# 2007 Europa Explorer Mission Study: Final Report


Task Order #NMO710851 JPL D-38502 29 August 2007

NASA APL JPL

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## APPENDICES



*Cover art provided courtesy of Michael Carroll.*

# Europa Explorer

Fact Sheet

## Science Goal: Explore Europa and investigate its habitability

## Science Objectives

*Priority 1*

**A. Europa's Ocean:**
Characterize the ocean and deep interior.

**B. Europa's Ice Shell:**
Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange.

**C. Europa's Chemistry:**
Determine global surface compositions and chemistry, especially as related to habitability.

**D. Europa's Geology:**
Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.

**E. Europa's External Environment:**
Characterize the magnetic environment and moon-particle interactions.

*Priority 2*

**F. Europa's Neighborhood:**
Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons.

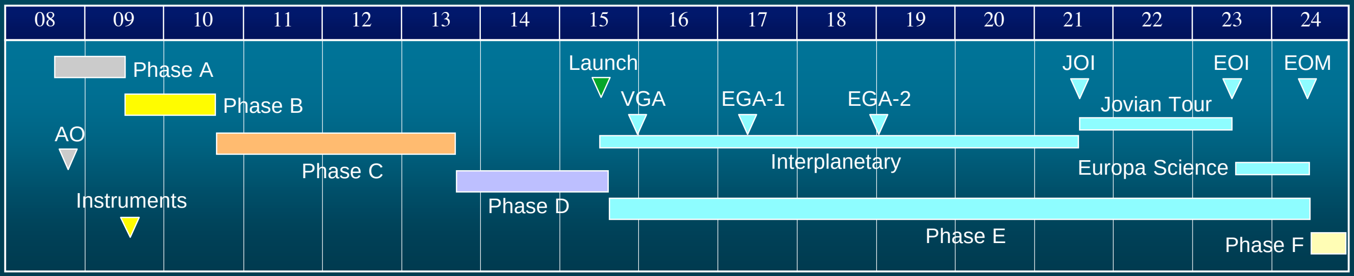
## Baseline Planning Payload

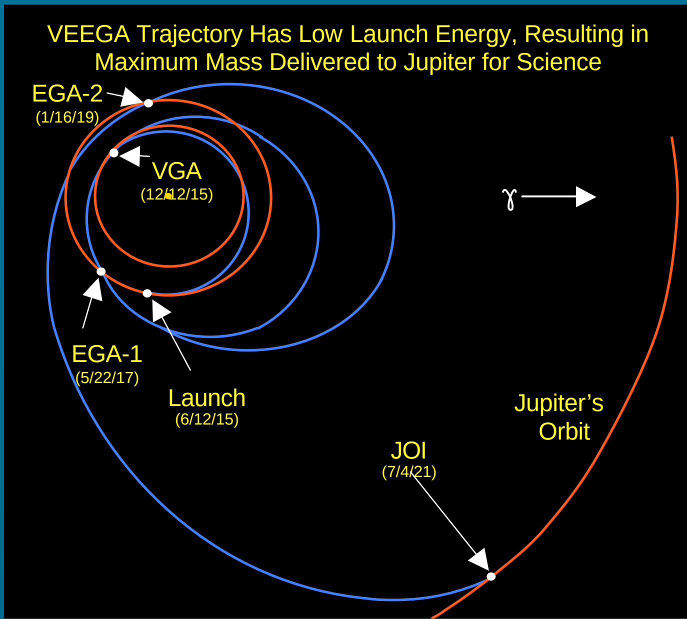
| *Investigations/Instruments* | *Characteristics* |
|---|---|
| **Wide-Angle Camera (WAC)** | 3-color+panchromatic; IFOV of 1 mrad, framing mode |
| **Medium-Angle Camera (MAC)** | Stereo optics; panchromatic; IFOV of 0.1 mrad; pushbroom mode |
| **Narrow-Angle Camera (NAC)** | IFOV of 10 µrad; Framing and pushbroom modes |
| **IR Spectrometer (IRS)** | 0.4 to 5 µm, 6 nm spectral resolution below 2.5 µm, and 12 nm above 2.5 µm; 558 spectral channels |
| **UV Spectrometer (UVS)** | EUV 55–110 nm, FUV 110–190 nm, NUV 190–350 nm Both nadir and limb viewing |
| **Laser Altimeter (LA)** | Multi-beam, 5-spot cross pattern; 1.064 µm |
| **Ice Penetrating Radar (IPR)** | 5 MHz dipole & 50 MHz Yagi antennas with 1 and 10 MHz bandwidths |
| **Thermal Instrument (TI)** | 2 bands in the 8–16 µm range, Visible channel for surface albedo |
| **Magnetometer (MAG)** | Dual sensors; 10 m boom; 0–1000 nT |
| **Ion & Neutral Mass Spectrometer (INMS)** | 1–300 Daltons & resolution > 500; $10^{-6}$ to $10^{-17}$ mbar for neutrals and < 100 eV ions |
| **Particle & Plasma Instrument (PPI)** | 100's keV to 10 MeV electrons; Up to 100's MeV ions |
| **Radio Science – Gravity** | 2-way Doppler, X- & Ka-band via telecom subsystem |

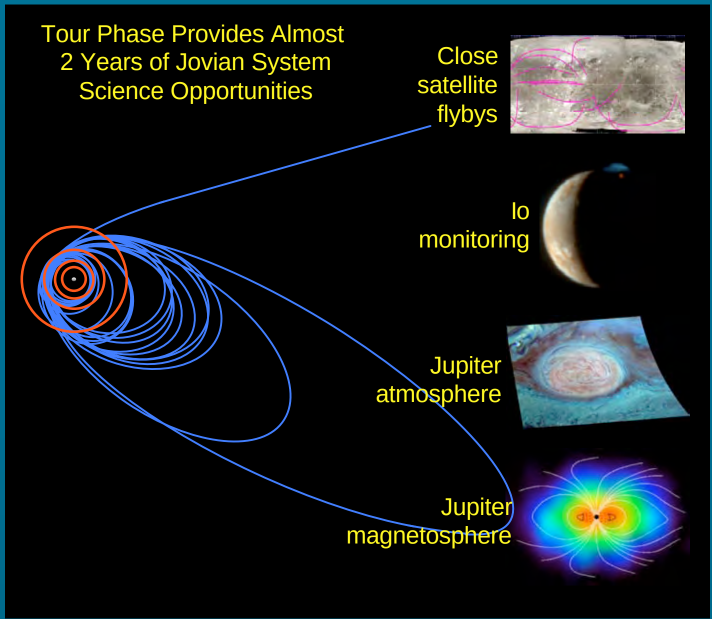
## Why Europa? Why Now?

- Europa continues to be the highest priority outer planet exploration target per 2007 NASA Science Plan, the 2006 Solar System Exploration Roadmap, and the 2003 planetary sciences "Decadal Survey"
- Investment over last decade has matured key technology such as rad-hard electronics and radioisotope power sources
- Galileo has revolutionized our understanding of Europa and its putative ocean, pointing the way to the next exploratory step
- Robust payload will answer compelling questions about Europa's ocean and its potential habitability following a required ~two-year Jovian system tour rich in Europa, Ganymede, and Callisto encounters, monitoring of Io, and observations of Jupiter's magnetosphere and atmosphere

## Schedule

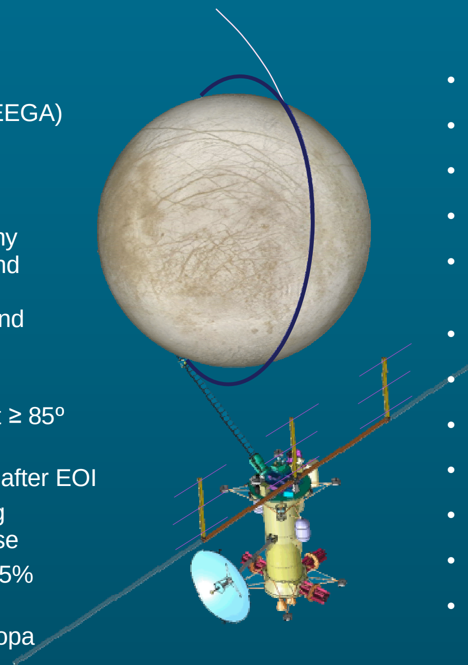





## Mission Overview

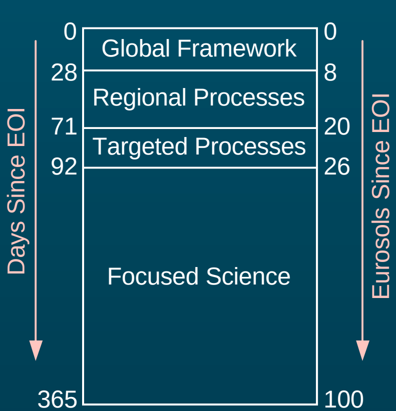
- Launch on Delta IV-H in June 2015
- Venus-Earth-Earth Gravity Assist (VEEGA) trajectory
- Jupiter Orbit Insertion in July 2021
- 23 month tour of Jovian system, including additional science from many flybys each of Europa, Ganymede, and Callisto, continuous magnetospheric monitoring, regular monitoring of Io and Jupiter's atmosphere
- Europa orbit insertion in June 2023
- Initial, circular 200 km altitude orbit at ≥ 85º inclination
- Transfer to 100 km orbit ~one month after EOI
- 70m-equivalent DSN coverage during encounters and Europa Science phase
- One year Europa Science phase at 75% confidence
- Flight system eventually impacts Europa



