pixel) icy Jupiter satellites (**Figure 4-1**). Global maps will be produced with the resolution allowed by the data volume available (which represents the main limitation to the resolution at given coverage). Higher level products are DTMs and geological maps.Io monitoring is achieved by full-disk imaging in different wavelengths from the visible to the near-IR. Jupiter atmospheric mapping and monitoring with different time scales (hours to months) in different broad and narrow-bands allow for the sounding of the different atmospheric layers. Imaging will also provide the necessary context for most of the other instruments onboard JUICE. Finally images will be acquired for specific astrometric purposes, allowing for a precise determination of the positioning of the satellites and definition of their orbits.

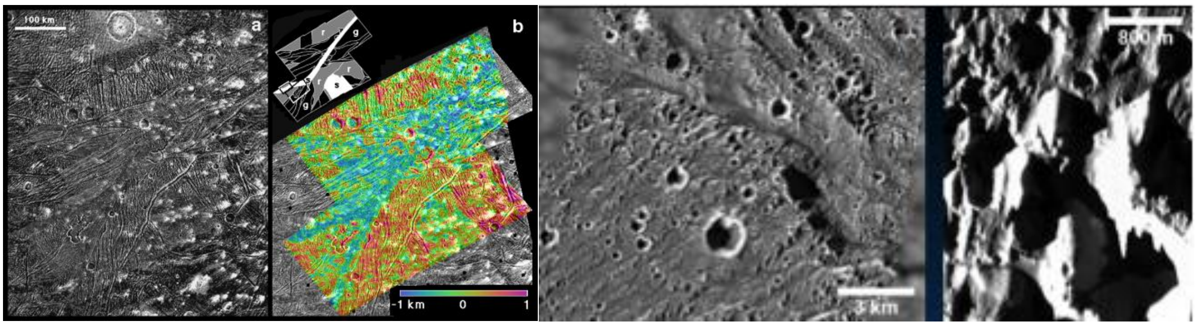


Figure 4-1. *Examples of the Galileo/SSI data products, including images at different scales and derived DTM (second from the left) illustrating the expected JANUS products. (Credits: NASA, DLR.)*

The JANUS telescope has been dimensioned to provide high optical quality and good signal levels in the visible-NIR spectral region once coupled with a CMOS framing detector.

A sketch of JANUS optical head is shown in **Figure 4-2** together with its main characteristics.

Specification	Value
Entrance Pupil Diameter	100 mm
Effective Focal Length	467 mm
F/#	4.67
Field of View	1.72 x 1.29 degrees^2
Detector format	2000 x 1504 pixels^2
Pixel size	7 µm
Pixel scale	15 µrad/pixel
Spectral range	350 – 1050 nm

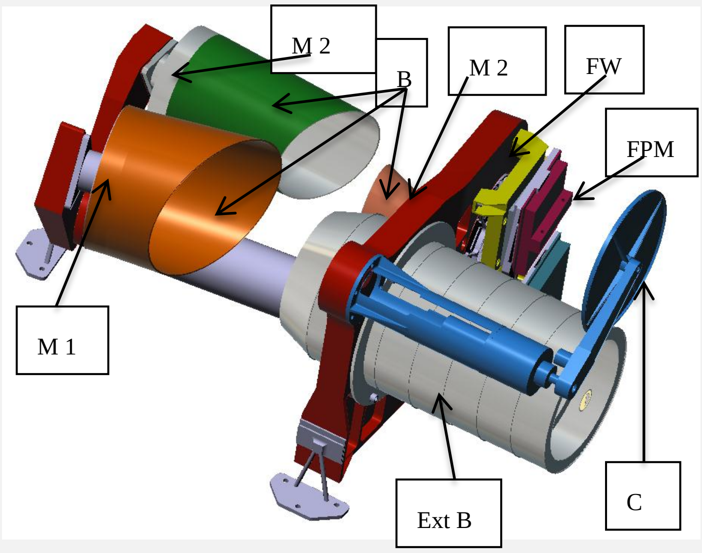


Figure 4-2. *The* main characteristics of the *JANUS telescope with schematic showing the main modules: the Mirror (M2), the Filter Wheel (FW), the Focal Plane Module (FPM), including the detector, the cover (C) and the baffles (B).*

The thorough trade-off between different design solutions has led to the following architectural choices and instrument capabilities when used within the JUICE mission:

- a catoptric telescope with excellent optical quality is coupled with a CMOS detector, avoiding any scanning mechanism; no mechanisms are needed or implemented for yaw steering compensation;
- a fine tuning of instrument parameters allows us to have an instrument designed to perform low, medium and high-resolution imaging on different targets in the Jupiter system taking advantage of the complex mission design;
- instrument operations are flexible enough to optimize the acquisition parameters with respect to the many different observation requirements and conditions that JANUS will face. The instrument design will allow us to adjust the resolution through binning, the field of view through windowing, the signal levels and SNR through integration time, the instrument calibration parameters through in-flight calibration and data pre-processing;
- cold redundancy is implemented for all critical electronic parts;
- use of broad-band and narrow-band filters is allowed by the implementation of a filter wheel with high heritage and high redundancy

Figure 4-3 allows comparing JANUS IFoV and FoV with several targets dimension at their minimum distance from JUICE; resolved targets are above the line of the spatial resolution, while targets above the line for the image width fill the JANUS FoV JANUS will improve dramatically previous coverage of all its targets and resolution at a given coverage; it will be able to observe almost all of them with SNR >100. Filters properties are given in **Table 4-1**.

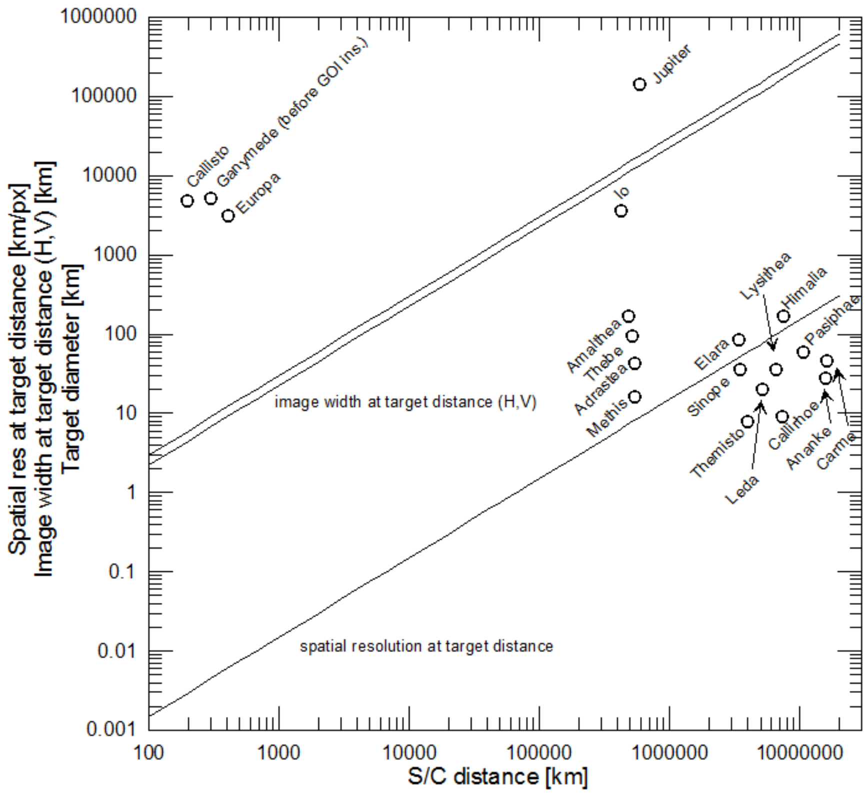


Figure 4-3. *JANUS spatial resolution and image swaths as a function of distance from a target. Circles mark the distances to the surface at closest approach (horizontal axis) and the object diameter (vertical axis) for Jupiter and several satellites based on the existing JUICE orbital tour.*

Table 4-1. *JANUS baseline filters spectral characteristics.*

Filter	**λ/width, nm**	**Note**
FPAN	650/500	Panchromatic – monochromatic imaging
FBLUE	450/60	Blue – satellite colours
FGREEN	530/60	Green, background for Na – satellite colours
FRED	656/60	Red, background for Ha– satellite colours
CMT medium	750/20	Continuum for strong Methane band on Jupiter, geology
Na	590/10	Sodium D-lines in exospheres
MT strong	889/20	Strong Methane band on Jupiter
CMT strong	940/20	Continuum for medium Methane band on Jupiter, Fe^{2+} on satellites
MT medium	727/10	Medium Methane band on Jupiter
Violet	410/80	UV slope of satellites surfaces
NIR 1	910/80	Fe^{2+}, Io lava spots
NIR 2	1000/ 150	Fe^{2+}, Io lava spots
Ha	656/10	Hα-line for aurorae and lightning

JANUS operational principle is very flexible; single images of a distant target can be acquired as well as mosaics of close targets at high resolution, either working with a spacecraft slew or a combination of inertial pointing. During Ganymede orbits, images are typically acquired in push-frame mode.

JANUS heritage comes from cameras developed for the BepiColombo, DAWN and Rosetta missions and is also based on know-how acquired by the team in other projects (e.g. Mars Express).

4.2 Visible-IR imaging spectrometer (MAJIS)

MAJIS will provide spectral imaging of all the objects of interest in the Jupiter system from the visible to the thermal IR range (0.4 - 5.7 µm). The main science goals addressed by MAJIS are:

- Composition and physical properties of the surfaces of Ganymede, Europa and Callisto (ices, salts, minerals, organic compounds); cryovolcanic activity and space weathering effects; relationship between the surface composition and the geological history of these satellites
- Composition, structure, spatial and temporal variability of the exosphere of Ganymede, Europa and Callisto; relationship between the exosphere, the surface and external sources.
- Composition, structure, dynamics and evolution of the atmosphere of Jupiter from the troposphere to the stratosphere; major and minor species, hot spots, clouds, circulation, aerosol photochemistry, auroras.
- Composition and physical properties of Io, small moons, rings and dust in the Jupiter system

The MAJIS Vis-NIR imaging spectrometer will provide unprecedented spatial resolution (0.125 mrad), spectral resolution (1280 spectral bands from 0.4 µm to 5.7 µm) and coverage (3.4° FOV, ~500 pixels across the track) (**Table 4-2**).

Table 4-2. *MAJIS expected performance parameters.*

Attribute	MAJIS expected performance
Spectral range	0.4-5.7 µm
Spectral sampling	2.3 nm (0.4-1.9 µm, VIS-NIR channel) 6.6 nm (1.5-5.7 µm, IR channel)
FOV	3.4°
IFOV	0.125 to 1 mrad/px
Aperture	75 mm
Focal length	240 mm
Operating temperature	≤ 140 K (for the OH and VIS-NIR FPA) ≤ 90 K (for the IR FPA)
Readout speed	≤ 80 ms per frame

Figure 4-4 provides examples of expected MAJIS science products for the Galilean moons and Jupiter. As demonstrated by **Figure 4-4 (right)**, the SNR will exceed 100 for major science goals. The instrument operational modes have been optimised for the JUICE mission phases. Binning and on-board compression will make it possible to obtain global maps of Ganymede and Callisto with a pixel size of 2.5 to 5 km and Jupiter during its rotation with a pixel size of 125 km within bandwidth constraints. Regions of interest will be targeted during close fly-bys of Europa, Callisto and Ganymede and during the circular orbit phase around Ganymede. The upper atmosphere of Jupiter and the exosphere of satellites will be observed with stellar occultation and limb scanning modes.

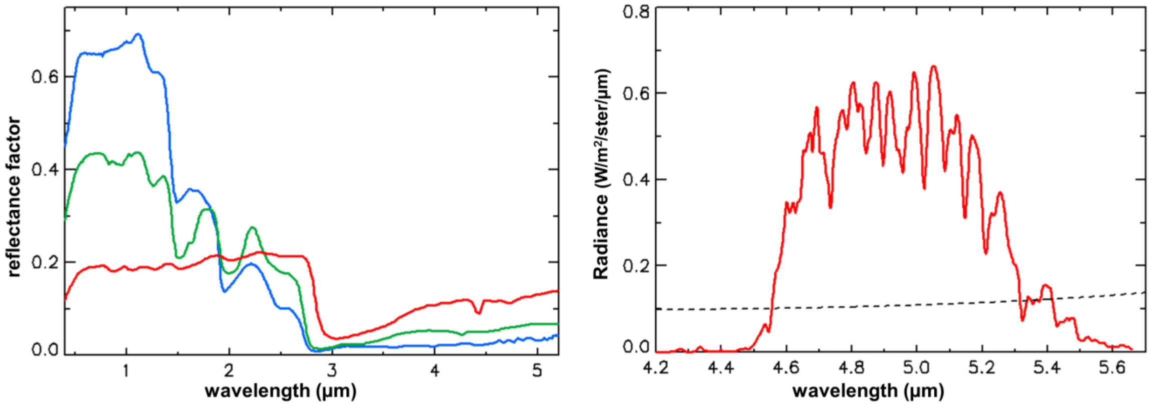


Figure 4-4. Left: *Reflectance factors of bright regions of Europa (blue) Ganymede (green) and Callisto(red) from NIMS/Galileo observations. The SNR of MAJIS for icy satellites depends on solar incidence, exposure time and spatial binning (from 1x1 at approach and departure during flybys to 4x4 on GEO-5000). The SNR will exceed 100 except in deep water ice absorption bands at HR.* ***Right:*** *Model radiance of a Jupiter hot spot taking into account the spectral resolution of MAJIS. MAJIS will provide very high S/N for hot spots at maximum spatial and spectral resolution, as demonstrated by the dashed line, which indicates the model radiance providing a SNR of 100 for an exposure time of 0.8 s in this wavelength range.*

This major step forward is made possible by the experience of the consortium partners in building and operating successfully VIS-NIR imaging spectrometers on solar system exploration missions. The optical design of the instrument (**Figure 4-5**) presently implements a double Czerny-Turner design with a dichroic beam splitter and two spectrometry channels (VIS-NIR: 0.4 – 1.9 µm; IR: 1.5 – 5.7 µm) so as to maximize SNR over the spectral range. A set of two radiators cool the optical bench along the VIS-NIR and IR detectors to their required operating temperatures (140 K and 90 K respectively). Active cooling may be considered as a back-up for the IR detector. A scanner provides an autonomous pointing capability of ± 4.1° in the direction across the slit for motion compensation at low altitudes (close satellite fly-bys, low circular phase around Ganymede) and extended coverage both in nadir pointing mode (swaths across the surface) or in 3-axis pointing mode (e.g. limb scanning for exospheres). An internal calibration lamp will make it possible to monitor the evolution of the detectors during the orbital phase around Jupiter then Ganymede.

The instrument consists of three units:

- Main electronics module
- Proximity electronics module, close to the optical head
- Optical head and radiators

The main electronics is controlled by a command and control processing unit (CPCU) that manages uplink and downlink with the spacecraft. It switches on and off subsystems through a Power Conditioning and Distribution unit (PCDU). Two Compression Units (CU, one per channel) provides a processing capability of 2 Mpixels/channel with spike filtering so as to cope with the harsh radiation environment. The proximity electronics controls data acquisition from the two detectors and auxiliary mechanisms (scanner, shutter, internal calibration lamp).

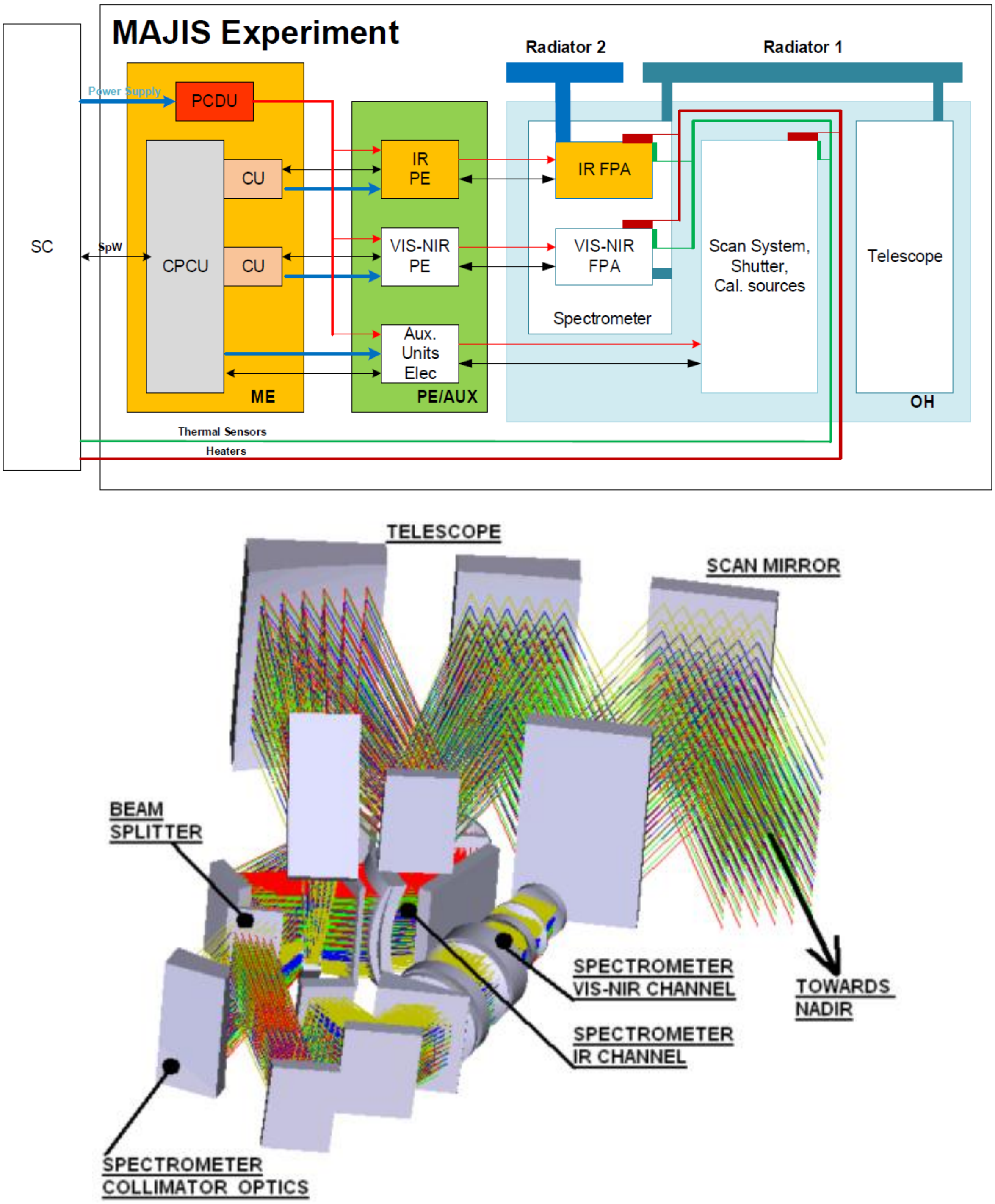


Figure 4-5. *MAJIS block diagram (top) and optical design (bottom).*

4.3 UV Spectrograph (UVS)

UVS is a long-slit ultraviolet imaging spectrograph, with a spectral bandpass including extreme and far-ultraviolet wavelengths in the 55-210 nm range, which will be used to: 1) Explore the atmospheres, plasma interactions, and surfaces of the Galilean satellites; 2) Determine the dynamics, chemistry, and vertical structure of Jupiter's upper atmosphere, from equator to pole; and 3) Investigate the Jupiter-Io connection by quantifying energy and mass flow in the Io atmosphere, neutral clouds, and torus. UVS will obtain excellent airglow and auroral observations, stellar and solar occultations, Jupiter transit, mutual event and surface albedo maps to address JUICE science goals even in the worst-case radiation environment near Europa. The main characteristics of the JUICE-UVS are provided in **Table 4-3**.

Table 4-3. *Main performance characteristics of UVS.*

Attribute	**JUICE-UVS Expected Performance**
Wavelength Bandpass	55-210 nm
Effective Area	0.6 cm^2 at 125 nm for AP
Slit FOV	0.1°x7.3° + 0.2°x0.2°
Spectral Resolution (PSF)	<0.6 nm FWHM, bandpass average
Spectral Resolution (filled slit)	1.2 nm FWHM, bandpass average
Spatial Resolution (PSF)	Nyquist sampled: 0.16° - AP/SP; 0.04° - HP
Pixel Resolution	0.02°
Stray Light Rejection	$<10^{-6}$ at 7° off-boresight
Detector Deadtime	τ_D ~ 1.2 μs; ~30% loss at 360 kHz
Detector Global Background Rate	Total array: ≤20 counts/s during cruise; 2.5 counts/s on ground; typically 1-100 kHz
Detector Output	Continuous, time-tagged pixel list or programmable histogram mode with “ping-pong” memory fill.

These UVS minimum requirements were successfully met or exceeded in ground and flight calibrations by its heritage instruments Juno-UVS, LRO-LAMP, and Pluto-Alice. The key requirements for successful UVS science are 1) pixel angular resolution, 2) wavelength bandpass, 3) spectral resolution (point source & filled slit), 4) spatial resolution, and 5) effective area. UVS requires the following resources: 6.28 kg (nominal unshielded), 9.7 W, each including contingency. It is largely based on the Juno-UVS imaging spectrograph, built for the Juno mission to Jupiter (Gladstone et al., 2014). The *UVS* instrument consists of a single assembly comprising a telescope section, a spectrograph & detector section, and an electronics section, as shown in **Figure 4-6.**

The telescope feeds a 15-cm Rowland circle spectrograph with a spectral bandpass of 55-210 nm. The telescope has an input aperture 4×4 cm^2 and uses an off-axis parabolic (OAP) primary mirror. Light from the OAP is focused onto the spectrograph entrance slit, which has two contiguous segments with fields-of-view (FOV) of 0.1º×7.3º and 0.2º×0.2º projected onto the sky (the 0.2°×0.2° box is used to accommodate the 0.11° diameter Sun during solar occultations). Light entering the slit is dispersed by a toroidal diffraction grating that focuses the UV bandpass onto a curved microchannel plate (MCP) cross delay line (XDL) detector with a solar blind, UV-sensitive CsI photocathode. Tantalum/Tungsten (TaW) plates contiguously surround the detector and electronics assemblies, shielding the detector and sensitive parts from general particle radiation and high-energy electrons in particular. The detector electronics are located behind the detector. In a chamber beside the spectrograph are located the high-voltage power supply (HVPS), low-voltage power supply (LVPS), command and data handling (C&DH) electronics, heater/actuator activation electronics, and event processing electronics. The detector electronics receive event pulses from the detector and provide a digital indication of the spatial and spectral location of each event to the C&DH. Event processing electronics receive valid individual events and process them into a 1) pixel list (a time ordered record of detected events) or 2) programmable histogram.

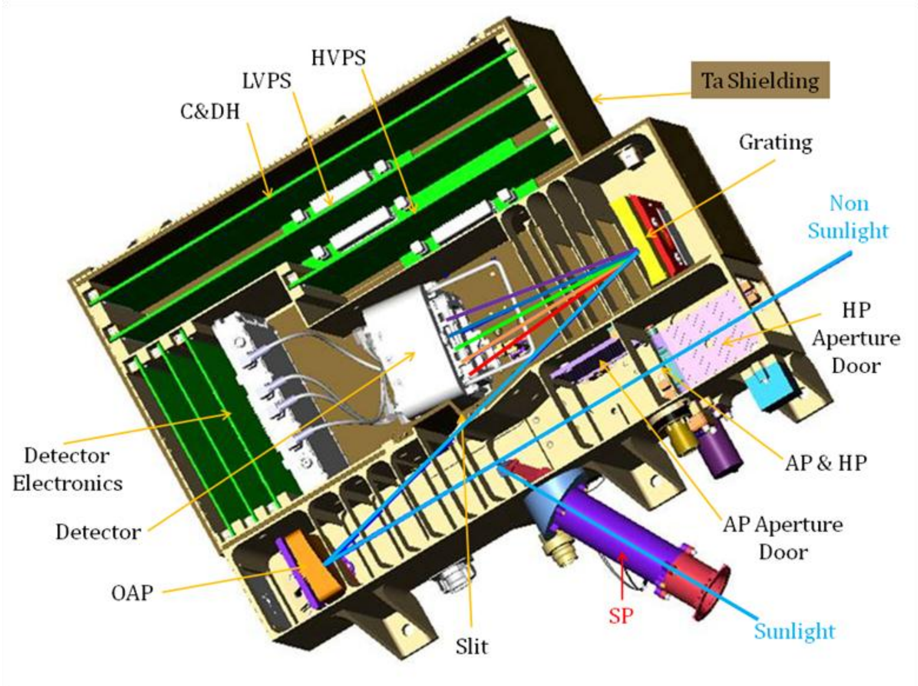


Figure 4-6. *UVS instrument conceptual drawing***.**

A main entrance "airglow port" (AP) is used for most observations (e.g., airglow, aurora, surface mapping, and stellar occultations), while a separate "solar port" (SP), at an angle of 60° to the AP, allows for solar occultations. Another aperture door, with a small hole through the centre, is used as a "high-spatial-resolution port" (HP) for detailed observations of bright targets. Time-tagging (pixel-list mode) and programmable spectral imaging (histogram mode) allow for observational flexibility and optimal data management. The effects of penetrating electron radiation on electronic parts and data quality are substantially mitigated through contiguous shielding, filtering of pulse height amplitudes, management of high voltage settings, and careful use of radiation-hard, flight-tested parts. Substantial heritage from the Juno-UVS instrument development is utilized and improved upon in the UVS radiation mitigation strategies.

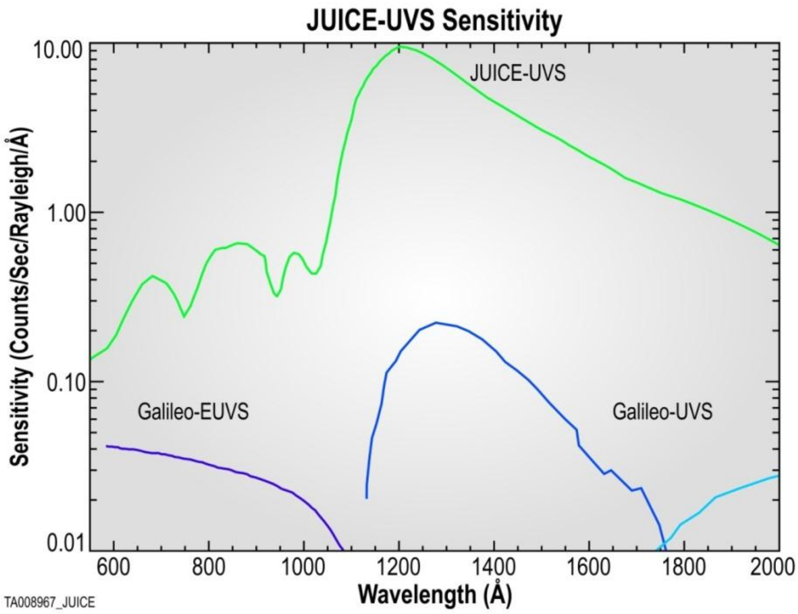


Figure 4-7. *Sensitivity of the JUICE-UVS spectrograph as compared to the EUVS and UVS instruments onboard Galileo.*

The progress in the detector technology made in several past decades led to higher sensitivity, large format imaging arrays, and radiation noise mitigation. The UVS instrument onboard JUICE will have 1-2 orders of magnitude higher sensitivity than similar instruments EUVS and UVS onboard Galileo (**Figure 4-7**). Another advantage of JUICE-UVS is that it covers the key parts of both EUV and FUV ranges of the Galileo instruments with one instrument and one detector.

An example of a UVS spectral image of Europa, in the presence of substantial background radiation, is shown in **Figure 4-8**.

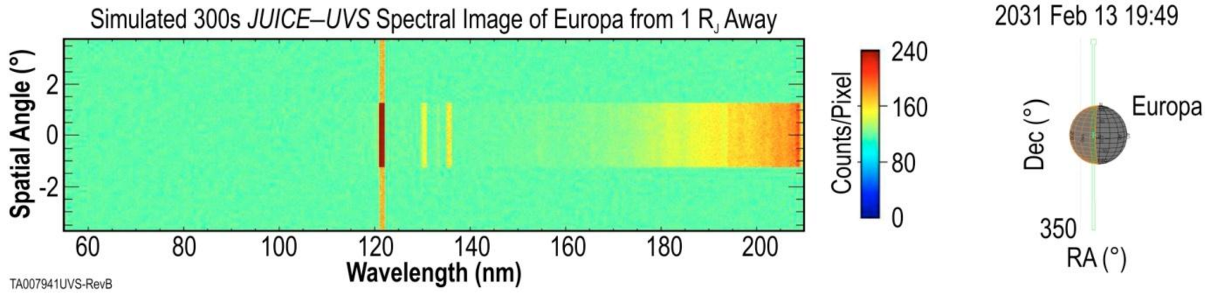


Figure 4-8. *Simulated UVS spectral image of Europa (left panel). The spectrum of Europa includes diagnostic atomic oxygen emissions at 130.4 nm and 135.6 nm, atomic hydrogen emission at 121.6 nm, and reflected sunlight at longer wavelengths. The simulated spectral image is for a 5-minute observation at 10 hours following the E9 closest approach, with the UVS slit aligned north/south along the evening terminator (right panel).The emissions of interest (yellow-orange-red) remain detectable even with substantial background radiation noise (green).*

4.4 Sub-millimeter wave instrument (SWI)

SWI is the heterodyne spectrometer that measures thermal emission from Jupiter and its moons in the Far Infrared (FIR) with very high spectral resolution. It will measure and map temperatures, Doppler winds and chemical species (e.g. CO, CS, HCN, H_2O) in Jupiter's stratosphere, unveiling the dynamics, circulation, and chemistry and their interactions in this poorly studied part of Jupiter's atmosphere and its coupling with the lower and upper atmosphere. SWI will perform a characterisation of the tenuous atmospheres/exospheres of Galilean satellites in a unique and unprecedented manner, in terms of their horizontal distribution and vertical structure. It will also measure thermophysical and electrical properties of satellite surface/subsurfaces and correlate them with atmospheric properties and geological features.

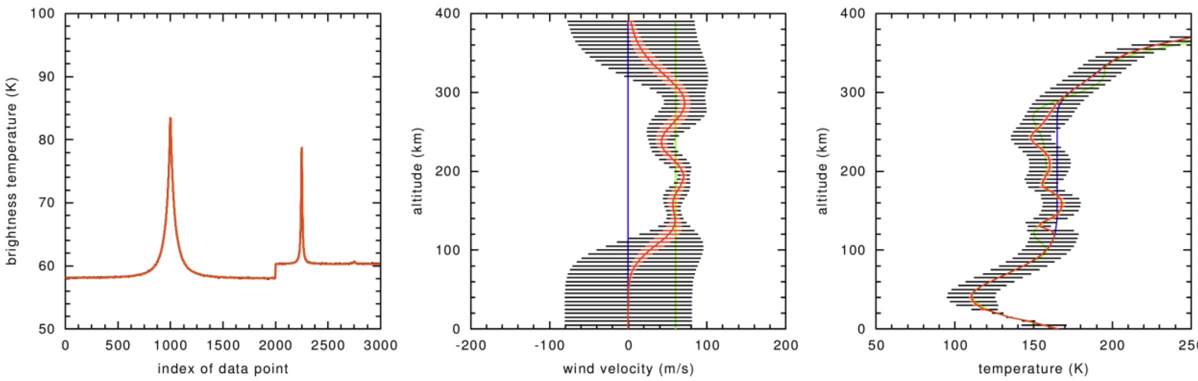


Figure 4-9. Left*: synthetic SWI limb spectrum of Jupiter's stratosphere with two water lines at 557 and 621 GHz. .* ***Middle and right****: retrieved wind velocity and temperature profile. Retrieval simulation: a priori (blue lines), true profile (i.e., the initial profile used for the forward calculation of the spectral line that simulates the measurements) (green lines), retrieved profiles with measurement noise error (red) and null space error included (black). Altitudes are given above 1 bar level.*

SWI will for the first time provide direct measurements of winds in the Jovian stratosphere (**Figure 4-9).** SWI will determine the key isotopic ratios in Jupiter's and satellite atmospheres, especially the deuterium-to-hydrogen ratio, diagnostic of the formation and evolution of Jupiter's satellite system.

SWI will determine the composition, structure and dynamics of Io's atmosphere. On Europa, Ganymede and Callisto, SWI measurements will detect active regions, generally determine sources and sinks of the atmospheres, their interaction with magnetospheric plasma; the interaction of Ganymede's magnetosphere with the Jovian magnetosphere will be derived.

