LAPLACE
A mission to Europa and the Jupiter System for ESA’s Cosmic Vision Programme
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Executive summary

The exploration of the Jovian System and its fascinating satellite Europa is one of the priorities presented in ESA’s “Cosmic Vision” strategic document. The Jovian System indeed displays many facets. It is a small planetary system in its own right, built-up out of the mixture of gas and icy material that was present in the external region of the solar nebula. Through a complex history of accretion, internal differentiation and dynamic interaction, a very unique satellite system formed, in which three of the four Galilean satellites are locked in the so-called Laplace resonance. The energy and angular momentum they exchange among themselves and with Jupiter contribute to various degrees to the internal heating sources of the satellites. Unique among these satellites, Europa is believed to shelter an ocean between its geodynamically active icy crust and its silicate mantle, one where the main conditions for habitability may be fulfilled. For this very reason, Europa is one of the best candidates for the search for life in our Solar System. So, is Europa really habitable, representing a “habitable zone” in the Jupiter system? To answer this specific question, we need a dedicated mission to Europa. But to understand in a more generic way the habitability conditions around giant planets, we need to go beyond Europa itself and address two more general questions at the scale of the Jupiter system: to what extent is its possible habitability related to the initial conditions and formation scenario of the Jovian satellites? To what extent is it due to the way the Jupiter system works?

ESA’s Cosmic Vision programme offers an ideal and timely framework to address these three key questions. Building on the in-depth reconnaissance of the Jupiter System by Galileo (and the Voyager, Ulysses, Cassini and New Horizons fly-by’s) and on the anticipated accomplishments of NASA’s JUNO mission, it is now time to design and fly a new mission which will focus on these three major questions. LAPLACE, as we propose to call it, will deploy in the Jovian system a triad of orbiting platforms to perform coordinated observations of its main components: Europa, our priority target, the Jovian satellites, Jupiter’s magnetosphere and its atmosphere and interior. LAPLACE will consolidate Europe’s role and visibility in the exploration of the Solar System and will foster the development of technologies for the exploration of deep space in Europe. Its multi-platform and multi-target architecture, combined with its broadly multidisciplinary scientific dimension, will provide an outstanding opportunity to build a broad international collaboration with all interested nations and space agencies.

Scientific objectives

LAPLACE is a multi-platform mission aiming at an in-depth, quantitative study of the Jupiter system and its moons, which focuses on three major and interrelated scientific questions.

1 - What have been the conditions for the formation of the Jupiter system?
LAPLACE will complement investigation of the origin of Jupiter by focusing on its satellite system, its origin and evolution. It will study the irregular satellites as witnesses of the early epochs of Jupiter system evolution. It will study the cratering records of the Galilean satellites and search for signatures of their formation scenario. LAPLACE will also complement JUNO’s investigations of Jupiter’s core and internal structure by means of a dedicated seismology experiment.

2 - How does the Jupiter system work?
The diversity of objects composing the Jupiter system forms a complex system coupled by a small number of universal processes: gravitational interactions, such as the ones locking Io, Europa and Ganymede in the LAPLACE resonance responsible for the maintenance of tidal coupling between them; electrodynamic interactions between the different objects of the system and the plasmas and fields of the magnetosphere; hydrodynamic and radiative coupling processes between the different layers of Jupiter’s atmosphere, its deep interior and its space environment. LAPLACE will perform a quantitative study of these processes, with special emphasis on their consequences for the evolution and habitability of Europa.

3 - Is Europa habitable?
To address this central question of the mission, LAPLACE will perform a detailed investigation in Europa orbit, possibly complemented by a surface experiment. Its Europa orbiter will look for the different habitability conditions: presence of liquid water in a subsurface ocean, possible direct contact of the ocean with a silicate floor, chemical and dynamical characteristics of Europa’s surface and subsurface, exchanges between the surface, sub-surface and ocean, and finally possible bio-signatures. The other two LAPLACE spacecraft, placed in Jupiter orbit, will place our quest for Europa’s habitability in the broader context of the origin and evolution processes of the Jupiter system.
PLATFORM AND MISSION REQUIREMENTS
Our exploration of Europa and the Jupiter System will proceed by successive phases, prepared and supported by adequate Earth-based observations using the major facilities of the time. The cruise phase will provide an opportunity for an attempt at detecting the global modes of oscillation of Jupiter. After Jupiter Orbit Insertion, a multiple-year orbital tour by two or three independent platforms will follow. The “core” Europa mission will then be performed by one spacecraft injected on a polar circular Europan orbit to study Europa’s surface, interior and exosphere for a period of at least a few months. A second spacecraft will be placed in an orbit resonant with Europa to serve as a relay for the storage and further transmission to Earth of the huge data volume produced by the Europa orbiter. A third spinning spacecraft will monitor the magnetosphere. After completion of the Europa mission by crashing on the satellite’s surface, the investigation of the Jupiter system will continue for at least two years.
Despite the difficulty of implementing a surface element, we recommend to study possible options during the assessment study phase. As a minimum, the observing program of the Europa orbiter will help planning future missions to Europa’s surface.

PAYLOAD COMPLEMENT APPROACH
The measurement requirements will be satisfied using three complementary categories of scientific investigations:
• measurements of Europa’s geometry and its main planetary fields and to a lesser extent those of the other satellites (gravity, magnetic field, geodesy and surface topography), including their response to tidal forcing, to retrieve the main characteristics of Europa’s ocean and determine the internal structure of the different satellites,
• multi-spectral remote sensing measurements of the surfaces, atmospheres and gas tori, and possibly sub-surfaces of the different bodies of the Jupiter system, to retrieve their composition and dynamics and improve our understanding of the vertical coupling mechanisms between the different layers,
• in situ remote sensing of the plasma, fields, energetic particles gas and dust populations of Europa’s exosphere and Jupiter’s magnetosphere, to quantitatively understand the mutual interactions between the different bodies of the Jupiter system and its space environment.

KEY TECHNOLOGICAL CHALLENGES
A mission to Europa and the Jupiter System offers a set of very stimulating technological challenges for ESA and its partners, tentatively identified in our proposal which will have to be addressed in depth during the technology assessment phase. These include high-precision navigation necessary to retrieve the internal structure of the satellites, on-board solar power and possibly nuclear energy sources, data transmission and storage capabilities, protection of on-board systems and instruments against the extremely high radiation doses produced by Jupiter’s radiation belts, and the compliance with Planetary Protection standards.

INTERNATIONAL COLLABORATION
The broad spectrum of scientific themes and of technological challenges, its multi-platform architecture, and the large community of interested disciplines, scientists and institutes in Europe and abroad, all point to the strong benefit that such a mission will draw from international, possibly world-wide collaboration. Our proposal will identify potential partners (NASA, JAXA, RosCosmos and beyond) and propose a limited set of preferred collaborative mission scenarios potentially offering the best science return, to be validated by a joint assessment study if the mission is selected.

CONTRIBUTIONS TO SCIENTIFIC COMMUNICATION AND EDUCATION
The discovery of Jupiter’s main satellites by Galileo Galilei in 1610 was made possible by the invention of the telescope – a milestone in the understanding of Cosmos by mankind. The fact that 400 years later the first observational objects of the first telescope are becoming subjects of detailed in-situ investigation by the LAPLACE mission has a huge educational potential. The mission will exploit this potential emphasizing the mutually beneficial interaction between astronomy, planetary and space science on one hand and cutting edge developments in technology on the other hand. It will associate from its early study and development phases the public and the education bodies in Europe and beyond, building a bridge across four centuries between one of the founding events of modern astronomy and one of the most challenging scientific and technological endeavors of our time: exploring distant words, to better understand our own Solar System, its origin and its destiny.
b°/ Introduction: a Cosmic Vision of the Jupiter system

Galileo Galilei’s January 1610 observations of the four main satellites of Jupiter represent in a sense the first time a “planetary system” was ever observed from outside. Today, while we prepare the celebration of the 400th anniversary of this breakthrough in our understanding of the Solar System, the place of the Jupiter System in planetary science and discovery is even more central:

- The most recent simulations of the dynamical evolution of the early Solar System show that Jupiter has played a key role in the formation and early evolution of its sister planets and of the populations of small bodies and has controlled the amount of water delivered to terrestrial planets, thus influencing the habitability and emergence of life on our own planet.
- With the discovery of over 200 extrasolar planets since 1995, Jupiter appears as a “template”, available in our own Solar System, for the numerous gas giants found around other stars. Progress in our understanding of how Jupiter and its satellite system were formed and migrated, and of how Jupiter works today, can therefore be translated into an improved basis for the planning and later understanding of observations of extrasolar planets.
- Finally, the naïve idea that the Jupiter system is indeed a “mini-solar system” has been only reinforced by the Pioneer, Voyager, Ulysses, Cassini and recently New Horizons fly-bys of the system, and by Galileo’s extended orbital tour. The Voyager fly-by of its moons first revealed the unique aspects of its satellite Europa as a potential “ocean moon”, and opened the possibility for the existence of a “habitable zone” in the Jupiter system. Moreover, simulation studies strongly suggest that the formation scenario of the Jupiter system displays many similarities with the formation of the solar system as a whole, involving the dynamical evolution and condensation of a Jovian sub-nebula.

Thus it is no surprise that the Jupiter System plays such a prominent role in the Cosmic Vision Plan proposed by the European Agency to build its ambitious scientific programme over the period 2015-2025. Three key questions about the Jupiter System and its habitability strongly resonate with the major scientific questions identified by the Cosmic Vision Plan.

They are the Science Goals of our proposed mission:

- What have been the conditions for the formation of the Jupiter system? How do they relate to the formation scenario of the solar system and other planetary systems? How do they contribute to the possible emergence of life? (Cosmic Vision theme 1).
- How does the Jupiter system work? How well do we understand it at the “system level”? (Cosmic Vision Theme 2). How does the system contribute to the conditions for habitability?
- Is Europa habitable? Does it represent the “habitable zone” of the Jupiter system? Does Europa actually harbour life? (Cosmic Vision Theme 1).

c°/ Scientific Objectives

To assess Europa’s habitability, our priority science goal, we first need to understand how the Jupiter system was formed (question 1), and what coupling processes link its many objects (question 2). We will then focus on our in-depth exploration of Europa.

c.1°/ How did the Jupiter system form?

i°/ Formation scenarios for the Jupiter system

The history of the Jovian system can be divided into three main phases: the formation of Jupiter, the formation of its satellite system and its secular evolution to its present day state.

The first phase (first line in Figure 2), the formation of Jupiter, took place during the nebular epoch of Solar System history, when the gaseous component was still present and the solid component was slowly giving birth to planetesimals by means of accumulation processes. Two competing models are generally proposed to explain the formation of giant planets. In the first approach, the nucleated instability model, one assumes that planetary cores form by accumulation of planetesimals, in a way
similar to the one generally accepted for the formation of terrestrial planets. When a critical mass is reached, the cores start to capture ever increasing quantities of nebular gas, leading to a phase of gas accretion where the planets grow to their final masses. This scenario has been shown to be compatible with our present day very limited knowledge of Jupiter’s internal structure and atmospheric composition. The second scenario assumes that giant planets are formed by gravitational instabilities in the massive proto-Solar Nebula, leading to the rapid formation of density enhancements - or clumps - with solar chemical compositions and masses probably larger than the present ones of the giant planets. Key issues with this model are how to justify the a posteriori formation of a core and the large amount of heavy elements suspected, but not yet definitely proven, in Jupiter and Saturn.

The second phase (second to fourth lines in Fig. 2) begins when Jupiter’s region of gravitational influence (quantified by its Hill’s radius) enlarges and exceeds its outer radius. This results from the accretion of a massive gas envelope, and leads to the generation of a Jovian subnebula, a structure similar to the Solar Nebula, which had the ability of capturing gas and small planetesimals from it. The captured planetesimals then can grow further in mass due to mutual collisions and build up the regular Jovian satellites (Fig. 2, second and third lines): the content of ices can vary from satellite to satellite, since part of the original planetesimal could have lost their volatile species (in particular water ice) due to the temperature and pressure condition prevailing in the Jovian subnebula. At the end of this process, all of the subnebular gas and the majority of its small scale solids would be accreted into Jupiter. The formation of the Jovian regular satellite system ended at an epoch between the subnebular phase and the Late Heavy Bombardment, an event which has recently been suggested to have been triggered by a chaotic phase of orbital rearrangement of the outer Solar System. Depending on the capture mechanism, the presence of subnebular gas or the dynamical rearrangement could have supplied the conditions necessary for the gravitational capture of the irregular satellites of the giant planets.

Finally, the completely formed Jovian system would have started its evolution phase towards its present day state, as a consequence of impacts and the various coupling processes acting inside the system.

![Figure 2](image_url) - A scenario of Jupiter system formation.

First phase: Jupiter forms, its Hill and outer radii coincide, and no subnebula can exist (first line).

Second phase: formation of the satellite system. A subnebula appears, fed in its infancy by gas and gas-coupled solids originating from the solar. Planetesimals, some of them having lost their volatile due to temperature and pressure conditions prevailing in the subnebula, grow to form satellites (second and third lines). When the subnebula disappears (fourth line), the irregular satellites are captured.

### ii°/ LAPLACE contribution in unveiling the origin of the Jovian system

Understanding the formation of Jupiter and its satellite system therefore requires that we look at the traces of the first and second phases just described above. The strategies devised for the LAPLACE mission are presented in the three points below, complemented by composition measurements of regular satellites (see Sect. c 2 ii).