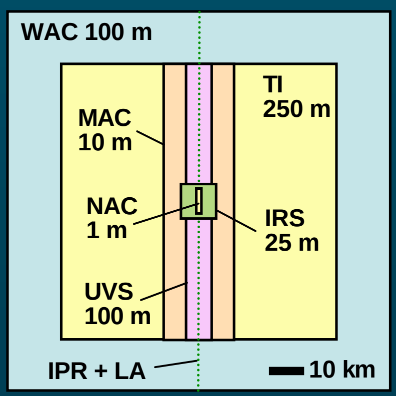
## Flight System

- 7045 kg wet mass
- 158 kg planning payload
- Six MMRTGs provide power
- Two-axis gimbaled HGA
- Two-way doppler at both X-/Ka-band for radio science gravity investigation
- 200 kb/s to 70m from 5 AU at X-band
- Up to 20 Gb/day during Europa Science phase
- Dual-mode propulsion system; 2755 m/s
- Redundant key subsystems including dual main engines
- Rad-hardened electronics
- 2.6 Mrad radiation design point
- Bioburden reduction plus radiation environment for hardware sterilization supports planetary protection

## Europa Science Campaigns




1st Campaign – 200 km
2nd & 3rd Campaign – 100 km
4th Campaign ≤ 100 km




Nested FOVs provide for coordinated targeted observations (resolution/pixel indicated)

## Science Definition Team

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Bob Pappalardo, Co-Chair (JPL)
Bruce Bills (Goddard Space Flight Center)
Diana Blaney (JPL)
Don Blankenship (University of Texas)
Krishan Khurana (UCLA)
Tom McCord (Bear Fight Center)
Bill Moore (UCLA)
Chris Paranicas (APL)
Louise Prockter, JSO Co-Chair (APL)
Mitch Sogin (Marine Biological Laboratory)

## Cost

| Total Mission Cost $BFY07 | Baseline | Floor |
|---|---|---|
| | Best Estimate: $3.3<br>Range: $2.9 to 3.5 | Best Estimate: $2.4<br>Range: $2.1 to 2.6 |

29 Aug 2007

# 1.0 EXECUTIVE SUMMARY

*An orbital mission to Europa continues to be a top priority for exploration, as recommended by the 2007 NASA Science Plan, the 2006 Solar System Exploration Roadmap, and the 2003 planetary sciences "Decadal Survey."* This high priority arises from the very strong indications that Europa has the "ingredients" necessary for life: a vast subsurface ocean, energy sources, and the elements from which organic molecules can be constructed. With its recent geological activity and potential surface-ice-ocean exchange of watery material, Europa is the archetype for understanding the habitability of icy satellites.

NASA has studied several approaches for meeting Europa science objectives. The present Europa Explorer study builds on previous work and shows that a flagship-class Europa-orbiting mission can now go forward, requiring only engineering developments while having significantly more capability and returning considerably more science data than envisioned in previous concepts.

NASA chartered the Europa Explorer study with direction to build on the results of prior Europa mission development, concentrating on three principal areas: (1) the science return; (2) the trade space of cost, schedule, and risk; and (3) the residual radiation risk. Eleven members of the science community were identified by NASA Headquarters to serve as a Science Definition Team (SDT) to refine the goal and objectives for the Europa Explorer (**Table 1-1**). The SDT worked closely with the technical team to design a mission to achieve the Priority 1 objectives, and which retains flexibility to achieve the Priority 2 objectives and extended science.

***Table 1-1.*** *Goal and Objectives of the Europa Explorer Mission.*

| *Goal:* Explore Europa and Investigate its Habitability. | |
|---|---|
| Priority 1 Objectives: | |
| A | Europa's Ocean: Characterize the ocean and deeper interior. |
| B | Europa's Ice Shell: Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange. |
| C | Europa's Chemistry: Determine global surface compositions and chemistry, especially as related to habitability. |
| D | Europa's Geology: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration. |
| E | Europa's External Environment: Characterize the magnetic environment and moon-particle interactions. |
| Priority 2 Objective: | |
| F | Europa's Neighborhood: Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons. |

Several different architectures were considered for achieving the science objectives, including flyby missions, sub-satellites, orbiter and simple lander combinations, and a sophisticated lander only. The SDT rated the ability of those architectures to meet each of the science objectives. The single orbiter concept fully addresses all the science objectives, while the single sophisticated lander and flyby missions are deficient in all objectives to some extent or considered to have a high cost and risk.

The baseline mission concept consists of a single flight system launching in 2015, traveling to Jupiter on a Venus-Earth-Earth gravity assist (VEEGA) trajectory, and reaching Jupiter about 6 years later. The large main engine places the flight system into orbit around Jupiter for a Jovian tour phase lasting 23 months. This tour phase minimizes the required amount of propellant by using repeated Galilean satellite gravity assists to lower its orbit, until a final burn inserts the flight system into orbit around Europa. The Europa Science phase lasts for one year.

At an altitude of 100–200 km, the flight system orbits Europa approximately 11 times in an Earth day. The current best estimate for the planning payload (11 instruments) is 158 kg and an average of 106 watts in Europa orbit. The flight and ground systems are sized to provide an average data volume of 20 Gbits per Earth day. Operating scenarios were developed with the SDT to meet the science objectives in a prioritized order using methods based on current missions, most notably Mars Reconnaissance Orbiter.

The design lifetime of the flight system is ultimately limited by radiation dose. The flight system's radiation design point is 2.6 Mrad[1]. This implies a 75% probability of lasting over a year in orbit around Europa. Because the Priority 1 science objectives will be largely achieved within the first 26 eurosols[2] (~92 days), with the remaining 9 months to respond to discoveries, this system design is robust.

[1] Defined as radiation dose behind 100 mils of aluminum assuming a spherical shell model.
[2] One eurosol is one Europan day = 3.551 Earth days.

Europa Explorer is enabled by recent significant advances in radiation hardened component technologies, proven larger launch capabilities, and well-understood trajectory options. The concept relies on a traditional chemical propulsion system (similar to Cassini and Galileo), a power source consisting of the Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs, as employed by the 2009 Mars Science Laboratory), and a real-time continuous data downlink (except during occultations). The major characteristics of the baseline mission are listed in **Table 1-2**. The design includes robust margins, based on principles that have been developed and used successfully over several decades.

Instrument development drives the schedule for a 2015 launch. The project has planned a vigorous effort to support the Announcement of Opportunity solicitation, including educating the instrument community early on radiation and planetary protection approaches to mature instrument proposals. Overall, the development risk for the Europa Explorer flight system is comparable to that for Galileo and Cassini. Electronic circuits must be redesigned to accommodate radiation hardened parts. Long-lead items such as MMRTGs and propulsion systems need to be initiated early in the design process to ensure availability for integration. Challenges exist for meeting both the radiation and planetary protection requirements for bioburden reduction, but their nature is one of engineering rather than technology development.

The best estimate of the cost of the baseline mission is $3.3 BFY07, with an uncertainty of +$0.2, –$0.4 BFY07. As part of managing the development cost challenges, a deep descope plan has been developed that maintains a science floor that is still scientifically attractive. The floor mission takes advantage of a reduction in the science payload, replacement of the MMRTGs with the lower mass and cost ASRGs, and the lower cost of the Atlas V launch vehicle. The floor mission estimated cost is $2.4 BFY07, with an uncertainty of +$0.2, –$0.3 BFY07.

Continued advancements in areas such as power sources, data storage, and DSN capability could further enhance the mission, but are not required. Issues related to fuel availability for radioisotope power are crucial and need attention not only for this mission, but for any NASA missions that will depend on radioisotope power systems.

***Table 1-2.*** *Key Mission Characteristics of the Europa Explorer Baseline Mission Concept*

| | |
|---|---|
| Architecture | Single Orbiter at Europa |
| Launch Vehicle | Delta IV-H |
| Launch Date | 6/2015 |
| Trajectory | Venus-Earth-Earth Gravity Assist (VEEGA) |
| Flight Time to Jupiter | 6 years |
| Jovian System Science Ops Duration | 2 years |
| Number of Europa Encounters During the Jovian Tour | 5 |
| Number of Ganymede Encounters During the Jovian Tour | 14 |
| Number of Callisto Encounters During the Jovian Tour | 4 |
| Radiation Design Point* | 2.6 Mrads |
| Europa Orbital Lifetime | > 1 year at 75% confidence |
| Phase A-D CBE Cost ($MFY07) | 2540 |
| Phase E CBE Cost ($MFY07) | 770 |
| Total Mission Cost ($BFY07) | 3.3 |
| Science Investigations<br>Remote sensing<br>Fields and particles<br>Radio science (gravity) | <br>8 instruments<br>3 instruments<br>1 – uses telecom system |
| Average Data Volume Return | 20 Gb/day |
| Cumulative data volume through Jovian Tour | 1.8 Tb |
| Cumulative data volume through Europa Science Phase | 5.4 Tb |

*Behind 100 mils of Al

Analysis was also performed for launch opportunities later than the 2015 baseline. The Europa Explorer flight system design will serve for VEEGA launch opportunities in 2017, 2018, 2019, and 2020, with only minor propulsion tank size changes and with increasing mass margins for the later opportunities.

NASA's investment in planning for the next flagship mission to the outer planets has paid off in the form of Europa Explorer, which is ready to move into Phase A in support of a launch as soon as 2015. Europa Explorer promises dramatic strides in the goal to:

***Explore Europa and investigate its habitability.***

# 2.0 EUROPA SCIENCE GOALS AND OBJECTIVES

## 2.1 The Relevance and Prominence of Europa Exploration

*Nearly 400 years after Galileo Galilei's discovery of Jupiter's moons advanced the Copernican Revolution, one of these moons, Europa, has the potential for discoveries just as profound.*

Europa's icy surface is believed to hide a global subsurface ocean with a volume more than twice that of Earth's oceans. The moon's surface is young, with an estimated age of 60 million years, implying that it is most likely geologically active today. The molecular constituents of life have rained onto Europa throughout solar system history, are created by radiation chemistry at its surface, and may pour from vents at the ocean's deep bottom. On Earth, microbial extremophiles take advantage of environmental niches arguably as harsh as within Europa's subsurface ocean. If the subsurface waters of this Galilean moon are found to contain life, the discovery would spawn another revolution, this time in our understanding of life in the universe.