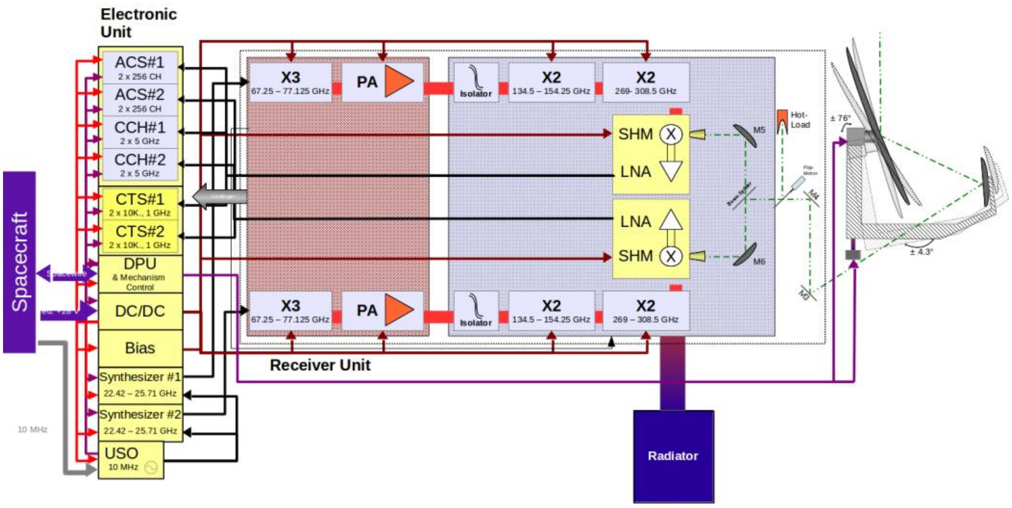


Figure 4-10. *SWI block diagram.*

SWI is a heterodyne spectrometer covering the frequency range from 530 GHz to 625 GHz using two receivers with vertical and horizontal polarization (**Figure 4-10, Table 4-4**). The submillimetre wave radiation is collected by a diffraction limited elliptical reflector with projected 30 cm aperture and collimated into the Receiver Unit. The reflector can be rotated by ± 76° along track (Jupiter) and ±4.3° cross track. The signal is down-converted by multiplication with a tunable local oscillator (LO) signal to an intermediate frequency band (IF) from 4 to 8 GHz (C-band) using passively cooled (Radiator) subharmonically pumped mixers (SHM). The LO consists of K-band synthesizers, frequency controlled against an Ultra Stable Oscillator (USO), E-band triplers and Power Amplifiers (PA) and

Table 4-4. *SWI performance specifications.*

Attribute	**SWI expected performance**
Frequency Band, GHz	530-625
Field of View [mrad]	2
DSB Sensitivity [K]	2000
IF Bandwidth [GHz]	4
CTS Bandwidth [GHz]	1
CTS Spectral Resolution [MHz]	0.1
Δf/f	1.6×10^{-7}
ACS Bandwidth [GHz]	4
ACD Spectral Resolution [MHz]	16
Frequency Stability Δf/f	10^{-8}

two cascaded G-band doublers. The final frequency doubling takes place in the SHM. After amplification using a Low Noise Amplifier (LNA) the IF-signal feeds high resolution Chirp Transform Spectrometers (CTS) broadband Autocorrelation Spectrometers (ACS) and continuum channels (CCH). The main observing modes are limb and nadir sounding (Jupiter: pointing, Ganymede, Callisto and Europa: scanning), complemented by solar occultation measurements. Since SWI is a single pixel instrument with low data rate, mapping observations require the instrument to operate permanently. SWI merges heritage of a number of space borne microwave heterodyne spectrometers the team was involved in: the Microwave Atmospheric Sounder (MAS), Odin, the Microwave Instrument for the Rosetta Orbiter (MIRO) and the Heterodyne Instrument for the Far Infrared (HIFI).

Should the technology for 1200 GHz receiver becomes available to the team, it could replace one of the 600 GHz channels. This would allow the instrument to use spectral lines of uniformly distributed methane for temperature and wind sounding and to measure abundance of additional species in the Jovian atmosphere.

4.5 Magnetometer (J-MAG)

Science outcome from the J-MAG magnetometer will lead to an understanding of the formation of the Galilean satellites, a characterization of their oceans and interiors, and will provide deep insight into the behaviour of rapidly rotating magnetized bodies and how they accelerate particles. The instrument will measure the DC magnetic field vector (in the bandwidth DC to 64Hz) in the spacecraft vicinity. It is a dual sensor fluxgate configuration combined with a scalar sensor. The fluxgates have mature design and considerable space flight heritage and the scalar is an optically pumped atomic magnetometer but in a new configuration known as CDSM (Coupled Dark State Magnetometer).
The science objectives addressed by J-MAG at Ganymede include:

- Resolve the ocean properties by uniquely constraining both depth and conductivity.
- Determine depth, conductivity and extent of any ocean
- Characterize the internal dynamo magnetic field, to octupole and higher order, and determine its generation
- Establish the properties, and processes in, Ganymede’s unique mini-magnetosphere
- Define the nature and controlling factors of Ganymede’s auroral processes

At Callisto J-MAG will:

- Confirm the presence of a global sub-surface ocean, and potentially determine its depth and conductivity
- Define how it couples with the Jovian magnetosphere and ionosphere

At Europa J-MAG will:

- In conjunction with RADAR measurements, potentially constrain ocean conductivity
- Detect signatures of possible outgassing from geologically young terrain

In the Jovian magnetosphere J-MAG will:

- Reveal how moons affect the properties of the magnetospheric plasma and its dynamics
- Determine the processes that heat, transport, and accelerate the Jovian plasma
- Understand how magnetospheres work by comparison of their dynamics and energy transfer at Earth, Jupiter and Saturn.

The prime J-MAG science objective is resolution of the properties of a Ganymede subsurface ocean. The technique which will be used relies on the fact that a time-varying magnetic field generates eddy currents in a subsurface conductor such as a liquid ocean. J-MAG will measure for the first time the induction response at multiple frequencies. It has been shown that induction responses at multiple frequencies can be inverted uniquely to place limits on the subsurface conductivity profiles of the icy Galilean moons (Khurana et al. 2002, Seufert et al. 2011). Ganymede's induction response has so far been tested only at the synodic Jovian rotation period (10.53 hr).

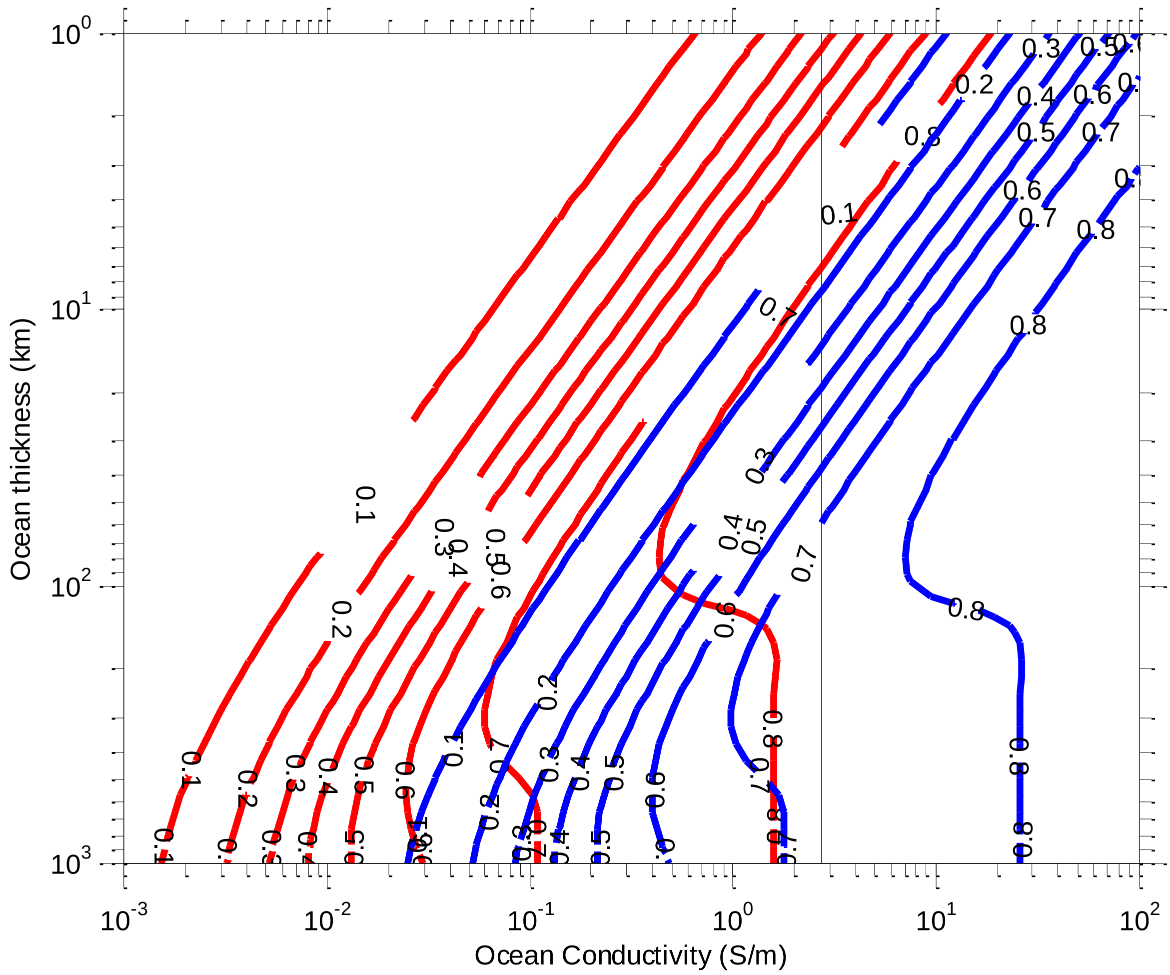


Figure 4-11. *Normalised response (induction/primary field ratio) as a function of the conductivity and thickness of the ocean for two primary frequencies [synodic period (red) and orbital period, 171.72hr (blue)]. The assumed ice thickness is 150km and the mantle conductivity is 10^{-4} S/m).*

Figure 4-11 shows the response of Ganymede at the synodic (10.53 hr, red trace) and orbital (171.72 hr, blue trace) periods as a function of ocean conductivity and thickness. For a limited range of parameter space, where the contours of the two responses intersect, the thickness and the conductivity can be uniquely evaluated. However, the response of Ganymede at longer wave-periods (broad-band excitations from sources internal and external to Jupiter's magnetosphere) may be required to place firm limits on the thickness and the conductivity of the ocean.

The three magnetometer sensors shall be boom mounted, with the scalar sensor furthest from the spacecraft, the outmost fluxgate sensor designated the Outboard (OB) sensor and the sensor closer to the spacecraft body designated the Inboard (IB) sensor, with an electronics box housed within the spacecraft body (**Figure 4-12**). One set of fluxgate sensors and associated front end electronics is provided by Imperial College London and one set by Technische Universität zu Braunschweig, the scalar sensor and its front end electronics will be provided by the Institut für Weltraumforschung, Graz. The remaining part of the J-MAG instrument (i.e., Power Controller Unit, Instrument Controller Unit, Mechanical housing) will be provided by Imperial College. The sensors will be located externally on a project-provided magnetometer boom, the instrument electronics in a box within the body of the spacecraft and connected to the sensors via a boom and platform harness. A dual fluxgate design yields two advantages - enhanced reliability as the instrument will still measure science data if one of the two sensors fails, and improved calibration as data from the two sensors can be combined to help estimate the magnetic field generated by the spacecraft (gradiometer technique). Mounting the sensors separately and at a distance from the spacecraft on a dedicated magnetometer boom, reduces the influence of spacecraft magnetic fields (AC and DC) and enables use of the gradiometer technique. The scalar sensor enables in-flight calibration of the fluxgate sensors by providing an absolute field reference point. This means that in-flight calibration after JOI can occur without the need for regular spacecraft rolls and this is especially important during the Ganymede phase where the natural field variation occurs on timescales that are too short for rolls to be effective anyway. It also enables a relaxation of some of the stringent J-MAG EMC and alignment stability requirements.

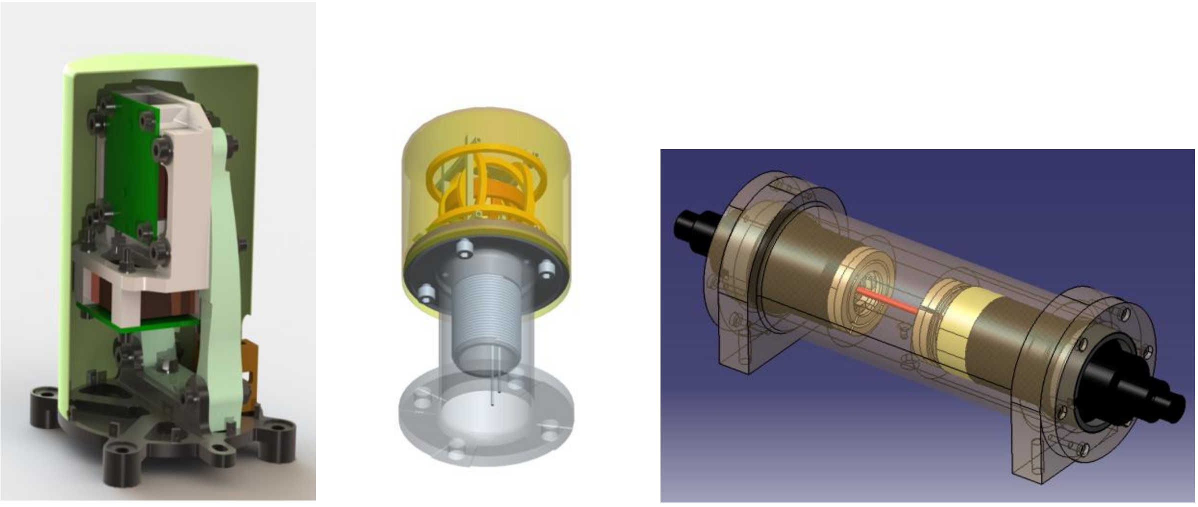


Figure 4-12. *J-MAG sensors: Outboard Fluxgate (Imperial College, London) (left), Inboard Fluxgate (Technische Universität zu Braunschweig) (middle), CDSM sensor (Institut für Weltraumforschung, Graz) (right).*

The required noise performance of the magnetometer can be determined by considering the typical spectral properties of physical signals over the JUICE orbit. A sensitivity of 10pT/√Hz amply satisfies the requirement that the physical signal be measured at all relevant frequencies over the orbit. **Table 4-5** shows J-MAG performance parameters.

Table 4-5. *J-MAG performance characteristics.*

Parameter	Units	Value
Instrument noise performance	pT/√Hz	<10 (at 1 Hz)
MAGOBS/IBS orthogonality (calibrated)	°	< 0.01°
Offset stability (fluxgate)	nT/hour	<0.5nT/100 hours
Offset stability (scalar)	nT	<0.1
Linearity	%	<0.05
Operating temperature range for MAGOBS/IBS/SCA sensors	ºC	-75 to +60 (TBC)
Survival temperature range for MAGOBS/IBS/SCA (measured at the MAG T_{SENS})	ºC	-150 to +80 (TBC)
Measurement ranges (MAGOBS/IBS operational)	nT	±8000, ±50000
Bits per field component	N/A	20
Resolution (MAGOBS/IBS ranges)	pT	1, 6
Resolution (MAGSCA)	pT	10

Accuracy and stability are issues that have been heavily studied by the J-MAG team because they are critical items for J-MAG science. The instrument fluxgates are expected to show stability of <0.5nT per 100 hours due to offset drift. To meet the science measurement requirements, which are more stringent, both regular in-flight calibration is required and strict requirements have to be placed on the total, system-generated (spacecraft and payload) magnetic field in both DC and AC domains. The scalar sensor has an absolute accuracy of 0.2 nT and this will permit calibration of the magnetic field vector data from the fluxgates to an accuracy sufficient to resolve the higher order moments of Ganymede's dynamo field as well as the 171 h and 27 day induction signals from Ganymede's ocean.

The J-MAG instrument is relatively mature with both OB and IB sensor designs having flown on many missions such as Cassini and THEMIS. The ICU and PCU will be derived from those currently being developed for the Solar Orbiter mission, which has almost an identical data and power interface to the spacecraft bus. The scalar sensor is a new development and features important advantages over previously flown optically pumped scalar sensors such as on Cassini and Ulysses in that it features much lower resources and has no dead zones (i.e., it is able to measure the field magnitude at any point on the 4π sphere). The CDSM instrument has no space heritage; however, its technology development is currently funded by ESA and is expected to reach TRL 5 by the time of mission adoption. A first demonstration of the CDSM in space (TRL 8) will take place end of 2016 through participation in the Chinese LEO mission called Electro-Magnetic Satellite (EMS). Apart from the CDSM technical development the majority of the J-MAG design effort in the early implementation phase will concentrate on tailoring of existing technology for the specific mission environment and interface to the spacecraft. In reality this means that the two boom mounted fluxgate sensors will experience the more extreme limits in terms of radiation dose, thermal cycling and mechanical loads. As a stable temperature environment is important for calibration stability, both sensors will use insulating stand-offs to isolate the fluxgate rings cores from the boom interface, with the operational temperature controlled by instrument AC heaters. Radiation analysis has indicated that some of the passive components inside the sensor may require small spot shields to reduce the total dose to a safer level. Shielding of components inside the platform mounted electronic box is also expected to be limited to one or two components.

Operationally, J-MAG is fairly simple and is intended to be largely autonomous in operation. Most commanding will be to set the cadence to the bus consistent with the overall mission planning. The J-MAG instrument will be designed to include functionality for implementing selective downlink.

4.6 Radio and Plasma Wave Instrument (RPWI)

The Radio & Plasma Wave Investigation (RPWI) provides an elaborate set of state-of-the-art electromagnetic fields and cold plasma instrumentation, where several different types of sensors will sample the thermal plasma, DC electric fields, electric and magnetic signals from radio, plasma waves and micrometeorite impacts, as well as monitoring the spacecraft potential and integrated EUV flux. The proposed RPWI instrument has outstanding new capabilities that have not been available to previous missions to the outer planets and that are crucial to answer several fundamental science objectives of the JUICE project. Among them are:

- The capability of four Langmuir probes to measure the vector electric field from DC to 1.47 MHz, and plasma convection (ExB drift) thereby allowing the investigation of plasma electro-dynamics in the Jovian system and, in particular, how the sub-surface oceans and ionospheres of the icy Galilean moons couple electro-dynamically to the highly variable Jovian magnetosphere.
- The capability of a tri-axial search coil, together with the Langmuir probes ability, to measure the vector magnetic and electric fields simultaneously below 20 kHz to identify Alfvén and whistler waves, filamentary currents, flux ropes and electrostatic structures involved in the momentum and energy transfer between different particle populations in the interaction between the Jovian magnetosphere and the conducting ionised exospheres around the icy Galilean moons. An example of expected wave observations is given by the original detection of the ionosphere and magnetosphere of Ganymede by the Galileo/PWS instrument in **Figure 4-13**.
- The significantly enhanced capability of using both passive and semi-active methods to infer the cold (<100 eV) plasma characteristics. The proposed methods also include the capability to infer the bulk ion drift speed.

- The capability of three electric antennae to fully characterize radio emissions, making it possible to determine source locations and polarization of radio emissions from the aurora, Jupiter's magnetosphere, Ganymede's magnetosphere, and characterize their variability with time and response to external forcing.
- The capability to monitor electrically charged dust properties and identify any dust-plasma interactions. This type of study on open versus closed magnetic field lines at Ganymede, and the direct observations of the electric field vector accelerating these particles toward the surface, will give insight to surface sputtering processes and their effect on the icy surfaces and atmospheres.
- The capability to directly measure in-situ the partly ionized gas exhaust of water-rich plumes above active surface regions on the icy moons.

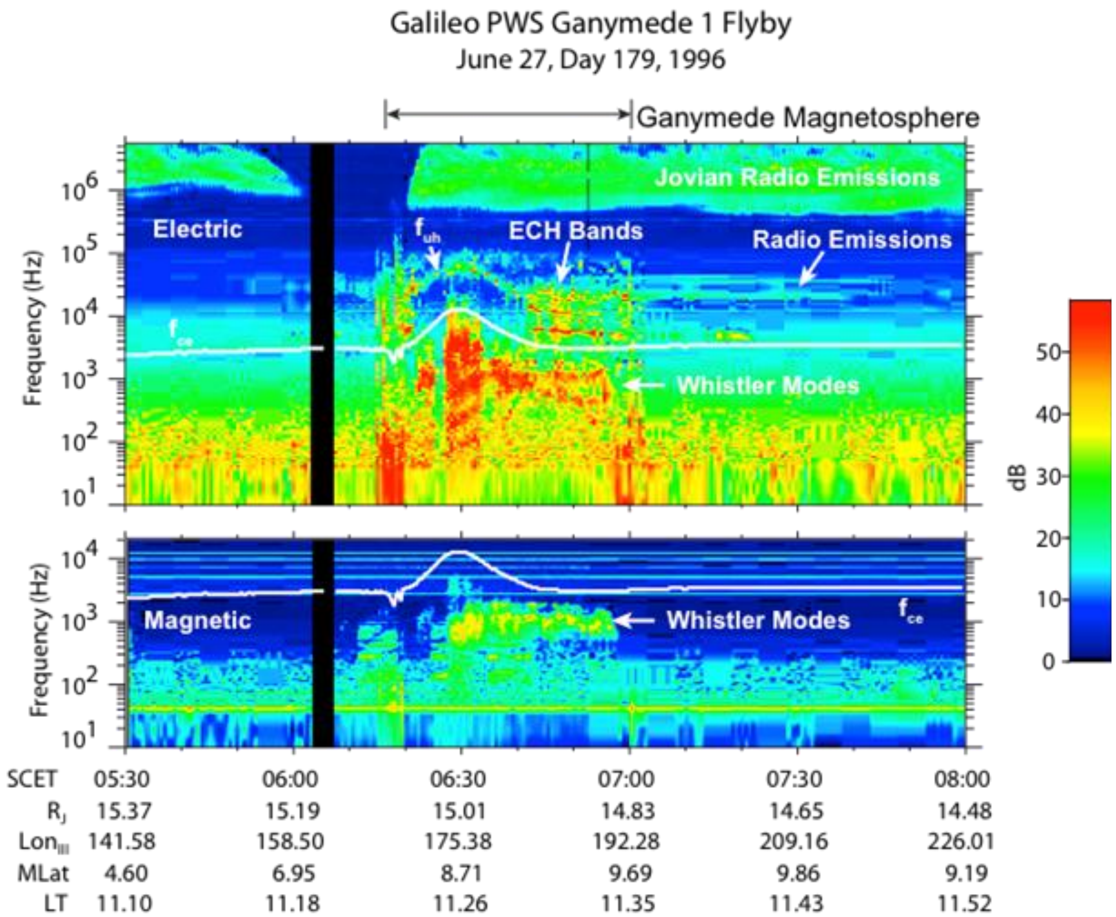


Figure 4-13. *The original detection of a magnetosphere and ionosphere around Ganymede (Gurnett et al., 1996). The electric antenna (upper panel) and the magnetic search coil (lower panel) detect plasma and radio waves that can only be explained by the presence of a local magnetosphere filled with dense plasma.*

RPWI focuses, apart from cold plasma studies, on the understanding of how, through electro-dynamic and electromagnetic coupling, the momentum and energy transfer occurs in the surrounding space environments and with the icy Galilean moons. I In Ganymede orbit, in-situ measurements by RPWI of the electric coupling between any sub-surface ocean, the ionosphere and magnetosphere will provide constraints on the physical characteristics of a sub-surface ocean. The performance of the RPWI experiments is given in **Table 4-6**.

The RPWI consortium consists of very experienced international teams who provide a long heritage record from, and has collaborated with each other on, several previous ESA/NASA/JAXA missions.

The team also includes members who are experts in numerical modelling of all relevant physics and environments, thereby enhancing the science return from the investigation. The operations concept

Table 4-6. *Summary of the RPWI instrument performance.*

Measured Quantity	Range	Error/Sensitivity
Electric field vector, δ**E**(f)	DC – 1.6 MHz Dust detection Polarization with δ**B**(f) Poynting flux with δ**B**(f)	Error at DC: <7 mV/m in Jovian Magn. <0.1mV/m Ganymede ionosphere Spectral sensitivity: 2μV/m/√Hz (>500Hz)
Magnetic field vector, δ**B**(f)	0.1 Hz – 20 kHz Polarization with δ**E**(f) Poynting flux with δ**E**(f)	8 pT/√Hz (at 1 Hz) 6 fT/√Hz (at 1 kHz & 20 kHz) 4 fT/√Hz (at 4 kHz)
Density inhomogeneities (δn/n)	$10cm^{-3}$ – 10^5cm^{-3} <10kHz	<10%
δ**E** or δn/n interferometry	<1000 km/s	<10%
Radio: Electric field vector, δ**E**(f)	 80 kHz – 45 MHz Wave vector (δ**k**) Polarization	 10 nV/m/√Hz (at 10 MHz) ~1° (at 10 MHz) ~10% (at 10 MHz)
Cold Plasma Properties: Electron density (Ne) Ion density (Ni) Electron temperature (Te) Ion drift speed (V_{di}) Ion temperature (Ti) upper constraints Spacecraft potential (Usc) Integrated solar EUV flux	 10^{-4} – 10^5 cm^{-3}, <1Hz 1–10^5 cm^{-3}, <1 Hz 0.01 – 100 eV, <1 Hz 0.1–200 km/s, <1 Hz 0.02 – 20 eV, <1 Hz ±100 V, <1 Hz	 <5% (>$10cm^{-3}$) <20% <15% <20% Constrained by <$mV_{di}^2/2e$ <10% Res. 0.05 Gphotons/cm^2/s

will be based on this heritage experience. A set of adjustable operation modes applicable for survey, nominal and burst data taking will be available and designed to be carried out for particular science phases like flybys of icy moons. For example, the burst mode is intended for magnetosphere and ionosphere boundary crossings and auroral regions of Ganymede. The telemetry use is optimized, and makes use of iterative schemes with certain duty cycles, and the RPWI instrument can flexibly adjust its telemetry use to meet the science objectives of RPWI or other science instruments.

To achieve the science requirements RPWI consists of 10 sensors and 3 receivers. A top-level block diagram of the RPWI is shown in **Figure 4-14**. The sensors consist of four 10 cm Langmuir probes (LP-PWI) on deployable 3m booms, a triaxial search-coil magnetometer system (SCM) on the MAG boom, and a deployable tri-axial 2.5 m dipole antenna system (RWI) for radio measurements. The RPWI system is built up around a main electronics box (EBOX), which houses dual redundant Low Voltage Power Supplies (LVPS) and Digital Processing Units (DPU) that serve three different receiver subsystems: the Langmuir Probe (LP), Low Frequency (LF), and High Frequency (HF) receivers. A backplane inside the EBOX distributes the analogue and digital signals, the different voltages, and a clock signal, which is generated by dual redundant crystal oscillators on the LVPS board. The LP receiver is connected internally to the LF receiver, for which it provides single-ended and differential signals from the Langmuir probes (LP-PWI). To minimise volume, mass, and power requirements, the main driver behind the RPWI design is to share resources by means of an integrated system, and makes sure the various measured electromagnetic fields and cold plasma parameters are measured simultaneously.

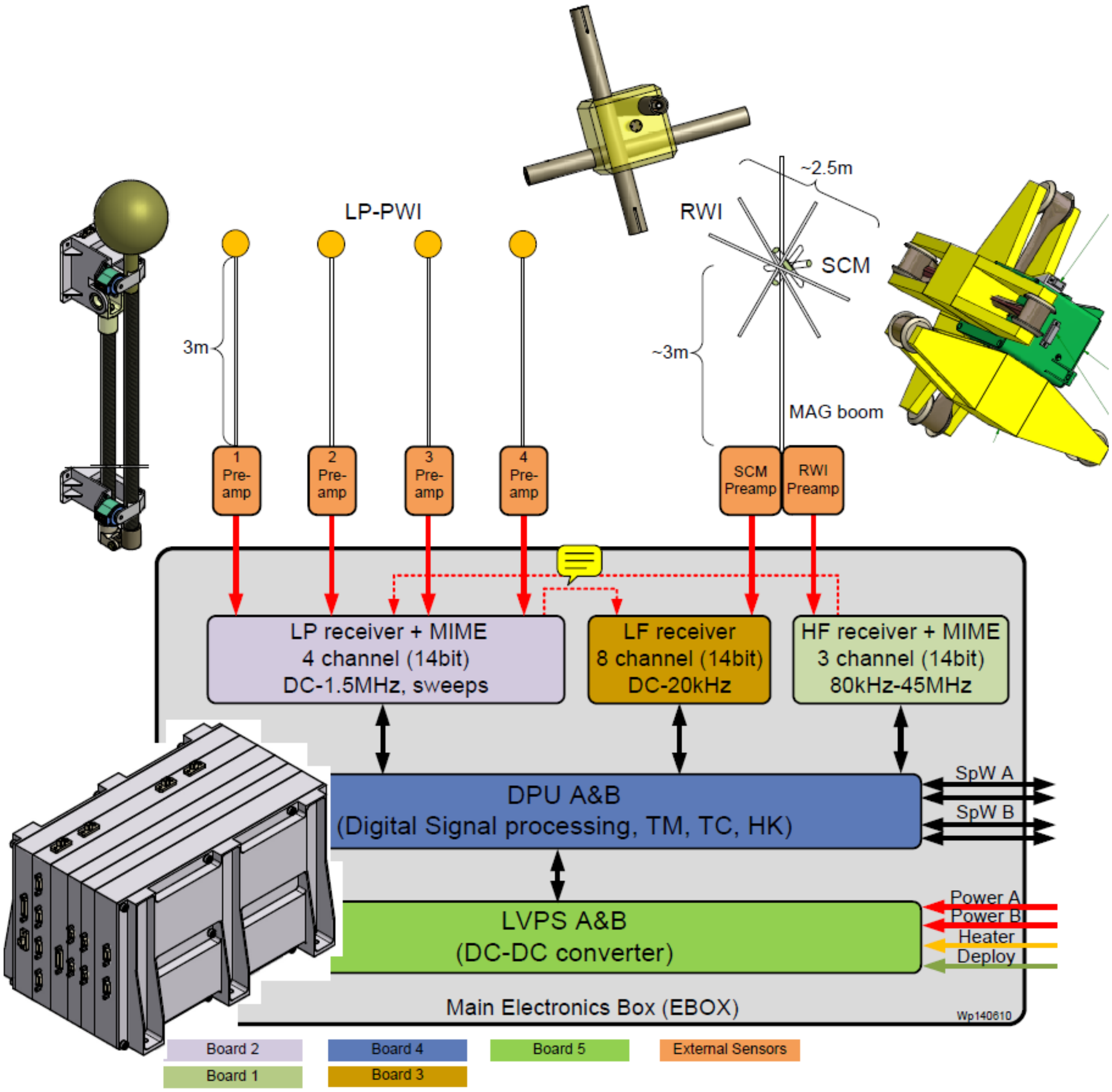


Figure 4-14. *Schematics of the RPWI instrument.*

4.7 Particle Environmental Package (PEP)

PEP is a suite of six sensors (**Figure 4-15)** that together provide comprehensive in-situ measurements and remote Energetic Neutral Atoms (ENA) imaging of particle and plasma environments of the Jovian system and its moons. The PEP suite measures positive and negative ions, electrons, exospheric neutral gas, thermal plasma and ENAs present in all domains of the Jupiter system over nine decades of energy from <0.001 eV to >1 MeV with a wide near-instantaneous angular coverage (**Figure 4-16**).

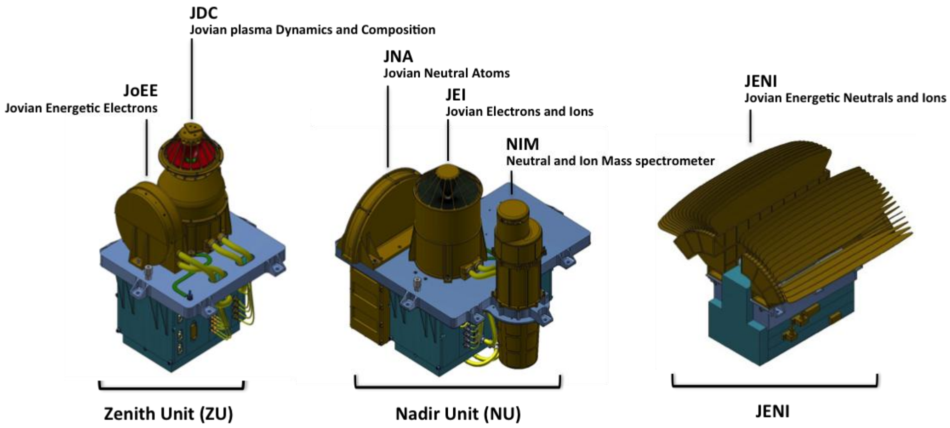


Figure 4-15. *PEP mechanical configuration including Nadir Unit, JENI (Jovian Energetic Neutrals and Ions) and Zenith Unit.*

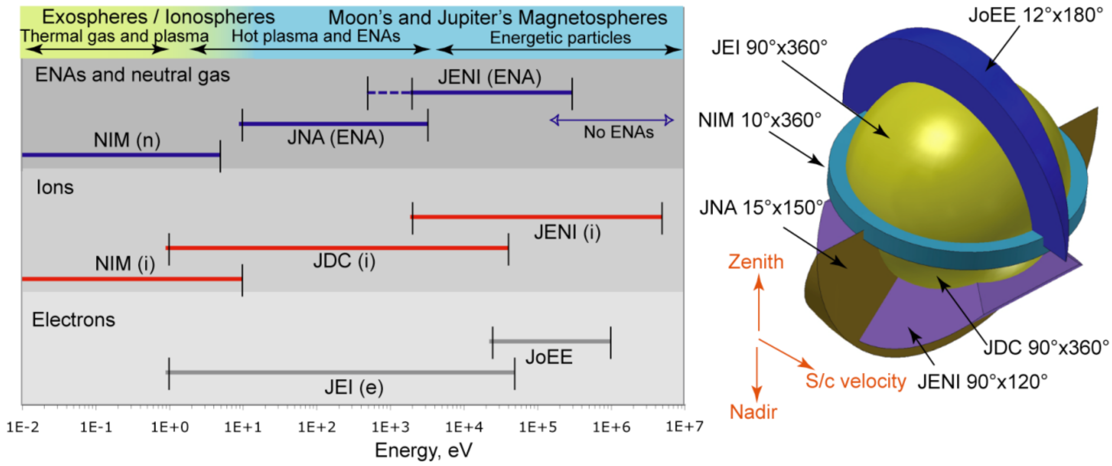


Figure 4-16. *PEP energy coverage (left) and angular coverage (right).*

The main science objectives addressed by PEP are:

- Understanding of the physics of the magnetized plasma interaction of the moons
- Determine composition and characteristics of the moons exospheres and ionospheres and their relation to landform composition
- Understand the global, long-term evolution and principal sources of the Europa and Io plasma and neutral tori
- Understand the mechanisms that release material in to space from Europa and its associated alteration of the exosphere and surface.
- Understand how processes at different scales transport and accelerate particles to MeV energies
- Understanding of how the magnetodisc is created and maintained

The six sensors have an optimized accommodation on three units on the zenith and nadir decks to satisfy the specific requirements on angular coverage and pointing that are unique to plasma and particle measurements. The Zenith Unit hosts JDC, JoEE, redundant DPU (Digital Processing Unit), power system with redundant DC/DC converters for DPU, and a single interface to the spacecraft. The Nadir Unit accommodated includes JEI, NIM, JNA, redundant DPU, power system with redundant DC/DC converters for DPU, and a single interface to the spacecraft. JENI is also accommodated on the spacecraft nadir deck and interfaces electrically with the Nadir Unit. **Table 4-7** shows key performance parameters of the PEP sensors.