**Probing Jupiter’s interior**

In order to determine Jupiter’s internal structure, two approaches are available. The first one, which will be used by the NASA JUNO mission, relies on the determination of the planet’s gravitational moments. Since their interpretation in terms of density structure and of the presence or absence of a core is not unique and strongly depends on the correct knowledge of H and He equations of state, uncertainties in the equations of state will affect the achievable resolution.
An alternative way to obtain information on Jupiter’s interior is the seismology approach, namely the study of the oscillations of the planet. Observations aimed at detecting oscillation modes of Jupiter have shown promising results, but so far they have been limited by instrumental and windowing effects and by the effect of Earth’s atmosphere. Combining this method with the gravitational moment data which JUNO will provide has the potential of determining the whole internal density profile of Jupiter, thus giving the mass of its internal core and the amount of heavy elements. It can also constrain the level of homogeneity of Jupiter’s envelope, key information to interpret Galileo measurements of volatile species in a global context.

Looking for the origins of the irregular satellites
The study of the irregular satellites will allow testing of the capture hypothesis, the reality of the dynamical families found from Earth and to define their physical nature without having to rely only on the information-poor colour indexes and the limited spectral range accessible with ground-based observations. LAPLACE will perform at least one close fly-by of one of the major irregular satellites and will remotely observe as many of them as possible, with special emphasis on possible family members of the close fly-by target. It will perform high-resolution imaging and visual-near infrared spectroscopy of the satellite surfaces and dust collection and analysis (dynamics and composition) in their orbital region and during the fly-bys. Observing the Jovian irregular satellites also offers the possibility to look back to the early phases of the evolution of the Solar system and sample the conditions that existed in the primordial planetesimal disk.

Reading the history of the Galilean satellites in their surface morphology.
The study of the cratering history of the Galilean satellites will provide information to date the Jovian system and the epoch of the Late Heavy Bombardment and the possibly related chaotic orbital rearrangement of the giant planets. High resolution imaging and visual/near infrared spectroscopy of a few selected site, coupled with coverage of the satellites surfaces at a medium resolution (better than Galileo) will provide us with new insight into the history of the Jovian and, more generally, the Solar System.

c.2°/ HOW DOES THE JUPITER SYSTEM WORK?

i°/ A diversity of objects and coupling processes
The Jupiter system comprises a broad diversity of objects, including Jupiter itself, more than 60 outer irregular small satellites (1 to 100 km class objects), the four large Galilean Satellites, Io, Europa, Ganymede, and Callisto (1000 km class objects), the four inner satellites Metis, Adrastea, Amalthea and Thebe (10-100 km class objects) and the Jovian ring system, located in the inner region. All these objects experience gravitational interactions among themselves, and electrodynamic interactions of variable concentration and strengths of Jupiter’s magnetospheric particles and fields. The magnetosphere itself is strongly coupled to Jupiter’s upper atmosphere and interior by electrodynamic interactions. The complex interactions between these components (see Figs. 3, 5 and 6) redistribute momentum and energy among them and drive the magnetospheric engine which generates Jupiter’s radiation belts. Finally, redistribution of momentum and energy among different layers of Jupiter’s atmosphere is governed by hydrodynamic and radiative processes.

ii°/ Gravitational coupling, structure and composition of Galilean Satellites
The astonishing diversity of features which shape the surfaces, interiors and dynamics of Galilean Satellites still challenges our understanding: the most intense volcanic and geologic activity in the solar system is found on Io; subsurface oceans are likely to exist within Europa, Ganymede and Callisto; the smallest solar system magnetosphere is found at Ganymede, comparable only to Mercury. The diversity of geologic features on Europa and Ganymede, or the incomplete differentiation of Callisto and the completely different evolutionary paths of all four Galilean moons, are all still waiting for a satisfactory explanation. Still, all this diversity must result from the same mechanisms which shaped and still drive the evolution of their interiors and surfaces. Among them, the Laplace resonance between Io, Europe and Ganymede plays a particularly important role in dragging energy from Jupiter to maintain tidal heating at these satellites, and to drive their internal dynamics and modify their surfaces. Interactions with the exosphere and magnetosphere also shape their surfaces via space weathering. Understanding and untangling these driving factors is an essential prerequisite to any attempt at detecting biosignatures at the surface of Europa and - why not - of its sister moons.
The Laplace Resonance and Tidal Heating

Stable resonances by which orbital periods are kept in a fixed ratio play an essential role in the Jupiter system. Unique in the solar system is the three-body resonance – the so-called Laplace resonance – by which the orbital periods of Io, Europa, and Ganymede are kept in a ratio of 1:2:4. The resonance maintains the orbital eccentricities of the moons and therefore enables tidal interactions to operate on geological timescales. The vigorous volcanism of Io, the innermost Galilean satellite, is the most obvious consequence of internal heating due to tidal friction.

Figure 3: The rotational energy of Jupiter is a huge reservoir of energy for the three inner Galilean satellites. Orbital energy gained by Io due to tidal torques exerted by Jupiter is distributed among Io, Europa, and Ganymede, due to the Laplace resonance. The resonance is therefore essential for ongoing tidal heating inside Europa, and may allow for the existence of an ocean inside Europa over billions of years.

As illustrated in Figure 3, gravitational coupling redistributes rotational energy and angular momentum between the three moons and Jupiter. The resulting tidal heating significantly contributes to the internal heat sources of Io and of Europa. Europa’s tidal deformation and Io’s intrinsic heat flow derived from mapping surface temperatures will yield constraints for the amount of energy dissipated inside Io and Europa. The thermal activity of the moons will be inferred from searching for temperature anomalies at the surfaces. Additionally, astrometric determination of the satellites’ positions will precisely characterize the orbital state of the system. By studying the Laplace resonance and tidal heating in the Jupiter system, constraints for the habitability of Europa over geologic timescales can be inferred.

Internal Structure of the Galilean Satellites

Models of the internal structure of the Galilean satellites are mainly based on the determination of the mean density and the moment of inertia about the rotational axis by the Galileo mission. However, hydrostatic equilibrium assumed in such models has been directly confirmed only at Io, where polar and equatorial flybys could be analyzed independently. Whereas Io, Europa and Ganymede are strongly differentiated into an outer ice layer, a rock mantle and an iron rich core, these phases are only partly separated in Callisto although its size and mean density is very similar to Ganymede’s. How these different states came to be is still an open question. The low-degree static gravity field of the Galilean satellites has been determined with a precision of a few percent from flybys by the Galileo mission. A Europa orbiter as part of the LAPLACE mission will obtain detailed information on the gravity field of Europa allowing for a great improvement of internal structure models. Moreover, LAPLACE will measure the topography of Europa, which in case of the absence of gravity anomalies can constrain ice shell thickness variations. The degree of differentiation of Europa will be inferred from determining the moon’s obliquity, constraining the moment of inertia independently. For the other satellites an order of magnitude improvement of the gravity field is expected by using radio and VLBI tracking from the Earth during the flybys, coupled with altimeter, camera and astrometric (both ground-based and space) data. Deviations from hydrostatic equilibrium and local mass anomalies could be detected and characterized.

One of the most intriguing features with important astrobiological implications is the possible presence of subsurface oceans inside the icy moons of Jupiter. Evidence for liquid water layers inside Europa, Ganymede and Callisto has been obtained by Galileo mainly by the detection of induced magnetic fields generated close to the surface at all three satellites. In the case of Europa observed
surface features related to tectonics and cryo-volcanic processes (Fig. 8) provide additional evidence. Possible structures of the H$_2$O shells of Europa, Ganymede and Callisto are shown in Figure 4. To further constrain these models and to provide unambiguous evidence for these oceans, in particular at Europa, is a key goal of LAPLACE. Whereas the ocean in Ganymede and Callisto is expected to be enclosed by thick (~100 km) ice layers, the ocean of Europa can be close to the surface (~ 50 – few km) and in contact with silicate rock.

**Figure 4:** Possible locations of liquid layers in the icy moons of Jupiter are plotted here as a function of depth: 1) completely frozen; 2) three-layered structures impeding any contact between the liquid layer and the silicate floor; 3) thick upper icy layer (>10 km) and a thick ocean; 4) very thin upper icy layer (3-4 km). Structures 3-4 are the most probable for Europa (indicated in black in the lower part). The larger moons Ganymede and Callisto are located in the left region (1 or 2) where internal pressures are sufficient to allow for the formation of high-pressure ice-phases. Oceans in Ganymede and Callisto - if they exist - should be enclosed between thick ice layers.

LAPLACE will determine the presence of oceans by measuring the tidal response in addition to the detection and characterization of the induced magnetic fields of the satellites. The large tides predicted for Europa, with estimated amplitudes of about 30 m if a subsurface ocean exists and only a few m without an ocean, will be measured from the gravitational perturbations on the spacecraft and from altimeter measurements with a precision of about 1%. In combination with determining the libration amplitudes (order of 100m at Europa’s equator) this will constrain the thickness of the icy shell. Independent from tidal interaction LAPLACE will measure the electromagnetic response, i.e. the induced magnetic fields, of the ocean at multiple frequencies at Europa. This will constrain the thickness of the ice shell, the thickness of the ocean and its electrical conductivity. Similar measurements during flybys will allow for the detection and characterization of subsurface oceans at Ganymede and Callisto with reduced precision as compared to Europa, depending on the number and geometry of the flybys.

Galileo has found a self generated magnetic field of Ganymede, a unique feature among solar system satellites. To better understand the magnetic field generation in the iron core and to constrain interior structure and evolution models of Ganymede, a detailed characterization of the field structure will be obtained.

**Physical Characteristics, Composition and Geology of the Surfaces of the Galilean Satellites**

The surfaces of satellites contain valuable information of the moons’ histories. Surface features were formed by external sources including impacts and particle bombardment and by geologic activity caused by internal dynamics. Galilean Satellites offer a perfect illustration of these two processes: the surface of Io is almost completely formed by endogenic activity, whereas Callisto’s surface was almost entirely altered externally early in solar system history. At Europa and Ganymede different phases of endogenic activity have formed the complex icy surfaces of these bodies. The inner satellites are exposed to stronger radiation in the inner part of the Jovian magnetosphere which leaves its traces at the surfaces and exospheres of the satellites. LAPLACE will study these surface processes by a diversity of approaches:

- Geologic mapping, including significant improvement of global coverage
- Laser altimetry or stereo imaging to derive topographic maps
- Searching for geologic activity from limb scans, thermal anomalies, and image comparison
- Monitoring of Io’s volcanic and thermal activity on day- and nightside
- Determination of global and regional surface ages from the cratering record
- Characterization of the non-ice components and search for organic compounds
- Determination of chemical, elemental and isotopical composition by dust collection and analysis.
- Mapping of surface alterations due to the radiation environment
Our goal is to improve the global coverage of surface imaging and spectroscopy, compared to Galileo, for all Galilean Satellites (50% of surfaces with 200 m/pixel and 500 m/pixel for total surfaces in the visible and near infrared ranging from 350 - 5000 nm). High resolution images at local regions at < 10 m/pixel will be obtained from close flybys.

\[ iii°/ \text{Electrodynamic coupling and the jovian magnetospheric engine.} \]

Just like gravitational coupling, electrodynamic interactions also operate at a global scale within the Jupiter system. Magnetospheric charged particles, mainly produced by the ionization of Io’s neutral torus, populate the whole Jovian magnetosphere and form an extended magnetodisk near the magnetic equator. This magnetodisk interacts with each satellite in a variety of modes, depending on the satellite’s internal plasma sources, on the properties of its exosphere and surface, and on its degree of magnetization. It is also coupled to Jupiter’s rotation via a system of electric currents which flow along magnetic field lines and into Jupiter’s upper atmosphere, where they generate the main auroral oval. The complex interplay between plasma generation at the satellites, satellite-magnetosphere interactions and Jupiter-magnetosphere interactions, produces the Jovian radiation belts, the harshest radiation environment in the Solar System, which directly affects habitability on the surfaces of the jovian moons.

\[ \text{Figure 5:} \]

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

The jovian magnetosphere - basically a giant magnetized environment, driven by the fast rotation of its central spinning object and populated by ions coming mainly its moons - is thus the most accessible environment for a direct investigation of general astrophysical processes regarding: (i) the dynamics of magnetodisks, with different mechanisms of angular momentum exchange and dissipation of rotational energy ("fast rotator" theme), (ii) the electro-dynamical coupling between a central body and its satellites ("binary system" theme) and, (iii) the global and continuous acceleration of particles ("giant acceleration" theme).

\[ \text{The fast magnetic rotator} \]

The fast jovian rotation, combined with the continuous creation of ion populations due to Io’s volcanism, leads to the formation of a magneto-disc. Its structure varies with distance from Jupiter. Starting at Io’s orbit as a torus of neutrals and ionized particles in rigid co-rotation, the torus progressively thins and becomes a disc-like system of limited vertical extension. It increasingly departs from rigid co-rotation with the distance to Jupiter, with magnetic effects as important as the thermal and rotational ones. At 50-60 Rj from Jupiter, in the anti-solar direction, the disc transforms into a magnetotail with a strong ‘planetary’ wind. This disk is driven in rotation by an electro-dynamical coupling with Jupiter materialized by a system of currents circulating along the magnetic field lines and closing at the ionosphere. This current system
transfers angular momentum from the outer layers of Jupiter atmosphere to the disc. As this coupling is not perfect, it leads to particle acceleration, resulting in auroras, energy deposition in the upper layers of the atmosphere and powerful radio emissions. These effects are particularly important where co-rotation breaks down, at 15-25 Rj.

The structure of the disc and its coupling with Jupiter also strongly vary with local time. Establishing the 3D structure of this disk, and its variability, is an important goal of a new exploration of Jupiter, crucial for further analysis of all angular momentum transfer processes in magnetized, ionized media. Indeed, the disk - this 3D structure - is not a stationary system, it is highly dynamic. Galileo observations have revealed that it is periodically reconfigured over global scales, with sequences of loading-unloading of the disk by new plasma and injections of energetic populations both in the inner magnetosphere and the outer disk. Various processes contribute to the radial transport, from the Io torus to the external magnetosphere and, at the end, the interplanetary medium: microscopic diffusion, meso-scale interchanges, global sporadic disruptions of the disk and magnetic reconnection. All these processes trigger variations in the transport rate of the iogenic plasma and its radial re-distribution.