Although it is now recognized that water may exist within several of the solar system's icy satellites, Europa's relatively thin ice shell and potentially active surface-ocean exchange elevate its priority for exploration [*SSER 2006*]. A Europa mission is the first step in understanding the potential for icy satellites as abodes for life.

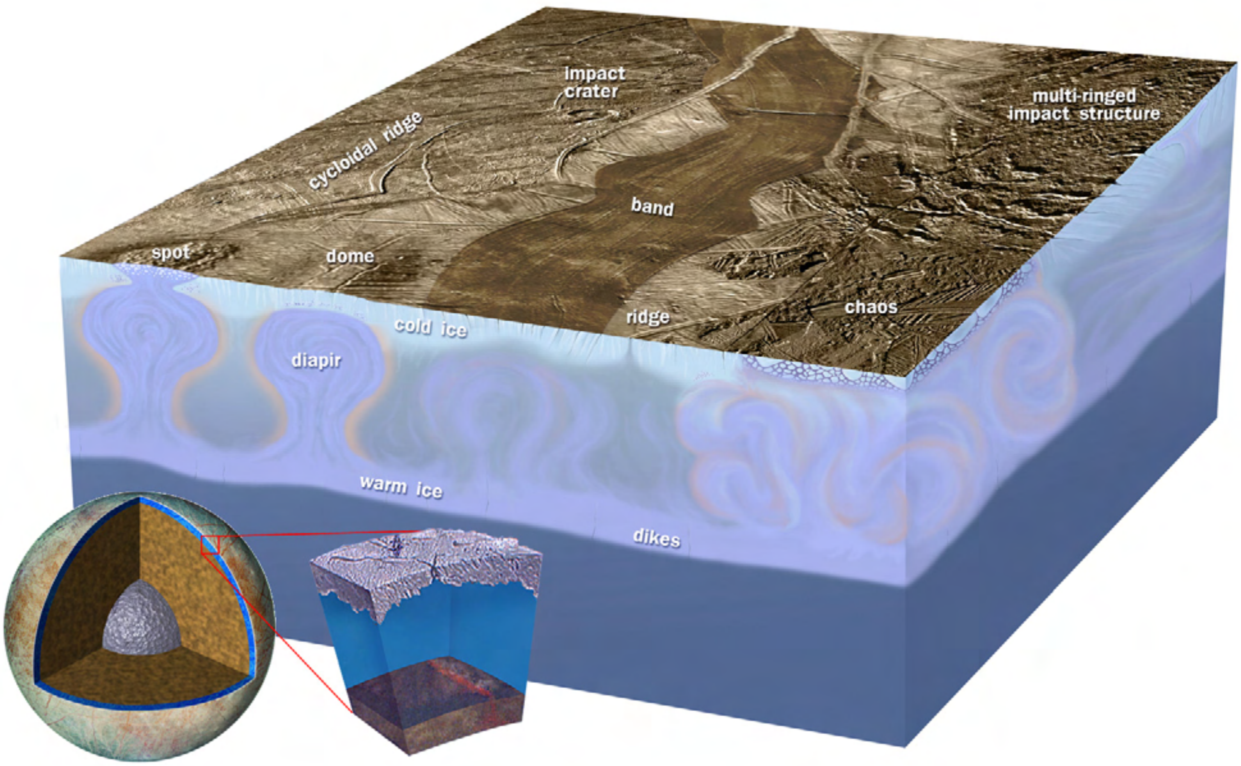



***Figure 2.1-1. Schematic models of Europa's interior structure.*** *Galileo gravity data suggests that Europa is differentiated into an iron core, rocky mantle, and $H_2O$-rich outer shell about 100 km thick, and Galileo magnetometer data implies that some of the $H_2O$ is a liquid, forming a global ocean (foreground). Galileo imaging data reveals a wide variety of enigmatic surface features. Shown in cross-section, roughly to scale, is a representation of possible ice shell processes that may have contributed to surface feature formation. Europa is unique among large icy satellites in possessing a rocky mantle in contact with liquid water, a relatively thin ice shell, abundant surface oxidants, and probable ongoing geological activity could allow "communication" between its ocean and surface. Europa is a very high priority for astrobiological exploration, and informs of the fundamental geophysical processes that govern icy satellites.*

Europa's high astrobiological potential and its complex interrelated processes have been recognized by the National Research Council (NRC) and by NASA as making Europa an extremely high priority for future exploration. The NRC's Committee on Planetary and Lunar Exploration [*COMPLEX 1999*] recognized that Europa "offers the potential for major new discoveries in planetary geology and geophysics, planetary atmospheres, and, possibly, studies of extraterrestrial life. In light of these possibilities … , COMPLEX feels justified in assigning the future exploration of Europa a priority equal to that for the future exploration of Mars."

The Solar System Exploration Survey ("Planetary Science Decadal Survey") convened by the National Research Council of the National Academy of Sciences [*SSES 2003*] identifies a Europa Geophysical Explorer as the top priority Flagship mission for the decade 2003–2013. This is principally because such a mission addresses the fundamental science question: "Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?"

NASA's scientific community-based Outer Planets Assessment Group (OPAG) "affirms the findings of the Decadal Survey, COMPLEX, and SSES, that Europa is the top-priority science destination in the outer solar system" [*OPAG 2006*].

These recommendations are reflected in the NASA Science Mission Directorate's 2006 Solar System Exploration Roadmap [*SSER 2006*], which states that "*Europa should be the next target for a Flagship mission*." The Roadmap calls out five high-level "Science Questions" (traced from the Decadal Survey's "Scientific Goals"), four of which are directly addressed by an orbital mission to Europa:

- How did the Sun's family of planets and minor bodies originate?
- How did the Solar System evolve to its currently diverse state?
- What are the characteristics of the Solar System that led to the origin of life?
- How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?

Noting that Europa's neighbors Ganymede and Callisto are also believed to have internal oceans, the Roadmap further states: "It is critical to determine how the components of the Jovian system operate and interact, leading to potentially habitable environments within icy moons. By studying the Jupiter system as a whole, we can better understand the type example for habitable planetary systems within and beyond our Solar System."

NASA's 2007 Science Plan [*NSP 2007*] echoes the many previous recommendations, calling out Europa as "an extremely high-priority target for a future mission." Acknowledging that several icy satellites are now believed to have subsurface oceans, it states: "Although oceans may exist within many of the solar system's large icy satellites, Europa's is extremely compelling for astrobiological exploration. This is because Europa's geology provides evidence for recent communication between the icy surface and ocean, and the ocean might be supplied by above and/or below with the chemical energy necessary to support microbial life." The Science Plan affirms the priority of Europa exploration in addressing fundamental themes of Solar System origin, evolution, processes, habitability, and life.

The NASA Astrobiology Roadmap [*Des Marais et al. 2003*] includes as a goal: "Explore for past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System." A subsidiary objective is to "provide scientific guidance for outer Solar System missions. Such missions should explore the Galilean moons Europa, Ganymede, and Callisto for habitable environments where liquid water could have supported prebiotic chemical evolution or life." A letter from the NASA Astrobiology Institute's Executive Council to the Europa Explorer (EE) SDT reaffirms that a Europa orbiter mission as represented by EE "is in its highest priority mission category for advancing the astrobiological goals of Solar system exploration" (Appendix I).

If a Europa orbital mission finds that Europa is a habitable environment today, with active communication between subsurface water and the near surface, then a Europa Astrobiology Lander has been recommended an important next step in the satellite's exploration [*SSES 2003; SSER 2006*]. Present exploration of Europa would feed forward to a future landed mission.

All of these recommendations are consistent with the Vision for Space Exploration document [*VSE 2004*], which places high priority on robotic exploration across the solar system, "In particular, to explore Jupiter's moons … to search for evidence of life, [and] to understand the history of the solar system. …"

The scientific foundation of a mission to Europa has been clearly laid out. Next are summarized key aspects of the state of knowledge regarding Europa, providing the framework for the Europa Explorer mission.

## 2.2 Science Background

While studies of Europa go back to the pre-spacecraft era, our understanding of the satellite has increased greatly in the past decade, during which the Galileo spacecraft made over a dozen close fly-bys of the satellite. Below are summarized the current state of knowledge regarding Europa, ties to broader cross-cutting themes including habitability and planetary processes, the key outstanding science issues, and why it is important to address these issues. The Jupiter system is considered only briefly here, as the guidelines of the EE study require that Jovian system science is a secondary priority.

### 2.2.1 Astrobiology

*Europa's subsurface may harbor the key "ingredients" required for life: liquid water, the building blocks of organic molecules, and a source of energy that can be utilized by life.*

The evidence that Europa has a global subsurface ocean at the present day is compelling. Thermal modeling predicts an ocean beneath an ice shell a few to tens of kilometers thick, considering the expected tidal heating rate in the ice shell and possibly within the rocky mantle [*Ojakangas and Stevenson 1989; Moore 2006*]. A subsurface ocean is consistent with Europa's broad range of geological features (**Figure 2.1-1**) [*Pappalardo et al. 1999*], and formation of Europa's cycloid-shaped features require the action of significant "diurnal" stresses produced by orbital eccentricity, implying an ocean at the time of their formation [*Hoppa et al. 1999*]. Compositional data indicates hydrated salts on Europa's surface, suggesting that oceanic material has erupted [*McCord et al. 1998a,b*]. Ultimately the Galileo magnetometer data is the most conclusive evidence of a subsurface ocean today, implying an induced magnetic field, produced by interaction of Jupiter's magnetic field with a globally connected shallow subsurface conducting layer, probably a salty subsurface ocean [*Kivelson et al. 2000*].