Table 4-7. *PEP key performance.*

PEP sensor	Key Performance
JDC - Jovian plasma Dynamics and Composition: Design using reflectron and reflecting surface. Instantaneous 3D distributions of positive, negative ions, constraining charge states, electron measurement capability	Plasma ions and electrons 1 eV – 41 keV, ΔE/E=12% M/ΔM=30 Hemispheric, ΔΩ=5.5˚x19.5˚
JEI - Jovian Electrons and Ions: Instantaneous 3D distributions of plasma electrons, ion measurement capabilities	Plasma electrons and ions ~1 eV – 50 keV, ΔE/E=4.9% Hemispheric, ΔΩ=20˚x10˚
JoEE - Jovian Energetic Electrons: Ultra-lightweight energetic electron sensor built on the Galileo energetic particle detector technique. Instantaneous pitch-angle distributions and spectra.	Energetic electrons 25 keV – 1 MeV, ΔE/E≤20% FoV: 12˚x180˚, ΔΩ=12˚x22˚
NIM - Neutral gas and Ion Mass spectrometer: Compact design based on TOF and reflectron. First-ever exospheric neutral gas and thermal plasma mass spectroscopy at Jupiter's moons.	Thermal neutrals and ions (< 5 eV) Mass range: 1-1000 amu M/ΔM=1100 Sensitivity: 2 cm^{-3} (~10^{-16} mbar)
JNA - Jovian Neutrals Analyzer: ENA camera based on successful instrument on the Lunar Chandrayaan-1 mission. Imaging of Io plasma torus, backscattered and sputtered surface products.	Low-energy ENA 10 eV – 3 keV (H) ΔΩ=7˚x25˚
JENI - Jovian Energetic Neutrals and Ions: Combined energetic ion and ENA camera based on Cassini, IMAGE and Juno. Global ENA imaging of magnetosphere and neutral gas tori (see also Section 2.2.2).	ENA and ions (H, He, O, S) ~0.5 – 300 keV (ENA), 5 MeV (ions) FoV: 90˚x120˚, 2˚ resolution (>10 keV H)

The sensors of the PEP suite configuration work together to address the JUICE plasma and particle objectives. Two examples below demonstrate the capabilities of the instrument and expected science products.

JDC, JEI and JENI will characterize plasma density, temperature, velocity patterns and pressure with a fidelity and resolution not possible previously, both outside and inside of the Ganymede magnetosphere (**Figure 4-17**). This will enable PEP to determine how the highly variable Jovian magnetospheric plasma distorts Ganymede's magnetosphere. These plasma parameters will be essential for retrieving the relatively weak magnetic induction signal from Ganymede's interior (necessary to characterize the subsurface ocean) and build models of Ganymede's auroral regions.

Sputtering or sub-surface venting is arguably the most important processes for promoting material in to the exosphere. NIM will directly measure the chemical and isotopic composition, density, temperature and scale height of neutral exosphere for the first time around Jovian moons and resolve important trace species such as Mg and Na, that are not water ice related (McCord et al., 2001). NIM will obtain the first direct mass spectra of Europa's exospheric gas (**Figure 4-18**). The low (30 cm^{-3}) detection threshold of NIM enables detection of yet undiscovered species, with the likely candidates Mg, Al, Si, Ca, that will help understand the mineralogical composition of the surface. Sputtering agents and other weathering agents will be characterized by JDC, JENI and JoEE and the resulting sputter products and backscattered neutrals will be imaged by JNA. These measurements will be used to estimates of mass release rates and build partial maps and estimates of particle energy input to the surface of Europa.

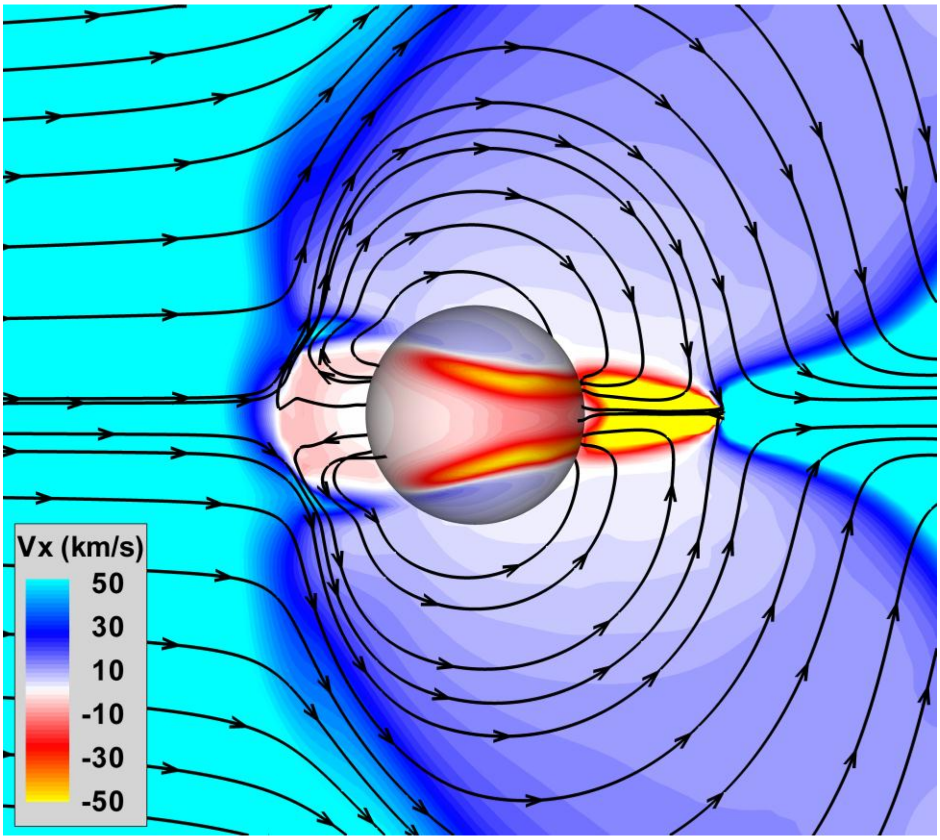


Figure 4-17. *PEP will determine plasma velocity, density and pressure around Ganymede, important for understanding its unique interaction and contribute to resolving the magnetic induction signal used to probe its interior. The figure shows a modelled example plasma velocity patterns from Jia et al. (2009).*

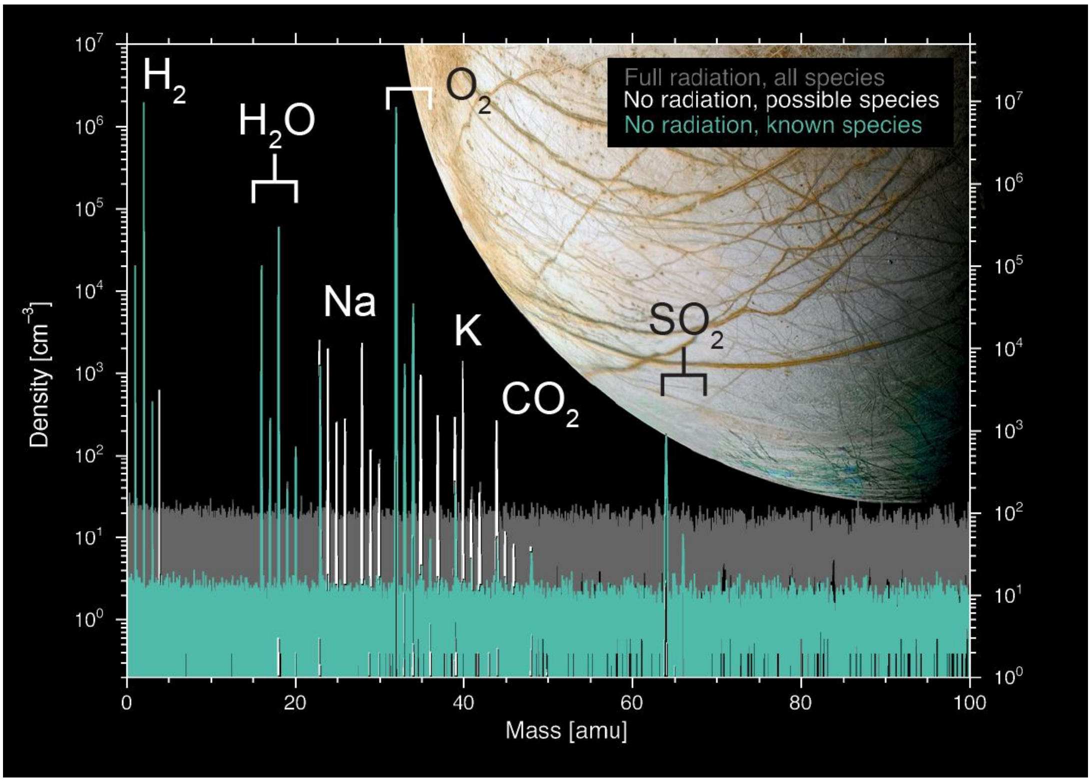


Figure 4-18. *NIM provides the first direct sampling of Europa's exosphere.*

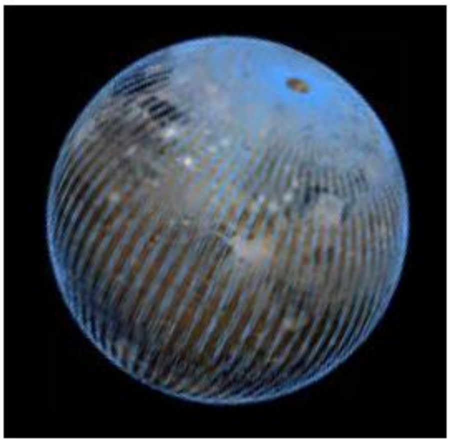
PEP is designed for operating in and measuring the harsh Jovian environment. Radiation dose and background is mitigated by employing a mutual shielding approach, single to triple coincidence detection schemes in all sensors, minimized detector areas with focusing electrostatics, minimized sensor volumes to minimize radiation-induced secondary emissions, dedicated monitoring of penetrating radiation for background subtraction, and use of radiation insensitive Ceramic Channel Electron Multipliers (CCEM).

All PEP sensors and subsystems have TRL≥6 and are built on direct flight and team heritage from Galileo, Cassini, Juno, Mars Express, Venus Express, Rosetta, SOHO, New Horizons, Chandrayaan-1, IMAGE, and the Van Allen Probes.

PEP operates continuously within the spacecraft constraints with flexible telemetry (TM) modes (time, energy, mass, angular resolution) depending on the special domain under study. The number of PEP TM modes is minimized but the individual sensor mode definition is kept flexible and re-programmable in-flight to take full advantage of the comprehensive PEP measurement capabilities and achieve flexibility in the performance optimization.

4.8 Laser Altimeter (GALA)

The Ganymede Laser Altimeter (GALA) will investigate the surfaces of Ganymede, Europa, and Callisto. By measuring the time-of-flight of a laser pulse transmitted from the instrument, backscattered at the moon's surface, and detected in the instrument's receiver telescope, height profiles can be obtained in along-track direction. Combining many of these tracks, the local, regional, and global topography of Ganymede can be obtained (**Figure 4-19**). From the pulse-spreading of the returned pulse the surface roughness on the scale of the laser footprint (order of a few tens of meters depending on S/C altitude) can be obtained. Additionally, information on the albedo at the laser wavelength (1064 nm) can be gained from the intensities of the transmitted and returned pulses.



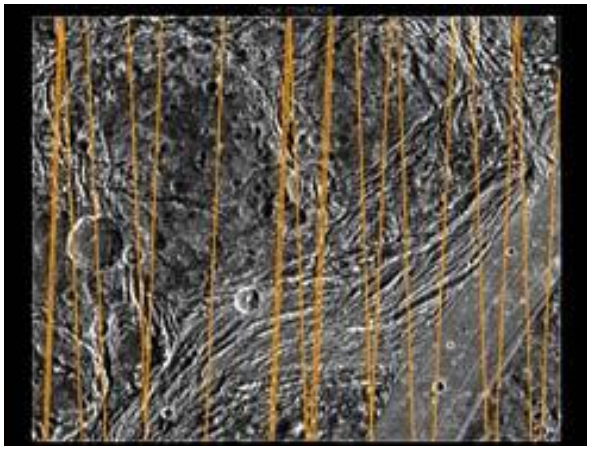


Figure 4-19. Left: *Global coverage for shape and tidal deformation (not all tracks are shown);* ***Right:*** *GALA ground-tracks across different geological units on Ganymede (Nicholson Regio: LAT=(-16°,-13.5°); LON=(-13.2°,-10°)).*

GALA is one of the JUICE instruments focusing on the characterisation of Ganymede's subsurface water ocean. By obtaining not only good spatial coverage but also temporal coverage with laser ground-tracks the tidal deformation of Ganymede's ice shell along Ganymede's orbit around Jupiter will be measured. From the tidal signal (expressed in terms of the radial tidal Love number h_2), the presence of an ocean can be verified. While the tidal signal is expected on the order of several meters in case of a subsurface ocean (**Figure 4-20**). Without an ocean, this signal will be few tens of centimetres only. To realize measurements of tidal response, we will analyse intersecting ground-tracks at different tidal phases. From h_2, the extension of Ganymede's ice shell can be constrained, especially when combined with measurements of the tidal potential by the radio science experiment (3GM).

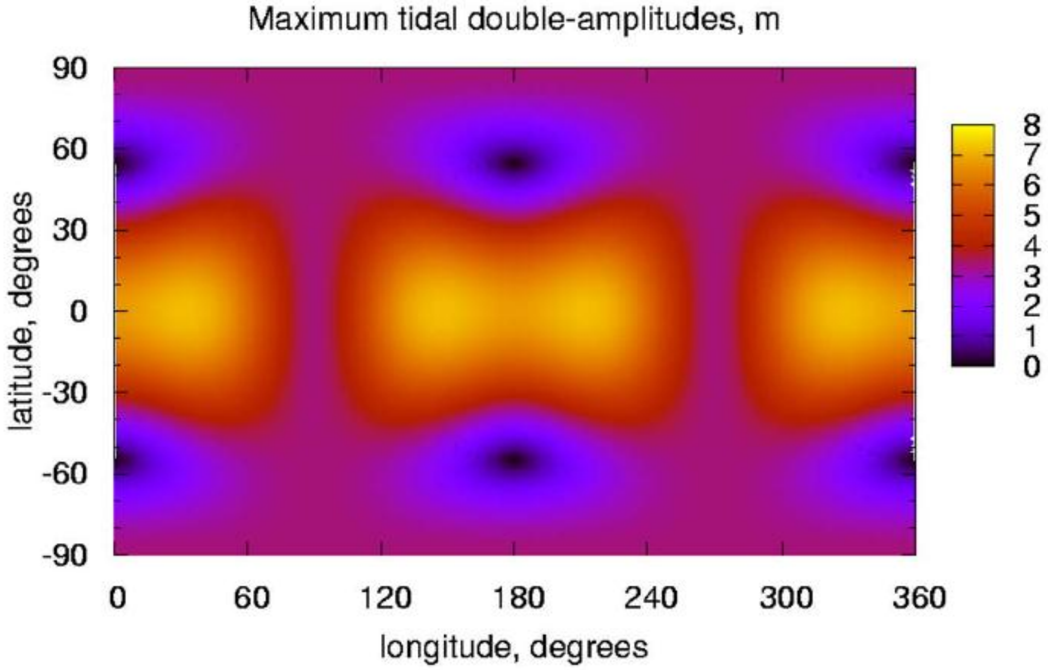


Figure 4-20. *Expected pattern of maximum tidal amplitudes on Ganymede's surface.*

GALA will contribute to the exploration of the surface morphology and physical properties of Ganymede, Europa and Callisto. Combining stereo-data sets from the camera (JANUS) with altimetry data will provide topography and digital terrain models that are essential for geological analysis as well as for interpretation of the reflected radar signals of the RIME instrument.

Table 4-8. *GALA baseline instrument parameters.*

Instrument Parameter	**Value**
Laser wavelength	1064 nm
Pulse energy	17 mJ
Pulse length	6 ns
Pulse repetition rate	1 to 50 Hz (variable)
Beam divergence	100 μrad (full cone)
Spot size on surface	50 m (in 500 km orbit)
Receiver telescope diameter	0.25 m (F/1 telescope)
Altitude resolution	~10 cm at optimal conditions

GALA can be operated on day- and night-side from ranges smaller than about 1000 to 1300 km (depending on the different albedo values of Europa, Ganymede and Callisto) during flybys and orbital pericenter passages. The main phase for acquiring data at Ganymede is the GCO-500 orbit, where continuous operations are possible. Measurements can be acquired without gap along track on ground-tracks separated by a few kilometers on average with better coverage at high latitudes.

GALA uses the "direct-detection" (classical) approach of laser altimetry. The instrument emits laser pulses at a wavelength of 1064 nm by using a actively Q-switched Nd:Yag laser. The detector measures the emission time of each pulse. The returning laser pulse is refocused onto a silicon avalanche photodiode (APD) through back-end optics. The APD-signal is then amplified, sampled and fed to a digital range finder. The data is passed to a digital processing unit, which controls the operation of the complete instrument and communicates with the spacecraft. Main instrument characteristics are summarized in **Table 4-8**.

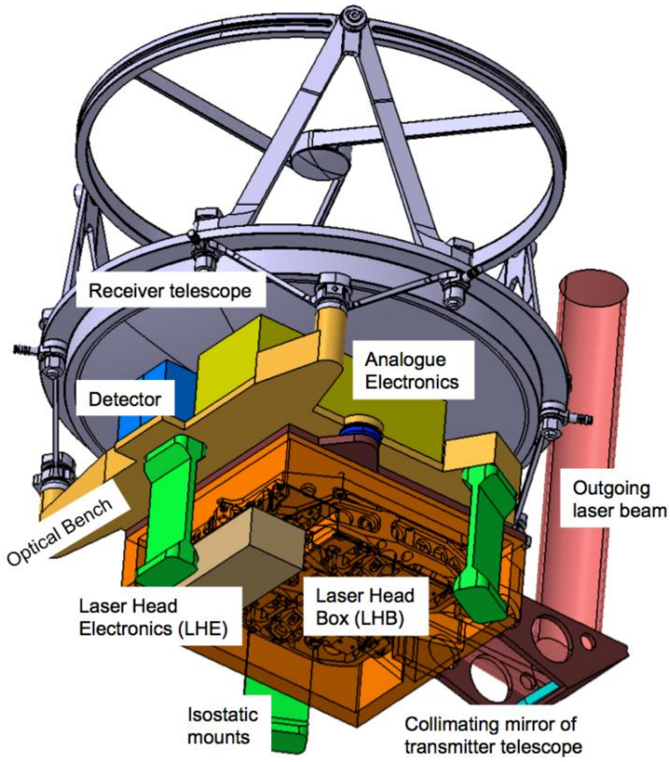


Figure 4-21. *Schematics of the GALA instrument.*

Figure 4-21 shows schematics of the GALA instrument. Heritage for GALA comes from the BepiColombo Laser altimeter (BELA), the first European Laser altimeter for planetary exploration, and from the altimeters flown on Kaguya/Selene to the Moon and on Hayabusa to asteroid Itokawa.

4.9 Ice Penetrating Radar (RIME)

Radar for Icy Moon Exploration (RIME) instrument will contribute to the following overall science objectives of the JUICE mission: (i) characterise Ganymede as a planetary object and possible habitat, (ii) explore Europa's recently active zones, and (iii) study Callisto as a remnant of the early Jovian system. The science objectives of RIME at Ganymede are to characterise the ice shell, understand the formation of surface features, search for past and present activity, and constrain the global composition, distribution, and evolution of surface materials. RIME observations will be relevant for the exploration of *Europa*'s recently active zones. Europa's geologically active icy crust, potentially overlying a subsurface ocean and likely harbouring shallow subsurface liquid water within, is the best candidate in the Jovian system for exploring extra-terrestrial habitability. The RIME science objectives on Europa include investigating the composition of non-ice material, and looking for liquid water under active sites. During flybys, RIME will acquire subsurface profiles of *Callisto*, thus contributing to the study of the moon as a remnant of the early Jovian system. RIME observations will provide new insights into the processes that have contributed to the formation of geologic features on Callisto. In particular, the science objectives of the RIME at Callisto are to characterise the outer shells, including the ocean, determine the composition of the non-ice material, and study the past activity.

The above scientific objectives will be achieved by the RIME instrument that is optimised for the penetration of the Galilean icy moons, Ganymede, Europa and Callisto, up to a depth of 9 km. RIME is a nadir-looking radar sounder instruments which transmits radio waves with the unique capability to penetrate deeply into the subsurface. When these radio waves travel through the subsurface, their reflected signal varies as they interact with subsurface horizons and structures with differing dielectric constants. These varying reflections are detected by the radar sounder and used to create a depth image of the subsurface (referred herein as radargram). Because of the high electromagnetic transparency of ice at radar low frequencies and hence its ability to map unexposed subsurface features, RIME is a key instrument for achieving ground-breaking science on the geology and the geophysics of Ganymede, Europa and Callisto. RIME heritage is on the radar sounders currently operating at Mars, i.e., the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on-board ESA's Mars Express S/C and the SHAllow RADar (SHARAD) on-board NASA's Mars Reconnaissance Orbiter. **Figure 4-22** shows an example of radargram acquired by SHARAD radar sounder at Planum Boreum (north polar plateau) of Mars.

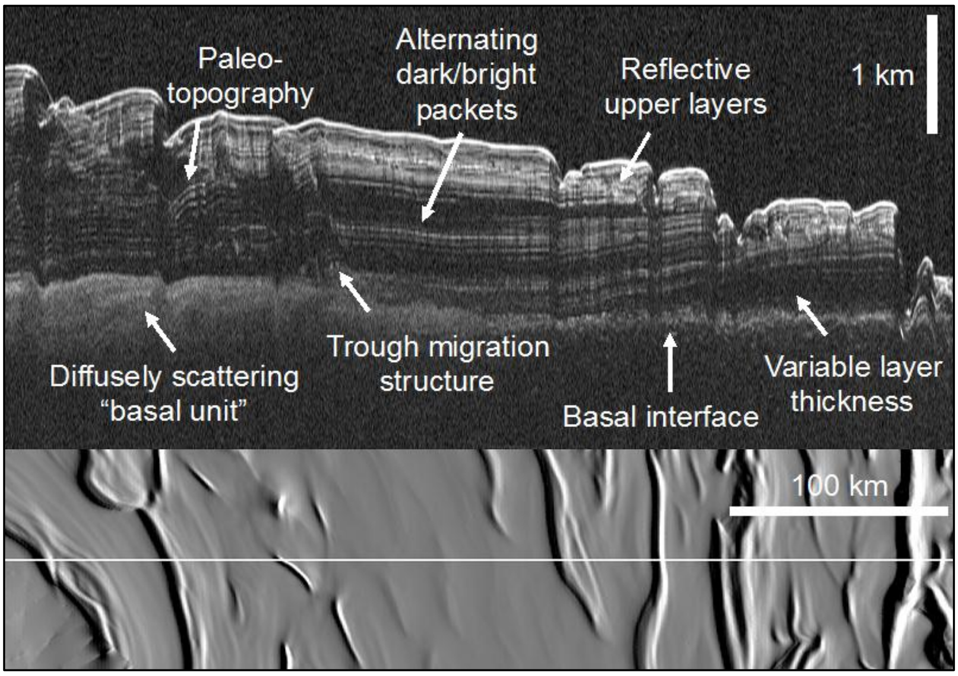


Figure 4-22. *The upper panel shows a SHARAD radargram of north polar plateau of Mars at a resolution of 30 m in ice. The lower panel is shaded relief topography from the Mars Orbiter Laser Altimeter (MOLA), with the nadir ground track shown as a white line.*

To achieve the aforementioned science goals, the RIME central frequency is selected to be 9 MHz, which is an optimal choice for meeting the penetration requirements and for reducing the effect of clutter induced by the topography of Ganymede, Europa and Callisto surfaces. RIME is designed for achieving a maximum penetration depth of 9 km with two measurement modes that result in high vertical resolution (maximum of 50 m in ice with a chirp bandwidth of 3 MHz) or low vertical resolution (140 m in ice with a chirp bandwidth of 1 MHz). The RIME nominal data rate in the circular orbit phase around Ganymede is in the range 210–217 kbps depending on the measurement mode, whereas it is 2784 kbps during flybys. It is important to mention that within the high and low resolution modes, parameters can be adjusted to change the output data rate and obtain intermediate acquisition modes. The RIME antenna is a dipole with a tip-to-tip length of 16 m. The operation power is 25.1 W for orbit mode and 28.5 in flyby mode (including margin). The main parameters of RIME are shown in **Table 4-9**.

RIME will operate on the anti-Jovian side of the icy moons to avoid the interference of the Jupiter radio emission, which can significantly decrease the SNR of measurements. A detailed analysis of the orbits associated with the anti-Jovian acquisitions confirms that all the targets associated with the science goals are present in the predicted anti-Jovian coverage. Instrument modes during operations will be selected according to the expected characteristics of the observed area and of the intended scientific analysis of the data, resulting in a desired profile of spacecraft (S/C) resources utilization

Table 4-9. *Main parameters of the RIME experiment.*

Main Instrument parameters	Parameter values
Transmitted central frequency, MHz	9
Antenna type	Dipole
Antenna length, m	16
Maximum penetration, km	9
Cross-track resolution (km)	2-10
Along-track resolution (km)	0.3-1.0
Pulse repetition frequency (Hz)	200-500
Chirp bandwidth (MHz)	3, 1
Vertical resolution in ice (m)	50-140
Chirp length (μs)	50-100
Receiver window length (μs)	117-226

(pointing, power, data rate, data volume) for the duration of the observation. Two main operation scenarios are foreseen for RIME: flyby observations and orbital operations around Ganymede. Because flybys of Europa and Callisto provide unique scientific opportunities for RIME, it is considered desirable to downlink data in their simplest form, and to perform processing exclusively on the ground to achieve flexibility in the processing modes and thus to optimize science return. During the orbital phase at Ganymede, it is expected that the radar will routinely operate using modes employing on-board pre-summing for reducing the data rate.

Figure 4-23 depicts the RIME instrument block diagram. The instrument is divided into two main parts: (i) RDS (Receiver and Digital Subsystem), containing the receiver module and the DES (Digital Electronics section) which includes the digital and conversion functions; (ii) The Transmitter Tx and Matching Network, which provide the high power amplification for the signal for transmission and impedance matching to the antenna.

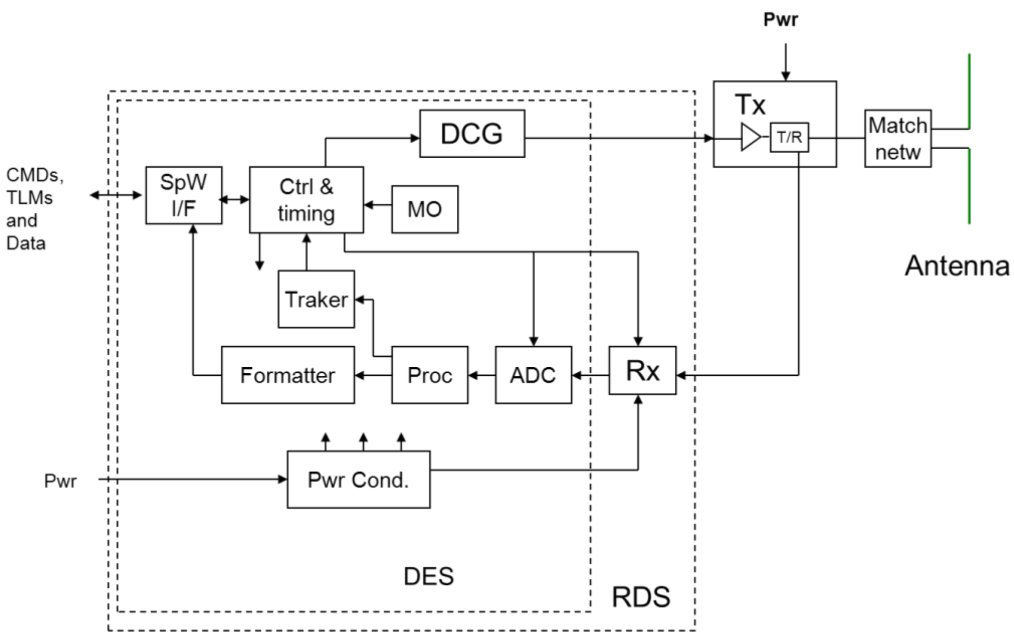


Figure 4-23. *Rime Instrument General Block Diagram.*

4.10 Radio Science Experiment (3GM)

3GM (Gravity and Geophysics of Jupiter and the Galilean Moons) addresses JUICE scientific objectives pertaining to gravity, geophysics and atmospheric science with radio occultations.

3GM on JUICE will revolutionize our understanding of the origin, evolution and structure of the Galilean icy satellites through highly precise spacecraft tracking. By itself and in combination with altimetry and other measurements, radio tracking will provide information on the static gravity fields of Ganymede, Callisto and Europa, on the rotational state and tidal deformation of Ganymede and Callisto, on the presence of density variations within the ice shell of Ganymede, and on dissipation within the Jovian interior. Specifically, 3GM will:

- Determine the gravity field of Ganymede to degree and order 15 or higher, enabling the identification of density anomalies within the body. In combination with altimetry, this will determine the extent to which topography is expressed on the gravity field or is instead well compensated, the role of a silicate core, the possible role of convection, and the presence of regional differences in the outermost ice shell. This will be the first time that the high degree gravity field of a large, mostly solid icy body will be characterized.
- Determine the nature and extent of the likely internal ocean within Ganymede and the thickness of the overlying ice shell through four different methods: (1) Time-dependence of gravity at degree 2 arising from the eccentricity tide; (2) Combination of this result with the corresponding change in topography from this tide; (3) Determination of the obliquity of Ganymede and its possible time variation; (4) Detection and determination of the amplitude of libration of the deep interior and the outermost ice shell, and possible asynchronous rotation of the satellite.
- Determine or set a lower bound to the tidal Q of Ganymede through measurement of the phase lag in response to the eccentricity tide.
- Determine the degree 2 and 3 gravity field of Callisto with a precision sufficient to assess the extent of differentiation within that body and extent of hydrostatic equilibrium, thus removing the current ambiguity in the interpretation of Galileo results. Extent of differentiation plays a central role in our understanding of the timescales and energetics of satellite formation.
- Determine the presence or absence of an internal ocean within Callisto by measuring the time-dependence of gravity at degree 2 arising from the eccentricity tide.
- Independently determine the J_2 and C_{22} of Europa, further constraining the moment of inertia and extent of hydrostaticity for that body.
- Contribute to the improvement of the ephemerides of the Solar system and the Jovian satellites and carry out tests of laws of gravity.

A key component of the 3GM experiment is the radio occultation measurements of neutral atmospheres and ionospheres of Jupiter, Ganymede, Callisto and Europa. Additional science goals will be achieved by means of ring occultations and bistatic radar observations. 3GM will:

- Measure vertical profiles of atmospheric densities in Jupiter’s troposphere and stratosphere, enabling us to infer vertical profiles of atmospheric pressure and temperature. These measurements will allow us to infer zonal wind velocities and determine the latitudinal shape of Jupiter’s atmosphere.
- Identify atmospheric wave characteristics and infer their roles on atmospheric temperatures and winds.
- Probe Jupiter’s ionosphere to determine horizontal and vertical structures and variability of electron densities, constraining chemical processes as well as ionization sources and enabling to study magnetosphere-ionosphere coupling processes on Jupiter.
- Measure ionospheric electron densities of the Galilean icy moons, in particular Ganymede, and use models to infer neutral densities.