The chain of processes involved in the exchanges of angular momentum and the dissipation of rotational energy, from the global dissipation of the rotational energy to the microscopic mechanisms responsible for non-ideality is unknown. Determining their spatial/temporal scales, quantifying their relative efficiency and how they vary with the activity of Io is a central objective.

As all objects in the solar system, Jupiter interacts with the solar wind which drives a part of the magnetospheric dynamics and possibly triggers major storms when solar perturbations hit the magnetosphere. To what extent is this huge system, endowed with its own powerful dynamics, affected by and responsive to external perturbation? This question concerning the respective importance of external and internal processes in the regulation of the activity of a magnetic environment can also be best studied at Jupiter.

The magnetized Binary system

Different ‘objects’ move in the Jovian environment, each of them interacting with the magnetospheric plasma by a large variety of processes. Moons, with their exospheres, are conductive bodies. As they move through the Jovian magnetic field, they create a specific current system (the unipolar dynamo). This electro-dynamical coupling is not stationary. It generates Alfvén wave structures, called ‘Alfvén wings, that couple the jovian ionosphere to the exosphere of the moons. Once again, this coupling is not perfect. Part of the electromagnetic energy is converted into kinetic energy of accelerated particles, with the formation of particular auroral features, including the generation of non thermal radio emissions.

Europa, Ganymede and Callisto are in complementary situations. The interaction at Io is the most powerful. It has an extended exosphere, able to fill the environment with matter, and moving in a dense and highly magnetized plasma (the inner Io torus). Ganymede, the unique (to date) magnetized moon, constitutes another remarkable situation. We don’t know how this mini-magnetosphere is coupled to Jupiter’s huge one. We only know that this interaction is powerful enough to create an intense auroral footprint at Jupiter. The coupling with Europa is apparently much less powerful, even if it seems able to generate intense waves. By contrast, Callisto is the most quiet.

The parameters that determine the strength of the coupling, the way magnetic fields are distorted and large–scale fluctuations are generated, are ignored, as are the details of the interaction itself. Furthermore, the moons are not passive, more or less conductive bodies. Each moon generates a large level of plasma waves, they locally heat and accelerate the ion populations, enhance the spatial diffusion and lead to a more efficient assimilation of the exospheric ions by the Jovian magnetosphere. The Io torus is another original system. In some sense, its innermost region presents similarities with an ionosphere, where populations of neutrals interact with ionized ones. However, it is fundamentally different in terms of boundary conditions, spatial scales, geometry and forces that regulate the equilibrium. How does this system evolve when the volcanic activity of Io changes? How are the different ion species mixed, and at what scales? What is the importance of turbulence? How does the torus feed the magneto-disk? Answers to these questions will greatly help to quantify fundamental mixing, heating, energy exchange processes in dilute, multi-phase media.

All these topics relate to whether a planet immersed in a strong radiation environment can host complex compounds able to react chemically. They are also of central importance for the interpretation of precise spectral analyses of Europa surface, dedicated to the search for pre-biotic components.
The giant particle accelerator
A further, largely unresolved problem of a fundamental nature regards the Jovian magnetosphere as a tremendously efficient particle accelerator. There is no question that Io is the primary source of particles in the Jovian environment. The new plasma populations have, however, typical energies of a few 10’s eV at best. At what time and spatial scales, and by what mechanisms, does a significant part of them reach MeV energies and populate the harshest radiating environment of the solar system? The fact that such environments can exist has direct relevance to the notion of ‘habitability’. A large and highly variable level of radiation may actually modify or control the emergence of life. Jupiter is also a ‘prototype’ of powerful exo-magnetosphere, possibly powerful enough in radio to be detected at stellar distances. One interesting outcome of in-situ measurements in this radio sources is to determine the highest level of wave energy reachable inside the radio sources and then, to better estimate their possible detection by a very distant observer.

Critical measurements with LAPLACE
The basic magnetospheric measurements concern the characterisation of the different plasma populations (electrons and ions species) thus, the density, velocity and pressure, including their distribution functions. This requires plasma mass spectrometers capable of making measurements at sufficiently high energies (up to a 100 Kev/q) and dedicated high energy instruments. The characterisation of electromagnetic field will be done by measuring the static magnetic field, the magnetic and electric components of high frequency fluctuations.

On orbiting spacecrafts, neutrals and dust must be determined, with possibilities of chemical characterisation. Complementary diagnostic measurements in visible, IR, UV, X that will be used to monitor the aurora, the energy deposition in Jupiter atmosphere and, the variability of the Io torus are needed. Sequences of simultaneous in-situ measurements and remote sensing observations of ‘magnetospheric’ targets (aurora, torii) are required.

The determination of scales, temporal and spatial, is fundamental. They define the dynamical processes and guide any theoretical or simulation analysis. LAPLACE, with the possibility of performing simultaneous measurements in at least two points, will permit completely original analysis. The first phase of the orbital insertion, with spacecraft exploring the magnetosphere, at variable inter-spacecraft radial and azimuthal distances, will be fundamental. The main requirement is to broaden as much as possible the parameters of the exploration, in terms of local time, distances from Jupiter and inter-spacecraft distances.

Radiative and hydrodynamic coupling in the jovian atmosphere
Even after the GALILEO mission, some of the most important questions concerning the atmosphere of Jupiter remain: How does Jupiter radiate its internal energy to space, and what are the dynamics and coupling in its atmosphere? LAPLACE will address these questions in a very complementing way to JUNO, extending the measurements to low latitude and equatorial atmosphere and focusing on different scientific questions. Three different layers will be sounded to address these questions.

The upper atmosphere
This outermost layer is connected to outer space, and its mesospheric, thermospheric and ionospheric structure and dynamics must be deciphered. Despite three decades of limited measurements of Jupiter’s upper atmosphere from ground and space, our knowledge and understanding of the region still remains in its early infancy. LAPLACE will address three science topics which are closely coupled. Firstly, the thermosphere of Jupiter, like those of all gas giants, is far hotter than expected from solar EUV heating alone. The energy balance on Jupiter and other gas giants is yet not understood. This problem will remain under-constrained even after JUNO: a systematic measurement of waves on Jupiter at low to mid latitudes is needed, with implications for all gas giants within our solar system and beyond. Secondly, despite limited observations from the ground, observations by Galileo and forthcoming observations by JUNO, the dynamics of the thermosphere at low and mid latitudes will remain poorly known. For example, it is unclear whether the zonal jets observed in the stratosphere are present also in the thermosphere; the importance of wave acceleration and ion drag in thermospheric winds is unclear. Knowledge of the dynamics is therefore crucial in order to understand how energy and material are distributed horizontally and vertically in the upper atmosphere. Thirdly, a major unknown on Jupiter is its ionosphere, not only its structure, but also its relation to the H₂ bulge, the nature of the most important ionization processes, the distribution of ions and the nature of energy deposition processes. Only few vertical profiles of
Jupiter’s ionosphere are known, and each of them differing substantially from the others, and none of them have been reproduced by photochemical models. LAPLACE will perform a systematic exploration of total electron densities via radio science, and infrared observations at low latitudes will trace H$_3^+$, a key molecule in Jupiter’s ionosphere. LAPLACE will shed light on the nature of coupling between the thermosphere, ionosphere and magnetosphere of Jupiter at low latitudes, which is essential to understand the processes that drive the entire coupling between the planet and outer space as well as the outer atmosphere and deeper interior of Jupiter. This also has key implications for our understanding of atmospheric loss, and thereby of the atmosphere evolution.

Figure 6: The three layers of the Jupiter atmosphere studied by LAPLACE:
1) The dynamics of the troposphere will be studied with special emphasis on the source of vorticity, and its relation to global circulation. Storm activity is suspected of being a major source of vorticity, which is an important ingredient in the atmospheric circulation, and can also be the source of gravity waves dissipating in the upper atmosphere.
2) The circulation of the stratosphere (image at the cloud top ~100mbar level, as observed at 3.5 micron; VLT/ISAAC image, P. Drossart, priv. comm.) is poorly known. Doppler resolved spectroscopy can measure wind velocity at the limb and thermal waves can be imaged in the mid-IR and studied in the long term to observe the spatial and temporal scales (Cassini/CIRS observation).
3) Dynamical changes in the upper atmosphere can be studied by observing H$_3^+$ or CH$_4$ emissions in the mid-IR to visual range (VLT/ISAAC image at 3.2 micron, P. Drossart, priv. comm.), indicating connections to the magnetosphere in the auroral regions or to internal phenomena.

The stratosphere
The stratosphere couples the deeper layers of the troposphere to the upper atmosphere. Its structure, circulation and composition are still poorly determined. Direct estimation of winds is not possible in the absence of discrete clouds. However, knowledge of the stratospheric circulation is vital in understanding the transport of hazes and minor species. Temperature fields are known from Voyager/Cassini and ground observations, but temporal variations are organized along many different time scales, the longer known being the quasi-quadiennal oscillation, observed from the ground. Wind measurements in the stratosphere are known only from thermal wind equation retrieval, which unfortunately excludes the equatorial regions where important phenomena take place, and from the dispersion of dust and chemical elements since the Shoemaker-Levy 9 collision in 1994. Missing elements are, to date, clues on the meridional and equatorial circulations and the vertical structure of
the winds. Moreover, the question of the origin of stratospheric water is still open, and has implication on the origin of water in the Solar System: latitudinal variations of H\textsubscript{2}O would provide important clues on this origin. Finally, the remnants of the Shoemaker-Levy 9 collision (CS, HCN) are still observed 13 years later and used as tracers of stratospheric mixing. LAPLACE will follow up these observations, in relation with ground-based or space-borne observations (ALMA, Herschel).

**The troposphere**

**The troposphere will be the deepest level sounded by LAPLACE: its meteorology in a global sense is poorly understood.** In particular, the exact origin of the global circulation of Jupiter, the structure of the band system, its relation to differential rotation and the connection of this meteorological system with deep and outer layers are unknown. One way of progressing in this field is to constrain models by direct measurements of the quantities involved in meteorological equations, such as velocities, thermodynamics quantities and the “potential vorticity”, which is conserved in non-dissipative flows like a passive tracer, and which is directly calculated in the models. This latter quantity can be deduced from observations of the wind field, together with temperature profiles of the atmosphere. Moreover, long term monitoring of Jupiter at medium scales (300 km) with potential vorticity retrieval at different time scales would constrain the evolution of waves, of atmospheric structure and of winds from the models. The distribution of lightning storms on Jupiter, detected by Galileo with a non-uniform density, is still mysterious. The importance of local convection as a source term for global circulation remains to be proven at a global scale. These convective cells can also be a source of strong gravity waves propagating up to the thermosphere, and contributing to upper atmosphere heating. Finally, internal waves already described in section C.1 connect the troposphere to the interior of Jupiter and complete the picture that LAPLACE could give of the Jupiter atmosphere from the uppermost layers to the deep interior.

### c.3°/ LOOKING INTO EUROPA TO ASSESS ITS HABITABILITY

#### i°/ How can an icy moon be habitable?

The potential habitability of Europa rests on the fulfilment of four conditions (Figure 7): the presence of liquid water, an adequate energy source to sustain the necessary metabolic reactions, a source of chemical elements (C,N,H,O,P,S, etc), which can be used as nutrients for the synthesis of biomolecules, and relevant pressure and temperature conditions.

The fulfilment of the first condition is directly related to the putative existence of an ocean. The existence of this ocean has been inferred from the interpretation of the induced magnetic field measured by the Galileo mission and the interpretation of geological features (Figure 8).

Europa is not unique among the four Galilean satellites, as subsurface oceans may also exist at Ganymede and Callisto. But according to current models, it represents the only case in which liquid water is in contact with a silicate core. Such conditions are favourable for interactions between the ocean and silicates, particularly if a volcanic, and consequently hydrothermal activity exist. This would provide a variety of chemicals that could play a role in sustaining putative life forms at the ocean floor as discovered 30 years ago at Earth deep-sea hydrothermal vents.

Another potential player in Europa’s habitability is its surface, which is exposed to the harshest radiation environment in the Solar System. This very high level of radiation may modify or alter the development of sub-surface prebiotic chemistry, and dissociate organic molecules at the surface. But it may also provide an energy source, via the storage of chemical free energy in the irradiation products.
Assessing Europa’s habitability

Thanks to its Europa Orbiter, LAPLACE will assess all the elements that play a role in Europa’s potential habitability, focusing on the characterization of its ocean, its sea-floor, and of its surface.

Looking for Europa’s ocean

After the Galileo mission around Jupiter, both geological evidences (tectonic features and surface composition) and geophysical data (induced magnetic field and gravity field) are strongly in favour of the existence of a deep liquid layer below an icy crust. However, although very probable, the existence of a liquid internal ocean is still not proven. If it exists, its depth is still unknown. It could be very close to the surface (1-2 kilometers) or much deeper (20 km or more). The most robust method to prove the existence of the ocean is to use an orbiter on which accurate gravimetric and altimetric measurements can be achieved. Indeed, the presence of an ocean strongly modifies both the value of the periodic Love number $k_2$ and the amplitude of surface libration due to tidal forcing. Such measurements were not achieved with Galileo because of orbital and instrumental constraints (only flybys, no altimeter), but may become possible with the LAPLACE Europa orbiter. If the gravity potential surface is obtained at degree 2 using a precise navigation system, it is possible to estimate the $k_2$ love number value and prove the existence (or absence) of Europa’s ocean. If in addition an altimeter is added to the system, it is possible to have a direct and independent proof of the existence of the liquid layer by measuring the amplitude of surface motions due to tidal forcing. The in-situ, gravimetric and altimetric measurements at Europa will be supplemented by ultra-precise VLBI and Doppler tracking of the LAPLACE spacecraft by the Earth-based network of radio telescopes. Characterization of the liquid layer is more challenging. It requires the determination of its depth, thickness and composition. The interface between the icy crust and the ocean is expected to be relatively flat: since it corresponds to a thermodynamical equilibrium between a solid ice and its liquid counterpart, temperature and pressure along the interface must be almost constants, which impedes significant depth variations. Furthermore, the flat topography of Europa is not in favor of large roots of ice below high mountains as we see on Earth. Two specific instruments can be considered for providing direct constraints on the icy crust thickness. First, a Ground Penetrating Radar (GPR) seems very attractive. If the icy crust is relatively thin, this instrument will provide a global mapping of the ice I / liquid interface, provided that the crust is not thicker than the penetration depth, which is not guaranteed. A GPR is thus challenging but risky. A more robust instrument is a seismometer. If the final mission can afford a lander or a penetrator, a seismometer will provide without ambiguity the position of the ocean interface. To our knowledge, this is the only direct measurement of the position of the ocean that can be envisaged and which will provide information regardless of the internal structure. A third technique is based on interpretation of topography and gravity field at different degrees. It requires a laser or radar altimeter in addition to the determination of the gravity field by radio measurements, including VLBI, two-way Doppler and delta-doppler ranging techniques.