The hypothesis that Europa has a global subsurface ocean hidden beneath a relatively young (< 60 Ma [*Schenk et al. 2004*]) icy surface has profound implications in the search for past or present life beyond Earth's biosphere. Coupled with the discovery of active microbial life in seemingly uninhabitable terrestrial environments (microbial growth at sustained temperatures below –20°C, in highly concentrated brines, and under conditions of high radiation flux) [*Rothschild and Mancinelli 2001*], Europa

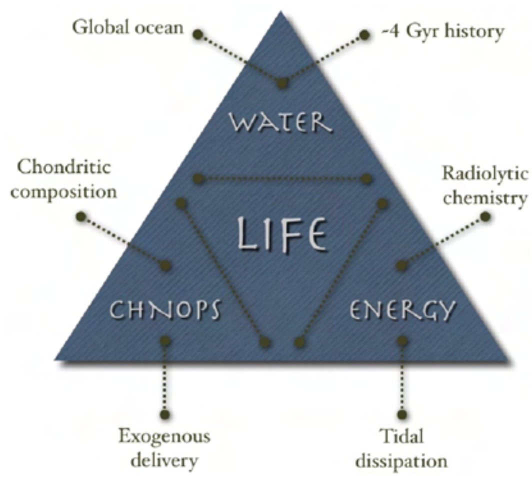



***Figure 2.2-1. Pyramid of habitability.*** *Our present understanding of the conditions for life can be distilled down to three broad requirements: 1) a sustained liquid water environment (Europa's global ocean, which has likely existed for 4 Gyr), 2) elements (e.g. C,H,N,O,P,S) that are critical for building life (derived from Europa's primordial chondritic composition, plus exogenous delivery over time), and 3) a source of energy that can be utilized by life (surface radiolytic chemistry, and possible hydrothermal activity driven by tidal heating). The cycling of chemical energy into Europa's ocean over geological time scales is key to understanding habitability of the satellite. [Figure courtesy Kevin Hand.]*

takes on new importance as a primary target for exploring habitable worlds. Life as we know it **(Figure 2.2-1)** depends upon liquid water, a photo- or chemical-energy source, complex organics, and inorganic compounds of nitrogen, phosphorus, sulfur, iron and as many as 70 trace elements. Europa appears to meet all of these requirements and is distinguished by the potential presence of enormous volumes of liquid water and geological activity that promotes the exchange of surface materials with the sub-ice environment.

If previous life existed on Europa or persists today, two competing hypotheses explain its origin. The first suggests transfer of life to Europa from Earth or other worlds; however, survival seems unlikely given the intense radiation flux on Europa and the ~24 km/sec collision velocities of meteorites with its surface [*Gladman et al. 2006*]. The other hypothesis suggests independent origins of indigenous biology. Despite extensive knowledge about life on Earth, it is not certain about when or how many times prebiotic chemistry in our solar system crossed the threshold to a microbiological world. Impact histories likely constrain the persistence of the earliest terrestrial evolutionary lineages to the end of the period of intense bombardment, although subsurface chemoautotrophs at kilometer depths could have survived even the largest impact events [*Chyba 1993*]. Alternatively, the biosphere may have recovered from such cataclysmic events by secondary life origins.

Given current information, it is not known if life ever existed or persists today on Europa. However it can be determined whether Europa is a habitable environment today, i.e. whether extant conditions are capable of supporting living organisms. Key to this question is the occurrence of liquid water beneath the icy surface and whether the geological and geophysical properties of Europa can support the synthesis of organic compounds and provide the energy and nutrients needed to sustain life.

Life on Earth occupies ecological niches sufficient in the supply of either chemical or radiation energy. Europa's global ocean has probably persisted from the origin of the jovian system to present [*Cassen et al. 1982*], although its chemical characteristics likely evolved. Inferences from Europa's young surface and models suggest that an ocean and hydrothermal system may lie beneath a sheet of ice a few to tens of kilometers thick [*Greeley et al. 2004*]. Tidal deformation may drive heating and geological activity within Europa, and there could be brine pockets within the ice associated with impurities, partial melt zones, and clathrates. The potential occurrence of hydrothermal systems driven by tidal heating or volcanic activity could serve as a favorable environment for prebiotic chemistry or sustaining microbial chemotrophic organisms. Cycling of water through and within the ice shell, ocean, and the permeable upper rocky mantle could maintain an ocean rich with oxidants and reductants necessary for the chemistry of life [*Chyba and Phillips 2001*]. In order to address this aspect of Europa's habitability a better understanding of the mantle and ice shell is needed.

Radiolytic chemistry on the surface is responsible for the production of $O_2$, $H_2O_2$, $CO_2$, $SO_2$, $SO_4$, and other yet to be discovered oxidants [*Carlson et al. 1999a,b*]. At present, mechanisms and timescales for delivery of these materials to the sub-surface are poorly constrained. Similarly, cycling of the ocean water through seafloor minerals could replenish the water with biologically useful reductants. If much of the tidal energy dissipation occurs in the mantle, then there could be significant cycling between the ocean water and rocky mantle. Conversely, if most of the tidal dissipation occurs in the ice shell, then the ocean water could be depleted in the reductants needed for biochemistry. Chemical cycling of energy on Europa is arguably the greatest uncertainty in our ability to assess the habitability of Europa [*Lipps and Rieboldt 2005*].

Geophysical measurements will set constraints on the potential for biology. A high priority will be to characterize the ocean and its dynamic relationships with the ice shell including the nature of ice-ocean exchange. Assessments of the geochemical environment as it pertains to habitability will directly address the questions: Is the surface composition and chemistry of Europa compatible with sub-surface life? Does it harbor trace signatures of prebiotic or biological processes?

While a lander could lead to the identification of minimal biological requirements for reductants and oxidants and how they flow through the system, orbital remote sensing could reveal evidence for habitability and the possible existence of past or present life. Important measurements will focus on relative terrain ages and chemical composition. Identifying the youngest regions of direct exchange, or "communication," with the ocean is the first step in discovering chemistry of endogenous origin. Spectral analysis of these regions, especially of those known to be younger and less radiolytically processed, will then allow distinguishing among the variety of chemical signatures on the surface. Results would lead toward understanding the chemistry of the ocean.

Distinguishing biosignatures from the ocean chemistry requires instruments that can resolve complex organic and mineral chemistry. Any life forms in a Europan ocean would consist of microbial chemotrophs capable of synthesizing a vast array of complex organics. The detection of large, complex compounds with diverse functional groups (e.g. with N and P) in the youngest ice, but not in older ices, would be of great astrobiological interest. Were photosynthesis possible in the near surface, detection of related pigments could provide a biosignature [*Greenberg et al. 2000*].

The combined physical, compositional and surface age mapping described above could yield a strong, compelling case for a habitable and possibly inhabited subsurface ocean.

### 2.2.2 Geophysics

*Europa continually flexes as it orbits, tugged and deformed by Jupiter's gravity; as it responds by bending, breaking, churning, and heating, the characteristics of its ocean and ice can be inferred.*

The surface of Europa suggests recently active processes [*Johnson 2005*]. Jupiter raises gravitational tides on Europa, which contribute to thermal energy in the ice shell [*Ojakangas and Stevenson 1989*] and produce near-surface stresses responsible for some surface features [*Greeley et al. 2004*]. Although relatively little is known about the internal structure, most models include an outer ice shell underlain by liquid water, a silicate mantle, and iron-rich core [*Anderson et al. 1998*]. Measurements to constrain these models include those of the gravitational and magnetic fields, topographic shape, and rotational state of Europa, each of which includes steady-state and time-dependent components. These models can be used to characterize the ocean and the overlying ice shell. Radar sounding will also elucidate structure within the ice shell, and may possibly image the ice-ocean interface (see §2.3.4 B).

#### 2.2.2.1 Gravity

Observations of the gravitational field provide information about the interior mass distribution. For a spherically symmetric body, all points on the surface would have the same gravitational acceleration, while in those regions with more than average mass, gravity will be greater. Lateral variations in gravitational field strength thus indicate lateral variations in internal density structure.

Within Europa, principal sources of static gravity anomalies are expected to be those due to ice shell thickness variations, or topography on the ocean floor. Gravity anomalies that are not spatially coherent with ice surface topography are presumed to arise from greater depths.

One of the most diagnostic gravitational features is the amplitude and phase of the time-dependent signal due to tidal deformation [*Moore and Schubert 2000*]. The forcing from Jupiter is well known, and the response will be much larger if a fluid layer decouples the ice from the interior, permitting unambiguous detection of an ocean, and characterization of the ocean and ice shell. Because the distance to Jupiter is 430 times the mean radius of Europa, only the lowest degree tides are expected to be detectable.

**Figure 2.2-2** illustrates the tidal potential variations on Europa during a single orbital cycle. The tidal amplitude is directly proportional to this potential. Measurement of tidal effects, and their relationship to the ocean and ice shell, are discussed in more detail in §2.3.4 A.