- Since the tenuous atmospheres of the icy moons are generated mostly from surface sputtering and sublimation (and possibly cryovolcanic activity on Europa), determine surface sputtering rates and thereby basic surface properties from radio occultations.
- Using numerical atmosphere models in tandem with observations, infer ionization processes and examine atmosphere-magnetosphere coupling processes.
- Use radio occultations to probe Jupiter's rings, especially during relative geometries allowing low opening angles and using the uplink one-way mode, which ensures a high signal-to-noise ratio.
- Carry out, in synergy with PRIDE's VLBI antennas, bistatic radar observations of the icy moons (in particular Ganymede and Callisto) to determine average surface slope, near-surface dielectric constant and, under certain assumptions, the surface porosity from the target scattering properties.

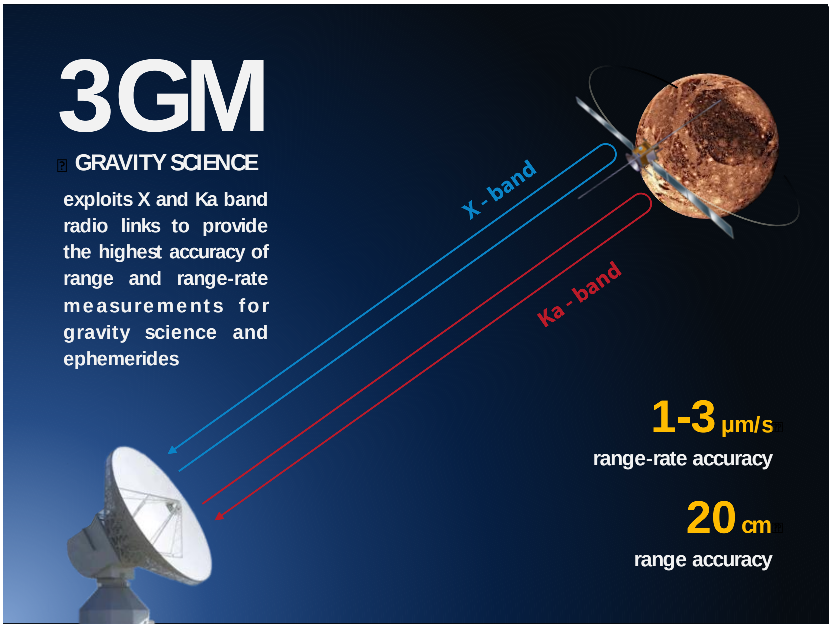


Figure 4-24. *3GM goals in geodesy and geophysics rely on very precise measurements of the spacecraft range and range-rate. Radio signals in X band (7.2-8.4 GHz, blue lines) and Ka band (32.5-34 GHz, red lines) are transmitted from the ground station to the spacecraft and coherently retransmitted back to Earth by means of transponders onboard the spacecraft. The two-way radio link configuration adopted by 3GM will provide radio metric observables approaching the ultimate capabilities of microwave tracking systems. The key component is a Ka band digital transponder with a very high frequency stability and supporting pseudo-noise ranging codes at 24 Mcps.*

The 3GM experiment comprises two separate and independent elements, namely a high performance Ka-band transponder (KaT) and an ultra-stable oscillator (USO). Although the payload elements will be independently designed, assembled, tested and integrated, they provide a unified and comprehensive approach to JUICE Radio Science Instrument package and the associated scientific goals. The 3GM elements are incorporated in the spacecraft TT&C system.

3GM observable quantities are obtained from spacecraft tracking at microwave frequencies by ESA ESTRACK stations. Gravity science requires precision measurements of the spacecraft's two-way range and range rate, while one-way open loop samples of the signal carrier (recorded at the ground station or on-board) are the fundamental observables for atmospheric science, rings, and bistatic radar experiments. 3GM is designed to provide radio-metric observables that approach the ultimate capabilities of microwave radio systems. The 3GM in its full configuration entails two independent elements:

- A Ka-band uplink, Ka-band downlink (34.3-32.5 GHz) transponder (KaT) with an intrinsic frequency stability (Allan deviation) of 4 x 10^{-16} or better (at 1000 s integration time) and an internal range delay calibration system. The KaT (**Figure 4-24**) enables routine two-way range and range rate measurements accurate respectively to 0.2 m and $3\text{x}10^{-6}$ m/s (at 1000 s integration times).
- An ultra-stable oscillator (USO), with a frequency stability (Allan deviation) of 2 x 10^{-13} or better at 1 to 100 s integration time (6 x 10^{-13} at 1000 s), enabling occultation and bistatic radar experiments (**Figure 4-25**).

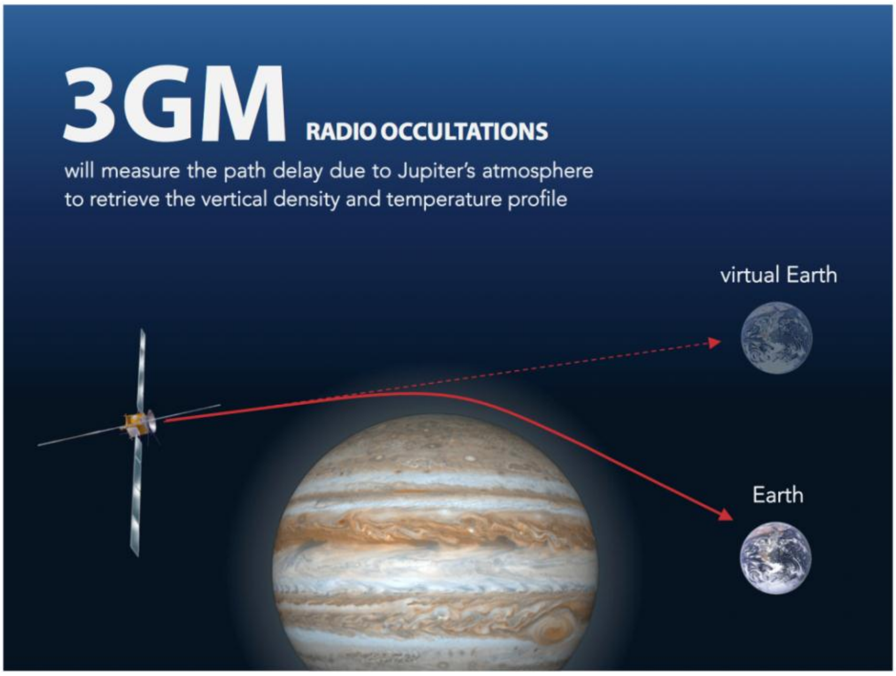


Figure 4-25. *3GM radio occultation experiments will measure the path delay experienced by the X and Ka band signals travelling through Jupiter's atmosphere up to a pressure level of 1-2 bar. This quantity will provide the vertical temperature and density profile. The measurement requires an accurate limb tracking maneuver to ensure that the deflected beam is received at the ground antenna. In this experiments the signal is generated onboard from an ultra-stable crystal oscillator (USO). The same technique can be used to determine the plasma density in the ionospheres of Jupiter and the Jovian moons.*

Gravity measurements will rely mainly on the Ka/Ka link enabled by the KaT. This radio link is highly immune to interplanetary plasma noise over a broad range of solar elongation angles. The TT&C, X/X and X/Ka radio link may be used together with the Ka/Ka link to reduce or even cancel plasma noise and to separate neutral and charged particles effects in uplink occultation experiments.

Heritage for 3GM, and in particular for the KaT element, comes from the BepiColombo radio science instrumentation (MORE), and the Juno KaT. Heritage for radio occultation and bistatic radar measurements comes from the Cassini mission, where these scientific experiments are carried routinely since 2005.

4.11 VLBI Experiment (PRIDE)

The Planetary Radio Interferometry and Doppler Experiment (PRIDE) is designed as a multidisciplinary experiment addressing those areas of JUICE mission science objectives which require precise determination of lateral position of spacecraft on the celestial sphere. The measurements are based mostly on the onboard service instrumentation and non-ESA Earth-based radio astronomy facilities (**Figure 4-26**). PRIDE will provide measurements of the spacecraft position directly in the International Celestial Reference Frame (ICRF) thus enabling an improvement of the ephemerides of the Solar System bodies, in particular, the Jovian satellites.

The scientific applications of PRIDE are based on two observable quantities: the radial range rate (Doppler shift of the service communication system carrier signal) and the lateral (transverse) celestial position of the spacecraft. The former is an “inevitable” ad hoc product of near-field VLBI tracking of the S/C while the latter is the main outcome of VLBI tracking as such. The PRIDE contribution will be in the following scientific areas:

1). Improvement of the ephemerides of the Galilean satellites; 2). Accurate input into definition of the Solar System reference frame; 3). Characterization of the Ganymede shape; 4). Statistical determination of surface slopes, near surface dielectric constant and surface density; 5). Vertical structure of the Jovian atmosphere.

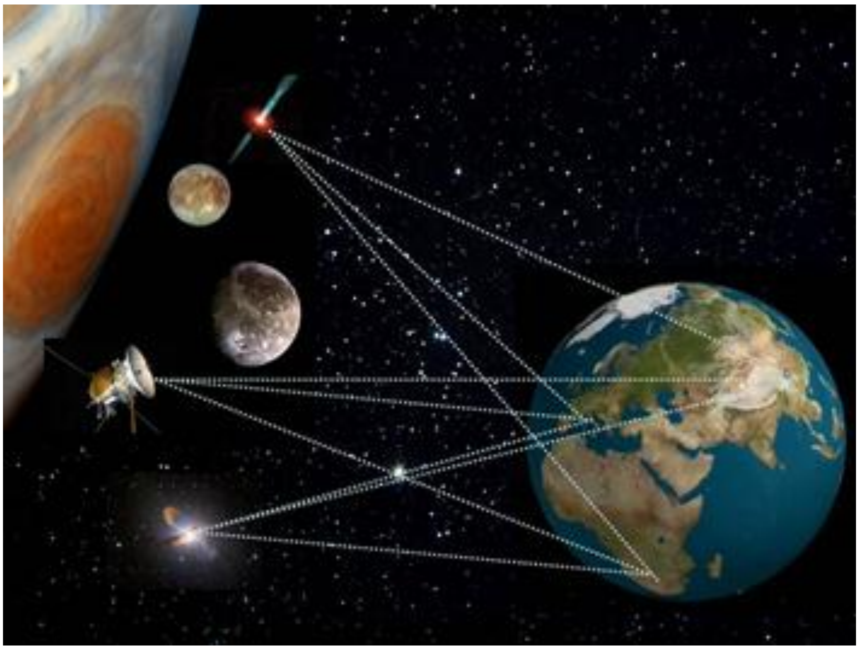


Figure 4-26. *Generic PRIDE configuration. The Earth-based segment of PRIDE combines a network of VLBI radio telescopes and data processing centres.*

In addressing scientific objectives 1 and 2 PRIDE will provide measurements of the S/C differential lateral position relative to the ICRF2 background extragalactic radio sources with the accuracy of 100-10 μas (1 sigma RMS) over integration time 60-1000 s.

Being large and massive bodies, the Galilean moons will strongly influence the JUICE orbit at different phases of the Jovian tour. This is especially the case during Galilean satellites’ flybys and the Ganymede's orbital phase. PRIDE will monitor the JUICE spacecraft and thus will contribute to the characterization of gravitational perturbations by the moons, allowing in turn accurate determination of their positions. In particular, PRIDE will be very useful to improve the inclination determination.

If a lateral spacecraft position measurement in International Celestial Reference Frame (ICRF) (Bourda et al., 2012) with the 1-sigma accuracy in the range 10-100 μas is achievable, it translates into 30-300 meters at opposition every 1000-60 seconds during PRIDE sessions. This would be 10^3 times better than ground based observations including mutual event observations. During the Ganymede orbital phase, this will be an improvement of a factor 10,000 compared to Earth-based optical astrometry. It is noteworthy that the amount of data to be produced by PRIDE will enlarge significantly the overall astrometric database on the Jovian system. The PRIDE experiment is a direct descendant of legacy VLBI experiments with the VEGA (Preston et al., 1986), Huygens (Lebreton et al., 2005), IKAROS (Takeuchi et al., 2011) and other planetary missions.

4.12 Synergistic payload capabilities

This section gives a summary of contributions of the JUICE experiments to the main science investigations and provides some important examples of synergies between the experiments when addressing the science objectives. A comparison is also made between the capabilities of the JUICE payload and those of previous Jupiter missions, and to the Galileo mission in particular. More detailed scenarios of joint payload operations can be found Table 6-1.

Table 4-10 reveals the contributions of different JUICE experiments in key science investigations. In summary, we conclude that the payload is fully capable of reaching the science goals of the JUICE mission.

Example #1. *Ganymede's ocean and icy crust.* The Ganymede *interior* will be studied by several experiments. The thickness and electrical conductance of the subsurface ocean will be constrained by resolving the magnetic induction signal at the synodic period of Jupiter, and the orbital period of Ganymede (**Figure 4-27**). This requires magnetic field measurements by J-MAG in orbit around Ganymede, characterisation of upstream plasma density and velocity patterns by PEP, and estimates of ionospheric conductance by RPWI. The ice crust thickness will be constrained by determining the tidal response using altimetry (GALA) and gravity potential (3GM) measurements, as well as estimations of the amplitudes of the physical librations using GALA with support from JANUS.

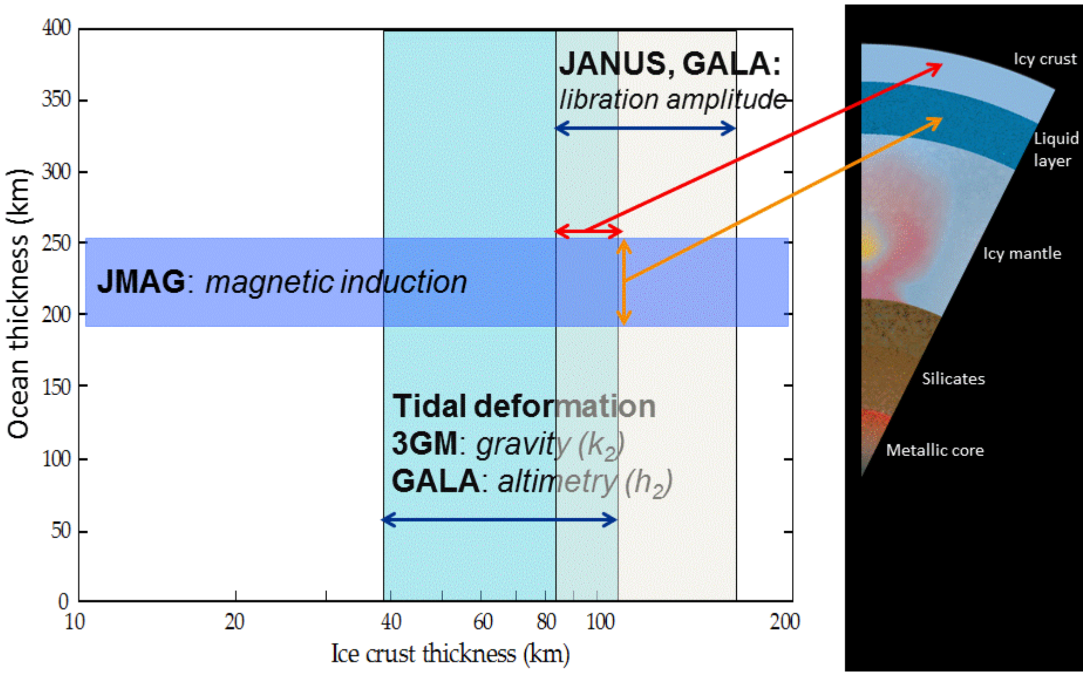


Figure 4-27. *Constraining the thickness of the Ganymede ice-shell and the ocean by the JUICE experiments.*

		JANUS	MAJIS	UVS	SWI	J-MAG	RPWI	PEP	GALA	RIME	3GM	PRIDE
Characterise Ganymede as a planetary object and possible habitat	Characterise the extent of the ocean and its relation to the deeper interior	Supporting				Primary	Supporting	Supporting	Primary		Primary	Supporting
	Characterise the ice shell	Supporting				Primary	Supporting	Supporting	Primary	Primary	Primary	Supporting
	Determine global composition, distribution and evolution of surface materials	Supporting	Primary	Primary	Supporting		Primary	Primary		Supporting	Supporting	Supporting
	Understand the formation of surface features and search for past and present activity	Primary							Supporting	Primary		
	Characterise the local environment and its interaction with the jovian magnetosphere			Primary	Primary	Primary	Primary	Primary			Primary	
Explore Europa's recently active zones	Determine the composition of the non-ice material, especially as related to habitability	Supporting	Primary					Supporting				
	Look for liquid water under the most active sites	Supporting							Supporting	Primary		
	Study the recently active processes	Primary	Supporting	Supporting		Primary	Primary	Primary	Supporting	Supporting		
Study Callisto as a remnant of the early jovian system	Characterise the outer shells, including the ocean	Supporting				Primary	Supporting	Supporting	Primary		Primary	
	Determine the composition of the non-ice material	Supporting	Primary	Primary				Supporting				
	Study the past activity	Primary	Supporting						Supporting	Supporting		
Characterise the Jovian atmosphere	Characterise the atmospheric dynamics and circulation	Primary	Primary	Primary	Primary							
	Characterise the atmospheric composition and chemistry	Supporting	Primary	Primary	Primary						Supporting	
	Characterise the atmospheric vertical structure	Supporting	Primary	Primary	Primary						Primary	Supporting
Explore the Jovian magnetosphere	Characterise the magnetosphere as a fast magnetic rotator					Primary	Primary	Primary				
	Characterise the magnetosphere as a giant accelerator	Supporting	Primary	Primary		Primary	Primary	Primary				
	Understand the moons as sources and sinks of magnetospheric plasma	Supporting	Primary	Primary		Supporting	Primary	Primary				
Study the Jovian satellite and ring systems	Study Io's activity and surface composition	Primary	Primary	Primary			Primary	Supporting			Supporting	
	Study the main characteristics of rings and small satellites	Primary	Primary								Supporting	

(green)	Primary
(yellow)	Supporting
(white)	N/A

Table 4-10. *Estimated contribution of the JUICE experiments in achieving major science objectives.*

Example #2. *Ganymede's surface and sub-surface investigations.* The imaging system JANUS will make a breakthrough in Ganymede surface imaging by increasing the surface coverage by a factor of ~50 compared to that obtained by the Galileo mission at given spatial resolution (**Figure 4-28**). Due to the changing orbit altitude at Ganymede from 5000 km to 500 km, the mission will achieve complete global imaging with spatial resolution of better than 400 m/px that will be complemented by high-resolution imaging of selected targets with resolution better than 10 meters. JANUS imaging and GALA sounding will provide Digital Terrain Models (DTM) of selected sites. The DTMs will be used for de-cluttering (compensation for the signal coming from side lobes) of the RIME data.

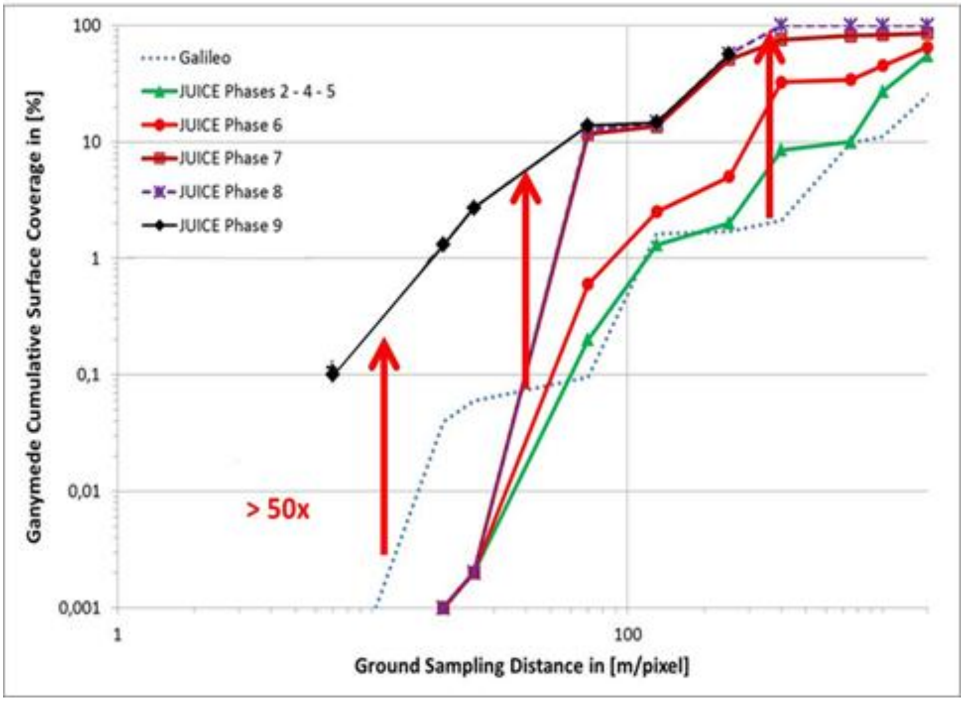


Figure 4-28. *Expected surface coverage vs. spatial resolution diagram for the JANUS surface imaging in different mission phases.*

The ice penetrating radar, RIME will provide breakthrough science in the study of the ice shell of Ganymede, Europa and Callisto, acquiring unique measurements of the subsurface, which are fundamental for the many science goals described in previous sections. Note that RIME will be the first instrument able to acquire direct subsurface measures of the Jovian icy moons (this is also the first time that a radar sounder will be used in the outer part of the Solar System). The measurements of the vertical properties of the subsurface acquired by RIME will be then integrated with the vertical structure on and above the surface measured by GALA and JANUS.

Surface properties will be monitored by the remote sensing instruments (JANUS, MAJIS, UVS, SWI, GALA, RIME) to provide a surface (and sub-surface) context to the fields and particle investigations. The fields and particle instruments (J-MAG, RPWI, PEP) will also address several science objectives related to surface (and sub-surface) properties of the icy Galilean moons. Energetic particles (ions, electrons, neutrals, dust), monitored by the PEP and RPWI detectors, bombard the icy moons and change the composition and structure of the surface material. The magnetospheric source regions of the accelerating fields (electric potential structures or waves) will be monitored by RPWI and J-MAG, and the mechanism for the restructuring of the icy surfaces by the space environment can be found. On Ganymede, the surface is clearly divided between regions belonging to open and closed magnetic field lines respectively, indicating a division in the precipitation of energetic charged particles toward the surface.

The instrument suite on-board JUICE will allow the integration of datasets into a comprehensive multisensor/multitemporal/multiresolution view maximizing the scientific return of the data. A GIS (Geographic Information System) system can ingest every spatially referenced information such as imaging, composition, sub-surface, topography, thermal, geophysical (**Figure 4-29**).

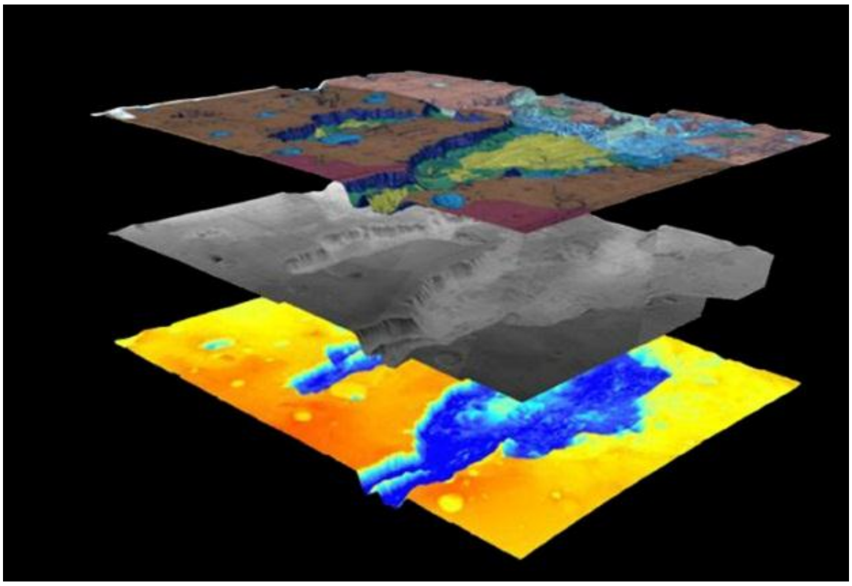


Figure 4-29. *Example of GIS layers with (top to bottom) DEM, high resolution image, compositional map from spectral data.*

Example #3. *Tenuous atmospheres of the moons.* When the energetic particles impact the icy surfaces they sputter material back into space and contribute to (or even dominate in some cases) the tenuous atmospheres/exospheres of the icy Galilean moons. Sub-surface breaching of volatiles, diffusion and sublimation may be other contributions. JUICE will monitor directly the tenuous atmospheres/exospheres in terms of structure (SWI, UVS), composition (PEP, MAJIS, SWI, UVS) (**Figure 4-30**) and dust content (RPWI). The surface sputtering process of energetic neutrals can be monitored directly by PEP.

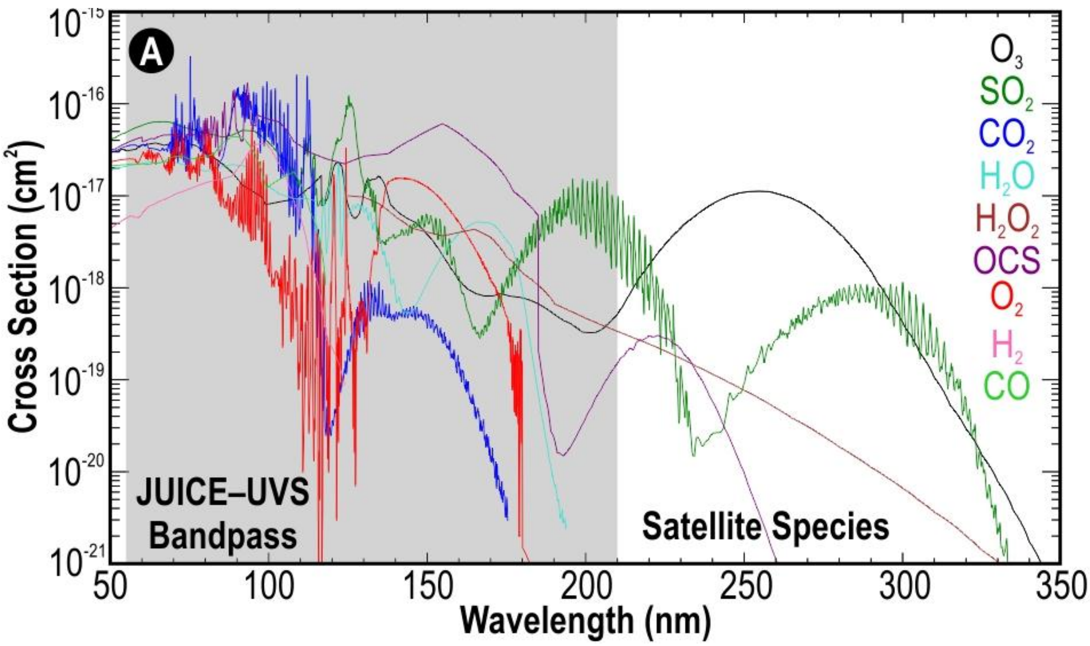


Figure 4-30. *Cross-sections of atmospheric species on Jupiter's moons. The UVS bandpass is marked in grey where sensitivity is highest.*

The tenuous atmospheres/exospheres are in turn partly ionized by solar EUV radiation and particle impacts from space (monitored by PEP and RPWI) and give rise to ionospheres. The ionospheres are readily monitored both by detailed in-situ measurements (RPWI, PEP) as well as by remote sounding by radio waves (3GM, PRIDE, RPWI). The magnetospheres interact with the ionospheres through electromagnetic fields and charged particles, and the fields and particle investigations monitor these processes. This electromagnetic coupling generates electric currents (monitored by J-MAG and RPWI) in the ionospheres, as well as in the conducting surfaces and sub-surfaces of the icy moons. On Ganymede, the interaction generates aurora along the open-closed magnetic field boundary, where UVS, MAJIS and JANUS will monitor the auroral emissions, while the fields and particle in-situ instruments will monitor the auroral acceleration processes themselves. A similar type of inter-instrument synergy exists with regard to observations of the Jovian auroral processes.

Example #4. *Composition and chemistry of Jupiter.* The JUICE spectrometers and spectro-imagers will cover the broad spectral range from UV to sub-millimeter wavelengths. The UVS spectrograph will take advantage of the largest cross sections and most distinctive spectral signatures of gaseous species in the FUV (50-150 nm) to study composition of the Jovian atmosphere in reflectance spectroscopy as well as in stellar and solar occultation geometry.

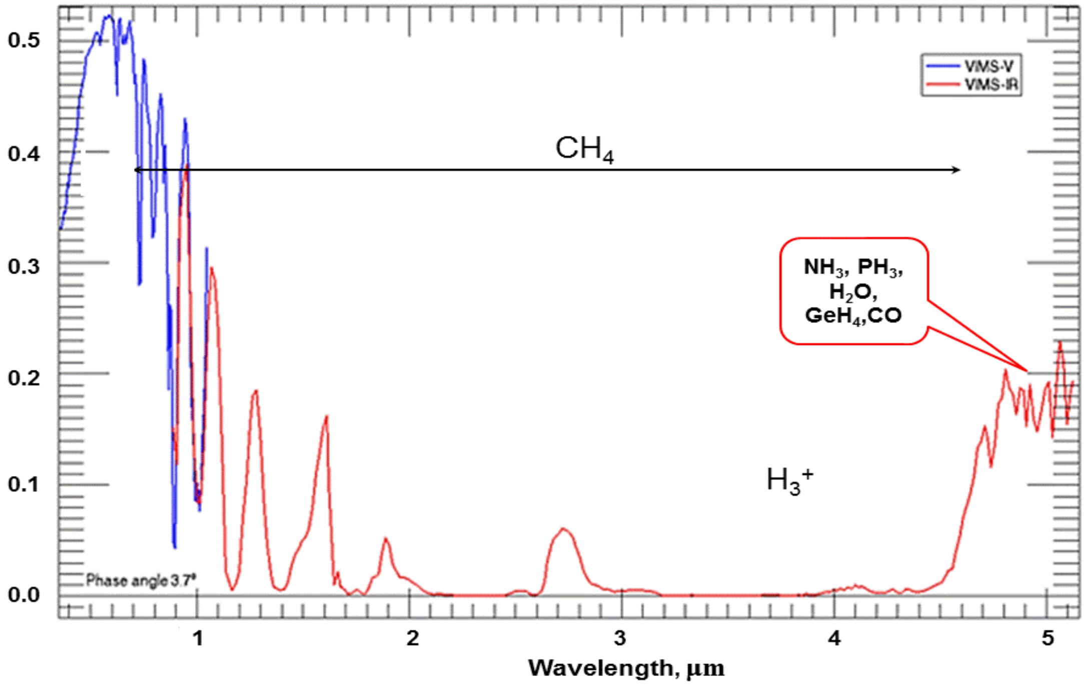


Figure 4-31. *Cassini-VIMS spectrum of Jupiter. JUICE investigations will include narrow band imaging by JANUS and spectral imaging by MAJIS in the visible-near-IR range.*

The visible and near-IR spectral range is very rich in characteristic bands of minerals and gases. Spectral mapping by MAJIS and imaging in narrow spectral bands by JANUS at 0.4-5.2 µm will be exploited for the Jovian atmosphere (**Figures 4-31** and **4-4** in Section 4.2).

Thermal radiation from the Jovian atmosphere will be sounded by SWI. The instrument will measure spectral lines of the gases present in the upper atmosphere of the giant planet with very high spectral resolution to determine composition, temperature structure and winds (**Figures 4-32** and **4-9** in Section 4.4). The first direct sub-mm measurements of middle atmospheric winds has the potential to reveal completely new insights into giant planet stratospheric dynamics. In summary, JUICE will exploit in full the power of remote sensing by combining moderate resolution imaging with very high resolution point spectroscopy covering broad spectral range from UV to sub-millimeter wavelengths. A similar type of inter-instrument synergy exists with regard to the composition of both surface and atmosphere of the icy moons.