Mapping Europa’s seafloor

If an internal ocean exists, Europa probably represents a single case, in which liquid water is in contact with a silicate core (Figure 7). These unique conditions on Europa allow water-rock interactions, especially if any volcanism exists. The determination of the topography and/or mass anomalies at the silicate core/liquid interface would provide hints on whether volcanism exists or has existed. We must keep in mind that this task is a very difficult one mainly because the presence of the icy crust above the Europa’s liquid layer decouples the surface topography from the ocean floor. But some constraints will be inferred from the accurate altimetry measurements and the precise determination of the gravity field at different altitudes. Moreover, magneto-meter measurements will be useful since the constraints provided on the induced magnetic field of Europa will help to define the depth of the magnetic source. Small scale features won’t be detectable on the silicate sea-floor, but medium-scale features (200 km) such as large volcanoes or long ridges will probably be detected if a microgradiometer is embarked on the Europa Orbiter. All these data (gravimetry, altimetry, magnetometry) will finally be used in models of the internal structure that will eventually give constraints on the ocean floor topography. It should be stressed that, although difficult, the determination of the ocean floor topography and the state of iron core as well have strong astrobiological implications, and can only be done if the mission design can provide very precise navigation measurements, and both altimetric, gravity and magnetometric measurements with very high accuracy.
Characterizing its surface dynamics and chemistry

Surface composition and chemistry.

Galileo has proven that the surface of Europa is not made of pure water ice. Whatever the origin of the non-water components was, either endogenous or exogenous, their characterization is important. The NIMS (Near Infrared Mapping Spectrometer) onboard the Galileo mission showed that composition is different along some geological features. Although there is still some controversy on the nature of non-ice components, compositional mapping of the interesting areas of the surface must be improved in the future with a higher spatial and spectral resolution infrared mapping spectrometer. With a field of view of 0.5 mrad, a resolution of 1 km/pixel on the region where non-icy material has been discovered would be obtained at 200 km altitude.

In addition to a NIR mapping spectrometer, the main neutral species as well as many ion species of Europa’s atmosphere and ionosphere can be easily measured with a mass spectrometer and dust analyzer on an orbiter at 200 km. Moreover, collecting dust expelled from the surface of Europa, and analysing their composition will constrain the origins of building blocks that took part to its formation (via the D:H ratio in ice if we assume that surface altering can be quantified with LAPLACE) and the thermodynamical conditions prevailing during Europa’s formation (via the abundance of volatile species like CH₄, CO₂, NH₃).

The composition of the surface, and even of the subsurface ocean (if connections between the interior and the surface exist or have existed) can then be inferred. However, it should be kept in mind that the surface environment has very extreme conditions, and materials from interior may be altered by depressurization, abrupt change in temperature, and particularly exposure to high radiation environment. These alteration processes must be studied, in particular by inferring the effect of radiation and energetic particles.

Studying its global surface morphology & dynamics.

The surface of Europa is very young: both crater counting and estimation of erosion rates by sputtering (constrained by the measurements of H₂O escape rates by Galileo) suggest an age of Europa’s surface between 10 millions and one billion years. This surface presents very intriguing tectonic and volcanic features (Figure 8). The size and geometry of linear features suggest surface motions enabled by ice-crusted water or soft ice close to the surface. Impact features suggest the existence of a low viscosity layer at about 5 to 20 km in depth that may be either a liquid layer or a soft ice layer. For some of these intriguing features, Galileo also provided topographic estimates using the shadows of the elevated terrains. Interpretations of these features gave some of the strongest arguments in favour of a deep liquid ocean below the icy crust. That is why one of the major goals of the LAPLACE Europa orbiter will be to study surface structures in more detail was achieved by Galileo.

Both a high-resolution camera, and a laser altimeter will be put on the Europa orbiter. The full coverage of the surface from a low orbit will permit the acquisition of high resolution images of every tectonic/volcanic feature. Laser altimetry measurements will bring new and valuable information on the topography, which will be of considerable importance for understanding geologic processes, and thus constraining the coupling between the putative ocean and the icy crust.

Finally, such high-resolution analysis of the surface will help to define astrobiologically interesting landing sites for future space missions.

Unraveling surface/exosphere/magnetosphere interactions.

The atmosphere of Europa is produced mainly from irradiation of its exposed outer surface by magnetospheric plasma (mainly sulphur and oxygen ions from Io) and UV photons. Its main component, molecular oxygen, has been indirectly observed by HST. Oxidized constituents produced by irradiation may also provide key components for life support within the subsurface ocean. The atmospheric composition of Europa is determined by both the water and oxygen photochemistry in the near-surface region, escape of suprathermal oxygen and water into the Jovian magnetosphere and exchange of radiolytic water products with the porous regolith.
Water ice is transformed into its gaseous state by sputtering processes and sublimation. Generally the water sublimation rate should be extremely low. However, around the dayside equator the observed increase of the sublimation rate of at least 4 orders of magnitudes than expected means that sublimation could be a major process for water vapour production. Cryovolcanic activity is another possible source of water vapour around satellites. "Boiling" water which may also exist due to thermal flexing and cracks in the surface will result in a highly increased supply of water vapour to the atmosphere and thus source regions will be easily detectable. Europa’s atmosphere interacts with the magnetospheric plasma by a large variety of processes including sputtering of the surface and exosphere and resurfacing due to intense bombardments by energetic particles. Energetic ions and electrons are the principal chemical agents in layers close to the surface of moons that could alter species originating from the deep interior and migrating to the surface. LAPLACE will monitor the incoming and reflected radiations, the structure and composition of the exosphere and ionosphere, surface composition to establish the net production, loss, and exchange of key chemical species between the magnetosphere, exosphere/ionosphere, surface and subsurface.

Characterization of potential environments and search for biosignatures
If Europa is (or was) habitable, the next exploration step should be the search for any signature of life that the environment is able to sustain. Remote detection of reliable biosignatures is very difficult, and in situ exploration is clearly preferable. That is why the mission study includes as an option a surface module (SE) that will allow to obtain environmental data (radiation, pH, eH, T, redox, chemistry) of the surface, and possibly of the near-surface. Geological evidences indicate that a link between the surface and the aqueous layer could have existed. Therefore, examination of endogenous materials, deep enough to avoid alteration effects by Jupiter’s radiation, may reveal some clues of the aqueous layer properties.

c.4°/ FROM SCIENCE GOALS TO MISSION CONSTRAINTS AND MEASUREMENT REQUIREMENTS

Our science goals address four different mission targets in the Jupiter system: Europa, the satellite system, Jupiter’s magnetosphere, and the planetary atmosphere. Through a careful analysis of the measurements to be performed, we have derived specific requirements for the measurements we need to perform on each of these objects, and specific constraints on the mission profile of LAPLACE. They are summarized in the following four tables, which represent the traceability matrix of the LAPLACE mission.
### LAPLACE MISSION TRACEABILITY MATRIX

#### I. Characterize Europa as a planetary object and a potential habitat

<table>
<thead>
<tr>
<th>Scientific objectives</th>
<th>Required measurements</th>
<th>Enabling instrumentation</th>
<th>Constraints on mission</th>
</tr>
</thead>
</table>
| **Existence & characterization of a subsurface ocean** | 1.1 Precise determination of the static and tidal gravity fields (up to 1 mGal)  
1.2 Determination of the induced magnetic response from the ocean  
1.3 Identification of tide-related surface waves & surface topography  
1.4 Determination of the amplitude of libration  
1.5 Search for an ice/liquid interface & determination of the ice-crust thickness | **Radio science**  
- **g-odometer** (16-11 kHz)  
- **Magnetometer** (Gravitational data collection)  
- **Laser altimeter**  
- **Passing Radar** (50 km depth, 20 mb/sec)  
- **Seismometer** (5 km/sec) | Using the g-odometer, the magnetic field of Europa is measured to a level of ±10 mG. The passing radar is used to determine the depth of the ice crust. The laser altimeter is used to measure the ice thickness. The seismometer is used to study the internal structure of Europa. |

**Silica-sea ocean surface topography** | 2.1 Determination of the topography and/or mass anomalies at the silica-sea/liquid interface  
2.2 Search for correlation between surface and subsurface structures  
2.3 Chemical characterization of global and local sea-floor surfaces | **g-odometer**  
- **Radio science**  
- **Laser altimeter**  
- **Passing Radar**  
- **Camera package (CF11)** | Using the g-odometer, the topography is measured to a level of ±1 m. The passing radar is used to determine the depth of the sea floor. The laser altimeter is used to measure the depth of the sea floor. The camera package is used to provide visual observations of the surface. |

**Mineral and chemical composition of the surface from orbit** | 3.1 Characterization of high-resolution (up to 1 m/beam) images of surface mineral, organic & inorganic compositional distribution | **X-ray imaging spectrometer** (0.5-13 keV)  
- **UV imaging spectrometer** (0.3-100 nm)  
- **Energetic Neutral Atom imager**  
- **X-ray imaging spectrometer** (60-600 nm) | Using the X-ray imaging spectrometer, the chemical composition of the surface is measured to a level of ±1%. The UV imaging spectrometer is used to measure the composition of the surface at a wavelength of 0.3-100 nm. The energetic neutral atom imager is used to measure the composition of the surface. The X-ray imaging spectrometer is used to measure the composition of the surface at a wavelength of 60-600 nm. |

#### II. Study the Jovian satellites' system and their connection to the population of minor bodies in the Solar System  

**Europa is discussed in I.**

<table>
<thead>
<tr>
<th>Scientific objectives</th>
<th>Required measurements</th>
<th>Enabling instrumentation</th>
<th>Constraints on mission</th>
</tr>
</thead>
</table>
| **Internal structure & long-term evolution of the Galilean satellites** | 1.1 Precise determination of low-degree static gravity fields  
1.2 Search for deviations from hydrostatic equilibrium & mass anomalies  
1.3 Study of the self-generated magnetic field at G | **Radio Science**  
- **Doppler Tracking**  
- **Laser Altimeter**  
- **Camera package** (HF)  
- **Magnetometer** | Using the Doppler tracking, the gravity field is measured to a level of ±1 mGal. The laser altimeter is used to measure the altitude of the satellites. The camera package is used to provide visual observations of the satellites. The magnetometer is used to measure the magnetic field of the satellites. |

**Physical characteristics, composition & geology of the Galilean satellites** | 2.1 Geologic mapping with significant improvement of global coverage  
2.2 Topographic mapping of large fractions of the satellites' surfaces  
2.3 Search for past and present geologic activity from limb scans thermal anomalies and image comparison  
2.4 Monitoring of Io's volcanic & thermal activity on day-night sides  
2.5 Determination of global & regional surface ages (centring records)  
2.6 Characterization of the main compositional and search for organic compounds in relation to geologic and tecno-chemical features  
2.7 Measurement of seasonal dust deposits  
2.8 Modeling of surface dynamics due to radiation effects | **Radio Science**  
- **Doppler Tracking**  
- **Laser Altimeter**  
- **Camera package** (HF)  
- **Magnetometer**  
- **VIR Imaging Spectrometer** | Using the Doppler tracking, the gravity field is measured to a level of ±1 mGal. The laser altimeter is used to measure the altitude of the satellites. The camera package is used to provide visual observations of the satellites. The magnetometer is used to measure the magnetic field of the satellites. The VIR Imaging Spectrometer is used to measure the composition of the surface at a wavelength of 0.3-100 nm. |

**Interactions between magnetosphere, exosphere & surface** | 3.1 Study of the induced magnetospheres of Io  
3.2 Detailed study of the inner magnetospheres of G  
3.3 Study of the ionspheres and exospheres of the satellites  
3.4 Study of escape rates and exogenic deposits | **Radio Science**  
- **Doppler Tracking**  
- **Laser Altimeter**  
- **Camera package** (HF)  
- **Magnetometer**  | Using the Doppler tracking, the gravity field is measured to a level of ±1 mGal. The laser altimeter is used to measure the altitude of the satellites. The camera package is used to provide visual observations of the satellites. The magnetometer is used to measure the magnetic field of the satellites. |

**Evolution of the Jovian system by investigating the small regular inner moon, the ring system, the irregular system of satellites** | 4.1 Physical characterization & chemical composition from Thera, Ananke & other small satellites by remote sensing  
4.2 Deterministic evidence of small satellites  
4.3 Measurement of thermal infrared albedo (surface temperature)  
4.4 Remote sensing of outer irregular satellites  
4.5 Radiometric determination of irregular satellites  
4.6 Imaging of the ring system & search for new satellites (outer/inward)  
4.7 Spectroscopy of dust particles  
4.8 Deterministic characterization of asteroids during interstellar passage | **Radio Science**  
- **Doppler Tracking**  
- **Laser Altimeter**  
- **Camera package** (CF11)  
- **VIR Imaging Spectrometer** | Using the Doppler tracking, the gravity field is measured to a level of ±1 mGal. The laser altimeter is used to measure the altitude of the satellites. The camera package is used to provide visual observations of the satellites. The VIR Imaging Spectrometer is used to measure the composition of the surface at a wavelength of 0.3-100 nm. |
### III. Study the Jovian magnetodisk/magnetosphere