#### 2.2.2.2 Topography

Characterizing the topography is important for several reasons. At long wavelengths (hemispheric-scale), it is mainly a response to tides and possibly shell thickness variations

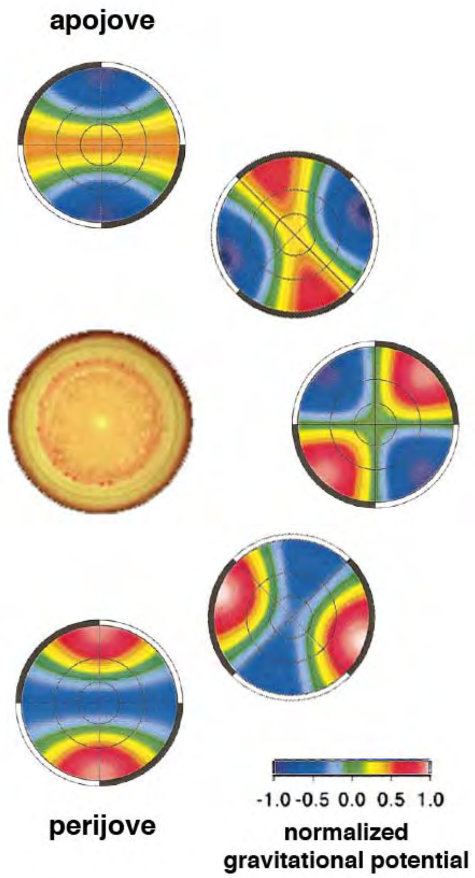



***Figure 2.2-2. Europa experiences a time-varying gravitational potential field*** *as it moves in its eccentric orbit about Jupiter (eccentricity = 0.0094), with a 3.551 day (1 eurosol) period. Europa's tidal amplitude varies proportionally to the gravitational potential, so the satellite flexes measurably as it orbits. In this adaptation of a figure from* Moore and Schubert *[2000], we look down on the north pole of Jupiter as Europa orbits counterclockwise with its prime meridian pointed approximately toward Jupiter. Measuring the varying gravity field and tidal amplitude simultaneously allows the interior rigidity structure of the satellite to be derived, telling of the properties of its ocean and ice shell.*

driven by tidal heating [*Ojakangas and Stevenson 1989*], and is thus diagnostic of internal tidal processes. At intermediate wavelengths (hundreds of kilometers), the topographic amplitudes and correlation with gravity are diagnostic of the density and thickness of the ice shell. The limited topographic information available shows Europa to be very smooth on a global scale, but topographically diverse on regional to local scales. At the shortest wavelengths (kilometer-scale), small geologic features will tend to have topographic signatures diagnostic of formational process (§2.2.4).

#### 2.2.2.3 Rotation

Tidal dissipation within Europa probably drives its rotation into equilibrium, with implications for both the direction and rate of rotation. The mean rotation period should match the mean orbital period, so that the sub-Jupiter point will librate in longitude, with an amplitude equal to twice the orbital eccentricity. The spin pole is expected to occupy a Cassini state [*Peale 1976*], similar to that of Earth's Moon. The gravitational torque exerted by Jupiter on Europa will cause Europa's spin pole to precess about the orbit pole, while the orbit pole in turn precesses about Jupiter's spin pole, with all three axes remaining coplanar. The obliquity required for Europa to achieve this state is ~0.1 degree, but depends upon the moments of inertia, and is thus diagnostic of internal density structure [*Bills 2005*].

The rate of rotation will be nearly constant, but the orbital angular rate varies slightly in an eccentric orbit. As a result, the sub-Jupiter point on Europa will librate in longitude. That, in turn, causes a torque on the body which makes it deviate slightly from uniform rotation. If the body behaves rigidly, the expected amplitude of this forced libration is expected to be ~100 m [*Comstock and Bills 2003*], but if the ice shell is mechanically decoupled from the silicate interior, then the libration could be three times larger. Similar forced librations in latitude are due to the finite obliquity, and are also diagnostic of internal structure in the same way. The rate of rotation will also change in response to tidal modulation of the shape of the body, and corresponding changes in the moments of inertia [*Yoder et al. 1981*]. An advantage of having a wide variety of different geophysical observations, all relevant to the internal structure of Europa, is that they reduce the ambiguity inherent in interpretations.

#### 2.2.2.4 Magnetic Field

Magnetic fields interact with conducting matter at length scales ranging from atomic to galactic. Magnetic fields are produced when currents flow in response to electric potential differences between interacting conducting fluids or solids. Many planets generate their own stable internal magnetic fields in convecting cores or inner shells through dynamos powered by internal heat or gravitational settling of the interior. Europa does not generate its own magnetic field, suggesting that its core has either frozen or is still fluid but not convecting.

Europa, however, is known to respond to the rotating magnetic field of Jupiter through electromagnetic induction. In this process, eddy currents are generated on the surface of a conductor to shield its interior from changing external electric and magnetic fields. The eddy currents generate their own magnetic field—called the induction field—external to the conductor. This secondary field is readily measured by a magnetometer located outside the conductor.

The induction technique exploits the fact that the primary alternating magnetic field at Europa is provided by Jupiter, because its rotation and magnetic dipole axes are not aligned. It is now widely believed that the induction signal seen in Galileo magnetometer data [*Khurana et al. 1998*] arises within a subsurface ocean in Europa. The measured signal was shown to remain in phase with the primary field of Jovian origin [*Kivelson et al. 2000*]), thus unambiguously proving that the perturbation signal is a response to Jupiter's field.

Modeling of the measured induction signal, although clearly indicative of a Europan ocean, suffers from non-uniqueness in the derived parameters because of the limited data. From a short series of measurements, the induction field components cannot be separated uniquely, forcing assumptions that the inducing signal is composed of a single frequency corresponding to the synodic rotation period of Jupiter. Unfortunately, single frequency data cannot be inverted to determine independently both the ocean thickness and the conductivity. Nevertheless, the single frequency analysis of *Zimmer et al.* [*2000*] reveals that the ocean must have a conductivity of at least 0.06 S/m. Recently, *Schilling et al.* [*2004*] determined the ratio of induction field to primary field at 0.96 ± 0.3, leading *Hand and Chyba* [*2007*] to conclude that the ice shell is < 15 km thick and the ocean water conductivity > 6 S/m.

In order to determine the ocean thickness and conductivity, magnetic sounding at multiple frequencies is required. The depth to which an electromagnetic wave penetrates is inversely proportional to the square root of its frequency. Thus, longer period waves sound deeper and could provide information on the ocean's thickness, the mantle, and the metallic core. Electromagnetic sounding at multiple frequencies is routinely used to study Earth's mantle and core from surface magnetic data [*Parkinson 1983*]. Recently, *Constable and Constable* [*2004*] demonstrated that data from orbit can be used for electromagnetic induction sounding at multiple frequencies.

Europa is immersed in various low-frequency waves that could be used for magnetic sounding, some of which arise from Io's torus at the outer edge of Europa's orbit. Dominant frequencies occur at the synodic rotation period of Jupiter (period = 11 hr) and the orbital period of Europa (period = 3.55 days = 85.2 hr). Over a broad range of parameter space, the induction curves at two frequencies intersect (**Figure 2.2-3**). In this range, the ocean thickness and conductivity can be determined uniquely. In order to sound at these two frequencies, continuous data are required from low altitude over times of at least one month. Further constraints on the ocean, mantle, and core would be provided by the broad-band (but weak) signal excited by Io's torus for which continuous observations of at least months are desirable.

#### 2.2.3 Composition

*Characterizing the surface organic and inorganic chemistry provides fundamental information about the properties and habitability of the subsurface and ocean, with the relationship of composition to surface features controlled by geological processes and communication with the interior.*

The composition of the surface and the chemistry that creates and modifies it are expressions of the history and evolution of Europa. Some surface materials are probably derived from the ocean and some are altered by the radiation environment.

Europa's bulk density suggests the presence of both water and silicates. Thermodynamic models and geophysical observations indicate

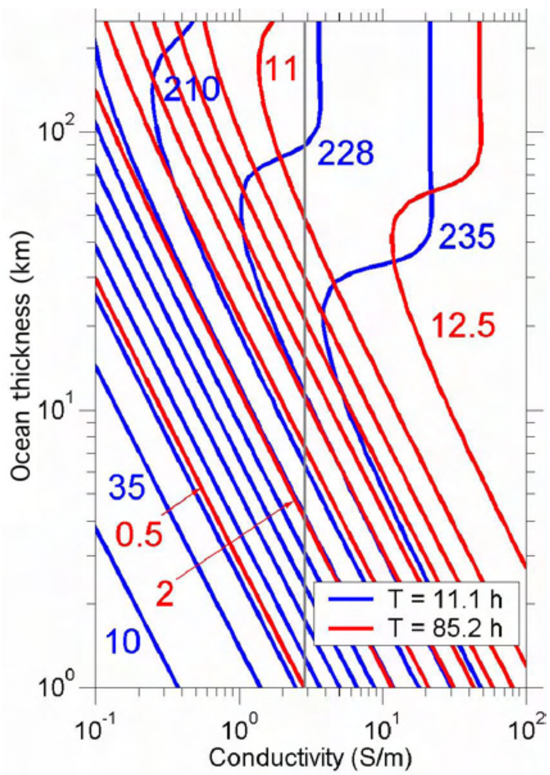



*Figure 2.2-3. Contours of the induced magnetic field (in nT) generated at the surface of Europa, predicted at Jupiter's synodic rotation period of 11.1 hr (blue) and at Europa's orbital period of 85.2 hr (red), as a function of ocean thickness and ocean conductivity. For relatively large values of ocean thickness and conductivity, the predicted induction curves intersect, permitting ocean thickness and conductivity to be uniquely determined from orbital measurements. [From* Khurana et al. 2002.*]*

that Europa differentiated into a silicate mantle and perhaps iron core with a water-ice crust. Magnetic field measurements suggest that the water-ice layer is at least partially liquid today. The differentiation process and resulting mixing of water with the silicates and carbonaceous materials that formed Europa, resulted in chemical alteration and redistribution including to the surface. Surface materials are subject to radiation by particles trapped in Jupiter's magnetic field and chemical alteration. The altered materials can be incorporated into Europa's subsurface by geologic processes and react with the ocean or can be sputtered to form Europa's tenuous atmosphere.

#### 2.2.3.1 Icy and Non-Icy Composition

Compositional information from Earth-based telescopic observations and data from the Voyager and Galileo spacecraft [e.g. *McCord 2000*] show that the surface is reflective at visible but absorbing at NIR wavelengths, suggesting an ice-covered surface. Absorptions of solid $H_2O$ in Europa's 1–2.5 µm spectrum demonstrated that water ice covers large parts of Europa's surface.

The icy parts of Europa are variable in space and time. Polar fine-grained deposits suggest frosts formed from ice sputtered or sublimated from other areas [*Hansen and McCord 2004*]. Equatorial ice regions are more amorphous than crystalline, perhaps due to radiation damage. Thus, mapping ice crystallinity can be used to determine overall age.