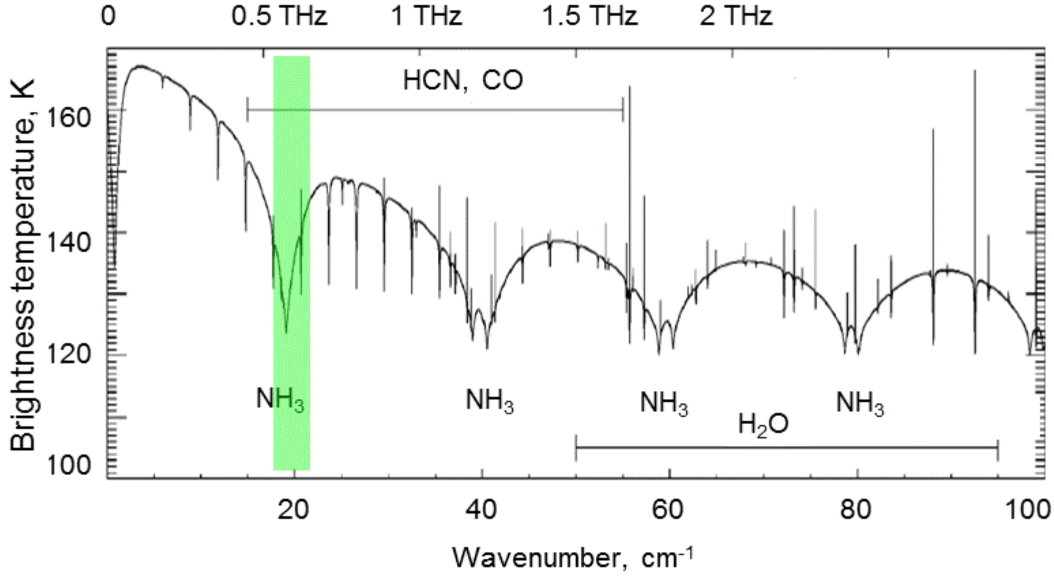


Figure 4-32. *Synthetic microwave spectrum of the Jupiter atmosphere. The spectral range covered by SWI channels is shown in green.*

Figure 4-33 compares the JUICE spectro-imaging capabilities with those of the Galileo mission. There are at least three advantages of the JUICE spectro-imaging suite. Firstly, inclusion of the far UV domain would enable higher sensitivity of the composition sounding due to larger absorption cross-sections (**Figure 4-30**) (see also **Figure 4-7** in Section 4.3). Secondly, the spectral resolving power of MAJIS exceeds by about a factor of 2 capabilities of NIMS/Galileo enabling better discrimination between different surface and atmospheric species. And thirdly, SWI will enable access to the sub-millimeter portion of the spectrum with spectral resolution higher than ever achieved by any orbiting spacecraft. This would offer new capabilities in sounding of the temperature structure, composition and dynamics in the middle atmosphere of Jupiter.

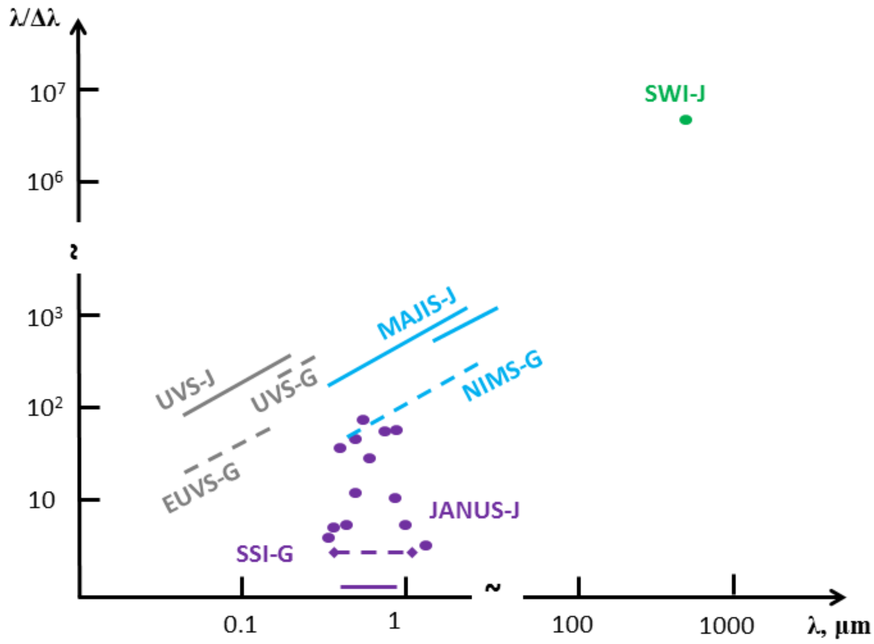


Figure 4-33. *Spectral resolving power vs spectral range for the JUICE (solid lines and dots, labelled by "J" in the figure) and Galileo (dashed lines) spectro-imaging instruments (denoted by "G" in the figure labels).*

Example #5. *Temperature sounding of the Jovian atmosphere.* Investigation of the temperature structure of the Jovian atmosphere will be performed by combination of three experiments: SWI, 3GM in radio-occultations, and UVS in stellar occultations (**Figure 4-34**). The first two experiments will sound the stratosphere of Jupiter (0-200 km above the visible cloud top). Despite the same altitude coverage, they complement each other in what concerns vertical resolution and longitudinal coverage. SWI is capable of providing temperature sounding at all longitudes with vertical resolution of ~15 km (half a scale height), while 3GM will achieve few hundred of meters vertical resolution but close to the terminator region and possibly probe to the topmost cloud deck. UVS will extend the sounded region into the middle and upper thermosphere. The JUICE investigation of the temperature structure will complement the JUNO studies of the troposphere below the cloud tops.

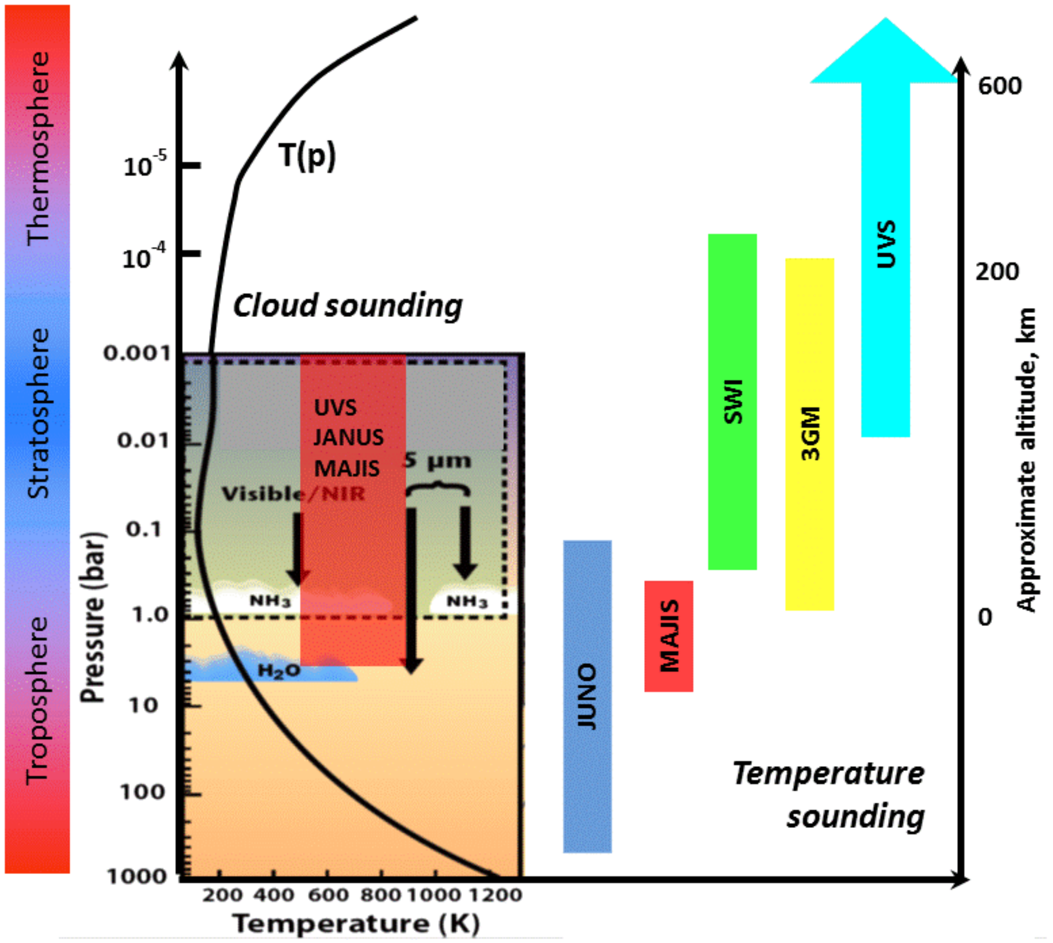


Figure 4-34. *Estimated vertical coverage in the cloud (left) and temperature (right) sounding in the Jovian atmosphere by JUICE experiments. Altitude ranges of the temperature sounding are shown by vertical color bars for MAJIS spectro-imaging (red), sub-millimeter spectroscopy by SWI (green), radio occultations by 3GM (yellow) and solar/stellar occultations by UVS (cyan). The blue bar shows altitude coverage by the JIRAM and MWR experiments onboard JUNO mission for comparison. The red bar on the left panel shows approximate range of the cloud sounding by JANUS, MAJIS and UVS. The black line shows typical temperature structure in the Jovian atmosphere.*

Example #6. *Particles and fields investigations in the Jovian magnetosphere.* The thermal plasma, DC electric fields, electric and magnetic signals from radio, plasma waves and micrometeorite impacts, as well as the spacecraft potential and integrated solar EUV flux will be sampled by the RPWI sensors. The RPWI measurements will cover all expected spatial and temporal scales to be encountered by JUICE. By contrast, the Galileo/PWS measurements did not cover frequencies below 10Hz, which missed all of the ion/fluid physics, and the electric measurements only reached 5.6 MHz, which missed a good portion of the Jovian radio emissions.

The fields and particle investigations will cover all energy ranges of interest for JUICE. The plasma particle population – 3D distribution functions of charged particle, plasma and neutral gas composition, as well as properties of the energetic neutral atoms (ENA), will be characterized by the PEP suite of six sensors. The PEP and RPWI experiments will together measure positive and negative ions, electrons, exospheric neutral gas, thermal plasma and energetic neutral atoms over more than nine decades from <0.001 eV to >1 MeV. In addition, micro-meteoritic impacts will be counted by RPWI, where energies of 1-10 micrometre dust grains moving with a few km/s have kinetic energies up to 10^{12} eV.

The field and particle investigations (J-MAG, RPWI, PEP) will also cover all expected spatial and temporal scales to be encountered by JUICE (**Figure 4-35**). By contrast, the Galileo/PWS measurements, compared to RPWI on board JUICE, did not cover frequencies below 10Hz, which missed all of the ion/fluid physics, and the electric measurements only reached 5.6 MHz, which missed a good portion of the Jovian radio emissions. The RPWI also have several other additional capabilities, and will constitute a much more complete science investigation.

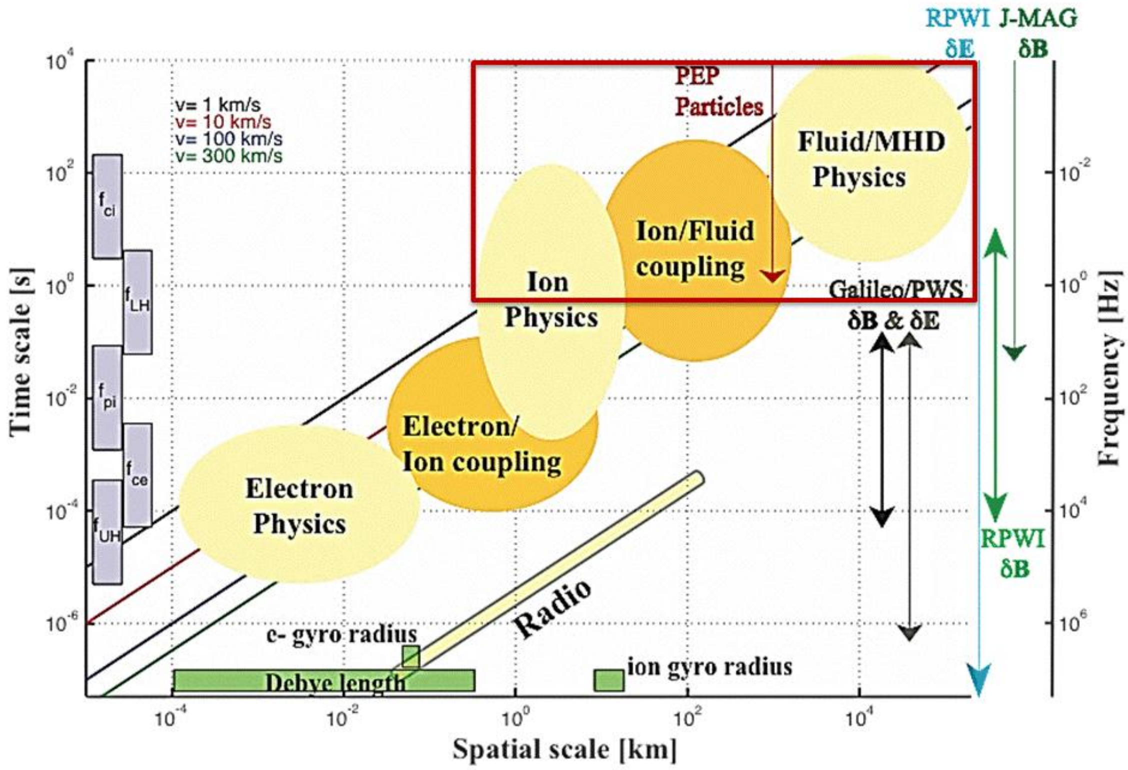


Figure 4-35. *The field and plasma measurements will cover all expected spatial and temporal scales to be encountered by JUICE. The local scales in the plasma are indicated, except for radio waves where the indicated spatial scale refers to their wavelengths. Colored arrows show the ranges covered by JUICE experiments (RPWI - blue, J-MAG - green, PEP - red). The coverage by the Galileo/PWS experiment is shown in grey. The lowest frequencies below about 100Hz have never been measured accurately before.*

5 Mission design

This section describes the mission baseline scenario developed to address the science, measurement and mission requirements described in the previous sections, and provides a brief overview of the spacecraft design and ground segment. In the context of a competitive study phase, detailed spacecraft designs including dry masses, available power and the corresponding system margins cannot be provided in this document. However, the competitive system studies performed within the framework of the mission design, resulted in system margins that are in line with requirements at this stage of project development.

5.1 Mission analysis

The mission profile can be divided into two major parts: a) an interplanetary transfer to Jupiter, and b) the transfer to a Ganymede bound trajectory during the science phase at Jupiter. The trajectories where optimised in both cases to require minimum Δv. In addition during the Jupiter part, the mission trajectory is optimised also considering the radiation exposure of the spacecraft in the Jupiter radiation environment (avoiding too low orbits around Jupiter). Furthermore, two Europa flybys and several inclined revolutions around Jupiter were included at low Δv cost. Therefore the following mission phases are identified:

1. Interplanetary transfer (cruise) (7.6-9 years)
2. Nominal science phase
   a. Jupiter equatorial phase #1 and transfer to Callisto (12 months)
   b. Europa flybys (~ 1 month)
   c. Jupiter high inclination orbit/Callisto flybys (6 months)
   d. Jupiter equatorial phase #2 and transfer to Ganymede (9 months)
   e. Ganymede phases (9.5 months)
      i. 1st elliptical phase
      ii. High altitude circular orbit (GCO-5000)
      iii. 2nd elliptical phase
      iv. Low altitude circular orbit (GCO-500)

The JUICE SWT has endorsed this baseline scenario as providing a science return in line with the science objectives of the mission.

5.1.1 ***Launch, cruise and Jupiter orbit insertion***

The nominal launcher for the JUICE mission is Ariane 5 ECA. The cruise phase involves fly-bys of Venus and the Earth, or the Earth, Venus and Mars depending on the launch opportunity. The launch mass could further be increased if the Earth gravity assist is combined with a Lunar gravity Assist. Several launch opportunities could be identified for each of the launch years 2022, 2023, 2024 and 2025 [D-2]. The launch opportunity in 2022 has a particular favourable transfer duration of 7.4 years, while the remaining opportunities require transfers of up to 9 years. During the Venus gravity assist the spacecraft has the closest distance to the Sun of 0.64 AU. An example of the interplanetary trajectory is presented in **Figure 5-1**.

The Jupiter Orbit Insertion (JOI) is the most critical manoeuvre of the mission. All other manoeuvres will either be without thrusting (Venus and Earth gravity assists), or will be occurring while the spacecraft will be in a bound orbit around Jupiter, when repetitive opportunities exist.

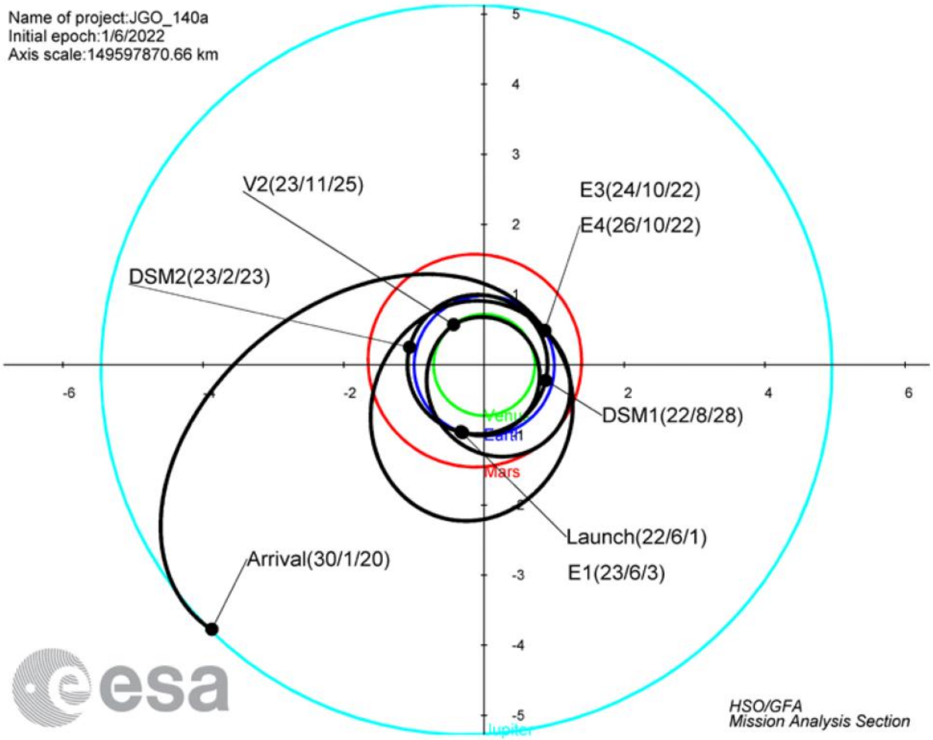


Figure 5-1. *Interplanetary cruise for a launch opportunity (01/06/2022) with a 7.6-years cruise duration to Jupiter.*

The main elements of the Jupiter tour presented hereafter were consolidated for one specific case, corresponding to the June 2022 launch. From this experience and due to the rather short repetitive constellations of the jovian moons, it can reasonably be assumed that such a trajectory can also be designed for other launch opportunities. The difference is mainly for avoiding superior solar conjunctions during flybys and trajectory control maneuvers, which disable communications with the spacecraft for 1 month.

5.1.2 *Jupiter equatorial phase #1 and transfer to Callisto*

Upon arrival at Jupiter, the infinite velocity w.r.t. Jupiter ranges from 5.59 km/s to 5.82 km/s (depending on the interplanetary transfer selected). In order to be captured in-orbit around the planet, the JOI is applied at perijove as shown in **Figure 5-2**.

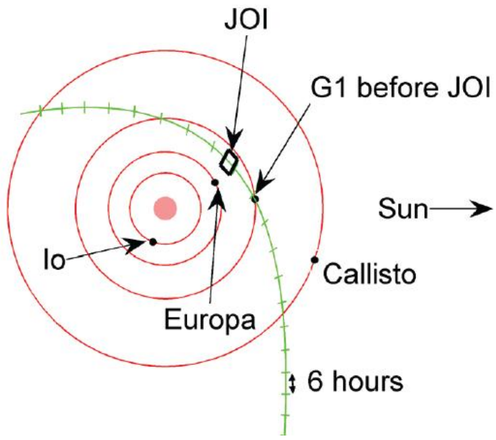


Figure 5-2. *Spacecraft capture at Jupiter.*

The size of the JOI is ~ 900 m/s (~1% gravity losses need to be considered). The JOI manoeuvre will be preceded by a Ganymede gravity assist with 400 km altitude. The distance from Jupiter at JOI was selected after a trade-off between the Δv gain (which improves as the spacecraft gets closer to Jupiter) and the radiation dose (which increases as the spacecraft gets closer to Jupiter). After this trade-off, the reduction in Δv provided by the Ganymede gravity assist (G1, **Figure 5-2**) before JOI is ~ 300 m/s. The time between G1 and the JOI is approximately 7.5 hours.

After the JOI the spacecraft is injected into a 38:1 resonant orbit with Ganymede (272 days) (**Figure 5-3**). At apojove a Perijove Raising Manoeuvre (PRM) is performed. The perijove raise reduces the arrival velocity at the next Ganymede swing-by (G2) by bringing the perijove closer to the orbit of Ganymede. This improves the efficiency of the following gravity assists with Ganymede. A higher perijove also reduces the radiation dose at the next passages close to Jupiter.

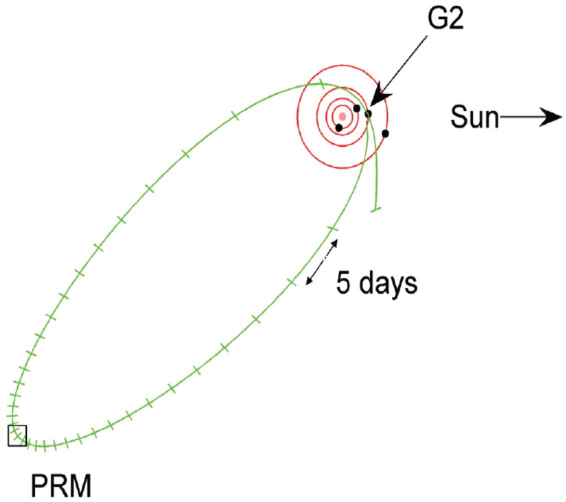


Figure 5-3. *1st orbit from JOI to the Ganymede G2 flyby in the 140a reference tour.*

The following two gravity assists with Ganymede, G2 and G3 reduce the period to 8 times, then 5 times the period of Ganymede (7.15 days). G1, G2 and G3 also modify the inclination of the orbit plane of the spacecraft making it equal to the equatorial plane of Jupiter (the orbital plane at arrival is at an angle to the equatorial plane of Jupiter (typically 3 to 5°). A 4th Ganymede gravity assist (G4) can then set the spacecraft on a transfer orbit to Callisto, which initiates the Europa phase. Additional satellite flybys can be required for achieving the adequate encounter conditions with Callisto at

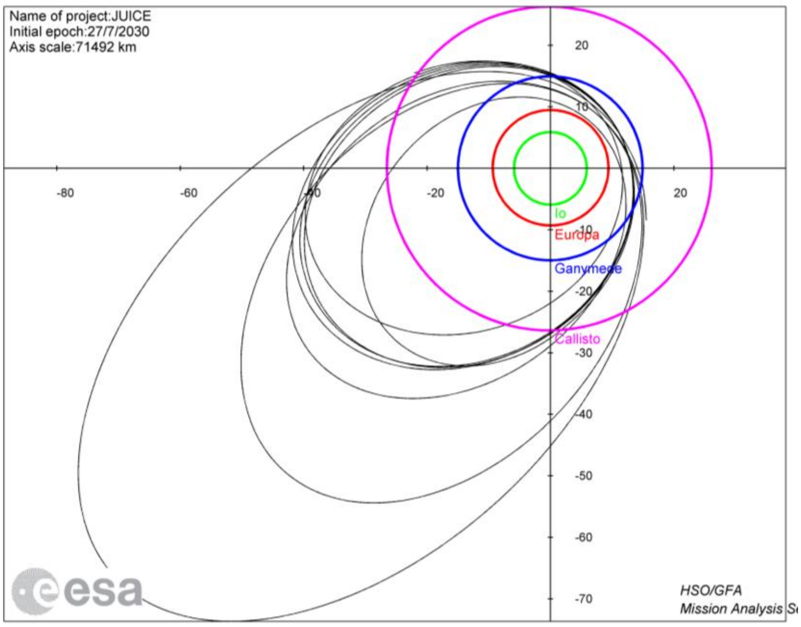


Figure 5-4. *Trajectory from G2 to the Callisto flyby preceding the transfer to Europa (C7 for the 140a).*

departure to Europa or for avoiding flybys during superior conjunction. The first Callisto swing-by must be performed at a safe altitude of >400 km. This minimum altitude constraint for Callisto flybys is then reduced to 200 km. An example trajectory for the transit to the Callisto flyby before initiating the Europa phase is shown in **Figure 5-4.**

5.1.3 *Europa phase*

Europa is within a hard radiation environment, with particle fluxes >20 times larger than at Ganymede. Europa flybys will be implemented with a Callisto (outbound) – Europa – Europa – Callisto (inbound) sequence with only two perijoves (those corresponding to the Europa flybys). The closest approaches to Europa must be on the far side (optimum for subsurface sounding with the radar) and with good illumination of the low altitude track (remote sensing). As the far side must be in sunlight, the encounters with Europa must be at a position on the orbit at most 35° away from the direction of the Sun as seen from Jupiter. Eight priority Regions of Interest (ROI) have been identified by the Science Team (squares in **Figure 5-5**). Seven of them are on the trailing side, but investigating the trailing-leading asymmetry is also of clear scientific interest.

This optimum sequence requires very specific encounter conditions with Callisto that must be 120° to 150° away from the direction of the Sun, so as to provide adequate illumination conditions during the Europa flybys. The relative velocity must be set very accurately (a few m/s) for a given relative phasing between Callisto and Europa and has range from 4.9 km/to 5.5 km/s, depending on the tour opportunities.

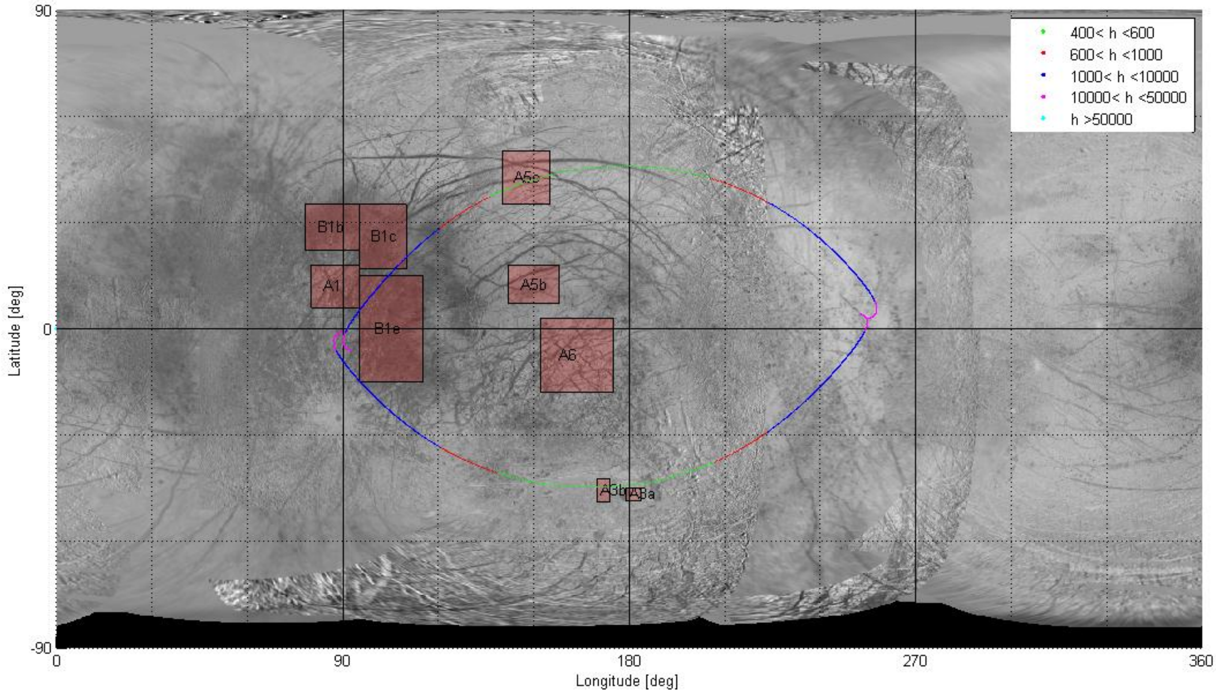


Figure 5-5. *Ground track of the spacecraft during Europa flybys. The image shows a Europa surface map with the areas of specific interest indicated by colour rectangles. The ground tracks of the two flybys are indicated in coloured lines, with the colour indicating the altitudes in 1000 km (see the colour legend in the upper right).*

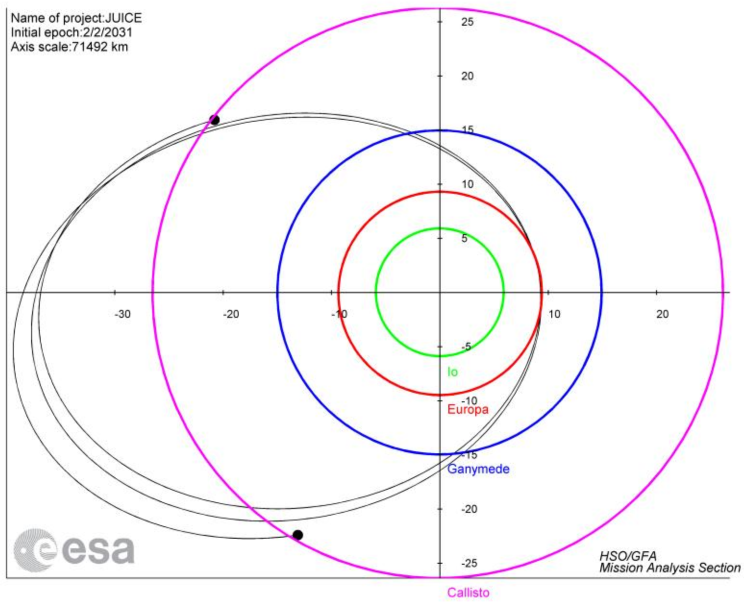


Figure 5-6. *Callisto – Europa – Europa – Callisto sequence. The orbits of Callisto (purple), Europa (red) and the spacecraft (black) are drawn on a Jupiter Solar Orbital (JSO) coordinate frame.*

The two flybys will take place at middle latitudes over the Northern and Southern hemispheres of Europa with a closest approach altitudes of ~ 400 km and within 15° of the 180° longitude (centre of the far side). The relative velocity for both Europa flybys ranges from 3.6 to 3.9 km/s. An example of the Callisto – Europa – Europa – Callisto sequence is provided in **Figure 5-6**. A comprehensive exploration of the parameter space has demonstrated that Callisto encounter conditions adequate for such a double Europa flyby sequence can be obtained for any relative phasing of Ganymede, Callisto and Europa at G2 (effective start of the Jupiter tour after the very long first orbit). The maximum Δv expenditure is < 30 m/s.

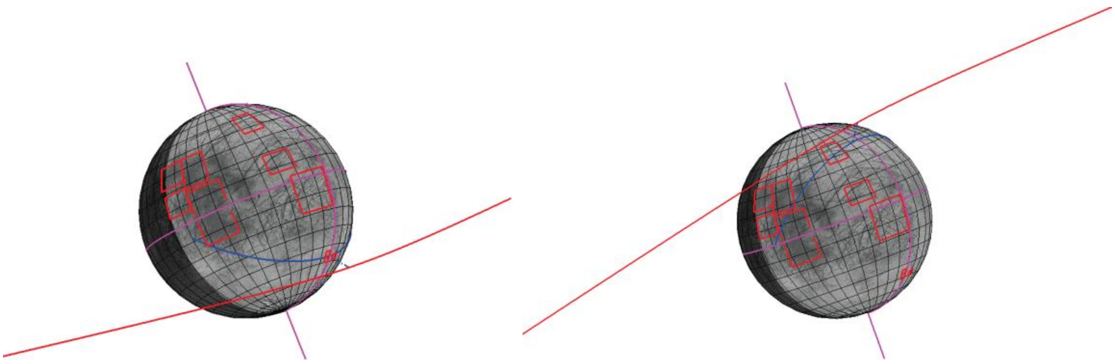


Figure 5-7. *3D representation of the first (left) and second (right) Europa flybys.*

The illumination conditions and ground tracks corresponding to the example in **Figure 5-6** are given in **Figures 5-5** and **5-7**. The ground tracks have been optimised so as to fly over 4 of the 8 selected regions of interest at low to moderate altitudes (400 to 2000 km). Two additional ROIs can be observed by slanting the spacecraft from an altitude of 3000 km. As demonstrated by **Figure 5-5**, the tracks extend over the leading side with good observation conditions, which make it possible to investigate the trailing-leading asymmetry of surface material on Europa.

At distances >10,000 km, the spacecraft moves radially along the infinite velocity direction, close to longitudes 90° and 270°. The rotation of Europa nearly compensates for the orbital motion, hence the velocity of the sub-spacecraft point is very small. As the Sun is close to the center of the far side in this example, observations during approach and departure provide a zoom-in of regions close to the trailing and leading terminators respectively. At closest approach, the sub-spacecraft point velocity is dominated by the spacecraft velocity and is just scaled down compared to the pericentre velocity: the inertial pericentre velocity is ~4.05 km/s at 400 km altitude and the sub-satellite point velocity is ~3.25 km/s with respect to the surface.