<table>
<thead>
<tr>
<th>Scientific objectives</th>
<th>Required measurements</th>
<th>Enabling instrumentation</th>
<th>Constraints on mission</th>
</tr>
</thead>
<tbody>
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<td><strong>Jupiter as a fast magnetic rotator</strong></td>
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<tr>
<td>1. Magnetodisk structure, dissipation of rotational energy, transfer of angular momentum</td>
<td>1. Characterization of the 3D properties of the magnetodisk</td>
<td>Magnetometers (static search coil, beam)</td>
<td>Global coverage of the magnetodisk; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
<tr>
<td>2. Global energy regulation in a complex magnetosphere</td>
<td>2. Characterization of the Magnetosphere/Atmosphere/Thermosphere coupling processes</td>
<td>Magnetometers (spacecraft package)</td>
<td>Global coverage of the energy budget; continuous monitoring by ground-based telescopes and spacecraft probes</td>
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<tr>
<td><strong>Jupiter as a magnetized binary system</strong></td>
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<tr>
<td><strong>3. Satellites/Magnetosphere interactions</strong></td>
<td>3. Characterization of the local ion-electron interaction</td>
<td>Magnetometers (plasma package)</td>
<td>Global coverage of the ion-electron interaction; continuous monitoring by ground-based telescopes and spacecraft probes</td>
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<tr>
<td><strong>Jupiter as a giant particle accelerator</strong></td>
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<tr>
<td><strong>4. Origin &amp; effects of the harsh radiation environment</strong></td>
<td>4. Characterization of high-energy particle properties</td>
<td>Magnetometers (plasma package)</td>
<td>Global coverage of the high-energy particle environment; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
<tr>
<td><strong>5. Imaging of high-energy electrons</strong></td>
<td>5. Imaging of high-energy electrons</td>
<td>Magnetometers (plasma package)</td>
<td>Global coverage of the high-energy electron environment; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
</tbody>
</table>

*Magnetospheric plasma package (electron sensor): 4π field-of-view, fast time resolution (500 E/T, 100 kHz), low energy (1-4 keV), field-of-view, 1,000 keV, 0.1-10 keV, fast time resolution variable measurements. Energy-particle detector: electron and ion, various sensors are used for a range of few keV to several MeV, with composition and charge state. NE/LE/High/low-energy, imaging spectrometer.|

### IV. Study the Jovian atmosphere and interior

<table>
<thead>
<tr>
<th>Scientific objectives</th>
<th>Required measurements</th>
<th>Enabling instrumentation</th>
<th>Constraints on mission</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynamics &amp; coupling in Jupiter’s atmosphere</strong></td>
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<tr>
<td>1. Stratospheric structure, circulation &amp; composition</td>
<td>1. Determination of the origin of water in the stratosphere &amp; its role in atmospheric chemistry &amp; dynamics</td>
<td>Sub-mm spectrometer (500-800 km)</td>
<td>Global coverage of the stratosphere; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
<tr>
<td>2. Upper tropospheric meteorology</td>
<td>2. Determination of the origin of water in the stratosphere &amp; its role in atmospheric chemistry &amp; dynamics</td>
<td>Sub-mm spectrometer</td>
<td>Global coverage of the upper troposphere; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
<tr>
<td>3. Thermospheric &amp; ionospheric structure &amp; dynamics</td>
<td>3. Determination of the origin of water in the stratosphere &amp; its role in atmospheric chemistry &amp; dynamics</td>
<td>Imaging spectrometer</td>
<td>Global coverage of the thermosphere; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
<tr>
<td>External structure &amp; composition of Jupiter</td>
<td>4. Formation of Jupiter</td>
<td>Imaging spectrometer (450-550 nm, spatial resolution)</td>
<td>Global coverage of the formation of Jupiter; continuous monitoring by ground-based telescopes and spacecraft probes</td>
</tr>
</tbody>
</table>

* Imaging spectrometer integrated IR instrument (including multi-channel p-390) from 2 to 20 μm, with 8 channels for imaging spectrometer and IR 4-50 μm, spatial resolution, high-resolution for cloud and continuum retrieval, IR 4-50 μm, spatial resolution, high-resolution for cloud and continuum retrieval.
Mission profile necessary to achieve these objectives

Platform and orbit requirements
LAPLACE will deploy an observing system to perform the key observations needed at each target. As shown in figure 9, this observing system will use a hierarchy of observing posts or platforms and strongly link Earth-based and space-based observations.

Earth-based and Earth-bound observations will be conducted on two distinctive sets of targets: the LAPLACE mission objects (Jupiter, Europa, other components of the jovian system and their environment) and the LAPLACE mission spacecraft.

The former will help to prepare the mission, and then place space observations in a broader context during the mission itself, sometimes even providing observational data not achievable by space-based mission instruments. These astronomical observations will be conducted in a broad range of wavelengths, from high-energy domain to low radio frequencies.

The latter will include VLBI and Doppler tracking of the spacecraft aimed at achieving very high accuracy of trajectory characterization of all mission spacecraft in various phases of their operations. In addition, the radio telescopes involved in VLBI tracking, as well as the Square Kilometre Array (SKA) which will be operational during the LAPLACE orbital mission, will provide a backup “eavesdropping” support to the nominal mission communication scenario enabling receipt of low data-rate signals during critical and high scientific value events of the mission.

The space segment will observe the targets at progressively closer distances: from interplanetary orbit, during the approach to Jupiter, then from Jupiter orbit; finally from satellite orbits, first at Europa, our priority target, and possibly at Ganymede. If resources and technology allow, a Europa surface element could be deployed. It will need to be an integrated, multi-platform observing system of our four target. Ideally, it should include the coordinated operation of three orbiters: The Jupiter Europa Orbiter (JEO), a nadir-pointing platform optimized for global coverage of the surface, subsurface and internal structure of Europa, will perform a multi-month mapping of Europa before impacting its surface.

The Jupiter Planetary Orbiter (JPO), a three-axis stabilized platform optimized for remote sensing observations of distant objects, will observe Jupiter, its satellites and probe their internal structures.

The Jupiter Magnetospheric Orbiter (JMO), a spinning platform optimized for in-situ fields and particles measurements, will monitor the magnetosphere, the moons exospheres and their interactions. These platforms will operate in strong operational synergy, as the JPO will be used as a relay satellite for the JEO data during the critical period of its operations in Europa orbit. They will also be in strong scientific synergy: multi-point studies of the magnetosphere; combinations of close, high-resolution
observations Europa by the JEO with more distant, synoptic views by the JPO; associations between ENA or radio imaging of various magnetospheric particle populations by one platform with in situ characterizations of these same populations by another platform.

**Expanded options, to be studied during the assessment phase**, include a Europa Surface Element (SE), and possibly a Ganymede Orbiter as the final configuration.

**ii°/ Launcher requirements and possible collaborative scenarios**

We have identified at least three possible scenarios to launch and deploy this observing system. The basic mission architecture - a multi-platform, multi-target integrated mission - clearly speaks in favour of a broad international collaboration. This is what our two **preferred scenarios (1 and 2)** assume. These scenarios will have to be explored and consolidated with the international partners by means of a joint assessment study. **One stand-alone ESA scenario (3)** is also proposed.

**Scenario 1** - Two medium capacity launchers (Soyuz/Fregat, HIIA and upgrades, Atlas V-5, ...)
- JPO + JMO on one launch
- JEO + (optional) SE on the second launch.

**Scenario 2** - One heavy launcher (Ariane 5, Atlas 5-5 ...) with the JEO +1 jovian orbiter (combining JPO and JMO). Its capacity for carrying SE (with JEO) or separate JPO and JMO spacecraft needs to be investigated during the assessment study.

**Scenario 3** - One Soyuz/Fregat launch (ESA-only mission) with two s/c: JPO/JMO and JEO. This more constrained scenario will address more limited but more focused objectives, mainly Europa.

**iii°/ Trajectories and ΔV budgets**

Figure 10 illustrates our basic mission timeline, showing in the top panel how each platform moves from orbit to orbit with time. Five mission phases can be distinguished, for which the assessment will have to find the best possible orbits, trajectories and maneuvers, to optimize the science and minimize the total radiation dose and ΔV budgets. **Phase 0** is the interplanetary trajectory. In all studied scenarios we suggest a 6-year long Venus - Earth - Earth swing-by trajectory with good launch opportunities in January 2017, March 2020 and June 2023. For **Jupiter Orbit Insertion (JOI)**, the Jupiter capture strategy relies on an Io gravity assisted capture with a perijove at 4Rj and a first apojove at ~400Rj, which is a good compromise between ΔV cost and radiation dose. A Perijove Raising Manoeuvre (to about 13Rj) is performed at the first apojove, after which the spacecraft are separated (JPO from JMO in scenario 1, JPO from JEO in scenarios 2 and 3). During **phase 1**, each spacecraft then starts its own Jovian tour, with multiple fly-bys of jovian moons (mainly Ganymede, Callisto and Europa) providing a unique opportunity for multi-spacecraft studies of the jovian system. For **phase 2**, the JEO critical Europa mission takes place for a period of 60 to 90 day, to be validated during the assessment phase. The JPO is placed on a 2:1 resonant orbit with Europa to serve as a relay satellite. For **phase 3**, the JPO moves to a safer orbit to reduce radiation doses and relays the JEO data to the Earth while performing multiple flybys of Ganymede and Callisto. JMO moves to a ~15x70Rj equatorial orbit to explore the middle magnetosphere and perform multiple satellite fly-bys.

**iv°/ Ground segment requirements**

The ground segment must support the spacecraft operations through TM/TC links in X/Ka-band and standard ranging, Doppler and ΔDOR navigation performance for navigating the spacecraft through the interplanetary transfer phase and the jovian tours including multiple Moon fly-bys and final Europa orbit insertion. Optical navigation using a dedicated spacecraft on-board camera will complement the ground tracking performance. Once in Europa orbit, precise localisation using a Huygens type VLBI network support might be necessary to meet the scientific objectives.
In terms of ground station, at least one ESOC station must be dedicated to support the mission in the routine phases. One JAXA station will support the JMO once separated from JPO. In all mission critical phases, and especially during the JEO 3-month orbiting phase, support from another ESOC ground station and from NASA DSN stations will be needed. Additional support from the Square Kilometer Array, foreseen to be operational (including X-band) in the 2020s, will be of great interest.
Special Requirements

The overall scientific optimisation of the Jovian tours of the different spacecraft will have to be done taking into account the two main special requirements affecting the mission: keeping the radiation doses received by the three spacecraft below an acceptable level, and fulfilling Planetary Protection requirements. The severe radiation environment forces one to optimise the spacecraft trajectories and flight system radiation tolerance such that the radiation doses remain acceptable. This affects the ∆V budget, the shielding mass to be considered to meet a given radiation hardening level for platform equipment and science instruments, and the spacecraft lifetime in operational orbit. This trade-off at mission / system level will have to be performed during the assessment phase. The Planetary Protection requirements of COSPAR for Europa flybys, orbiters and landers, including bio-burden reduction, shall be applied in order to reduce the probability of inadvertent contamination of an europan ocean to less than 1 x 10^{-4} per mission. In the case of JEO which impacts Europa at the end of its mission this will likely require bio-burden reduction. In the case of JPO and JMO, the option of reducing the probability of impacting Europa below 10^{-4} can relax or eliminate the need for contamination control and sterilization.

Critical issues

The tight mass budget limited by two medium sized (scenario 1) or one single heavy launcher (scenario 2), though much better than in scenario 3, requires stringent management of the mass allocations. The severe Jovian radiation environment and the remoteness from the Sun and the Earth also have implications for the mission and system design. Power must be provided with either high efficiency solar cells with concentrators or RTGs (an option that will have to be considered during assessment). The remoteness from the Earth and the limited power resources and lifetime of JEO poses a data volume and communications challenge which has been partly addressed by relaying data from JEO to JPO where it is stored and returned to Earth at a later time. This eliminates the need for a high gain antenna and high power transmitter on JEO mitigating the mass and power challenge for that spacecraft. Even so, relaying back to Earth the important data volume to be generated by the mission will require a specific strategy: design of on-board data compression and storage capacities with the appropriate robustness to radiations, data link capacities between spacecraft and to Earth, optimal use of Earth-based reception capacities, careful sequencing of observation phases to share the resources between all instruments and data acquisition and data relay sequences, will be major tasks for the assessment study phase.

Proposed payload instrument complement

Observation strategy

LAPLACE addresses a broad spectrum of scientific objectives covering all themes of planetary sciences. Let us now propose a possible payload instrument complement to meet these objectives. Three complementary categories of scientific investigations satisfy the measurement requirements of LAPLACE

- measurements of the main planetary fields of Europa, and to a lesser extent of the other satellites (gravity, magnetic field, geodesy and surface topography), including their response to tidal forcing, to retrieve the main characteristics of Europa’s ocean and determine the internal structure of the different satellites,
- multi-spectral remote sensing measurements of the surfaces, atmospheres and gas tori, and possibly sub-surfaces of the different bodies of the Jupiter system, to retrieve their composition and dynamics and improve our understanding of the vertical coupling mechanisms between the different layers,
- in situ remote sensing of the plasmas, fields, energetic particles gas and dust populations of Europa’s exosphere and Jupiter’s magnetosphere, to quantitatively understand the mutual interactions between the different bodies of the Jupiter system and its space environment.