Earth-based telescopes were used to detect $O_3$ (probably due to radiolysis of ice), and sulfur species thought to be linked to effects of Jupiter's magnetosphere [e.g. *Noll et al. 1996*]. *Brown and Hill* [*1996*] first reported a cloud of Na around Europa, and *Brown* [*2001*] detected a cloud of potassium and reported that the Na/K ratio suggested an endogenic source of the sputtered materials. Galileo's infra-red and ultraviolet spectrometers also detected absorptions due to hydrogen peroxide [*Carlson et al. 1999b*], which is likely due to radiolysis of ice.

In addition to water ice, the Galileo infrared spectrometer revealed various non-ice hydrated constituents, which originate from the ocean and/or from interaction with the radiation environment. Hydrated magnesium and sodium sulfate minerals are inferred in regions of surface disruption and are suggested to be from subsurface ocean brines [*McCord et al. 1998b, 1999*]. An alternative or complimentary hypothesis is that sulfuric acid is present in these deposits [*Carlson et al. 1999a*], perhaps created by radiolysis of sulfur from Io, processing of endogenic $SO_2$, or from ocean-derived sulfates. As on Callisto and Ganymede, $CO_2$ is located preferentially on the less icy parts of Europa [*McCord et al. 1998a; Smythe et al. 1998*].

Additionally, detecting organic molecular groups such as CH and CN, already found on the other icy Galilean satellites [*McCord et al. 1998a*], is important to understanding Europa's habitability. Measurements of isolated, potentially small exposure of organic rich-materials can lead to an understanding of their origin. Considering the extreme radiation environment of Europa, organic molecules or organic molecular fragments might survive in younger deposits in regions of lesser irradiation, but are not expected in older deposits and those exposed to greater degrees of irradiation (§2.2.5). Understanding whether and how organic compounds are associated with the subsurface would illuminate Europa's potential for life.

The abundance of molecular species and materials already identified on Europa's surface, and the active chemistry implied, indicate that there is much to be learned about Europa and its putative ocean from more powerful and complete observations of surface composition. Radiolysis and photolysis processes are important for creating and altering composition on the surface. These are of interest in themselves, and as they affect our interpretations of composition. A new window on Europa's composition will be provided by the combination of higher spectral resolution (to reduce existing ambiguities in interpretation), higher signal-to-noise ratio (to improve detection limits), and higher spatial resolution (to determine localized composition and enhance detectivity).

#### 2.2.3.2 Relationship of Composition to Processes

Galileo's instruments were designed to study surface compositions on the scale of the compositional provinces (**Figure 2.2-4**). Some surface features were found to be colored reddish by some pigment and contain hydrated materials apparently associated with the subsurface geology and geochemistry, which is distinct from the orangish and UV-absorbing stain centered on the trailing side that is believed to be exogenic and sulfur-related [*Lane et al. 1981*]. Moreover, the intense radiation striking the surface can alter the intrinsic materials as well as implant new components. Many of these surface features suggest processes that have compositional implications. In addition, the images help set the geological context for the compositional analysis.

Magnetic field measurements by Galileo of ion-cyclotron waves in the wake of Europa provide evidence of sputtered and recently ionized Cl, $O_2$, $SO_2$ and Na ions [*Volwerk et al. 2001*]. These observations suggest that implantation is a key part of Europa's composition story; however, much remains unknown about the chemistry of the materials being implanted and their sources.

The relative importance of endogenic versus exogenic sources of non-ice constituents depends on factors such as geologic setting, age, and the radiation

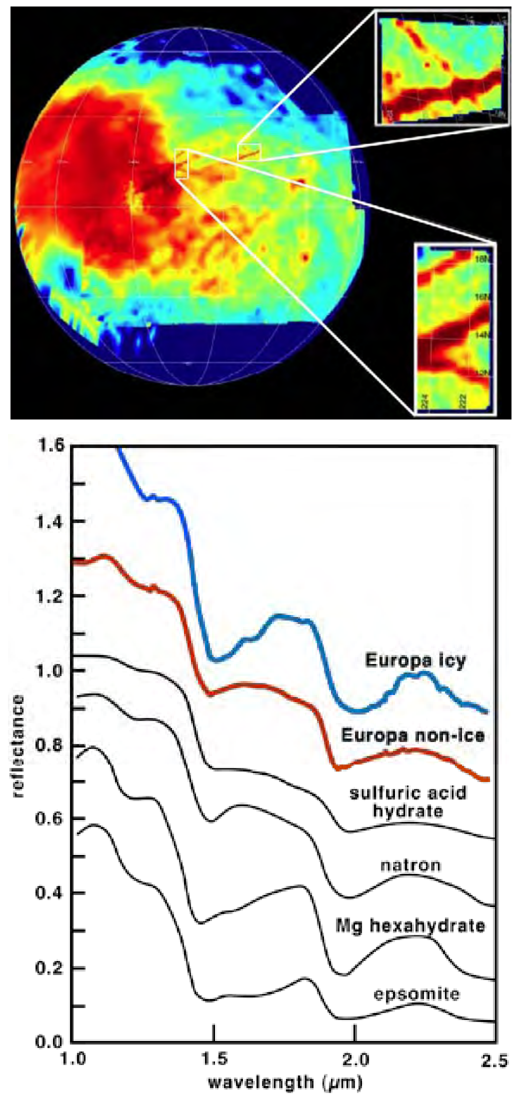



***Figure 2.2-4. Reflectance spectra of hydrated materials on Europa.*** *The distribution of hydrated materials on Europa (top, red) correlates with geologically disrupted terrains and triple bands (insets), and with the trailing hemisphere. Candidate materials for Europa's non-ice component (bottom) include sulfuric acid hydrate ($H_2SO_4$•$nH_2O$) and various hydrated sulfate salts. [*McCord et al. 1999, 2002*].*

environment. Surface composition probably results from combinations of several processes. For example, a process involving subsurface hydrated magnesium and sodium sulfate and sulfuric acid may be operating. Salts derived from the ocean could be a mixture of dominantly Mg and Na salts. Na sulfates would be more vulnerable to radiative disassociation, resulting in some sulfuric acid ($H_2SO_4$) [*McCord et al. 2001, 2002; Orlando et al. 2005*]. This allows the presence of both indigenous salts and sulfuric acid, and a source for Na and K around Europa [*Brown 2001*].

Compositional measurements are required at a scale sufficient to resolve geologic features and the transitions among them, in order to unravel these complicated processes. Sampling a wide range of latitudes and longitudes will be needed to understand global effects such as implantation rates, temperature dependence, and surface age. Ultraviolet to short wavelength infrared spectroscopy is needed to understand organic, ice, non-ice, and radiolytically generated materials.

A major open issue is the link between composition and the ocean. There is already an association found between composition and surface features plausibly linked with the ocean, including the presence of salt minerals [*McCord et al. 1998b, 1999*]. These may indicate direct contact with the ocean through melting or water eruption, or indirect contact through diapirism (see §2.2.4).

Another major issue is the origin (exogenic and/or endogenic) of volatiles such as $CO_2$ and their behavior over time. Finding the presence of organic molecular groups, such as CH and CN, and understanding their origin would be important to understanding the astrobiological potential of Europa, especially if there is demonstrable association with the ocean.

#### 2.2.4 Geology

*By understanding Europa's varied and complex geology, the moon's past and present processes are deciphered, along with their implications for habitability.*

At < 60 Ma, Europa's surface is young by solar system standards, and parts of it may be active today. This relative youth is inherently linked to the ocean and the effects of gravitational tides, which trigger processes that include resurfacing, cracking of the ice shell, and release of materials from the interior. Clues to these and other processes are provided by surface features such as linear fractures and ridges, disrupted terrain, and impact craters (**Figure 2.1-1**).

##### 2.2.4.1 Linear Features

Europa's surface is dominated by linear ridges, bands, and fractures (**Figure 2.2-5**). Ridges are the most common and appear to have formed throughout Europa's visible history. They range from 0.1 to > 500 km long, are as wide as 2 km, and can be several hundred meters high. Ridges include simple structures, double ridges separated by a trough, and intertwining ridge-complexes [e.g. *Greeley et al. 2004*]. Whether these represent different processes or stages of the same process is unknown. Cycloidal ridges are similar to double ridges, but form chains of linked arcs.

Most models of linear feature formation include fracturing in response to processes within the ice shell [*Greeley et al. 2004*]. Some models suggest that liquid oceanic material or warm mobile subsurface ice squeezes through fractures to form the ridge, while others suggest that ridges form by frictional heating and possibly melting along the fracture shear zone. Thus, ridges might represent regions of communication among the surface, ice shell, and ocean, plausibly permitting surface oxidants to enter the ocean. Some features, such as cycloidal ridges, appear to form as a direct result of Europa's tidal cycle [*Hoppa et al. 1999*].

Bands reflect fracturing and lithospheric separation, much like sea-floor spreading on Earth, and most display bilateral symmetry [e.g. *Sullivan et al. 1998*]. Their surfaces vary from relatively smooth in texture to heavily fractured. The youngest bands (indicated by their cutting across older features) tend to be dark, while older bands are bright, suggesting that bands brighten with time. Geometric reconstruction of bands suggests that a spreading model is appropriate, indicating extension in these areas, and possible contact with the ocean [*Tufts et al. 2000; Prockter et al. 2002*]. However, it is uncertain how the amounts of extension are accommodated by compression in other areas.