5.1.4 *Inclined orbit phase*

After a further Callisto – Ganymede – Callisto gravity assist sequence, which lowers the relative velocity with Callisto from ~5 km/s to ~4 km/s, the next mission phase is an excursion at moderate inclinations which is implemented by a series of three Callisto swing-bys for investigating regions of the Jupiter environment away from the equatorial plane. Three additional Callisto swing-bys bring the orbit back to the equatorial plane so as to initiate the final transfer to Ganymede. With this sequence of 6 flybys, the spacecraft reaches a maximum inclination of 22° and a maximum magnetic latitude of 26°. The most inclined orbit is a 7:8 resonant orbit with Callisto, making it possible to investigate the Jupiter environment and polar regions at the maximum inclination over a 117 days period. **Figure 5-8** shows the evolution of the orbit inclination for during this phase.

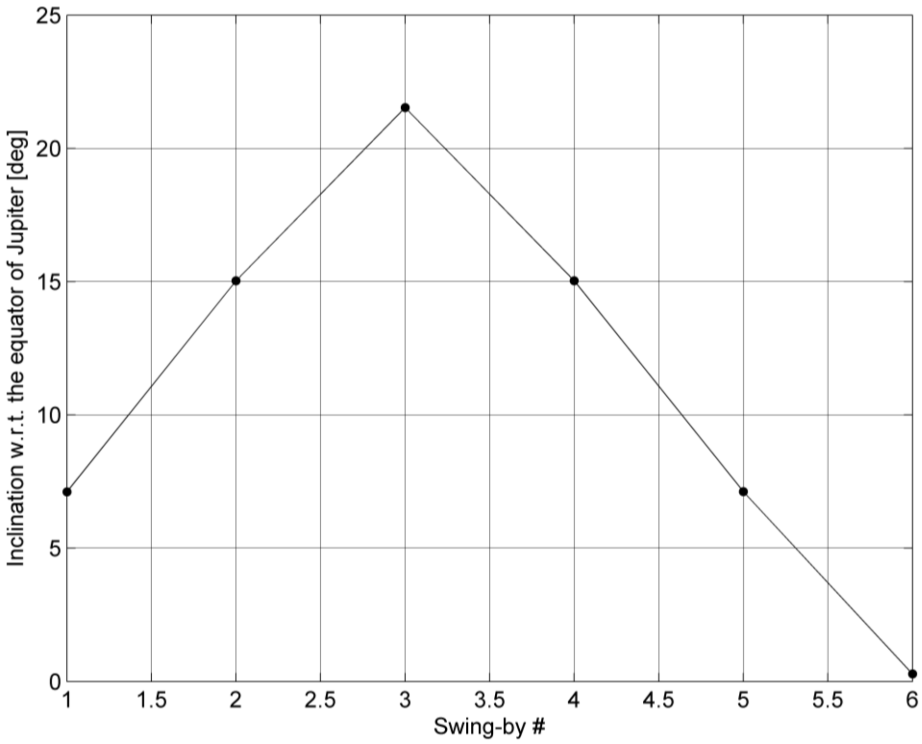


Figure 5-8. *Evolution of the orbit inclination.*

All fly-bys of this gravity assist sequence are performed at the same orbital position of Callisto and half of the closest approaches are on the night side. **Figure 5-9** shows the ground tracks at Callisto including that of the flyby setting the spacecraft on course to Ganymede.

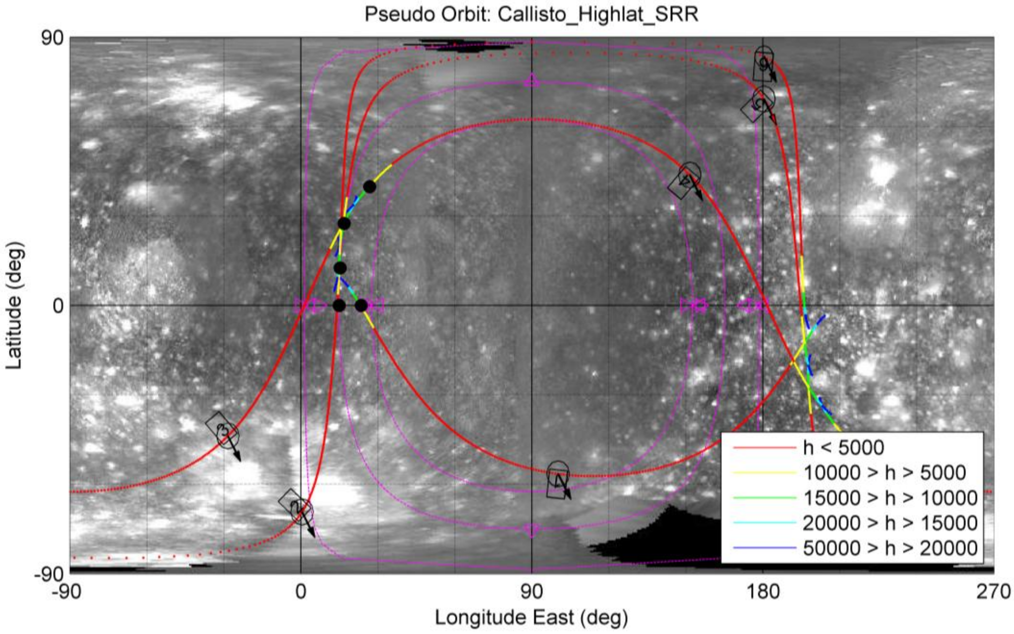


Figure 5-9. *Ground tracks of the Callisto flybys during the inclined phase. Colours indicate the distance to the surface.*

Table 5-1 provides the duration and inclination of orbits during this phase.

Table 5-1. *Sequence of orbits for the inclined phase. ~50% of the total radiation dose during this phase is accumulated during the 7:8 resonant orbit (8 x 14.6 = 117 days long).*

	Orbital period (days)	leg duration (days)	Perijove	Apojove	Inclination
C_N	16.7	16.7	13.5	39.1	7
C_{N+1}	16.7	16.7	14.7	37.9	15
C_{N+2}	14.6	117	14.9	33.3	22
C_{N+3}	16.7	16.7	14.7	37.9	15
C_{N+4}	16.7	16.7	13.5	39.1	7
C_{N+5}	NA	NA	NA	NA	0

5.1.5 *From Callisto to Ganymede Orbit Insertion (GOI)*

The primary objective of the mission is to perform extensive science in-orbit around Ganymede. At the end of the Jupiter high latitude phase, the infinite velocity with respect to Callisto is ~4 km/s and the orbit is 1:1 resonant with that of Callisto. The infinite velocity at arrival to Ganymede corresponding to a direct Callisto - Ganymede transfer is so large (3.8 km/s) that a GOI manoeuvre would be prohibitively expensive, in particular if gravity losses are taken into account. Therefore, the relative velocity to Ganymede must be drastically reduced before GOI which is achieved by a Callisto

– Ganymede – Callisto - Ganymede satellite-satellite gravity assist sequence (**Figure 5-10**) reducing the relative velocity to 1.6 km/s without spending Δ*v*. Additional Callisto gravity assists (with a minimum altitude of 200 km) are required for adjusting the angle of the orbit plane around Ganymede to the direction of the sun of 20-30° immediately after GOI (see Section 5.1.6).

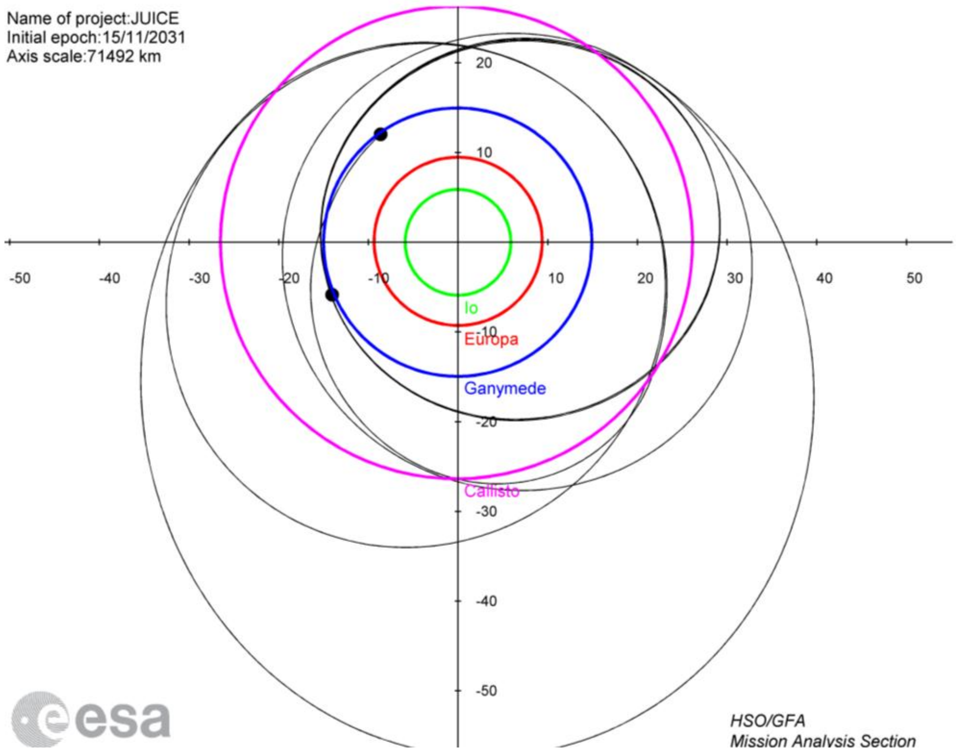


Figure 5-10. *Ganymede-Callisto-Callisto-Callisto-Ganymede leg.*

The next step for reducing the relative velocity to Ganymede implements a series of resonant orbits (e.g. 9:5, 7:4, 3:2, 7:5, 4:3) with flybys at an altitude 20000 km to 45000 km above the far side of Ganymede (close to the L2 point). Thanks to 3 body effects (Jupiter – Ganymede –pacecraft), the transfer from one orbit to the next can be performed without using propellant, except when a passage between Callisto and Jupiter modifies the perijove distance, which then needs to be brought back close to that of the L2 point of Ganymede at the next encounter(about 30 m/s). These orbits are long (40 to 64 days), so that the sequence can be adjusted for accommodating the superior conjunction between flybys if it occurs in this time range. A last Ganymede distant flyby enables an approach to Ganymede on a polar bound orbit. This extended series of distant Ganymede gravity assists reduces the magnitude of the GOI manoeuvre by more than 500 m/s compared to a direct insertion with a velocity at infinity of 1.6 km/s. It adds 200 days to the tour duration, but the large positive impact on the mass budget has been a major step forward for defining a robust mission scenario for JUICE. It is important to note that only Ganymede is involved in this phase, so that once a solution is found for reaching this satellite with a 1.6 to 2.2 km/s relative velocity, such a distant flyby sequence can be obtained for any opportunity. The spurious effects of Callisto distant encounters may differ, but this impact the Δ*v* budget by at most a few 10 m/s.

This approach makes it possible to implement a tour with a Europa phase, an inclined orbit/Callisto phase and a transfer to Ganymede with a final approach on a bound orbit with a deterministic cost in Δ*v* of only ~150 m/s from G2 (2nd Ganymede flyby) to GOI. This makes the overall mission strategy extremely economical, with two main incompressible items on the deterministic Δ*v* budget: Jupiter Orbit Insertion and PRM (900 to 950 m/s, depending on the interplanetary transfer option) then Ganymede Orbit Insertion (quite cheap from a weakly bound orbit: ~185 m/s) and Ganymede orbital phases (see the next section).

5.1.6 *Ganymede orbital phases*

The Ganymede orbital phase is constrained by the following elements:

- the requirement of avoiding eclipses on near polar operational orbits. The angle between the direction of the Sun and the orbit plane ("β-angle") needs to be increasingly large for low altitudes (e.g. > 60° for a circular orbit at 500 km).
- Jupiter perturbations, which impact the eccentricity of the orbit depending on the location of the pericenter with respect to the ascending node (it decreases when the argument of pericenter is close to 140° or 320°, and increases when the argument of pericenter is close to 50° or 230°).

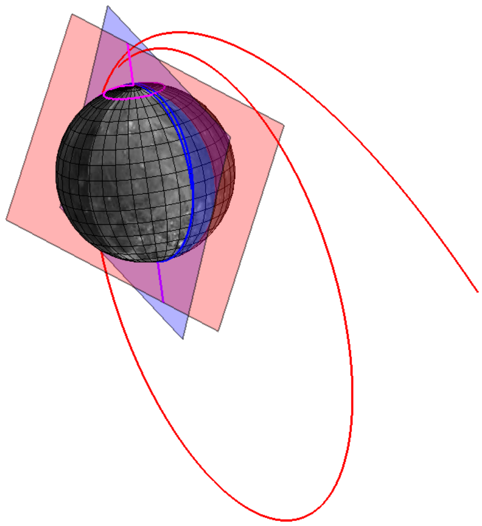


***Figure 5-11**. Baseline GOI geometry. The spacecraft's trajectory is shown as a red line, the orbital plane during the GOI is shown as a blue plane, the red plane indicates the meridian in the direction of the Sun.*

5.1.6.1 Ganymede Elliptical Orbit (GEO) phase

As shown by **Figure 5-11**, the first orbit after Ganymede Orbit Insertion (GOI) is highly elliptical. This requires only a relatively small insertion manoeuvre (~185 m/s) as the approach is on a weakly bound orbit. The period of this orbit is 12 hours. The angle between the nearly polar orbit plane and the direction of the Sun is between 20 and 30° (depending on the exact scenario). The pericenter argument has been set such that the Jupiter perturbation circularizes the orbit with an altitude of 5000 km after 20 days. This orbit can be maintained with minimum Δ*v*. After ~ 80 days on this nearly circular orbit (GCO-5000) and revoking orbit maintenance, the eccentricity begins to increase. After ~20 days, the pericenter has reached an altitude close to 500 km, which makes it possible to circularize the orbit at this altitude with a sequence of two braking manoeuvers. These changes of the pericentre and apocentre altitudes are presented in **Figure 5-12**.

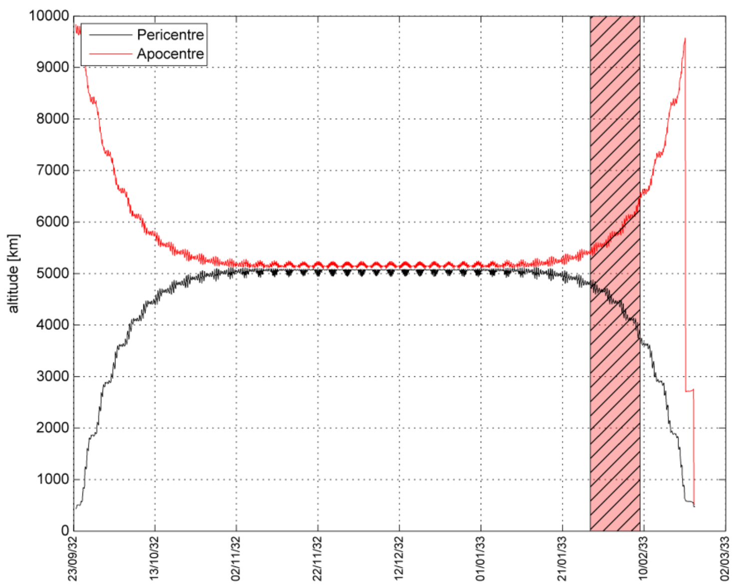


***Figure 5-12.** Evolution of the pericentre and apocentre altitude during the GEO GCO-5000 phases. The shaded area shows the period of superior conjunction for one reference case.*

The two elliptical phases at the beginning and the end of this sequence provide excellent opportunities to explore the environment of Ganymede at different distances. The initial β-angle needs to be in the 20° to 40° range so as to provide good illumination conditions at the sub-spacecraft point during the near circular phase (GCO-5000) while minimizing the impact of yaw steering on remote sensing coverage.
The evolution of the beta angle is nearly linear with time, and depends on the inclination of the orbit plane. The inclination has been set at ~87° so that the β-angle at the end of the GEO phase has increased to 60°, which is the minimum required for avoiding eclipses on a near polar circular orbit of altitude of 500 km. Short eclipses occur only for a few orbits at the beginning of the GEO phase, but this is acceptable as the period of the orbit is 12 hours, and science operations can be limited during these few orbits without major impact on the science return of the mission.

5.1.6.2 Ganymede Circular Orbit (GCO-500) phase

At the end of the GEO phase, a series of two braking manoeuvres sets the orbit in a nearly polar circular orbit with 500 km altitude (GCO-500). Once on this orbit, very small orbit maintenance manoeuvres are required. The altitude range will vary between 470 and 530 km for GCO-500. The inclination evolution is periodic with an amplitude of ~1° around a mean inclination of 86.3°. **Figure 5-13** shows the evolution of the β angle in this GCO phase. The eccentricity does not vary significantly and, therefore, the evolution of the beta angle is approximately linear. The β-angle is 62° in the beginning of the GCO-500 orbit reaching 83° by its end. Beyond the end of the nominal mission, the β-angle would grow further to 90° and then start decreasing.

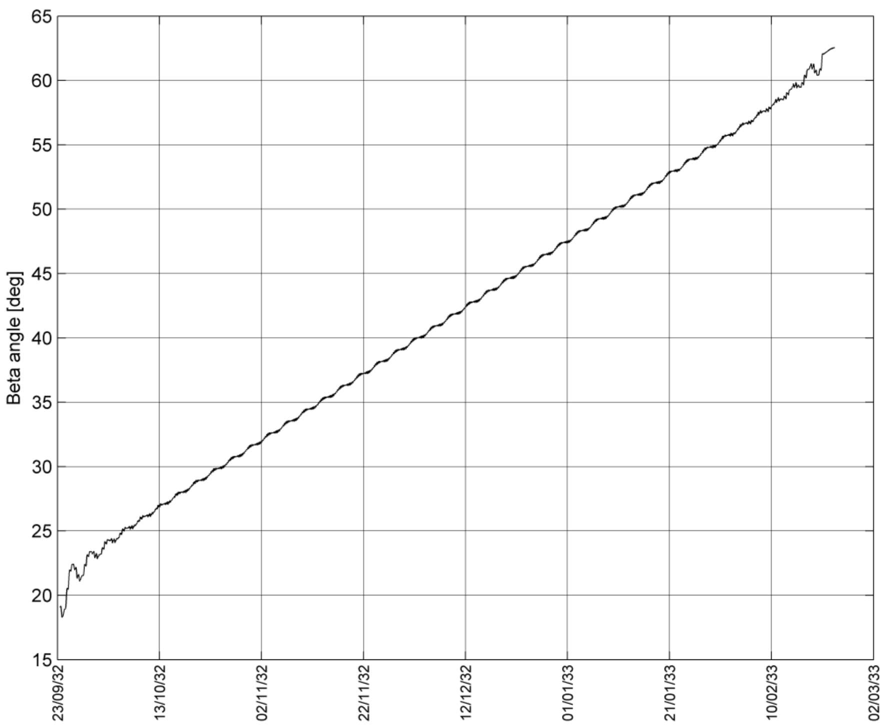


Figure 5-13. *Evolution of the β-angle during the GCO-500 phase.*

5.1.7 *End of the mission*

The nominal science mission ends after 280 days orbiting around Ganymede. A free evolution of the orbit leads to a disposition on Ganymede's surface within several weeks. It is possible to constrain the location of the impact with a modest fuel expenditure if required. The JUICE planetary protection approach is described in Section 5.3.

5.1.8 *Summary of the Jupiter tour*

The main elements of the reference Jupiter tour are presented in **Table 5-2**. The duration of transition phases (from G2 to the Europa phase, then from the end of the inclined phase to GOI) may vary with interplanetary transfer option. However, the characteristics of science driven phases (Europa phase, inclined phase, Ganymede orbit phase) are the same in all options, and the overall Δv budget after JOI is sufficiently similar for all cases.

Table 5-2. *Main characteristics of the Jupiter reference tour. The two main contributions to the Δv budget are the first orbit (GOI and PRM) and the Ganymede orbital phase.*

Tour phase	**Duration, days**	**Δv, m/s**
1st orbit (G1 to G2)	186	952
From G2 to departure from Callisto to Europa	193	27
Europa phase	35	30
Inclined phase	208	13
Transfer to Ganymede	353	60
Ganymede orbital phase	284	614
Full tour (JOI to EOM)	1259	1696

5.2 Main requirements of the spacecraft design

5.2.1 *Radiation Mitigation*

The radiation environment is dominated by the bound electrons in the Jupiter magnetosphere. Their fluence is dominating over the solar proton contribution by several orders of magnitude. The electron spectrum also has a high energy component, which extends to higher energies than exposed to in geo-stationary. At low energies of the electron spectrum, the expected total mission fluence is actually lower than a typical exposure for 10–15 year geostationary mission. Such 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 will be used, such as coating with conductive layers.

For the considerations of shielding the benefit of units shielding each other has been considered and evaluated with detailed radiation transport simulations. The required radiation tolerance was set at 50 krad at the outside of each unit.

5.2.2 *Power*

The other main mission drivers are related to the large distance from the Sun, and the requirements that the mission generate power by solar cells. The worst case solar intensity is 46 W/m^2. Together with detailed analysis of all critical mission phases, the requirements on the power generation were obtained resulting in a solar array area of close to100 m^2. This solar array size can only be obtained when eclipses in the final phases of the mission around Ganymede were excluded. Furthermore, when in Ganymede's orbit, the normal incidence of the sunlight onto the solar arrays will be maintained through one-axis solar array drive mechanisms combined with a rotation of the spacecraft around the nadir axis. 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.

5.2.3 *Thermal*

The entire spacecraft will be optimised for operations in the cold environment at Jupiter and will be covered by Multi-Layer Insulation. The albedo heating from the Jupiter moons is negligible. During the Venus gravity assist, the high gain antenna will be used as sun-shield, so as to avoid forcing the spacecraft design to also accommodate for this hot case in full. Passive thermal control will be achieved with radiators; only electrical heating will be provided.

5.2.4 *Propulsion*

The orbit insertions at Jupiter and Ganymede, the reductions of the altitude of the orbit around Ganymede, and the large number of gravity assists and flyby manoeuvres (>25) lead to a high Δv requirement, and consequently to a high wet/dry mass ratio (about 2.6:1). The spacecraft architecture will therefore need to include large volume of propellant tanks.

5.2.5 *Communications*

The large distance to Earth results in a signal round trip time of up to 1h 46m requiring careful pre-planning and autonomous execution of operations by the spacecraft. Additionally, a high gain antenna is required for data downlink. The data downlink system is sized for an average daily data volume of at least 1.4 Gb, assuming maximum telecommunication pass of 8 h/day.

5.2.6 *Attitude and Orbit Control Sub-system*

The attitude control sub-system is driven by the need for maintaining nadir pointing of the spacecraft during flybys for observations with the scientific instruments. In addition the spacecraft has a large angular inertia mainly due to the large area of the solar panels. The remaining deployable appendices (sub-surface radar antenna and magnetometer boom) add constraints on the pointing stability.

The attitude will be provided through the use of momentum wheels, supported by a propulsion system for off-loading. Off-loading will be scheduled outside science observation windows.

5.2.7 *Avionics*

The avionics sub-system provides for sufficient command storage to enable the required autonomy of operations. A storage for several days of science data will be included to provide sufficient flexibility such that the spacecraft can be pointed according to the needs of the science instrumentation, and buffer the data for downlink later.

5.2.8 *Mechanisms*

Mechanisms include the solar panels, the solar array drive mechanisms, the sub-surface radar boom, the magnetometer boom and the RPWI antennae. The appendices will be accommodated such that their deployment can be performed independently, and that they do not infringe the field-of-view of the optical and particle instruments, including stray light avoidance cones.

5.2.9 *Launcher*

The baseline launcher is Ariane 5 ECA from Kourou.

5.3 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 first option was taken as the baseline for proceeding. The risk of collision with Europa is limited to the period up to the Europa flybys. After this period the spacecraft has a perijove higher than Europa's orbit and a lower apocentre, such that collisions are sufficiently unlikely within the timeframe of concern (several 100 years). A dedicated study was performed analysing the likelihoods of impact, in case of spacecraft failures after each manoeuvre. Depending on the time and location of the manoeuvre, this ranges from below 5% to 40% (only for the case of the Europa flyby) for the duration during which it was estimated that the spacecraft would be sterilised by radiation (200 years). Consequently an allocation for the reliability of the spacecraft against total loss was allocated including a margin of at least a factor of two. A preliminary bottom-up assessment of spacecraft's subsystem reliabilities taking into considerations the lifetime and the exposure to the environment indicated that the overall allocated spacecraft reliability can be met. As for short term failures, i.e. loss of spacecraft control during approach for the Europa flyby, a re-targeting strategy will be performed: the spacecraft trajectory will be implemented such that Europa always remains outside the 3σ uncertainty, and small correction manoeuvres be performed during the approach (step-in procedure)

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"). 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-3] 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}. Some launch opportunities consider Mars gravity assists, and it will be demonstrated for these that neither the spacecraft nor any part of the launcher will impact Mars within this timescale. Early assessment confirmed this assumption.

5.4 Ground segment and operations

The JUICE mission will be planned and operated by ESA. The ground segment will consist of the Mission Operation Centre (MOC) and the Science Operation Centre (SOC). The JUICE Science Ground Segment (SGS) is made of the SOC and of the PI instrument teams and will be implemented according to the guidelines described in the Science Management Plan [D-4].

The S/C will be operated by an off-line monitoring and control approach. A pre-scheduled timeline (planned sequences of operations, defining S/C or instrument activities) will be uploaded by the MOC at regular intervals and stored on-board. During the nominal science operations, the ground station contact will happen daily, and will be used to upload new S/C and instrument commands, as well as to retrieve the scientific data together with the housekeeping data (for the S/C and instruments). No routine science operations are foreseen in the mission baseline scenario during the cruise phase.

The JUICE SGS is responsible for performing the science operations related to the implementation of the high-level science activities designed by the SWT.

Science operations encompass two main groups of activities, called hereafter the Uplink or Downlink side of Science Operations.

The Uplink activities are related to the generation of an instrument operations timeline to be uplinked to the Spacecraft. The SOC and the PI teams will consolidate and validate the science operations requests from individual instrument teams into an instrument operation timeline delivered to the MOC before being uplinked onboard the spacecraft.

In case of non-routine operations (reference measurements during the Earth and Venus flybys during the cruise phase) the SOC will assist the instrument teams in generating Pointing Timeline Request (PTR) files and delivering the instrument commanding directly to the MOC.

Figure 5-14 gives a top-level overview of the JUICE operations planning activities.

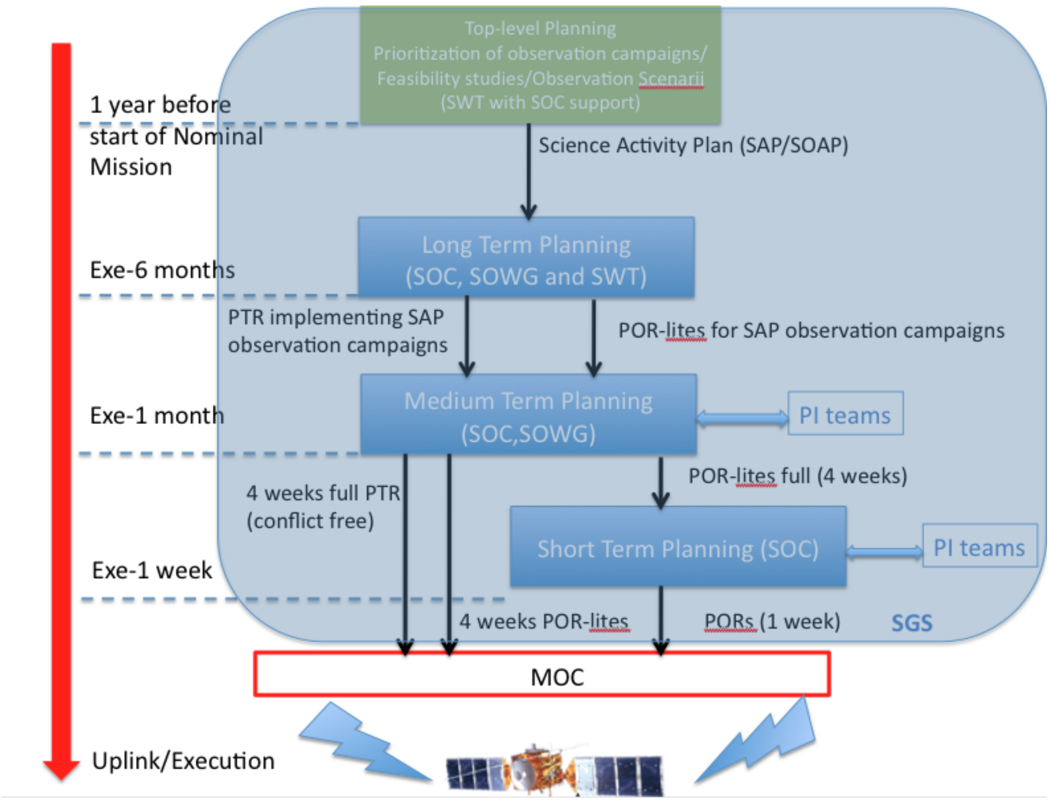


Figure 5-14. *Schematic timeline, workflow and interfaces of the different science planning levels, from the top level science activity plan to the uplink of instrument commands. The blue, semi-transparent box indicates all science planning related to SGS activities (PI teams and SOC).*

The nominal science operation planning will be divided in three steps. The first step is the Long Term Planning (LTP) covering 6 months of mission, addressing in more details the top-level planning with a refined knowledge of the S/C resources and constraints. The next step is the medium term planning (MTP) performed on a monthly basis. The main goal of the MTP phase is the finalization of the integration of the observations pointings as well as the validation of the associated instrument modes against the latest knowledge of S/C available resources, constraints and flight rules. The output of this phase is a frozen PTR file. The last step is the short term planning (STP), performed on a monthly basis, whose main goal is the finalization of the instrument commanding.

Downlink activities encompass all data handling and archiving tasks, from retrieval of instrument telemetry and auxiliary data from the Data Disposition System (DDS) under MOC responsibility and all subsequent processing to higher data levels, as well as quick look checks of the performed observations. Data archiving is performed at different levels of the data processing chain.

The SOC will process the telemetry data and distribute the resulting raw data to the instrument teams and to the archive. The raw data processing (telemetry into uncalibrated science data) is centralized at the SOC. Raw data product will be made available to the instrument teams about 4 hours after the telemetry packets are available on the DDS. Immediately after the data becomes available in the DDS, SOC retrieves, verifies and processes all spacecraft and instrument related telemetry (house-keeping and science data) obtained from the DDS. Telemetry integrity (science packets) will be checked by SOC. In addition, SOC retrieves any auxiliary data needed for science data processing, in particular the data from Flight dynamics: reconstructed spacecraft trajectory and attitude.

The instrument teams have the responsibility to generate their calibrated data and distribute them to the archive and follow the general requirements for science data archive format (PDS4). All calibration products (software, procedures and calibration files) must be delivered by the PI teams to the SOC and archived as PDS4 products. The SOC works closely with the instrument teams to facilitate the generation of these products in PDS compliant formats, thereby minimizing the additional effort required for this activity.

6 Observation strategy

To assess the scientific capabilities of the JUICE spacecraft for exploring the Jovian system, the science team developed a detailed strategy of observations for each target to understand the spatial and temporal coverage, and the resulting science return. In this section we summarise the key inputs and findings of this study [D-5] to demonstrate that the spacecraft and payload characteristics permit extensive science opportunities during the JUICE mission. Operational concepts for each instrument (e.g., occultations, mosaics, active sounding, in situ measurements, etc.) were grouped together into high-level **observation scenarios (Section 6.1)**, describing the way in which the payload would be used to achieve the science requirements in Section 3. These were considered as the building blocks for the construction of more comprehensive **observation sequences** (Sections 6.2 - 6.4), which described the timeline of observations for representative events during the JUICE tour: (i) a typical Jovian equatorial orbit; (ii) a Europa flyby; and (iii) the Ganymede 500-km circular orbit (GCO-500). GCO-500 and the Europa flyby sequences have been simulated using the ESA Mapping and Planning Payload Science (MAPPS). We note that the present simulation corresponds to the beginning of GCO-500. Later in the phase the science priorities will shift towards geophysics and in-situ investigations. Ultimately, these observing scenarios and sequences will be used as the conceptual building blocks to create the JUICE Science Activity Plan.

6.1 Observation scenarios

The diverse JUICE payload means that there are a wide variety of techniques that will be used to investigate the Jovian system, from active sounding and altimetry to remote sensing and plasma and fields science. The operational modes were grouped together into 18 distinct building blocks for the JUICE science sequences are described in detail in [D-5] and summarized briefly in **Table 6-1** below to provide a flavour of the planned activities. Remote sensing instruments are typically grouped together due to the similarity in their operations. Scenarios 1 - 9 deal with techniques for satellite science, including both the Ganymede orbital tour and the satellite flybys. Scenarios 10 - 18 deal with Jupiter atmospheric and magnetospheric science and investigations of the wider Jovian system. Pre-JOI science (e.g., cruise phase science during the interplanetary transfer) has not been included, as it is not a driver for the JUICE mission design.