Overview of all payload elements

An overview of the detailed list of instruments which address the objectives of LAPLACE is given in Table 1. The table shows how the instruments meet the stated scientific objectives listed in Section (c) and summarizes key resources for each of the instruments, in terms of mass, power and telemetry.
(when possible) budget. It also provides a synthesis in terms of pointing and alignment requirements and design constraints on mission elements. Instrument heritage is also shown, clearly revealing that the necessary experience and expertise is in place in order to design, build and fly such instrumentation. The resource figures rely mainly on state-of-the art and current technologies developed in European and foreign laboratories but the significant progress in instrument design and performances expected in the coming years will help in reducing the load on spacecraft resources (mass, power), as will be discussed later. In term of technology readiness level, most of these types of instrumentation have successfully flown on several planetary missions, including previous missions to Jupiter. A limited set of foreseen instruments are new and deserve feasibility studies during the assessment phase, as detailed in Section (e.3.iii). The stringent jovian radiation environment around Europa however places much higher constraints on spacecraft and instrument subsystems, as described in Section (e.4).

**e.3°/ AN EXAMPLE OF A POSSIBLE SET OF SCIENCE PAYLOAD ELEMENTS**

Using the list of instruments from Table 1 as our starting point, and a realistic estimate of spacecraft resources for each mission scenario and each platform, we have identified a possible payload complement, given for illustrative purposes. It consists of core scientific instruments, addressing high-priority science objectives, plus complementary instruments, for each scenario and mission elements. In addition, our payload complement includes specific high-priority instruments which require feasibility studies in order to demonstrate their ability to achieve the required science performance. Finally, we recommend inclusion of scenario-dependent instruments in case it is demonstrated during the assessment phase that our proposed expanded options are achievable.

**i°/ Scientific payload mass allocation and shielding strategy**

Preliminary investigations have been carried out in order to assess the scientific payload mass allocation on each platform and for each scenario. The outputs of these studies are detailed in Section (f). The resulting minimum/maximum achievable payload mass allocations including shielding are detailed in Table 2. The lower values arise from the consideration of a 5% launch mass margin at platform level and are the ones taken into account for the definition of our core payload complement. Our proposed additional complementary instruments, listed in order of priority, should be considered together with the maximum payload mass allocations. The stringent radiation environment around Jupiter forces us to consider high shielding masses for each of the instruments. This critical issue clearly will deserve further dedicated studies, both at platform and instrument levels, and will require a unified approach and an access to integrated and common facilities for all instruments in order to reach the required level of protection against radiation. Since definitive specification levels are not yet available, we choose to introduce realistic shielding coefficients in order to ensure we do not underestimate this issue. Therefore, we reduce payload mass allocations by 20% both on JPO and JMO, and by 40% on JEO in the case of scenarios 1 and 2, and by 20% on JPO and 30 % on JEO in the case of scenario 3 since we target a shorter lifetime for the latter spacecraft. At the end, these reductions enable us to consider the instrument masses given in Table 2 in order to fit our proposed core payload complement with the resulting mass budget.

**ii°/ Mission Element strategy**

The science objectives of LAPLACE will only be met by a combination of measurements from the various instruments onboard all the mission elements. In order to optimize scientific return, we have selected our list with the objective of maximizing complementarities and synergies between individual instruments, between different platforms and to each specific target. We have also made use of the specific pointing requirements of each platform (e.g. section d), by allocating preferably nadir-pointing instruments to JEO, remote sensing instruments to JPO, and particles-and-fields instruments to JMO.

Our payload mass allocations and shielding strategy result in similar payload mass allocations on the JEO for all three scenarios. Therefore, we propose at this stage to include the same core payload complement independently of the scenario considered. This is also valid in the case of our proposed additional instruments, except that these additional instruments are only considered for scenarios 1 and 2 owing to the strict limited achievable payload mass allocation for scenario 3. In the case of the JPO, our proposed core payload complement is very similar between scenarios 1 and 2 except on two counts. First, we propose to include a more reduced plasma package for scenario 1 compared to...
scenario 2 since the former scenario enables us to include the JMO with a complete magnetospheric instrument suite. Second, we choose to allocate more mass to the cameras for scenario 1 compared to scenario 2 in order to achieve a better resolution. Whereas our core payload complement does not differ significantly between scenarios 1 and 2, this is not the case for our proposed additional instruments, notably in term of prioritization. In the case of scenario 1, our first priority is given to a high-energy neutral atom imager on the JPO since this instrument will provide the overall context of the magnetospheric in-situ measurements taken from the instruments on the JMO. In the case of scenario 2, our first priority is given to supplementary mass allocation for the cameras. Finally, our proposed payload complement on the JPO for scenario 3 is severely constrained by the limited achievable payload mass allocation.

Table 1: Comprehensive list of instruments to be considered for LAPLACE, meeting the scientific objectives listed in section (e) and showing key specifications, resources and design constraints. The actual core payloads for each spacecraft can be extracted from this list once the available p/l resources are determined. The color code used is the same as in traceability matrix. Instruments that have never flown in the jovian environment are underlined, new ones are indicated.

A detailed description of these instruments is available at [http://jupiter-europa.cesr.fr/](http://jupiter-europa.cesr.fr/)
One last justification for our proposed payload complement needs to be highlighted. The LAPLACE mission will enable for the first time multi-point measurements of the jovian system to be obtained. To take advantage of this unique opportunity, we need to include similar instruments on-board several, if not all, of our mission elements, independent of the scenario considered. This concerns particularly the magnetospheric in-situ instruments. Magnetometers are essential instruments since they address both the planetary and magnetospheric objectives of the LAPLACE mission. It seems therefore logical to include such instrumentation on each platform. Charged-particle detectors covering energy range from a few eV to several MeV will be carefully designed to provide detailed information on composition and change state of the jovian magnetospheric plasma. These key measurements will enable us to go beyond the limited or incomplete measurements provided by the various spacecrafts which previously investigated the jovian magnetosphere.

### Table 2:
Proposed set of science payload elements for each spacecraft and for each scenario.
Core scientific instruments have been chosen to ensure the prime science objectives of LAPLACE are addressed, as well as fitting with the preliminary lower mass budget offered by each mission element. Additional complementary instruments are also proposed, if higher mass budgets are achievable.

To be studied and scenario-dependent instruments are also included. Color codes are used to designate the three main categories of instruments.

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<thead>
<tr>
<th>Core Scientific Instruments</th>
<th>Additional Complementary Instruments</th>
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<tbody>
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<tr>
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</tr>
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<td>Plasma wave sensors</td>
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</tr>
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<tr>
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</tr>
<tr>
<td>Accelerometers</td>
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</tr>
<tr>
<td>Environmental data (p, n, T, R, d/90, d/180, d/270, d/360)</td>
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</tr>
<tr>
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| Table 3: Proposed set of science payload elements for each spacecraft and for each scenario. |
| Compared to Table 2, highly-integrated instrument packages have now been introduced and make it possible to include as core payload several of the additional complementary instruments listed in Table 2, for the same payload mass budgets. |

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<th>Scenario 3</th>
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**Table 3**: Proposed set of science payload elements for each spacecraft and for each scenario. Compared to Table 2, highly-integrated instrument packages have been introduced and make it possible to include as core payload several of the additional complementary instruments listed in Table 2, for the same payload mass budgets.

The LAPLACE mission will use the jovian system to be observed.

The JPO will spend most of its orbital time at moderate but not close distances from the jovian satellites. Since the JPO will spend most of its orbital time at moderate but not close distances from the jovian satellites, we ensure that onboard framing cameras will be able to observe these objects with enough resolution and allocate them a larger mass than on the JEO. As a general rule, the more payload mass is available, the more is allocated to the cameras.
iii°/ Specific instruments to be studied during the assessment phase

**Penetrating radar**
A ground penetrating radar is a very attractive but challenging instrument that could provide a definitive answer concerning the presence of a sub-surface ocean at Europa as well as a unique diagnosis of the structure of the ice shell. Following the promising conclusions of the dedicated ESA CDF study ‘Europa Low Resource Radar’, a further instrument assessment study is recommended. On scientific aspects, a full-scale sensitivity study is required to estimate the effects of the external and internal structure of Europa (ionospheric effects, radio noise, radiation environment, surface properties, temperature profiles and ice dielectric properties) that can affect significantly the radar performances. Current models should be consolidated by analyzing all related data returned by the Galileo spacecraft. On technical aspects, further studies on the design, accommodation, deployment and data commissioning of the instrument are required. The feasibility study should also analyse the possibility of using the altimetric mode of this instrument.

**Micro-gradiometer**
A micro-gradiometer is expected to bring strong scientific added-value for the study of the internal structure of Europa by obtaining high-resolution gravity field information. But its implementation on the JEO imposes strong constraints on the spacecraft design. An instrument assessment study, following the dedicated ESA study ‘Gravity Sensor Technology for Future Planetary Mission’, is required to demonstrate that it can meet its science requirements: the instrument has to be exactly at the centre of mass of the spacecraft, or, alternatively, the position of its centre of mass has to be precisely monitored. Moving parts in the spacecraft (e.g., propellant in the tanks) must be precisely monitored in order to correct the gravity gradient measurements. This instrument requires a very accurate knowledge of the attitude (angular velocities and angular accelerations, which are part of the measurements), and an in-flight calibration system/strategy. In case this instrument can not be implemented on JEO, we will rely on a conservative approach based on classical Earth-based tracking (Radio Science experiment) in order to determine the gravity field of Europa and its time variation due to tidal deformation.

**Doppler spectro-imager**
The roadmap we are planning for jovian seismology will include a feasibility study, both to assess the feasibility of a space version of a Doppler velocity imager (with possible heritage from very similar helioseismic experiment) and to prove the capability of the space instrument to achieve the required performance for detection of the jovian oscillations. We are also considering the possibility to apply for support from the Framework Programme 7 Space Theme - Strengthening of Space Foundations Activity. The feasibility study will also include the analysis of the possibility to integrate the Doppler imager as a specific visible channel within a fully integrated spectrograph/camera package, allowing to consider it as a possible option for scenario 2.

**Penetrators**
For penetrators for the Europan surface the feasibility of such instrumentation requires analysis; confirming survival to very high-speed impacts and operations lifetime issues (thermal concerns due to cold conditions, insulation, batteries, RHU); communications (surface material transparency to radio, need for a trailing aerial). The ruggedness of seismometers is an issue as is heat flow measurement feasibility. An initial study of a mineralogy/astrobiology instrument should be carried out as well as miniature attitude control systems and selection and development of a de-orbit motor.

iv°/ Summary
A possible set of desired payload elements for each scenario and each platform has been identified and described in the previous section, which fits within the anticipated payload mass and power budgets, using inputs from Table 1 and outputs from Section (f). In addition, a tentative list of complementary instruments, ordered in term of priority, has been considered in case the payload mass budgets increase. These critical issues will require further study during the assessment study, which will also need to revisit the prioritization of payload elements on the basis of technical and scientific performance analysis.
In order to maximize the science return of LAPLACE it would be highly desirable to include the complementary instruments identified over and above the core payload already described. Our study has been performed using a rather conventional approach that considers the scientific payload as...
independent passengers. It is clear that the best way to optimize the science return with respect to the limited available resources (mass, power, telemetry) is to follow an integrated payload approach, where individual instruments share common subsystems such as DPU, electronics, and power, as described below.

**Recommendations**

**i)** Proposed procurement approach and international partners.
In order to design the best possible payload, and to open its scientific utilization to the best scientific teams, we strongly favour selection of all payload elements on all platforms to the broad scientific community, by the way of an open call to at least all countries contributing to LAPLACE, followed by international peer review and subsequent final selection decision according to the internal rules of each of the funding space agencies. This international opening of all platforms will also reinforce the international collaboration on LAPLACE, and is likely to push for instrument teams with broad geographical base and scientific expertise.

**ii)** Critical issues - The radiation environment and a highly integrated payload approach
A mission to the Jupiter system presents important technical and engineering challenges. The limited payload mass coupled with low power levels and the harsh radiation environment dictate that the design of both the spacecraft and the accommodation of science instruments follow a new approach. A Robust, Efficient, Autonomous Payload approach hereafter referred to as a highly integrated payload will maximize the LAPLACE mission science return in two ways: (1) by minimising overlapping resources and optimising the sharing and utilisation of available hardware within the payload (mass and power savings will be translated directly into increased accommodation for science instruments and enhanced flexibility of on-orbit operations); (2) the risks of premature instrument or mission failure due to radiation effects will be minimised by the design of spacecraft electronics including autonomous redundancy implementation and optimal use of instrument accommodation and spacecraft shielding.

Survival for an extended period of time in the jovian radiation environment rests upon the careful design and selection of the components and materials of both spacecraft and instruments. Space electronics and in particular mass memory and processors, are susceptible to a number of radiation induced effects which can lead to a variety of performance reduction and failure modes. These radiation effects are broadly separated into two categories: a) Total Ionising Dose (TID) damage and b) Single Event Effects (SEE). TID damage presents itself as a gradual degradation in operation and performance of electronic components and can have a considerable effect on the power production efficiency of solar panels. It is the less serious of the two effects and can be minimised and even reversed by various strategies such as minimal component power-on time and thermal annealing cycles. Also of concern is the SEE rate of mission critical components. A radiation induced SEE such as Single Event Latchup (SEL) could lead to a mission critical failure due to component burnout in the power or communications system for example and a SEE within a mission critical segment of the spacecraft memory could lead to software corruption with associated serious effects. It should be noted that the use of silicon-on-insulator (SOI) substrates can reduce component sensitivity to SEE’s.