Some models suggest that ridges and local folds could reflect such compression, but lack of global images, topographic information, and

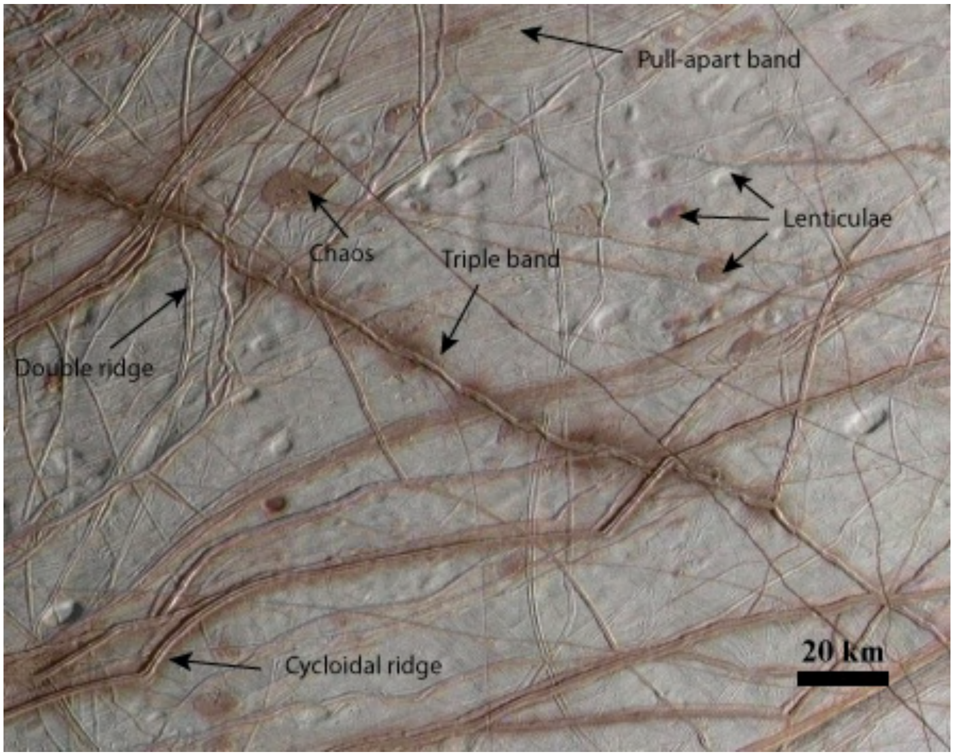



***Figure 2.2-5.*** *A selection of Europa's diverse surface features showing different types of surface deformation, which in turn provide information about geological processes and their possible connections to the tidal processes and the subsurface ocean.*

knowledge of subsurface structure underlying these features preclude testing these ideas. Fractures are narrow (from 100s of meters to the ~10 m limit of the highest image resolution images) but can exceed 1000 km in length. Some fractures cut across nearly all Europa's surface features, indicating that the ice shell is subject to deformation on the youngest time-scales.

The youngest ridges and fractures could be active today in response to tidal flexing, and subsurface sounding could help to identify zones of current or recent activity. Young ridges may be places where the ocean has communicated with the surface, and would be prime targets as potential habitable niches.

#### 2.2.4.2 Disrupted Terrain

Europa's surface has been disrupted to form circular features (lenticulae), and irregular-shaped chaos zones. Lenticulae include pits, spots, and domes that are typically about 10 km across, which may form by upwelling of lower density material through the ice shell. It is believed that they formed when convecting ice or slush in the ice shell broke through the surface permitting either direct communication (through melting) or indirect communication (through convection) between the ocean and surface. Geophysical models of convection have been used to estimate the thickness of the ice shell as at least 10–20 km thick at the time of their formation [*McKinnon 1999*].

Chaos is generally characterized by fractured plates of ice that have been shifted into new positions. Much like a jigsaw puzzle, many plates can be fit back together. Some ice blocks appear to have disaggregated and "foundered" into finer-textured matrix, while other chaos areas stand higher than the surrounding terrain. Models of chaos formation suggest whole or partial melting of the ice shell, perhaps enhanced by local pockets of brine. Chaos and lenticulae commonly have associated dark, reddish zones thought to be material derived from the subsurface, possibly from the ocean. However, these and related models are poorly constrained because the total energy partitioning within Europa is not known, nor are details of composition. Subsurface sounding, surface imaging, and topographic mapping are required to understand the formation of disrupted terrain, and its implications for habitability.

#### 2.2.4.3 Impact Features

Only 24 impact craters ≥ 10 km have been identified on Europa [*Schenk et al. 2004*], suggesting that the surface is very young on geological timescales. This is remarkable in comparison to Earth's moon, which is only slightly larger but far more heavily cratered. The youngest Europan crater is thought to be the 24 km-diameter Pwyll, which still retains its bright rays, and likely formed less than 5 Ma ago. Complete global imaging will allow more detailed determination of the age of Europa's surface, and may help to identify the very youngest areas.

Europa crater morphologies vary from bowl-shaped depressions with crisp rims, to shallow depressions with smaller depth-to-diameter ratios. Craters up to 25–30 km in diameter have morphologies consistent with formation in a warm but solid ice shell, while the two largest impacts (Tyre and Callanish) might have punched through brittle ice into a liquid zone at about 20 km depth [*Moore et al. 2001; Schenk et al. 2004*]. Characterizing the scars of impact processes at and below the surface (especially searching for cryptic, partially destroyed impact craters) provides insight into the ice shell and how it has deformed over time.

#### 2.2.4.4 Geological History

Determining the geological histories of planetary surfaces requires identifying surface features and subsurface structures and placing them into a time-sequence.

In the absence of ages derived from isotopic measurements of rocks, most planetary surface ages are assessed from impact crater frequencies, with more heavily cratered regions reflecting greater ages. The paucity of impact craters on Europa precludes this technique. Thus, superposition (i.e., younger materials seen "on top" of older materials) and cross-cutting relations are used to assess sequences of formation [*Figueredo and Greeley 2004*]. Unfortunately, current image coverage is both incomplete for Europa and disconnected from region to region, making the understanding of Europa's global surface history difficult. Where images of sufficient resolution exist, it appears that the style of deformation has evolved through time from ridge and band formation to disrupted terrain [*Greeley et al. 2004*]. Europa's surface features generally brighten and become less red through time, so albedo and color can serve as a proxy for age [*Geissler et al. 1998*]. Global imaging including color and topography, coupled with subsurface sounding, would enable models for this evolution to be tested, which could have implications for changes in the thickness of the ice shell with time.

Topography can be diagnostic of the origin of geological features and may show trends with age. Profiles across ridges, bands, and the diverse types of disrupted terrains will constrain their modes of origin. Moreover, flexural signatures are expected to be indicative of local elastic lithosphere thickness at the time of their formation, and may provide evidence of topographic relaxation.

#### 2.2.4.5 Landing Site Characterization

Although the EE mission is not expected to carry a lander (§3.2), a lander has been identified as a high priority follow-up to EE if Europa is found to be a habitable environment at present with communication between subsurface water and the near surface [*SSES 2003; SSER 2006*]. Therefore, characterization of potential landing sites is of relevance.

Future landed missions will require high-resolution imaging data (~1 m/pixel or better) to assess the surface on scales needed for safe landings. The roughness and overall safety of potential landing sites can also be characterized through radar scattering properties, photometric scattering properties, thermal inertia, and detailed altimetry. Such data sets will also illuminate fine-scale processes that create and affect the regolith including: mass wasting, sputter erosion, sublimation, impact gardening, and frost deposition. Along with corresponding high-resolution subsurface profiling, these data would help to assess possible mechanisms and likely sites of recent communication with the subsurface ocean.

Galileo results reveal a complex geology for Europa and suggest a wide variety of models for the origin and evolution of the surface. These models can be constrained only with new spacecraft data, including high resolution compositional and visible mapping, topographic data, and subsurface sounding.

### 2.2.5 External Environment

*Understanding particles and fields at Europa, including surface and atmospheric interactions, is critical in understanding the satellite's surface chemistry and habitability.*

Europa is located within Jupiter's powerful magnetosphere which dominates over the magnetized plasma of the solar wind. Jupiter's rotating magnetic field traps charged particles such as electrons, protons, and heavier ions. Most are low energy particles, referred to as the plasma. The magnetosphere can extend 60 to 100 times Jupiter's radius where it transitions to the surrounding solar wind.

The energetic particle radiation at the surface has important consequences for Europa's surface chemistry, and perhaps for life. The particle radiation in the near-surface ice produces many highly oxidized species that react with other non-ice materials to form a wide array of compounds. Such compounds, if transported to the ocean would provide an important source of chemical energy. At the surface, radiation processing alters any compounds that may have come from below, including any organics. To understand Europa's surface chemistry and thus its habitability, critical factors are its external environment and how that environment interacts with the surface.

The interface between Jupiter's magnetosphere and Europa's surface is Europa's tenuous atmosphere (**Figure 2.2-6**). Composed principally of $O_2$, the surface pressure is just ~$2 \times 10^{-12}$ bar [*McGrath et al. 2004*]. The atmosphere is principally maintained by ion sputtering of Europa's surface. Atmospheric molecules are subsequently ionized by electron impact, charge exchange, and solar photons.

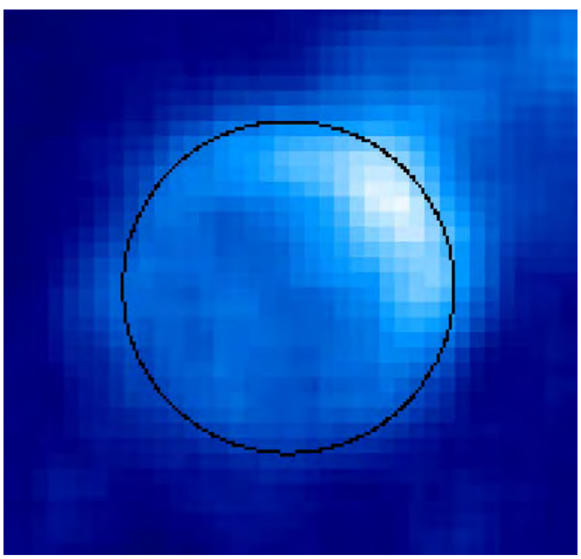


***Figure 2.2-6**. **Oxygen emission from Europa's atmosphere**, observed in ultraviolet wavelengths (1356 angstroms) with the Hubble Space Telescope [*McGrath et al. 2004*]. This image shows the atmosphere to be bright in the anti-jovian hemisphere, suggesting significant heterogeneity and complexity.*

Because the rotation speed of Jupiter's magnetosphere is faster than Europa's speed in its orbit, charged particles are continuously overtaking the satellite. Much like a fluid, some particles are diverted around the body while others impact its surface. Ionospheric conductivity is expected to be small (height integrated conductance ~10 S), but it is much higher than the Alfvén conductance (~2 S) of the medium at the location of Europa; it is large enough that a good fraction of the plasma flowing towards Europa gets diverted around the satellite.