The individual components of the eighteen observing concepts in **Table 6-1** were assembled into a set of typical observing sequences for the spacecraft, as detailed in the following sections. The observing sequences were carefully constructed to meet the specific requirements of each instrument. In some cases this implied simultaneous operation of instruments, particularly during periods of closest approach to satellites. The data rate was assumed to be 50 kbits/s at X-band (1.4 Gbits over an 8-hour ground-station pass, one pass per day). Particles and fields instruments were assumed to be operating at low data rates during the ground-station passes. The cumulative data volume over the duration of the mission, and the allocation between different instruments and targets, is recognised as a key challenge for science planning, hence the scenarios presented in this section are preliminary steps towards a detailed science activity plan. It is likely that downlink will be optimised, potentially by pre-selection of the most useful observations from brows data or by the use of additional ground stations during periods of intense activity. Satellite science will be the highest priority during closest approach for all targeted and distant flybys, whereas atmospheric and magnetospheric studies will take precedence during other mission phases (particularly the inclined phase).

Table 6-1. *Observing scenarios grouped by target and similarity of payload operations***.**

#	Title	Concept	Instruments (in alphabetic order)
1	**Satellite Stellar and Solar Occultation**	Inertially pointed observations at a star or the Sun to study the density/composition of atmospheres and tenuous exospheres of Galilean satellites (e.g., Europa plume searches) with a high vertical resolution.	JANUS, MAJIS, SWI, UVS
2	**Satellite Aurora, Exosphere and Airglow**	Imaging spectroscopy of disc (scans, mosaics, cubes) for atmospheric emission (airglow and aurorae) to study atmospheric structure/composition, relation of aurorae to sub-surface ocean inductance, limb scans for water/temperature profiles.	JANUS, MAJIS, PEP, SWI, UVS
3	**Satellite Surface Imaging and Spectroscopy.**	Mapping/scanning of surfaces to study surface geology & composition using both reflectance and thermal emission (e.g., thermophysical properties of subsurface), stereographic imaging of selected targets, ENA imaging of particle precipitation patterns.	JANUS, MAJIS, PEP, SWI, UVS
4	**Satellite Gravity and Geodesy**	Gravity field and spacecraft orbit determination via continuous radio tracking at closest approach to determine dynamic rotation state and gravitational tides, two-way range tracking to improve ephemeris during tour.	3GM
5	**Satellite Altimetry and Topography**	Laser altimetry topographic mapping of surfaces at closest approach, coupled with stereo imaging, to understand geologic processes (e.g., erosion, deposition), tidal deformation of icy crusts, surface albedo & roughness.	GALA, JANUS
6	**Radar Sounding**	Radar sounding of icy shells at 50-140 m resolution to study subsurface structures (stratigraphic patterns), physical properties and correlation with surface geology, and interaction between ice shell & oceans.	RIME
7	**Satellite Magnetospheric and Plasma Environment**	Continuous monitoring of induced and intrinsic fields to study subsurface oceans, local plasma environments and particle populations surrounding satellites, and coupling between the magnetosphere and satellite ionospheres.	J-MAG, PEP, RPWI
8	**Satellite Ionospheric Characterisation**	In situ measurements and occultation studies of electrical conductivity, structure and electron density, and current systems in the ionospheres and charged-particle populations around the moons.	PEP, PRIDE, RPWI, 3GM
9	**Remote Observations of Satellites, Rings & Tori**	Distant remote sensing of satellites and plasma tori, with particular focus on Io's volcanic activity and Europan plumes as a plasma source, variability and surface composition. Also distant observations of Jupiter's minor satellites and rings.	JANUS, MAJIS, PEP, RPWI, SWI, UVS

#	Title	Concept	Instruments (in alphabetic order)
10	**Jupiter Magnetosphere and Plasma Environment**	In situ sampling and remote ENA sensing of Jovian magnetosphere to study the configuration and dynamics of the magnetodisc as a function of distance, local time and latitude, from both equatorial and inclined phases. Near-continuous operation.	J-MAG, PEP, RPWI
11	**Jupiter Auroral Studies**	Remote sensing of Jovian auroral emissions, and relation to magnetospheric phenomena, in situ measurement of satellite footprints.	JANUS, J-MAG, MAJIS, PEP, RPWI, SWI, UVS
12	**Jovian Radio Emissions**	Radio remote sensing of electrostatic discharges to characterise the radiation environment, its time variability and the sources of radio emissions (auroral emissions, satellite footprints, lightning activity).	RPWI
13	**Jupiter Global Imaging and Spectroscopy**	Multi-wavelength spectral imaging from the UV to the sub-mm to study Jupiter's global atmospheric dynamics, meteorology, winds, chemistry and thermal structure.	JANUS, MAJIS, SWI, UVS
14	**Jupiter Regional Imaging**	As for case 13, but focussed on the evolution of discrete phenomena in the Jovian atmosphere such as giant vortices, plumes, waves, storms, etc.	JANUS, MAJIS, SWI, UVS
15	**Jupiter Limb Observations**	Limb scanning remote sensing observations to maximise the path through the Jovian atmosphere, sensitive searches for undetected chemicals and hazes, airglow and upper atmospheric circulation.	JANUS, MAJIS, SWI, UVS
16	**Jupiter Stellar/Solar Occultations**	Occultations of the Sun and stars by the upper atmosphere to provide high-resolution profiles of temperature, density and composition, requiring inertial pointing for a brief period.	JANUS, MAJIS, UVS
17	**Jupiter Radio Occultations**	Attenuation of the probe carrier signal as JUICE is occulted by Jupiter, sounds the structure and temperature of the neutral atmosphere, and the electron densities of the upper atmosphere.	PRIDE, 3GM
18	**Satellite Ephemerides**	Precise measurements of the lateral spacecraft position via radio tracking for estimates of the satellite ephemerides, improving the ephemeris of the Jovian system as a whole.	JANUS, PRIDE, 3GM

6.2 Observing Sequences for the Ganymede orbital phase

6.2.1 Introduction

The orbital phase around Ganymede consists of four phases designed to avoid eclipses, except in the beginning when short eclipses do not impose significant demand on the spacecraft power system (see Section 5.1.6). Science priorities are optimally distributed between the mission phases.

GEO and GCO-5000. 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 20-30° (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 be mostly used to provide global imaging and spectro-imaging to study geology and surface composition taking advantage of good illumination conditions (low β-angle in **Figure 5-13**) Global mapping of Ganymede from the UV to the sub-millimetre is envisaged for the elliptical and 5000-km circular orbital phases, providing full coverage at moderate spectral resolutions of 400 m/pixel for imaging and 2.5 km/pixel for spectro-imaging (**Figure 6-1**). Highly elliptical 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 and laser altimetry.

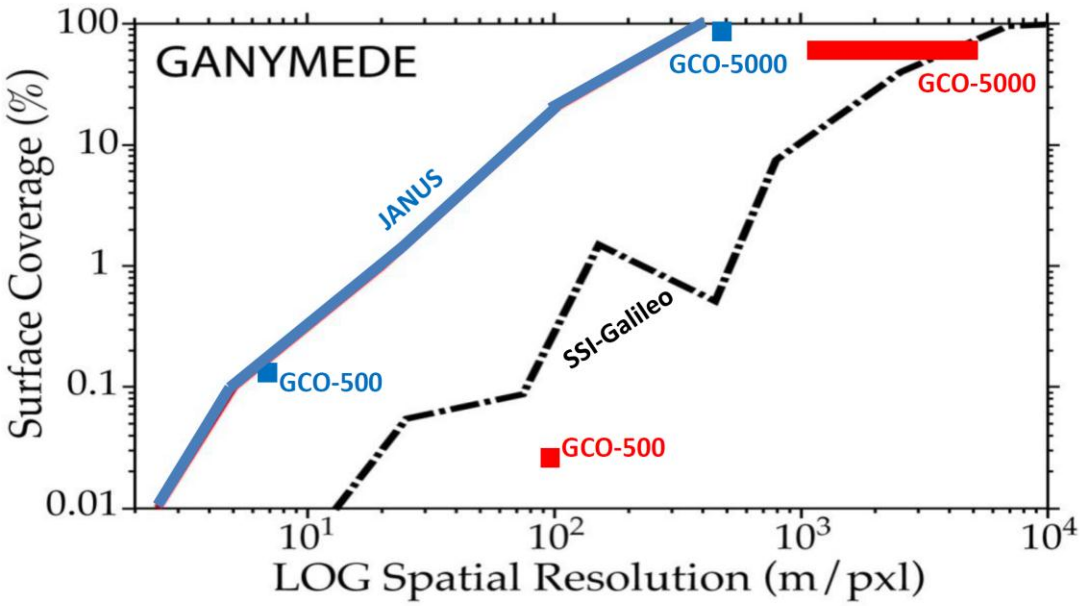


Figure 6-1. *Ganymede surface coverage as a function of spatial resolution expected from the JANUS camera (blue) and MAJIS imaging spectrometer in GCO-5000 and GCO-500 phases. The black line shows surface coverage by the SSI-Galileo camera.*

GCO-500. In this low circular phase, the priority will be given to the geophysical, exospheric and plasma investigations, that require close proximity to the satellite. The spacecraft will be transferred to the 500 km circular orbit at β ~ 62° to keep the spacecraft out of eclipses. JUICE will perform high-resolution imaging (<10 m/px) and spectro-imaging (~100 m/px) of selected targets. Routine topography study by the laser altimeter and subsurface sounding by the radar will occur during 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 and induced fields). The detailed analysis of GCO-500 is displayed in the next section.

6.2.2 *The Ganymede circular orbit at 500 km altitude*

The Ganymede 500-km circular orbit (GCO-500) is considered as the limiting case for the sizing of spacecraft resources (power and downlink capabilities), and has therefore been more comprehensively studied than previous Ganymede phases (elliptical and high circular), or the Jupiter and Europa sequences. GCO-500 consists of approximately 133 days, with a total of 1035 orbits around Ganymede. This is a crucial and important phase to fulfil JUICE's science objectives for Ganymede, providing the first opportunity for key geophysical measurements to characterise the shape of the moon, the gravitational field and the exploration of the subsurface. As for remote sensing, GCO-500 is dedicated to high spectral and spatial resolution mapping of regions of interest for geology, chemistry and exobiology (**Figure 6-1**), along with measurements of exospheric composition and dynamics. A small number of these may be of interest as future landing sites, to be scrutinised more closely if an extended mission profile at lower altitude is possible. Furthermore, GCO-500 is crucial for in situ measurements to characterise Ganymede's induced magnetic field embedded in the intrinsic and the Jovian magnetic field, as well as for studies of the Ganymede exosphere dynamics and plasma precipitation processes.

The JUICE science working team used the ESA Mapping and Planning Payload Science (MAPPS) tool to produce a detailed analysis of the constraints imposed by GCO-500 in terms of power and data volume limitations, but also respecting illumination conditions (UVS, JANUS, MAJIS), exposure to Jovian radio noise (RIME) and the need for simultaneous operations of some instruments. The rationale for the MAPPS simulation was to study the feasibility of the science objectives of GCO-500 sizing case (given the data volume and power figures available). The figures that had to be met were a daily data volume not higher than 1.4 Gb/day and a maximum instantaneous instrument power consumption of 167.48 W given an averaged data downlink of 8 hours per day using the Malargue ground station. For this purpose a semi-operational environment was created and iterations with different members of the SWT were performed to define an operations strategy to be implemented and analysed.

In this modelling exercise each instrument has been assigned a specific amount of time for observation using dedicated modes, and the cumulative data volume is approximately divided as 50% for remote sensing, 25% for in situ plasma and fields measurements and 25% for active sounding (RIME and GALA), although these instrument groupings have been mixed in a flexible way to optimise the payload activities. The GCO-500 phase has been simulated for the first 100 days to verify the feasibility of meeting the science objectives. Due to its stringent operation constraints, the start of the operations sequence was driven by RIME's need to operate in six specific periods on the anti-Jovian side of Ganymede to be shielded from Jupiter's radio noise), each lasting for 3 days. Therefore, during these six periods geophysical investigations were given highest priority. The remaining 82 days were shared among the three packages (remote sensing, geophysics excluding RIME, and in situ measurements). Instrument-specific observations are described below.

6.2.2.1 *Active sensing instruments (aka Geophysics)*

GCO-500 is the major opportunity for geodesy, laser altimetry and subsurface sounding to address the science objectives related to the deep interior, the ocean and the outer ice layers of Ganymede. In previous phases, such observations will only be possible during a few close flybys of Ganymede.

- **GALA:** GALA will provide the full characterisation of the shape of the moon from extensive ranging of the sub-satellite track. Due to the downlink limitations, the present simulation allocates 16 hours every day for this objective at a "reduced" rate. The shot-rate and shot frequency mode have been optimized taking into account a data volume allocation of 16 Gbits in the simulation. GALA will be operating whenever the subsurface sounding is operating as it provides the precise topography along track that will help to interpret the data. In **Figure 6-2**, the tracks of the GALA instrument (in blue) are plotted in the equatorial view. A detailed characterisation of the poles will be obtained, thanks to the mission profile, but it must be noted that GALA cannot work continuously at high frequency due to downlink limitations, which limits the coverage in equatorial regions (about 1 track every 20 km on average).

- **RIME:** The subsurface exploration of an icy crust is an entirely new science objective never addressed by any previous space mission, except by Mars Express and MRO for the ice caps. RIME operations should be focused on regions of interest (ROI) due to limitations in downlink, but since it must be operated on the anti-Jovian side of Ganymede, only the far side can be explored (see **Figure 6-2**). No yaw steering is permitted during the RIME observations. This will be complemented with additional operations during close flybys of the moon.

- **3GM:** Radio tracking will operate during the downlink phase when the HGA is pointed towards the Earth (i.e., 8 hours per day). This will permit precise measurements of the moon's gravitational field via perturbations to the spacecraft orbit. No on-board data storage is envisaged.

Figure 6-2 shows distribution of ground tracks on the Ganymede surface in the GCO-500 phase as simulated by the MAPPS tool.

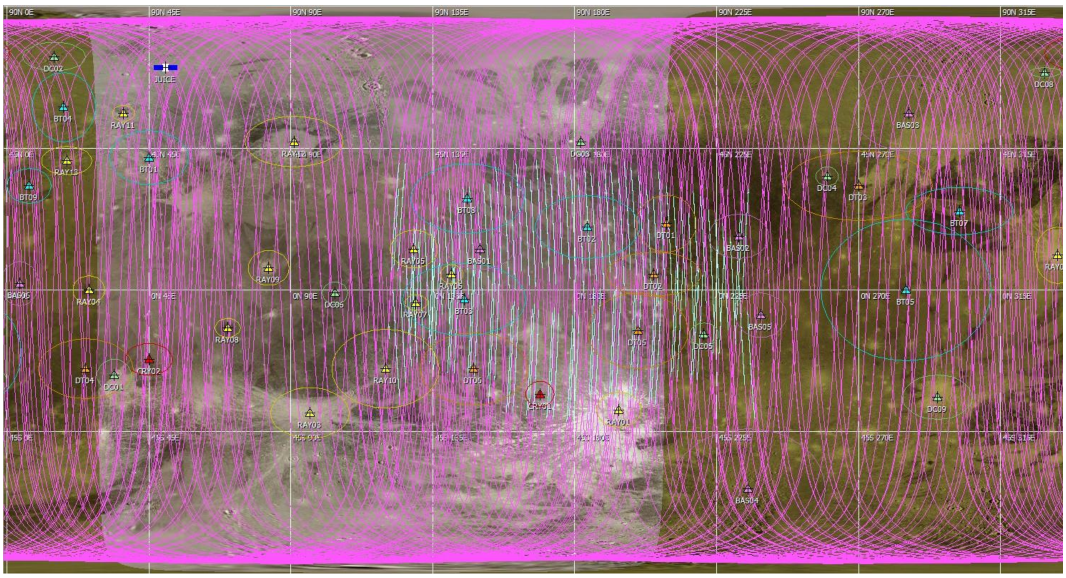


Figure 6-2. *MAPPS simulation of the observations for geophysics at Ganymede during GCO-500. Pink lines indicate ground tracks of GALA. Light blue swaths are the observations of the RIME instrument.*

6.2.2.2 *Remote sensing instruments*

The global coverage of the moon at all wavelengths and medium spatial resolution (400 m/pxl for imaging, ~2 km/px for spectro-imaging) will be provided during the previous flybys, the two elliptical phases and the high altitude GCO-5000 prior to GCO-500. Thus, GCO-500 is dedicated to the characterisation at high spatial and spectral resolution of the regions that will be identified as being of high interest for geology, chemistry, or exobiology (ROI). JANUS and MAJIS observations take only a relatively small portion of the orbital time, due to the very high data production rate of these instruments. Both instruments are "off" in the rest of the orbit. The instruments would be nadir pointed, with no yaw steering during the JANUS and MAJIS observations. Outside of the JANUS and MAJIS observations the spacecraft would return to yaw steering mode, during which time UVS would scan Ganymede for night-time aurora and daytime surface mapping; and SWI would scan the surface under both daytime and night-time conditions. In summary:

- **JANUS:** JANUS observations will be performed on selected targets, allowing operations during a fraction of the time spent in GCO-500. The equivalent data production should be about 2500 panchromatic images in nadir push-frame mode, covering approximately 1% of the surface at full resolution (7.5 m/pixel). In fact, the exact coverage will depend on the chosen tuning with the resolution that can span from 30 down to 7.5 m/px.

- **MAJIS:** As for JANUS, MAJIS operations will be limited to regions of interest, providing about 90 spectral cubes with a resolution of 60 m/px. MAJIS observations require a suspension of yaw steering.

- **UVS:** Unlike JANUS and MAJIS, the UVS observations will not be routinely targeted, and UVS is expected to operate semi-continuously to provide scans of the ground-track to explore surface characteristics, exospheric properties and aurorae. If observations were dedicated to surface studies alone, UVS would cover 73.5% of the surface during this phase.

- **SWI:** As for UVS, the SWI observations are not targeted and are expected to be continuous, providing access to surface features under both daytime and night-time conditions to study thermal inertia characteristics. Limb scans will be used to study the tenuous water atmosphere structure and composition.

- **PEP** provides imaging of the precipitating particles in backscattered ENAs to identify correlations with changes in IR spectrum (surface weathering) operating semi-continuously with the focus on the polar regions inside the open/close field line boundary (> 50° latitude).

Figure 6-3 shows an example distribution of the ROI's which could be observed by JANUS and MAJIS on the Ganymede surface in the GCO-500 phase.

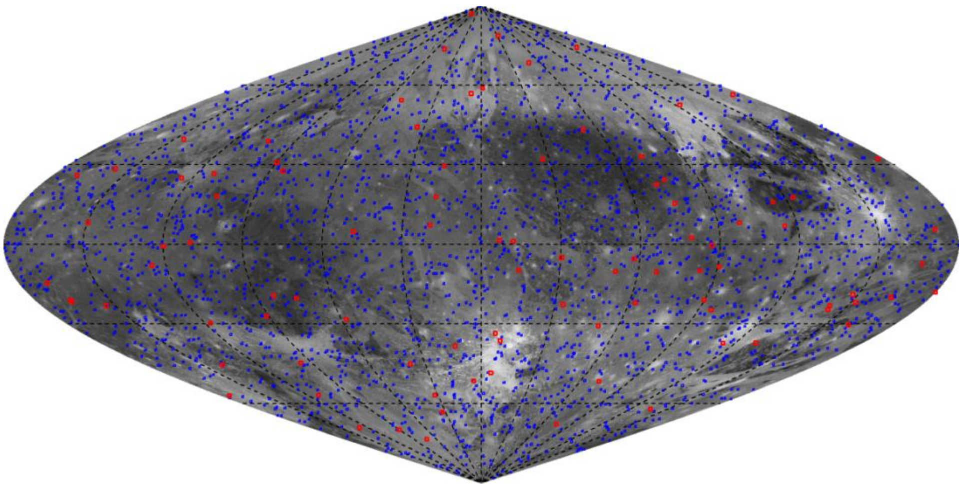


Figure 6-3. *MAPPS simulation of the remote sensing activities at Ganymede during GCO-500. For JANUS (blue) and MAJIS (red), observations are at high spatial resolution and very focused , but with no specific constraints on the location at this stage. This map showcases the excellent sampling of regions of interests which can be achieved by JANUS and MAJIS from GCO-500 km. Targeted observations on ROI will be implemented in future steps. SWI and UVS (not shown) are not targeted but work on a continuous basis to explore the surface characteristics, exospheric properties, and auroras.*

6.2.2.3 *In Situ Sensing Instruments (aka Plasma and Fields)*

In principle, the plasma and fields instruments (J-MAG, RPWI and PEP) should operate continuously during the GCO-500 phase. If there were no limitations regarding the total data volume per day, J-MAG would be in normal mode for 70% of the time and in burst mode for 30% of the time, RPWI in in-situ mode, and PEP in the 'medium' mode as an average with some peak activities. Due to the downlink limitations, the strategy of observations has been reformatted assuming a total data volume of about 25 % of the total data volume. No requirements were identified of the instruments to halt yaw steering for any moment during the orbit provided that the EMC requirements will be continuously fulfilled. The detailed operations of J-MAG, RPWI and PEP shall be coordinated to increase science return. This work will be carried out in the JUICE/SWT over the next few years, where each of the available 24 hours periods for the in-situ experiments can be devoted to different science tasks. Furthermore, certain regions of interest, such as the auroral latitudes at Ganymede or the polar region, are of particular interest and detailed planning is required for each orbit.

At this stage of the study, priority has been placed on satisfying the need for continuous acquisition. Therefore, J-MAG, RPWI and PEP are operating 16 hours per day (no downlink). J-MAG operates in the gradiometer mode, PEP operates in a low-rate mode 15 hours/day and in a high-rate mode 1 hour per day. The PEP high-rate mode can be up to 50 kbps for brief periods over certain regions of interest over selected orbits. This has not yet been considered in the simulation but will be introduced in future stages. RPWI operates in the Survey mode except for 20 minutes/day where the full mode is activated. RPWI operations are also envisaged during RIME observations since this provides important constraints to noise characteristics to aid in interpretation of the data.

The strategy of observations described above have been introduced in the MAPPS (Mapping and Planning Payload Science) software. This leads to sequences of instrument operations such as the two illustrated in **Figure 6-4** for about two days each. The top figure displays the operations of Remote Sensing and In Situ observations complemented by Geophysics and the bottom figure displays a Geophysics dedicated campaign with anti-Jovian side observations for RIME. For each orbit, all parameters (data volume, power, S/C pointing requirements) are computed so that any issues with respect to S/C limitations can be identified.

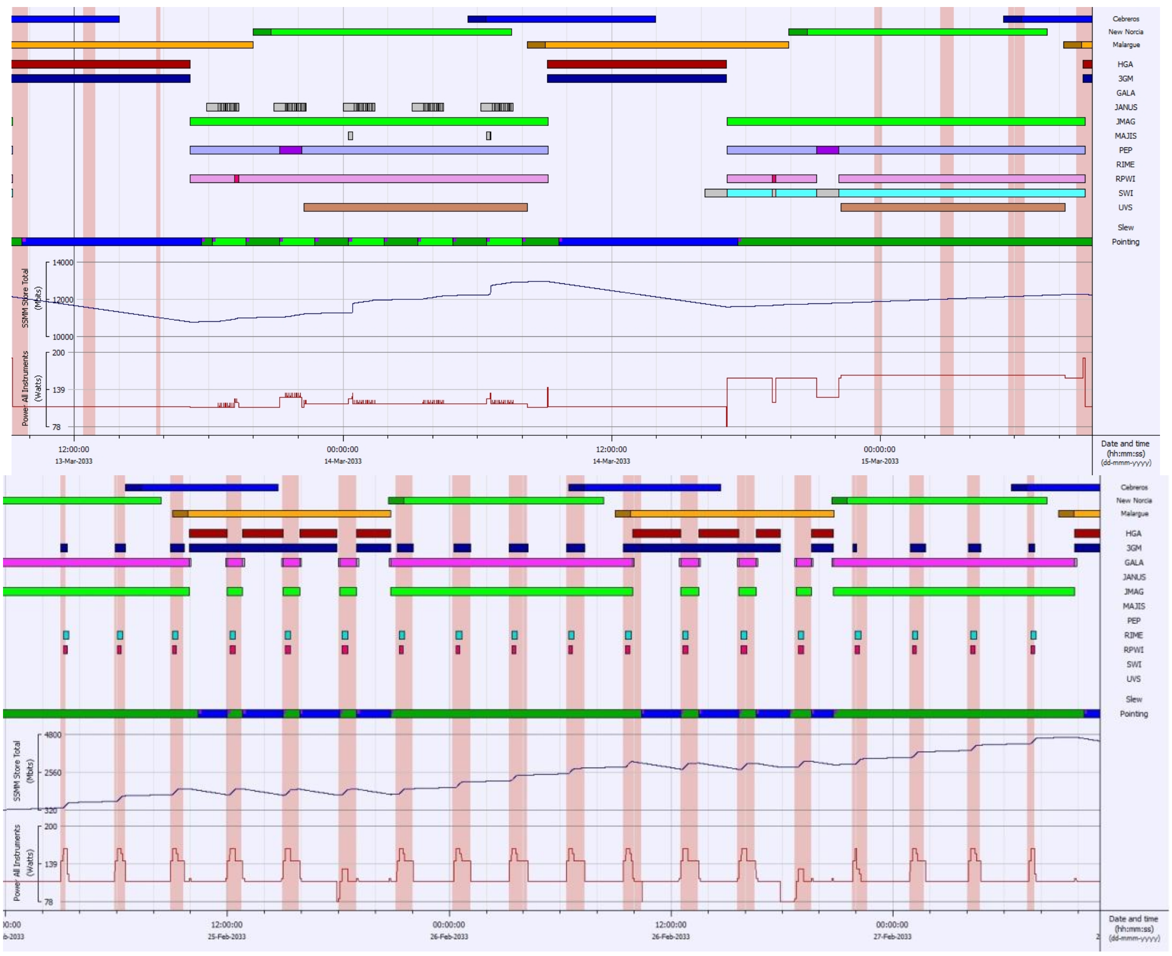


Figure 6-4. *A typical sequence of observations used in MAPPS for orbits devoted to remote sensing and in situ observation (top) and orbits devoted to geophysics (bottom). The top three lines indicate the Ground Stations visibility. The following colour bars illustrate the sequence of observations per instrument (various colors per instrument are for different modes. Instrument names indicated on the right legend). Finally the bar in the bottom indicates the pointing of JUICE (Earth pointing in blue and Nadir pointing in green) The two graphs at the bottom plot the total compressed data volume in memory and the total power variations through time.*

6.2.3 *Summary of the GCO-500 simulation*

The GCO-500 sequence simulation identified several data volume and power conflicts that led to strategy adjustments, avoiding power excesses and ensuring compatibility with the available data volume. **Table 6-2** shows the data volumes accumulated by each instrument based on this observing strategy, ensuring that the capabilities of the spacecraft are fully accounted for. The total amount of data (compressed data volume) per instrument has been estimated with this strategy of observation. These numbers are preliminary and must not be considered as the final allocated volume per instrument. Further iterations within the Science team are planned in the future to ascertain these estimates.

Table 6-2. *Summary of observing strategies and preliminary data volume over a 100-day period from MAPPS simulation of GCO-500 phase.*

Instrument	Uncompressed Data Rate, kbits/s	Cumulative Data Volume, Gbits	Remarks
JANUS	550	28.8	Observations focussed on regions of interest only, spatial binning used.
MAJIS	5740	33.5	1 acquisition every 12 orbits.
UVS	2.83	8.4	Continuous operation 16 hours per day.
SWI	5.23	9.3	Continuous operation 16 hours per day.
3GM	Negligible	Negligible	Carrier acquisition mode simultaneously with downlink.
GALA	7	12.7	Reduced shot rate and frequency, continuous acquisition every 3 days regardless of illumination.
RIME	250	28.0	Operation on anti-Jovian side only.
J-MAG	2.41	13.5	Continuous operation 16 hours per day, grad mode only.
PEP	1.6-8.1	9.3	Continuous operation 16 hours per day, low-rate mode (15 hrs) and high mode (1 h).
RPWI	0.96-55.7	12.8	Continuous operation 16 hours per day (mostly survey mode, 20 mins full mode).
PRIDE	0	0	
TOTAL		**143**	

In summary, the payload operations have been simulated for the first 100 days of GCO-500 to resolve conflicts between scientific requirements and spacecraft resources. The study demonstrates that the spacecraft is capable of achieving the scientific objectives of Section 2, given that GCO-500 is the main opportunity to perform geophysical observations in close proximity to Ganymede. The cumulative data volume respects the 1.4 Gbits/day downlink, whilst providing high-resolution remote sensing of regions of interest; near continuous monitoring of the interplay between the Ganymede and Jupiter magnetospheres, and the first surface and sub-surface characterisations by active sensing instruments. We note that the downlink capability is the key factor constraining the mission science return which would significantly benefit from an increased downlink.

6.3 Europa Flyby Sequence as an example of flyby science

6.3.1 *Instrument requirements*

Two Europa flybys will be focused on the sites with traces of recent activity (**Figure 6-5**). A Europa flyby sequence has been conceptually designed based on the scientific capabilities of the payload and the JUICE science requirements [D-1] and simulated using the MAPPS tool. The sequence will: (i) characterise the composition of the non-ice material, especially as related to habitability; (ii) search for liquid water under the most active sites; (iii) study the active processes. Among other observations, JUICE should provide imaging and spectroscopy of Europa's surface geology, composition and thermophysical properties across the broad wavelength range; radar sounding of the Europan sub-surface and laser altimetry of satellite topography at closest approach; limb observations to study aurorae, airglow and the tenuous Europan exosphere; satellite ephemerides and gravity measurements; detailed characterisation of the magnetospheric and plasma environment surrounding the satellite and a search for Europan plumes.

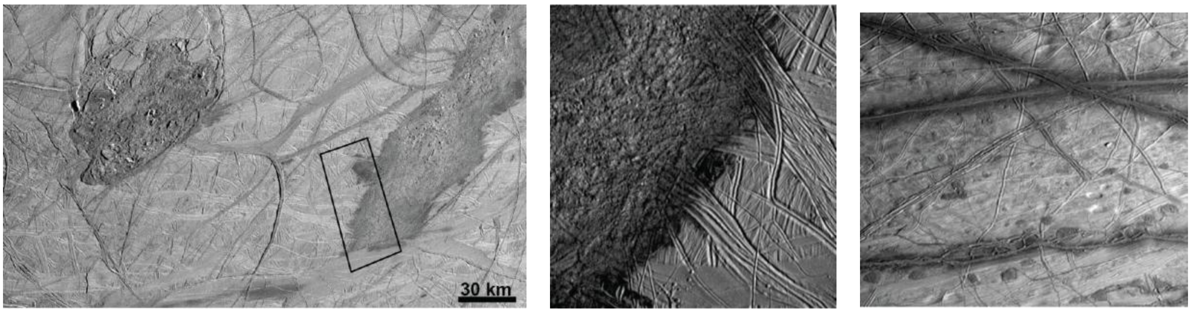


Figure 6-5. *Galileo-SSI images of Thera Macula and Thrace Macula(left), zoom on Thera Macula (middle), and intersection of Minus and Udaeus lineae with Cadmus linea.*

The Europa flybys represent the most highly packed observational sequences during the JUICE mission. Although we describe the specifics of a Europa flyby (Section 5.1.3), this could also be used as a template for flybys of either Callisto and Ganymede. Each flyby will last for several days, during which time the data will be collected and stored in the spacecraft mass memory. The data will be downloaded after the flyby, and will require a significant number of ground station passes (~8 hours each). Manoeuvering slews of the spacecraft in most cases will provide the scan mosaics required by the imaging experiments (MAJIS and SWI also have their own scanning capabilities) – 5 slews (3 for JANUS and 2 for MAJIS) are envisaged during each of the approach and departure phases within 12 hours of closest approach (CA) with yaw steering enabled to maximise spacecraft power. The slews extend beyond the disc to enable both surface imaging and remote sensing of the limb and exospheres. During the 120 minutes surrounding closest approach (CA±60 mins), the spacecraft suspends yaw steering. Spacecraft slews are executed for MAJIS, JANUS, UVS and SWI surface coverage until CA-30 mins, when nadir pointing is acquired and all instruments switch to push-frame mode (JANUS operating in single-filter panchromatic imaging for CA±17 mins; MAJIS using its scanning mechanism for motion compensation for CA±13 mins). GALA and RIME observations will operate within CA±7 mins when the distance to the surface is at a minimum. Finally, yaw steering is recovered at CA+60 mins and the approach sequence is repeated in reverse. Depending on the data volume constraints, distant observations of Europa (e.g., plume searches, satellite mutual events) will be executed during the pre- and post-flyby phases two days either side of closest approach. Instrument-specific observations are described below:

- **JANUS:** As the proximity to Europa decreases, JANUS will switch from full-frame imaging (8 colours); to mosaics of 4 - 8 images in 4+ filters using the spacecraft slews (5 slews either side of the CA, 3 devoted to JANUS); to surface scans in push-frame mode from CA-60 mins to CA-30 mins, before finally switching to nadir-pointing push-frame mode for single filter panchromatic images during closest approach. This sequence enables context imaging of half of the moon's surface (day side) with resolution from 2 km/px to 0.1 km/px in all JANUS filters and panchromatic imaging of the most active regions along the flyby trajectory with resolution up to 6 m/px.

- **MAJIS:** MAJIS will scan the Europan disc at least four times during approach and departure, switching from limb tracking for atmosphere/exosphere studies at large distances to full surface scans during the slews. This will provide global spectral imaging of the dayside with resolution of 6.6 km/px. During CA±60 mins MAJIS will perform surface scans and surface push-frame imaging, using motion compensation within CA±13 minutes to provide spectral imaging of regions of interest with resolution of up to 50 m/px.