As an example of the radiation environment, the TID behind 8 mm of Al shielding accumulated from a 66 day tour of Europa is of the order of 1 Mrad. A comfortable level of margin will therefore demand hardware that is hardened to the several Mrad level. This dose is well beyond the level at which current space qualified mass memory, processors and other components are rad hardened. The full realisation of the Jupiter mission science goals and those of the Europa orbiter (JEO) in particular, will rely on a trade off between spacecraft shielding and the radiation tolerance of the electronics. Any reduction in shielding requirements can be translated into an increased instrument capacity and thus science return. The use of alternative shielding materials such as Ta coupled with a multi-layered approach with different materials can serve to both reduce mass and increase the radiation resistance over a broader range of particle energies. Previous studies have shown that solar cells are also susceptible to degradation in an intense radiation environment with the result being an appreciable decrease in output power. A 1 MeV electron flux at Europa (9.3 R\(p\)) of \(10^{13}\) cm\(^{-2}\) day\(^{-1}\) integrated over a 60 day tour will lead to a 20 % reduction of the solar cell output. It is thus clear that mission planning and operations will have to account for the inevitable reduction in available power over the mission lifetime.
It is clear that the jovian environment drives the REAP instrument accommodation architecture where separation of the sensor from the rest of the instrument (instrument electronics, interfaces etc.) is a central feature and offers several distinct advantages. In order to minimize the risk of instrument failure, as much of the instrument as possible should be enclosed within a shielded environment with only the front end sensor exposed to the environment. This co-location of a large portion of the instruments also provides the opportunity to share resources; centralized DC/DC conversion for common electronic component standard voltages being one example. This resource requirement reduction is complementary with the second benefit of the REAP approach which is a high level of hardware redundancy.

This co-location of the majority of the instrument components provides an opportunity for a departure from the traditional instrument accommodation approach where each individual instrument is allocated a dedicated processor and mass memory. The instruments under the REAP approach will instead have access to multiple processors with a single processor at a time being operational (depending on the overall instrument suite processing load). This approach offers significant resource savings and ensures a high level of redundancy against radiation induced instrument loss. If a processor displays signs of radiation induced degradation then a replacement will be automatically assigned to service the instruments. A mechanism providing automatic switch over of the failed components without damaged in the switchover operations will be central to the implementation of the REAP architecture.

**AN EXAMPLE OF A POSSIBLE SET OF HIGHLY-INTEGRATED SCIENCE PAYLOAD ELEMENTS**

Table 3 illustrates the mission benefits gained from including a possible highly integrated payload approach. Such an approach will make it possible to include as core payload a number of the additional complementary instruments introduced in Table 2, thereby increasing significantly the science return of the LAPLACE mission. A specific study during the re-assessment phase of the BepiColombo payload of the Mercury Planetary Orbiter identified a possible mass reduction of about 60% by designing instruments towards a highly integrated payload suite.

Without addressing this issue at the level of the entire payload, here we introduce in Table 3 two categories of highly-integrated instrument package, a remote sensing one (consisting of optical and spectroscopic instruments) and a magnetospheric one (consisting of fields and particles instruments), for illustration purposes. We also propose an attempt to combine the laser altimeter receiver with a camera, for a targeted mass of 7 kg.

Our proposed camera and spectrometer compact packages (N.B.: each with different resolutions, hence different focal lengths) could be similar to the various approaches used in the case of the BepiColombo SIMBIO-SYS or proposed in the case of the Pluto Express HIPPS or Deep Space 1 MICAS packages. The latter attempted to combine two cameras, an ultraviolet imaging spectrometer and an infrared imaging spectrometer plus all the thermal and electronic control for 12 kg, all its sensors sharing a single 10-cm diameter telescope.

Our proposed magnetospheric packages (N.B.: each with different performances, without including a magnetometer) could be similar to the approach developed and used in the case of the Rosetta-RPC package, which combines five sensors - ion and electron sensors, an ion composition analyzer, a Langmuir probe, a mutual impedance probe together with a magnetometer - for 7.45kg and 12.1W.

We strongly recommend to study the feasibility and design of highly-integrated payload elements during the assessment phase, to ensure that this approach will preserve the expected science performances of individual instruments while providing additional resources. A clearly identified outcome of this assessment study could be the definition of a generic multi-mission concept for other future planetary missions, enabling more frequent launches and reducing the schedules.

**Basic spacecraft key factors**

The preliminary spacecraft design presented here is mostly derived from the recent ESA studies (JME and JSE) that have been performed by Astrium. Some new investigations and updates have been carried out especially for scenario 1 in order to assess more precisely the science payload mass allocation on each of the three orbiters: JPO, JMO and JEO. For scenario 2 a dedicated study should be carried out in the assessment phase when the potential heavy launcher and international partners are more precisely identified. If an Ariane 5 is assumed, then the payload mass allocations of JPO and JEO will probably be about the same as in scenario 1, with however the JPO payload combining now
the payload of JPO and JMO. For scenario 3 the JPO and JEO payload mass allocations are known from the JME ESA study results which have not been updated here.

i°/ Spacecraft Configuration

The three spacecraft configurations proposed in scenario 1 are shown in Figure 11. The JPO is based on the same concept as during the ESA studies, a square tube structure in CFRP fitting four Eurostar 2000+ propellant tanks and an Astrium-ST 500N main engine at the bottom. It also holds a fixed 1.5m X/Ka-band antenna and two 1 dof articulated solar arrays supporting in total 18m² of LILT solar cells and twice this area of solar concentrators, which are mandatory to provide enough power (350W EOL) at a reasonable weight. A small area of solar cells and OSRs is implemented at the back of the solar arrays to provide power when too close to the Sun, where using the solar concentrators is prohibited due to cells over-heating. The platform electronics, embedded in a radiation vault, and the payload instruments can be accommodated on one lateral wall that stays always in shadow during the transfer phase, thus optimising the thermal control system. The JMO spacecraft is a squared structure that interfaces with JPO though its four upper corners. It contains a small hydrazine propulsion system and two large solar arrays equipped of LILT solar cells (without concentrators because they can not be pointed exactly to the Sun due to the constraint to point the antenna boresight, aligned with the spin axis, to the Earth). The JEO is actually mounted on a carrier propulsion stage which is a recurrent JPO platform. This enables to optimise the JEO for its final Europa orbiting mission while minimising spacecraft development costs. JEO uses a bi-liquid propulsion system with four small tanks and a central ATV-like 250N thrusters of Isp around 300s. The JEO solar arrays are the same as JPO and can provide 300W at EOL. JEO accommodates a 2-axis articulated antenna which supports a more robust and flexible link with the Earth, allowing to maximise the science data acquisition and the spacecraft monitoring from the ground (full ground station coverage is assumed during the three months orbiting Europa). The platform electronics, embedded in a radiation vault, and the payload instruments can be accommodated on the upper wall (below the antenna) and on the Nadir pointed lateral wall.
A preliminary functional architecture is shown in Figure 12 for JPO. The JEO one is quite similar but with an articulated antenna and less thrusters. It is based on a highly integrated centralised avionics architecture embedding the processors, mass memory, Power Control and Distribution Unit, star tracker electronics, reaction wheels electronics, and Inertial Measurement Unit. This new development, which could be based on the ESA Highly Integrated Control and Data System pre-development performed (but finally not retained) for Bepi-Colombo, is an essential enabling technology for reducing the mass, volume, power consumption, and shielding mass required on JPO and JEO. A common digital processing and power distribution unit is also foreseen for the payload instruments for the same reasons. The AOCS architecture based on gyros, autonomous star trackers, Sun sensors and reaction wheels is classical of interplanetary missions but requires adaptations and upgrades for the radiation shielding of star tracker optics and reduction of gyros power consumption. The RCS thrusters configuration relies on 24 10N bi-liquid thrusters which provides pure torque attitude control and omnidirectional thrust capability, very useful near Venus to perform TCMs without exposing critical spacecraft faces to the Sun. The RF system uses a X/Ka-band system with attitude control and omnidirectional thrust capability, very useful near Venus to perform TCMs.

According to JAXA, the differences between JPO and JMO are: (1) JMO is a spinner and has an attitude control system including Sun sensor, star scanner, and nutation damper. (2) Integrated Data Management Controller (DMC), which is under development for BepiColombo, will take care of data flow, attitude, orbit, thermal, and power delivery control. (3) The propulsion system consists of 8–16 thrusters (3–10N-class) capable of 6-directional orbit control and pure-torque attitude control (monopropellant hydrazine system).

**Figure 12: JPO Functional Architecture**
iii°/ Spacecraft Budgets

Details of the spacecraft mass and power budgets preliminary estimates can be found at http://jupiter-europa.cesr.fr/

The estimated dry and wet mass budgets for the three spacecraft in scenario 1 (assuming two Soyuz-Fregat launchers) include classical maturity margins and a 20% system margin, as well as substantial allocations for shielding mass (15kg for JPO, 70kg for JEO, i.e. 2 to 3 times more than in the previous JME study). The maximum achievable payload mass allocations are about 75kg for JPO and JEO, and 25kg for JMO, including a provision for shielding (20% on JPO & JMO, 40% on JEO) and maturity margins. If a 5% launch mass margin is targeted, then the payload mass allocations drop to 50kg on JPO and JEO, along with a 20% reduction in shielding mass at platform level.

A preliminary power budget including a 20% system margin gives payload power allocations of 50W for JEO, from 20 to 100W for JPO (depending on the Earth communications mode), and 20W for JMO. Obviously the power budget is very tight and deserves a careful consolidation during the assessment phase. The JPO and JEO solar arrays are sized to produce respectively 350W and 300W at EOL, which just fit the needs. The JEO orbit around Europa shall avoid eclipses, otherwise a strong limitation in payload allocations or spacecraft lifetime will result. This means that the orbit local solar time shall be higher than typically 4:30pm on a 200km altitude circular orbit. At EOL the JEO power resources are just enough to recharge the battery in-between two eclipses by Jupiter, which can not be avoided. The JEO power budget supports simultaneous Nadir pointed science and Earth communications, using the articulated antenna, except during the Jupiter eclipse when science must be reduced for power saving purposes.

JPO can provide up to 50W of power to JMO while attached, which is expected to satisfy thermal control needs only. Full JMO check-outs at Jupiter will have to be done on battery power or without Earth communications. The JPO power budget can not support simultaneously full remote sensing science and high data rate Earth communications, which is not a real problem as JPO remote sensing science phases will be mostly during short duration jovian moons fly-bys, with the fixed HGA off-pointed from the Earth. The rest of the time 20W is allocated for low power in-situ field and plasma instruments.

The RF link budgets are not detailed here but they are expected to be quite similar to those studied in the recent ESA studies.

iv°/ Critical Issues and Open Points

There are several critical issues that deserve more detailed investigations in the future assessment phase. Radiation shielding and hardening is probably the most serious one. It has been computed with the latest radiation model developed for ESA, based on Divine & Garrett, GIRE and Salammbô; that the three spacecraft would experience the following doses on their respective orbits:

- JPO: 600krads behind 4mm Al or 300krads behind 6mm Al
- JEO: 1100krads behind 12mm Al or 850krads behind 14mm Al
- JMO: 250krads behind 4mm Al

The shielding mass allocations (15kg on JPO and 70kg on JEO) are enough to shield a volume about 0.15m³ with 4mm and 14mm thick Aluminium walls respectively on JPO and JEO. Therefore if it can be proven in the future assessment phase that this volume covers all platform electronics equipment, then a radiation hardening qualification level up to ~600-800krads should be targeted for electronics parts. Actually a dedicated study and technology predevelopment program is required to adequately prepare the LAPLACE mission with respect to radiation issues. Possibly the most critical electronics part deserving the highest attention are memory components, for which state-of-the-art is very far from those levels. It is recommended to investigate alternative solutions like hard discs, to be space qualified. The preliminary estimates of the needed mass memory sizes amount to typically 50Gbits for JEO, which represents a week worth of science data volume, and about 500Gbits for JPO, which corresponds to the accumulated JEO science data during its 3-month mission, assuming a limited JPO downlink capacity during that same time due to the required sharing of the same ground stations, and the priority given for the monitoring and commanding of JEO.

The 1MeV equivalent fluences experienced on the spacecraft trajectories have been computed with the same radiation models, assuming coverglass thicknesses of 500µm for JEO and JPO, and 130µm for JMO. The results amount to $2.75 \times 10^{15}$/cm² for JEO, $5.75 \times 10^{14}$/cm² for JPO and $3 \times 10^{15}$/cm² for JMO, which, using recent LILT test results from ESA, Astrium and JPL, correspond to radiation degradation...
factors of 0.86 for JEO, 0.92 for JPO and 0.86 for JMO. Accounting for some margins and other factors, the sizing of the solar arrays has been done with EOL degradation factors of 0.75 for JEO, 0.85 for JPO and 0.8 for JMO, and assuming a LILT solar cell efficiency of 34% at low temperature, which is the best state-of-the-art today. Here again, a dedicated pre-development program is required to confirm the availability of such LILT solar cells for the LAPLACE mission.

Solar concentrators are strictly mandatory for JEO and JPO. The V-trough reflectors concept proposed in the baseline design, already flown by Hughes or JAXA with different outcomes, are expected to improve the solar array efficiency by 75% for an over-weight of less than 7%. Other concepts like Fresnel lens systems could also be envisaged in the future assessment phase. Furthermore it can not be excluded that next generation US RTGs with high specific power efficiencies become available for European spacecraft in international cooperation missions like LAPLACE. Therefore this option shall also be studied in the assessment phase.

Highly integrated centralised avionics systems are also necessary to reduce the overall mass and volume of the Data Handling System. A relevant ESA pre-development initiative was the Highly Integrated Control and Data System performed for Bepi-Colombo even if it was finally not selected at project start. This effort shall be resumed with even more ambition, to integrate the star sensor and reaction wheels electronics, and the Power Distribution Unit.

**Other Mission Scenarios**

The previous description of the basic spacecraft key factors applies to the mission scenario 1 with two launches by medium launchers. The second envisaged scenario consists in a single launch by a heavy launcher like Ariane 5 ECA or Atlas 5. In that case the launch composite would consist in a JPO-like spacecraft carrying a JEO. The JPO-like orbiter could be very similar to the one in Scenario 1, except that its payload should integrate the JMO payload as much as possible. The JEO spacecraft mass allocation (nearly 2 tons) would be typically twice the current mass estimate of the wet JEO (~1 ton) on top of its propulsion stage in Scenario 1, but the required propellant load would also double. Overall a small increase of the JEO payload mass allocation can therefore be anticipated. This mission scenario could well support an international collaboration with NASA through a NASA-provided JEO spacecraft on top of the ESA JPO orbiter in an Ariane 5.

The back-up all-European scenario consists in the JME scenario where JPO and JEO are launched by a single Soyuz-Fregat. This scenario has been studied by ESA and Astrium, and its characteristics are well known. Its major drawback is the limited payload mass and power allocations (less than 35kg / 20W on JEO and 20kg / 15W on JPO). Its main other technical limitations, which are all mitigated by the selected Scenario 1 with two Soyuz-Fregat launches, are the requirement for radhard electronics up to 1Mrads (because of limited shielding mass), a shorter life-time around Europa, less flexibility and robustness in the communications concept (no 2-axis articulated antenna on JEO, less frequent JEO – JPO relay), and in the AOCS (less capable reaction wheels, no pure torque thrusters configuration), and less conservative mass and power budgets.

Finally two other mission options were considered. The first one consists in inserting JPO in orbit around Ganymede after its JEO relay mission is over. However it has been checked that elliptical orbits around Ganymede are instable, and the ΔV cost to acquire a circular orbit around Ganymede is too high and not compatible with carrying the JMO spacecraft to Jupiter, unless a more powerful launcher than Soyuz-Fregat is used, for example the H-II(A). Indeed JAXA has checked that if the H-II(A) is used for the JPO-JMO launch, an estimate shows that the total mass (wet) after the Jupiter orbit insertion can be increased by 400kg. There are several options to utilize this increased resource to enhance the science of the mission. To list a few of them:

1. Increase the payload mass on JPO and/or JMO.
2. Increase the power supply to the payloads.
3. Use it to load the propellant on JPO so that the spacecraft will be inserted into a stable circular orbit around Ganymede in its final stage.

The last mission option consists in carrying a small Europa surface impactor on JEO, but this seems not feasible unless a heavy launcher is selected and the penetrator weight is much less than 100kg, which deserves a dedicated study in the future assessment phase.
Science operations and archiving

Mission Operations concept

The precise mission operation scenario will mainly depend on the level of international cooperation: the general principle is that after spacecraft separation, each Agency controls the spacecraft under its responsibility, with its own means. ESA will be responsible for the coordination of all ground infrastructures. Dedicated communication links shall be considered. ESOC will have the responsibility for the mission operations of ESA-led spacecraft elements (JEO and JPO). ESAC will perform the scientific payload operations on ESA-led elements, in relation with the PI teams.

Ground Segment Facilities

The ground facilities will consist of:

- The ground stations and communication network of involved agencies and partners (radio astronomers)
- The Mission Operations Centre (MOC): hosted at ESOC, responsible for all spacecraft-related issues, which includes mission planning, orbiter monitoring and control, orbit and attitude determination and control, communications with the spacecrafts, data downlink
- The Spacecraft Operations Centre (SOC): hosted at ESAC, responsible for the coordination of the long- and short-term scientific planning of the mission, preparing with the PI teams the detailed operational timelines and delivering them to the MOC
- The PI teams: interacting with the SOC, to prepare operational timelines for their instrument and to provide high-level scientific data for long-term archiving.

Mission Operations

The operations of simultaneous spacecrafts will take advantage of the methods of interplanetary mission operations developed for Rosetta, as well as of the collaboration schemes developed for Cassini-Huygens and BepiColombo.

In the frame of the recent Jupiter System Explorer study, the specific impacts of operating two spacecraft flying to Jupiter at a one-week interval was assessed with ESOC and considered feasible with a modest increase in ground station coverage. The mission operations will also be adapted to the high level of autonomy foreseen for the spacecrafts, especially for the JEO.

The orbit determination during all the mission phases will use two-way range and coherent two-way Doppler tracking data with the help of ground stations. During the critical phases of the mission, an overall support of all Agencies ground facilities should be foreseen, in partnership with other ground facilities, such as SKA radio telescopes, for direct-to-Earth downlink or radio science. The coordination between ESOC and radio astronomers will require a dedicated operational interface to be specified.

Data Processing and archiving

The data processing and archiving strategy will be defined at a later stage of the mission design. However, the multidisciplinary scientific aspects of the mission will require a coordinated approach to ensure full data availability to interdisciplinary studies.

Proprietary data policy

The proprietary data policy will comply with the rules of each international partner, and defined in the MOU signed between all agencies contributing to LAPLACE. The proprietary data period should be just long enough to allow for the validation of the data by the PI teams, but as short as possible to allow quick access of all data to the broadest possible community of users via the long-term ESA archive (the Planetary Science Archive) and international data centers.
As any deep space projects, the LAPLACE mission will have to deal with several critical technologies such as intelligent on-board data processing and storage, long distance communications (which require low noise receivers and large Earth stations), resources minimisation (mass, volume, power). The Galileo mission and the JUNO mission under development demonstrate that U.S. technologies are suitable for the jovian environment. For Europe a number of specific key technologies will have to be developed, particularly for overcoming the radiation issues and planetary protection aspects while keeping the mass low, and high accuracy navigation required for the science.

Radiation issues
A first step to be done in the short term is to assess the sensitivity of the foreseen instruments, particularly for detectors and electronics. On the other hand, the mass issue is such that miniaturized instruments are also necessary. Unfortunately, highly integrated electronics is quite often very radiation sensitive and trade-off will have to be done to optimise the instruments. The correct identification of these difficulties is vital for the national agencies funding the instruments to start new developments as early as possible.

In parallel, the same radiation assessment is to be done on the existing European technologies used for platform subsystems (power generation is a critical example). This step is also essential to identify the fields where new developments are necessary or collaborations must be discussed. At spacecraft level, sectorial analysis will also play a major role to optimize the shielding where necessary/possible, with acceptable mass penalty. To cover these analyses, accurate radiation models, powerful simulation tools and later on test facilities will be required.

In case of the use of radioactive devices (RHUs or RTGs), a specific analysis will also be required.
Planetary protection
A careful early analysis of the problem is there also necessary to size the requirements to the real needs, because they may have a huge impact on the technical definition of the spacecrafts and their mission. However, on this field, European expertise exists at ESA level and partly at national level.

Precision navigation
The science return expected on the internal structure of the moons and planet requires very accurate navigation, in an environment characterised by the radiation aspects, the presence of numerous bodies and a large distance from the Earth. Early modelling studies are to be performed immediately to assess the criticality of the problem and extract constraints on the orbits, the spacecrafts and other mission elements.

i°/ Preliminary programmatic and costs

ii°/ Overall proposed mission management structure
The following organization is proposed, based on the BepiColombo organization scheme, is illustrated in Figure 14. Each Space agency has its own management office, composed of a program manager, a project manager and a project scientist. This “core” management team constitutes the LAPLACE Program Board.
Each Project Scientist manages the Science Working Team (SWT) which is the assembly of all instrument PIs, namely JEO/SWT, JPO/SWT, JMO/SWT. All PI instruments are also under the responsibility of a Payload Manager of the spacecraft engineering team. The assembly of all instrument’s PIs constitute the LAPLACE Science Working Team.

![Figure 14: Proposed LAPLACE mission management structure](image)

(1) The ESA project manager will also manage the launch segment and the ground segment facilities.
(2) The JAXA project manager will also manage the Japanese Ground Segment facilities and the launch segment if JAXA provides a H-II(A) launcher.
(3) Depending on the US contribution, NASA will also manage, in addition to its ground segment, any launch segment contribution to the LAPLACE mission.
(4) Roscosmos will also be included at the high-level of the management of the cooperation, and will monitor its own flight elements while sharing the conduct of science with other partners.

ii°/ Mission schedule drivers.
Technology developments (identified in section h) will be the first driver in the mission development timeline. According to the ESA plan for implementation of L-class missions, the corresponding studies and developments will come very early, being actually part of the selection process. On the side of JAXA, which plans to develop solar-power sail technology for outer planets exploration, the PrePhase-A study of the technology demonstration mission has been completed. Its launch is expected
to be in the middle 2010’s, in time for possible application to LAPLACE. So everything indicates that
in the early 2010’s substantial upgrades in the readiness of some of the new technologies usable for
the LAPLACE mission will have been accomplished.
As the mission preparation develops, lessons from JUNO will become available at the level of
mitigation techniques against radiations through the NASA partnership.
Good planetary windows are available starting in 2017, with additional ones in 2018 and later, so that
meeting a launch window will not very strongly constrain the mission.

### iii°/ Overall mission cost analysis.
The assessment study will identify the ESA-funded contribution to this mission, limited to the 650 M€
envelope ceiling, through discussions with identified partners (JAXA, NASA and RosCosmos). The
cost on the JAXA side is estimated to be lower than the largest science mission managed by JAXA to
date (SELENE). NASA’s current plans for a mission to Europa and/or the Jupiter system are for a
flagship-class mission, before consideration of a possible international cooperation for this mission.
Table 4 shows a very preliminary estimate of the cost breakdown and total ESA costs for each
scenario, if ESA provides the two launchers and all orbiting platforms except JMO. Provision of a
surface element by Roscosmos would be a separate budget item, not charged to ESA.

<table>
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<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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</tr>
<tr>
<td>Total</td>
<td>748</td>
<td>Total</td>
</tr>
</tbody>
</table>

Table 4

Cost estimates are given in M€; e.c. 2007

**Scenario 3**, the most studied so far, adds up to just 646 M€, and could therefore be a viable, stand-
alone mission option, should all international partnerships fail to materialise.

**Scenarios 1 and 2**, although they exceed the cost cap for L-class missions, represent the opportunity
of a large international cooperative mission, with a high level scientific return. In this context, NASA
cooperation would lead to the procurement of one spacecraft, thus leading to a cost for ESA lower
than the L-class cap. The cost of JMO is not estimated at this time, since it is procured and funded by
JAXA. The spacecraft industrial activities costs are ROM costs, including the H/W, system
engineering, management/PA, AIT and facilities, ground support equipment, and some common
developments for the spacecrafts. Planetary protection is explicitly addressed in the form of extra costs
for sterilisation procedures and induced system-level studies and techniques. The cost estimates do not
include technology development that must be led to be able to manufacture the various spacecrafts
(particularly: development of 1Mrad-class radiation hardened electronics, high power solar arrays):
they are supposed to be funded by R&D programs carried out for Space Science needs. Ground
segment and operation costs need to be assessed in the next phases, in order to take into account
existing facilities to be reused for the LAPLACE mission. In the meantime, an estimate of 15-20% of
the mission cost seems realistic. Launchers costs are the current costs for European launchers. Finally,
payload costs are not included in the ESA-funded budget estimates since, as proposed, instruments
will be procured and funded by national agencies after an international call for instruments.

**This very preliminary estimate validates the choice of scenario 1 as our favourite, with scenario 3 as a back-up ESA-only option.** A joint assessment study between ESA and all its international
partners will explore and compare additional scenarios to optimize the total budget and the use of the
resources and expertise areas of each partner.
j°/ Communication and outreach.

i°/ Content
Exploration of planets is a highly interdisciplinary field. We propose to use the framework of the LAPLACE mission to develop educational products that relate closely to the curriculum of European schools in the area of science and technology (physics, chemistry, biology, technology), but also in the areas of art, languages and history. As examples: 400 years of the discovery of the galilean satellites, exobiology (extremophiles), celestial mechanics (travel to Jupiter, travel in the jovian system), atmospheric physics, formation of the solar system (historic models like the one by LAPLACE, the current view, the importance of the formation of Jupiter for our understanding of the formation of the solar system), exoplanets...

ii°/ Organisation
Public Education is a very important issue for all space exploration missions. Therefore, it must be done professionally and as a consequence does require a full time dedicated person, the Public Education Person (PEP). The PEP must have experience in outreach / education and a strong scientific culture and interest. The PEP will co-ordinate the core group for Public Education Activities of the mission. This group will consist of the PEP and the National Public Education Persons (NPEP), one for each of the participating countries. The NPEPs can be scientists with experience in and enthusiasm for education, but do not need to be full time dedicated. The NPEPs will play an active role in the outreach activities in their country and will organise, co-ordinate and report on national activities. They will also translate news and education products into their national language.

The web site must be centralized and present a homogeneous and clear structure throughout. It will contain the standard information on the mission, as well as news and be a place to download educational materials. Similar to the ESA web site, the mission’s web site will contain links to national sections. In these sections is presented the basic information about the project and news flashes, all in the national language (translated by the NPEP) and a calendar of national activities. A tool for asking questions to team scientists will also be included. As the project grows, the web site will host educational material (presentation, suggestions for experiments).

iii°/ Activities
• Press Office activities: It is very important to have professional contacts with the media, and the PEP will be experienced in this area. The press office activities will include (1) Production of press releases and other printed packages, (2) Actively contact and pass information to science journalists, (3) Organisation of interviews with the team, (4) Support exhibitions and other public events throughout Europe (and elsewhere if possible). This last activity includes (a) the organisation of an exhibition about jovian exploration, moving through different places in Europe, (b) the organisation of yearly intense international seven day summer schools about jovian exploration (international jovian Exploration Summer School, iJOSS) at the level of tertiary and secondary education, (c) the organisation of seminars in the different countries, visits to schools.

• Production of printed materials for a general public: All kind of printed/printable material (leaflets, posters, lesson plans, gadgets) will be produced during the different phases of the mission (and translated into different languages). This material will be published on the web site for downloading. Printed packages will be prepared in different languages for distribution during activities.

• Production of educational films: The film media (DVD, internet) is becoming a more and more common tool to communicate science and education. We propose to produce (1) a suite of shorter (up to about 15 minutes) educational films on topics related to the mission and that closely connects to the curriculum in science taught at schools, (2) several larger documentaries aimed at the general interested public about topics related to the mission (possible topics are 2010: 400 years of jovian studies, the life of LAPLACE).