- **UVS**: UVS will conduct stellar occultations when within ±2 days of closest approach; switching to auroral and airglow imaging disc scans and limb stares from ±10hrs to ±1hrs; before switching to nadir surface+aurora imaging during the closest approach. UVS will conduct several long duration exposures during Europa nadir (terminator) pointed stares as available, in addition to the scan ride-alongs, including one targeted night side limb-stare to search for faint atmospheric emissions from any water vapour plume regions. Jupiter transit imaging at times > ±10hrs are conducted as available. UVS stellar occultations require the spacecraft to maintain inertial pointing for a short duration during the flyby sequence.

- **SWI:** SWI will scan across the disc (i.e., also viewing the Europan limb) from CA±10hrs to ±1hrs, before switching to nadir surface imaging for thermo-physical properties during the closest approach. SWI would permanently scan during the Europa flyby and slews to achieve maximum spatial coverage, subject to the requirements of other instruments.

- **3GM:** Although continuous spacecraft tracking is desirable throughout the flyby sequence, this will only be possible with an articulated MGA to permit continued remote sensing operations. Without the MGA, radio tracking via the HGA could be used from CA±12 hours to CA±9 hours to recover these science requirements.

- **GALA:** Surface altimetry will occur within CA±9 mins when the spacecraft is less than 1300 km from the surface of Europa.

- **RIME:** Subsurface radar mapping will be active when the spacecraft is within 1000 km of Europa's surface, within CA±7 mins.

- **J-MAG:** J-MAG operates continuously when within ±200,000 km of Europa; switching to burst mode for CA±60 minutes. J-MAG can operate during any spacecraft attitude.

- **PEP:** Operates continuously with all sensors on for the ±12 hours surrounding closest approach. The PEP instrument will operate in different modes during the flyby, switching to 'high-rate' data acquisition mode for CA±30 mins.

- **RPWI:** As with the other in situ instruments, RPWI will operate in a full in situ mode for remote measurements, and at a high data rate for 5-10 minutes during the four satellite - Jupiter occultations. The Europa flyby will be divided into two operation sequences for RPWI; one that investigates the interaction of the surrounding space environment (Europa torus, Europa plasma tail) with the induced magnetosphere/ionosphere of Europa; and one that provides detailed studies of the ionosphere of Europa (structure, dynamics, monitor dust, search for plumes, etc.).

6.3.2 *MAPPS simulation of Europa flybys*

The simulation of the sequence of observations at Europa was performed using a similar approach to that for GCO-500. The instrument and spacecraft modeling was performed and complemented by iterations with the science and engineering teams, taking some modeling assumptions as a starting point for the simulation: pre-defined data rate and power resources for each instrument mode, fixed SSMM size (256 Gbit), fixed downlink rate (48.6 kbps) and fixed downlink passes (8h over Malargüe per day). The instrument and spacecraft operations timeline was created using detailed inputs provided by the scientific and technical teams. Finally, to simplify the simulation exercise, it was agreed to use nadir pointing for the duration of the Europa flyby, considering only two basic variations: nadir optimised for solar array power in the approach/departure phases, and nadir aligned for push-frame imaging (slits perpendicular to the ground track) during the closest approach phase (±1 hour around pericenter). The capabilities for spacecraft slews will be added to the MAPPS simulations in future work. The detailed sequence of observation per fly-by is illustrated in **Figure 6-6**. The three panels below the instruments show the altitude (symmetric about closes approach); cumulative data volume and power for the first Europa flyby.

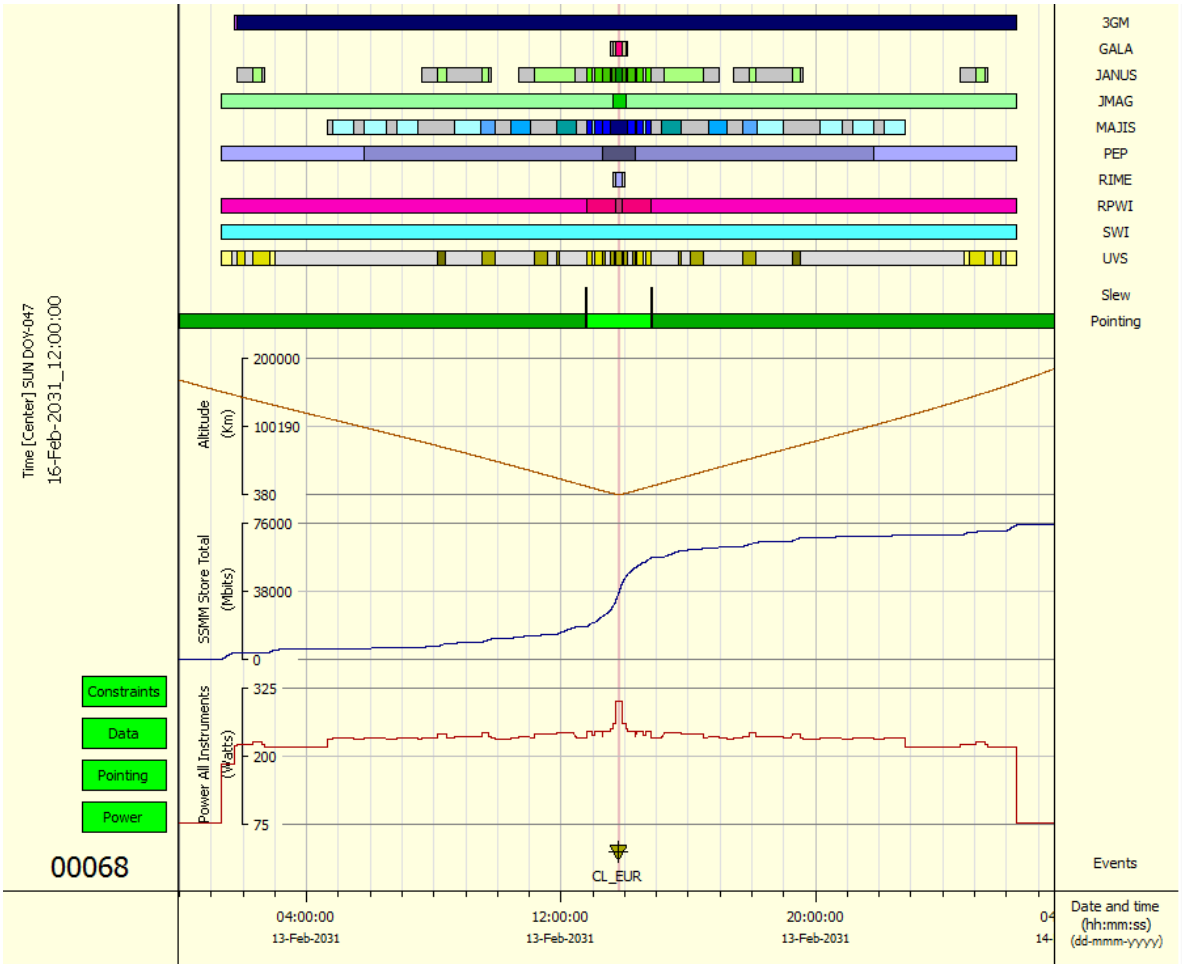


Figure 6-6*. MAPPS science operations timeline for the JUICE payload in the first Europa fly-by scenario. The three panels below the instruments show the altitude (symmetric about closes approach); cumulative data volume and power for the first Europa flyby. Each instrument switches between different observing modes, as indicated by the different coloured bars.*

The MAPPS simulation of the Europa fly-by phase was implemented and analysed following the modeling and operational inputs agreed with the SWT and engineering teams, leading to the following conclusions:

1 In general, the simulations demonstrate the robustness and the science value of the Europa phase, confirming the feasibility of the proposed science operations scenarios for both fly-bys, within the expected power and downlink allocations.
2 The simulation on payload data generation predicts an approximate amount of ~75 Gbit per fly-by scenario, resulting in a total of ~150 Gbit of science data generated by the instruments. About 90% of this total data volume will be shared among remote sensing instruments, 5 % for in situ measurements, and the remaining 5 % for geophysics.
3 The simulation on data downlink predicts the on-board science data to be fully dumped to ground slightly more than 3 months after the second fly-by, considering the daily passes of 8 hours on the Malargüe station.
4 The simulation on payload power consumption predicts an average power consumption of ~230 W for the 24h scenario around each flyby, with short (15min) peaks up to ~300 W during the closest approach mainly due to RIME and GALA operations.
5 Considering the results of the power simulation, the accumulated energy required for each fly-by is estimated to be ~5500 Wh, to be used as an input for the dedicated assessment on the spacecraft battery.
6 The simulation surface coverage is simplified due the limitation on the nadir pointing simulation, but the results are sufficient to demonstrate the good global coverage of the moon with the remote sensing instruments and the detailed science observations that can be achieved around the closest approach at very high resolution.
7 Scientific return can be significantly improved with dedicated pointing such as using mosaics for global coverage during the first fly-by and tracking of scientifically relevant targets for the second fly-by. This will be included in the simulation in later stages.

In summary, the two Europa flybys present a tantalising opportunity to study the tenuous exosphere, surface geology and composition, and sub-surface structures. The Europa flyby sequence is within the resources of the JUICE spacecraft (e.g., slew capabilities, power limitations, data storage), but the significant data volume for the two flybys (around 10% of the total mission data volume) presents a challenge for downlink. This will be resolved via improved strategies to reduce the size of individual observations; optimisation of downlink using pre-selection of files; and potentially increasing the downlink resources for the few days following these intense periods of JUICE activity.

6.4 Jovian tour

6.4.1 ***Observation sequences for magneto-spheric and Jovian science***

Between the targeted flybys of the Jovian satellites, and especially during the first year of the JUICE tour, the payload operations will be dedicated to the exploration of the Jovian system. To demonstrate the JUICE capabilities for Jovian atmospheric and magnetospheric science, a 22-day Jovian orbit between two consecutive flybys of Ganymede has been conceptually designed to demonstrate the potential observing strategies. These flybys coincide with dayside perijoves of 9 -10 R_J, and with the nightside apojove at about 50 R_J. We assume that dayside observations (e.g., reflectivity mapping) are clustered around the perijove, with nightside observations (thermal emission and lightning detection) clustered around apojove. Although the precise details will change from orbit to orbit depending upon the illumination conditions, orbital inclination and satellite/ring science, this sequence should be representative of each of the Jovian orbits, both in the equatorial and high-latitude phases. Instrument-specific observations are described below:

- **JANUS:** Data collection, in the form of single images or mosaics, will likely occur in bursts depending on the illumination, the desired filters and the region of the Jovian atmosphere to be mapped. Mosaics with regular repetitions will be used to trace cloud motions, permitting a reconstruction of the tropospheric wind field to study Jovian dynamics and circulation. Limb views will be used to search for high-altitude hazes, and specific features (storms, vortices, plumes, waves) will be targeted for closer scrutiny. JANUS dayside mosaics will be clustered around perijove on the dayside (**Figure 6-7**), although the scattering properties of aerosols will be derived by studying scattered light under a variety of phase angles. Nightside imaging at apojove will be used to identify the spatial distribution and frequency of lightning activity.

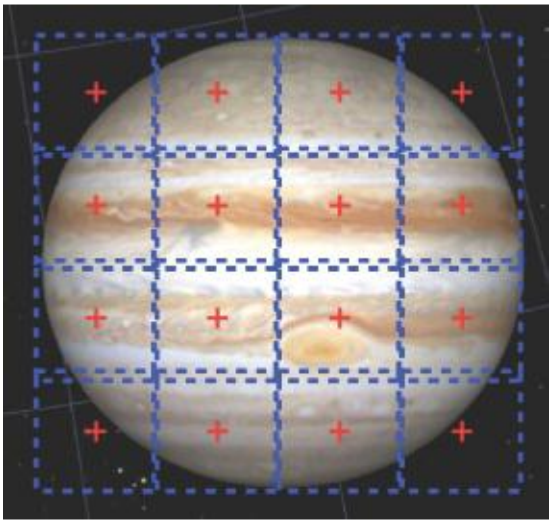


Figure 6-7. *Example of a JANUS mosaic scan pattern on Jupiter.*

- **MAJIS:** Near-infrared imaging spectroscopy at full spatial/spectral resolution produces data cubes too large for regular use, so these will likely be restricted to particular mission phases and targets (e.g., global mosaics and feature tracking will be performed only a few time during the mission). More regular image cubes (1-3 cubes on daily timescales) is desirable to monitor the evolution of Jovian clouds and composition over time, if the spacecraft downlink resources permit. Dayside cubes near perijove use methane absorption bands to study cloud albedo patterns at different depths, and trace the motions throughout the troposphere. Limb observations would observe airglows and aurora (e.g., H_3^+ emission from auroral heating), nightside observations at apojove would study 5-µm emission attenuated by the deeper clouds.

- **UVS:** Disc and auroral scans are repeated approximately once per day, spread throughout the 22-day orbit to study Jovian reflections and auroral / airglow emissions (days with views of the satellite footprints will be given priority). A focused campaign in a single day will feature 3 scans space 3 hours apart to construct a full 360-degree longitude map over a ten-hour rotation. Stellar occultations for high-resolution atmospheric sounding also occur frequently during the orbit (**Figure 6-8**), in addition to regular Io torus scans, and the short duration (60 mins) of these observations means that they can be scheduled with flexibility throughout the tour.

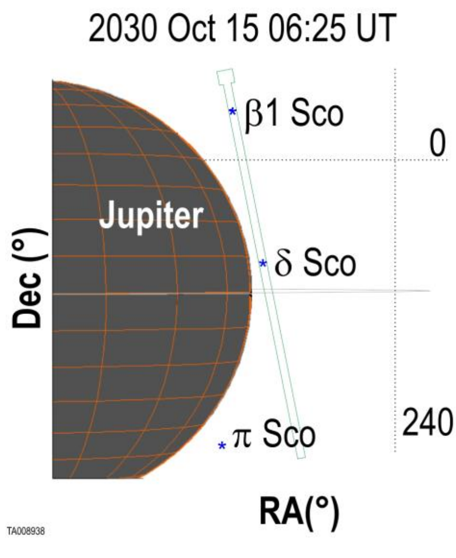


Figure 6-8. *Example of a stellar occulation by UVS during the Jovian tour.*

- **SWI:** SWI aims to operate near-continuously during the Jupiter orbits, both as lead instrument and as a rider, because acquisition of spatially resolved maps is rather time consuming with a single pixel instrument. SWI's own scan mechanism will be used to construct the maps, using measurements of stratospheric emission lines (e.g., water, HCN) to sound middle atmospheric temperatures and winds to understand

Jupiter's general circulation (zonal and meridional winds). Furthermore, SWI will use long nadir and limb integrations to search for previously undetected species. SWI can optimize its observations (spectral windowing, decreasing spectral resolutions, longer integrations) to fit within the allocated data volume.

- **RPWI:** Continuous in situ monitoring of the plasma environment and remote sensing of radio emissions from Jupiter (e.g., those associated with Jovian lightning) will require switching between RPWI modes, including remote modes and in situ modes. Continuous operation is envisaged during the 22-day period.

- **J-MAG:** J-MAG will operate continuously to characterize the magnetic environment of the Jupiter system as the spacecraft moves through the magnetosphere. J-MAG will switch between a 'normal' mode and a 'burst' mode depending on proximity to regions of interest within the magnetodisc.

- **PEP:** PEP will also operate continuously to map the Jovian magnetosphere, switching in and out of ENA imaging mode. Off-nadir pointing will be required to map the plasma co-rotation flow, so that it is desirable to operate at a low rate during downlink and 3GM radio occultations rather than impact the nadir pointing remote sensing studies. Short bursts of high-rate mode (~60 kbps) are envisaged for boundary crossings and dynamic phenomena, as for J-MAG.

- **3GM:** Although there are no specific Jupiter occultations for high-resolution sounding of atmospheric temperature/density structure in the chosen period, there will be a large number of opportunities (about 20) during the transfer to Ganymede, providing a regular sampling of latitudes from 50° S to 17° N. There are no data volume constraints if these occulations are performed in one-way downlink or two-way modes, but there are (limited) data volume requirements when performing the experiment in uplink mode.

Based on these payload operations during the Jupiter equatorial orbit, a full 22-day timeline was constructed [D-5] to understand how science activities could be scheduled. Although the Jovian orbit has not yet been studied via the MAPPs software, the operational concept of each instrument allows an estimate of the desired data volume return necessary to achieve their scientific goals. **Table 6-3** shows the representative example of data volume share between the instruments. The total data volume of 48.2 Gbits over 22 days is a factor of 1.5 larger than what can be downlinked during this period, requiring either (i) optimisation of the downlink via pre-selection of files; (ii) reducing the data volume of individual observations (spectral windowing, reduced resolution, etc.); or (iii) onboard storage for later transmission during periods of reduced activity. It is clear that the observations themselves require a small fraction of the total time on orbit, and that data downlink remains the limiting factor. Nevertheless, this data volume is sufficient to address the JUICE science requirements [D-1] on an instrument-by-instrument basis. Specific data-intensive campaigns (such as multi-day cloud tracking with JANUS and MAJIS) are omitted from this study, as these are likely to occupy a significant fraction of a single orbit, and will be repeated only once or twice during the mission. These types of observations can only be included in a more comprehensive orbit-by-orbit study that allows us to populate the entire Jovian tour phase.

In summary, within this single Jovian orbit, JUICE will characterise both atmospheric processes and the magnetospheric plasma environment, as well as conducting remote observations of Jupiter's satellites (in particular investigating the Io torus). In situ instruments will operate continuously to understand the processes shaping the magnetosphere and the source of radio emissions, and a series of remote sensing campaigns will provide multi-spectral imaging and spectroscopy of the planet. This includes both global and regional imaging of the clouds at visible and near-IR wavelengths; occultation studies to understand the atmospheric structure at high vertical resolution; observations of aurorae and airglow in the UV and IR; lightning searches at visible wavelengths; and nadir and limb sub-millimetre scans to study the temperature, composition and wind structure of the middle atmosphere.

Table 6-3. *Summary of the expected cumulative data volume for each instrument during a typical Jupiter equatorial orbit. All numbers are preliminary.*

Instrument	**Uncompressed Data Rate, kbits/s**	**Compression Factor**	**Compressed Data Volume, Gbits**	**Remarks**
JANUS		3.5	8.81	
MAJIS	22000 (peak)	3	9.46	
UVS	Multiple rates, 260 (for occultation)	N/A	3.1	UVS will tailor its data volume within an allocation of 10% of D/L for this phase
SWI	5.23 (compressed)	diverse	6.64	
3GM	Negligible	N/A	Negligible	Engineering Only
GALA			0	N/A
RIME			0	N/A
J-MAG	3.15		6.0	Representative value
PEP	~7 (medium rate) ~4 (low rate)	~1.4	8.1	Assumes PEP Jupiter medium rate 66% of the time and PEP Jupiter low rate during S/C downlink
RPWI	3.2		6.1	50% survey mode; 40% remote mode and 10% “All mode”
PRIDE	Negligible	1	Negligible	“Eavesdropping” on X-band carrier during comm sessions or other radio transmission operations.
TOTAL			**48.2**	

6.4.2 *Eclipses during the Jovian Tour*

Eclipses provide valuable conditions for science investigations in solar occultation geometry. The total number of eclipses during the JUICE mission may change depending on the mission profile, but we expect the following: ~62 by Jupiter, ~26 by Ganymede and ~7 by Callisto. The longest duration of eclipses by Jupiter is nearly 4 hours during the Ganymede science phase. Much shorter eclipses occur during the Europa, Ganymede and Callisto flybys the longest being of up to one hour eclipse by Callisto during the Jupiter high inclination phase. Short eclipses by Ganymede will take place at the beginning of the GEO phase because of the combination of the low pericentre altitude and low β-angle. The maximum duration of the eclipses by Ganymede is 38 min and they disappear after 11 days. The period of Ganymede being 7.1 days implies that there is a maximum of one overlap between an eclipse by Jupiter and an eclipse by Ganymede.

6.4.3 *Earth occultations*

The Earth, as seen from the spacecraft, can be occulted by Jupiter and its moons. It enables radio occultation studies of these bodies. Occultations by the Sun will also result in telecommunication outages. The radio occultations cover the regions close to the terminator (i.e., local time of 6 am and 6 pm).

6.5 Towards a full Mission Simulation

The three example observing sequences shown here (the Jovian equatorial orbit, Europa flyby, and GCO-500) cannot be considered in isolation, but must be viewed as components of the full Jupiter tour. The simulations of the Jupiter orbit must be completed to the same level as the GCO-500 and Europa sequences to ensure compatibility with spacecraft resources. Future representative sequences to be modeled include: (a) Jupiter high-inclination orbits, although these are likely to be rather similar in operational concept to the equatorial orbit; (b) Callisto flybys; (c) Ganymede elliptical orbits (providing global surface imaging); and (d) GCO-5000 orbit for magnetospheric measurements and remote sensing. Each of these sequences will have strong similarities with those already discussed, such that these three examples serve to illustrate the robust observational strategies being considered for JUICE to achieve the scientific aims of the mission.

7 Examples of science benefits of the mission flexibility

The baseline mission described in Section 5 reaches a system dry mass margin in line with the expectations of the mission development at the present time and takes into account the total Δv budget and the capabilities of the Ariane 5 ECA launcher. As shown in Section 6, this robust mission design can fully achieve the science objectives of the mission described in Section 2.

The constraints in mission design may be relaxed in the near future due to ongoing modelling work on the stochastic Δv requirements (20% of the total Δv budget), the development of new European launcher capabilities or a consolidation of the spacecraft design. Here we briefly describe some examples of the possible science benefit if additional Δv resources become available. Two examples are outlined below: a higher maximum inclination in the Jupiter system and a lower altitude circular orbit around Ganymede (Grasset et al., 2013). Such scenarios would be compatible with the current spacecraft design and complement the already outstanding science return of the baseline scenario.

Increased inclination of the orbit around Jupiter. In order to reach an inclination of, for example, 30° at Jupiter, eight additional Callisto flybys are needed at a total Δv cost of ~50 m/s. The potential science benefits are the following:

- For Jovian magnetospheric science, a 30° orbital inclination would extend the measurement range to ~40° above the magnetic equator. This would extend the analysis of the plasma flows to mid-high magnetic latitudes that map to the outer magnetosphere and magnetotail. The large-scale current systems that arise where rigid corotation of the plasma breaks down drive field-aligned currents that map into the main auroral oval. The 30° inclination would result in coverage of both the field lines and field-aligned current systems well poleward of the main oval into the polar region and potentially up to the edge of the open field lines. The higher-latitude ENA and UV imaging would enable much better understanding of the local-time structure and dynamics of the magnetodisc, Europa and Io torii.
- For Jupiter atmospheric and auroral observations, the higher inclination provides a different perspective for both remote sensing of the polar regions on a global scale and in-situ plasma measurements. The higher zenith angles for remote sensing will permit higher resolutions and greater spatio-temporal coverage of the turbulent polar clouds, zonal wind field, temperature structure and composition, exceeding that which is possible from the lower inclination orbits. In addition, statistical coverage of the high latitude Jovian radio sources, including the elliptical polarization region, would be improved..
- The eight additional Callisto flybys that are required to increase orbital inclination would bring the coverage of Callisto at a regional scale from 70 - 75° to almost complete, by extending longitudinal coverage at high latitudes. Coverage at high resolution would also be improved. The increased number of ground tracks would improve topographic models, ionospheric/exospheric models, global shape measurements, gravity field determinations and measurement of the tidal deformation. Time variability of the exospheric properties would be better constrained.

Lower altitude circular orbit around Ganymede. A Δv of ~ 90 m/s would be required to decrease the circular orbital altitude to e.g. 200 km at the end of the GCO-500 phase. The potential science implications are the following:

- A lower altitude orbit would allow for a finer characterisation of the internal structure via a description of both the gravity field and the intrinsic magnetic field to higher orders. Properties of the subsurface ocean would be further constrained due to the larger magnitude of the induced magnetic field signals. This would be supported by a better characterisation of the conductive ionosphere and more precise measurements of the amplitude of periodic surface deformations. Spatial resolution of all remote sensing instruments would be increased by a factor of 2.5.

- In particular, for geophysical sounding and altimetry, a smaller footprint and higher signal-to-noise on a 200 km altitude orbit would enable focused observations on regions of high interest identified in the previous phases. Moreover, the radar sounding experiment gains about 40% in coverage at 200 km (with respect to 500 km) due to the increased shielding from the Jupiter noise. Characterisation of the physical properties of the surface (albedo, roughness, conductivity) would also benefit from the lower altitude orbit.
- A 200 km orbit would better constrain the local environment around Ganymede and its interactions with the surface. The higher density of atmospheric species at 200 km altitude would enable a better understanding of the relationship of the exosphere and the surface via sputtering and sublimation processes. In particular, a low-altitude orbit is an asset for studying heavy molecular components of the exosphere. In addition, the 200 km orbit would make it possible study the lower altitude part of the in-situ acceleration processes for charged particles that is the origin of the auroral emissions at Ganymede.

8 Management

8.1 Industrial organization

After the mission adoption, ESA will issue an Invitation to Tender (ITT) for the Implementation Phase (B2/C/D/E1). The scope of this contract will be to implement all industrial activities leading to a launch and commissioning of JUICE in the requested timeframe. The successful bidder will be appointed as Prime Contractor in charge, amongst other, of system engineering and management of the sub-contractors.

In the Implementation Phase and following the selection of the prime contractor, each subsystem will nominally be procured through open competition in accordance with ESA "best practice" rules. The subsystem contractors will be in charge of the procurement activities at lower levels. The industrial team of the Prime Contractor and the selected contractors for the first subsystem layers constitute the project industrial Core Team.

8.2 Payload procurement and science management

The payload procurement and science management of the JUICE mission will follow the requirements indicated in the Science Management Plan [D-4].

8.3 JUICE schedule

A tentative schedule of the development phases is shown in **Figure 8-1**. Following mission adoption, which is assumed in November 2014, the Implementation Phase is planned to be kicked-off in September 2015. The major development phases and reviews are shown in the schedule. The implementation phase is expected to last slightly less than 6.5 years from kick-off to launch. The key delivery dates of instrument development models are also indicated in **Figure 8-1**.

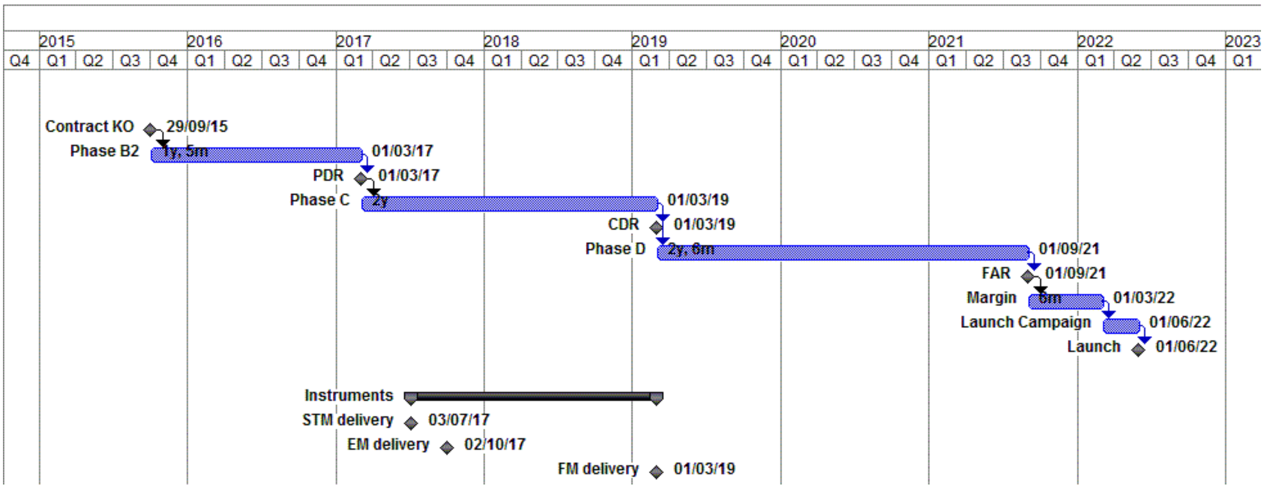


Figure 8-1. *Preliminary outline of the JUICE master schedule.*

8.4 Education and public outreach

The exploration of new frontiers in the outer solar system, particularly the unique worlds of the Jupiter system, has always captured the public imagination. Thanks to its major science themes related to habitability and processes in the Jovian system, JUICE is expected to attract broad public interest. Before arrival at Jupiter, the JUICE outreach programme will be prepared by growing public interest to the outer planets and their moons, fed by the exciting new discoveries of the Cassini and Juno missions. The JUICE outreach activities are also expected to get a strong boost from advances in exoplanet exploration. The possible discovery of water-rich exoplanets and icy moons around exoplanetary worlds will further increase the public interest to the question of the habitability in the outer solar system and beyond.

Hence, the mission will be given adequate exposure within the communication activities of the Science Programme. ESA will have the overall responsibility for planning and will be coordinating activities with national agencies, particularly associated with key milestones and major achievements of the mission. Such outreach activities will be supported by the members of the science team and experimental teams. The four main activities that are foreseen at this early stage and that require a specific attention in the next steps are:

- The communication activities will include publication of newly acquired results and high level data products with release of new images on a weekly basis to show fascinating diversity of the bodies in the Jovian system. The communication activities should use all available outlets (social media and traditional media) to build anticipation during the large number of very dynamic events during the cruise (Venus and Earth flybys), at Jupiter insertion, and then during the mission (gravity assists, flybys). As a result, the communication activities will exploit the advantage of nearly real-time outreach which usually attracts a very broad audience.
- By use of all kinds of communication activities: regular contacts with main newspapers, interviews, press and web releases, public events during flybys, contacts with museums and exhibitions at science conferences, the JUICE communication activity will embrace broad public of all nations, ages and professions. Social media platforms (including short-form micro-blogging like Twitter, and longer web-based video conferencing) will be utilised to make a direct connection between the project, media and the public, particularly for the younger generation, for immediate dissemination of new discoveries and images.
- Due to the long duration of the cruise, school-aged students should be involved at the earliest stages of the project so that they can follow the mission to Jupiter, to build anticipation for the exciting new discoveries. Learning materials in a variety of languages, both interactive and in the form of lesson plans for teachers, could be provided by the project and individual experiments. Interest from students at various key stages, from school to young adults, should be raised via the organisation of specific contests focused on observations to be performed by JUICE. Students could select 2 - 3 different objects proposed by the Project, write a proposal in their native language on which object would have their preference and why, mimicking the type of proposal-writing process supported by ESA/education and the teacher network across Europe. The best proposals would then be selected per country and an award ceremony could be organised in national institutes. Such a scheme organised at the European level regularly during the cruise would most certainly raise the interest of the younger generation over the first L class mission of the Cosmic Vision Programme.
- Observing Jupiter and its satellites through an amateur telescope remains one of the best ways to directly connect with the general public and to promote excitement in JUICE’s destination. The project should support direct links with the amateur astronomy community, both for science (atmospheric monitoring campaigns) and outreach (promoting amateur astronomical societies with interest in observing Jupiter). For example, websites could be used to coordinate observing sessions (for schools and the general public) surrounding key events.

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9.2 Documents

[D-1] JUICE Science Requirements Document (Assessment Phase), JUI-EST-SGS-RS-001, iss 2, rev 5, 10 July 2014.

[D-2] JUICE: Consolidated Report on Mission Analysis (CREMA), WP 578 iss 2 rev 0, 18 July 2014.

[D-3] J. Rummel, F.Raulin and P. Ehrenfreund, eds. 2010, COSPAR Workshop on Planetary Protection for Titan and Ganymede, COSPAR, Paris, 29 pp.

[D-4] JUICE Science Management Plan (SMP), ESA/SPC(2012)20, iss. 1, rev.1, 20 June, 2012.

[D-5] JUICE Science Observation Scenario, JUI-EST-SGS-TN-001, iss 1, 29 November, 2013.

10 Acronyms

Aka	“Also known as”
DDS	Data Disposition System
D/L	Downlink
EID-A	Experiment Interface Document Part A (requirements to instruments/PIs)
EID-B	Experiment Interface Document Part B (instrument/PI response)
FOV	Field of View
GALA	Ganymede Laser Altimeter
GIS	Geographic Information System
JANUS	Jovis, Amorum ac Natorum Undique Scrutator (camera instrument)
J-MAG	JUICE Magnetometer
JUICE	Jupiter Icy Moons Explorer
NECP	Near Earth Commissioning Phase
MAJIS	Moons and Jupiter Imaging Spectrometer (visible-near infrared hyper-spectral imager)
MAPPS	Mapping and Planning Payload Science tool
MOC	Mission Operation Centre
NA	Not applicable
PEP	Particle Environment Package
PI	Principal Investigator
PRIDE	Planetary Radio Interferometer & Doppler Experiment (ground based radio tracking experiment)
PS	Project Scientist
PTR	Pointing Timeline Request
RIME	Radar for Icy Moons Exploration
RPWI	Radio & Plasma Wave Investigation
SciRD	Science Requirements Document
SGS	Science Ground Segment
SOC	Science Operations Centre
SWI	Sub-millimetre Wave Instrument
SWT	Science Working Team
S/C	Spacecraft
UVS	UV Spectrograph
3GM	Gravity & Geophysics of Jupiter and Galilean Moons (radio-science)