Close to Europa, an interaction region is formed in which the plasma, electric, and magnetic fields are perturbed from their background values. For example, the plasma slows in the upstream region approaching the satellite, enhancing the magnetic field strength in that region. The nature and strength of this interaction field provides information on the ionospheric conductivity, the scale height of the atmosphere, and the plasma pick-up rate. *Neubauer* [*1980, 1998*] provide the theoretical underpinnings of this interaction. Recently, *Schilling et al.* [*2004*] used Neubauer's formalism to calculate the interaction field generated by the exosphere of Europa. Because Europa also produces its own induced magnetic field, which implies the existence of an ocean, the interaction region will reflect those contributions as well. Characterizing the perturbations from plasma near Europa is critical for studies of the ocean electromagnetic induction.

Above the plasma energies, the densities of charged particles decreases rapidly with increasing energy. Europa's orbit is deep within an intense radiation belt at Jupiter. Like the cold plasma, these radiation belt particles principally corotate with Jupiter and preferentially impact the trailing hemisphere of the satellite. Among the energetic particles, two subgroups are of interest: *medium energy ions* (tens to hundreds of keV) and *MeV electrons*. The medium energy ions deposit energy in the topmost layer of Europa's surface. A 100 keV proton penetrates in ice to a few tens of microns. Heavier ions, such as oxygen and sulfur ions, which are plentiful in Jupiter's magnetosphere, have an even shorter depth of penetration. Their energy contributes to sputtering, where molecules are ejected from the surface. Sputtering can eject water molecules, molecular oxygen, and any impurities within the ice [*Cheng et al. 1986*], contributing to the erosion of surface features. Some of these molecules are ejected fast enough to escape Europa, some add to the satellite's atmosphere, while others return to the surface, potentially brightening the surface though time (§2.2.4.4). Sputtering also has the potential to expose subsurface material which had not been in equilibrium with the atmosphere. Thus, probing the sputter-produced atmosphere of Europa is a means of studying surface constituents, from which parent molecules can be inferred (§2.2.3.1) [*Johnson et al. 1998*].

Some surface constituents result from exogenic sources. Io's volcanoes release $SO_2$ which is dissociated, ionized, and the ions accelerated. Some sulfur ions impact Europa and become incorporated into the ice, forming new molecules. It is important to separate surface materials formed by implantation from those that are endogenic. For example, the detected Na/K ratio is supportive of an endogenic origin—and perhaps an ocean source—for sodium [*Johnson et al. 2002*].

MeV electrons can penetrate the surface more deeply than ions of the same energy. As they decelerate, energetic electrons emit secondary photons that can penetrate even deeper. Therefore, a layer of the ice more than 1 m deep is affected by electron radiolysis. In this region bonds are broken in pre-existing molecules, including any organics, while other molecules including oxidants are created, generating a potential fuel for microbial life.

**Figure 2.2-7** shows radiation dose versus surface depth in pure solid ice, based on Voyager and Galileo data. The slight increase in electron dose below about 100 mm is due to

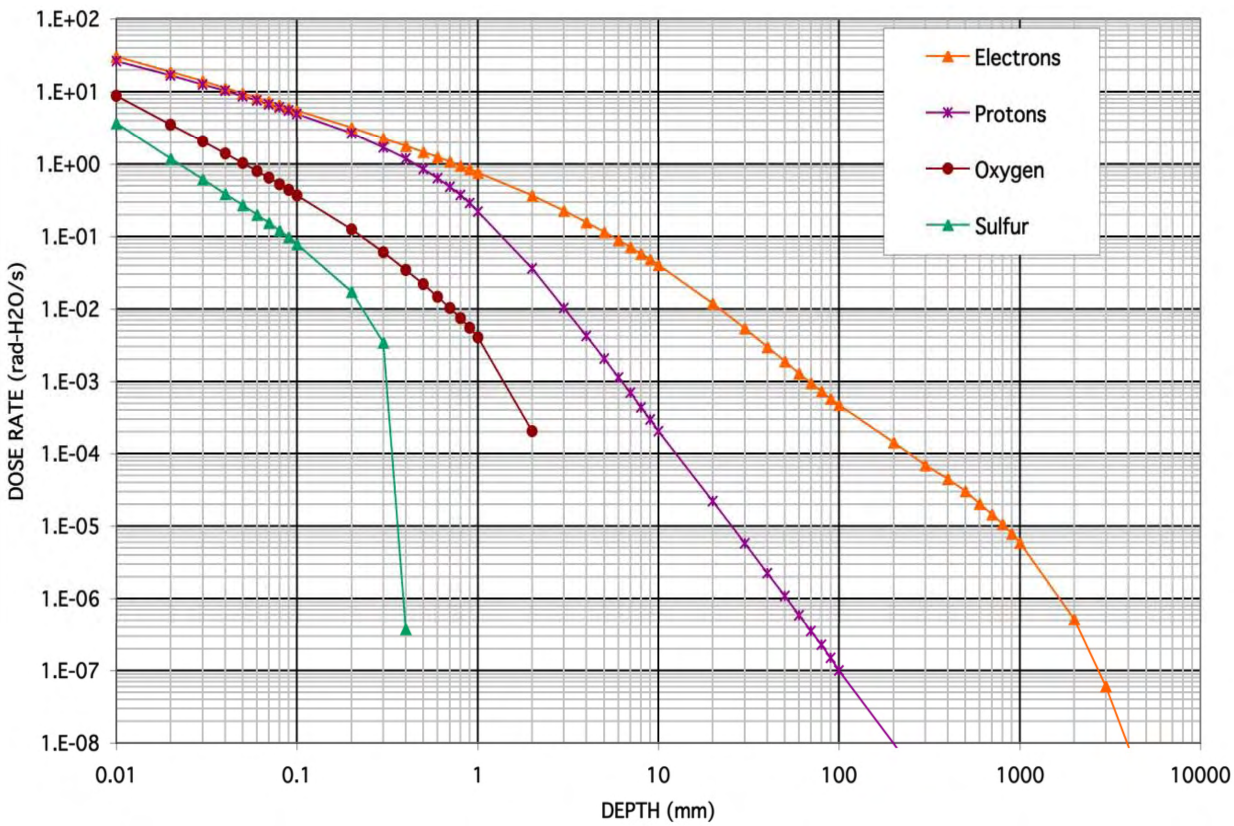



***Figure 2.2-7.*** *Estimated dose rate into Europa's trailing hemisphere as a function of depth in pure water ice. Molecular bonds will be broken and oxidants will be formed to these depths. Calculation uses energy spectra detected above Europa's surface by spacecraft and a model of the transport [*Paranicas et al. 2002*].*

secondary photons. Electrons near Europa dominate the particle energetics of most of the surface. Thus, it is important to study their bombardment pattern, which is predicted to vary as functions of longitude and latitude [*Paranicas et al. 2001, 2007*]. High radiation doses make it likely that surface constituents are processed and transformed. **Figure 2.2-7** implies that every $H_2O$ molecule down to 1 cm is ionized in just $10^4$ years, assuming bombardment of a pure ice layer. If salts or other impurities raise the material density, penetration depths will be lesser, while in more porous ice, penetration depths will be greater.

Recent research suggests that energetic electrons differentially bombard Europa and the model agrees well with Galileo data where comparisons can be made [*Paranicas et al. 2001, 2007*]. The trailing hemisphere receives most of the energetic electrons that are carried past Europa by the magnetosphere. This is consistent with visible and infrared observations which show that the leading and trailing hemisphere surfaces are very different in color and composition [*McEwen 1986; Carlson et al. 2005*]. If the leading hemisphere receives less energy, the chemical constituents that are directly linked to radiolysis should also be different. This implies that organic materials are most likely to survive longest on Europa's surface near its leading point of motion (0° lat., 90°W lon.).

Europa's external environment is intimately related to its surface chemistry through particle bombardment, to its surface geology and atmosphere through sputtering, and to its ocean through magnetic field interactions. Understanding this environment is fundamental to assembling a comprehensive picture of Europa's interrelated processes and thus its habitability.

### 2.2.6 Jupiter System

*Europa cannot be understood in isolation, but must be considered in the context of the entire Jovian system, through study of its parent planet Jupiter, its sibling satellites, and the magnetic field and particle environment.* Europa formed out of the Jovian nebula and has since evolved through complex interactions with the other satellites, Jupiter, and Jupiter's magnetosphere. In order to understand the development of potential habitats on Europa and in icy moons in general, it must be determined how the components of the Jovian system operate and interact. This requires observations of Jupiter itself as well as the other major and minor satellites of the system and of the Jovian magnetosphere. The EE mission concept includes two years in Jupiter's orbit, before orbiting Europa, enabling substantial Jupiter system science. The science questions considered here are necessarily more broad than those for Europa science, reflecting the EE study guideline that Jovian system science must receive secondary prioritization.

#### 2.2.6.1 Satellite Observations

Europa is an icy satellite, but its density indicates that a significant portion of its interior is rock and metal. It is this intermediate composition between large icy satellites such as Ganymede, Callisto and Titan, and large rocky satellites such as Io and Earth's Moon that makes Europa such an intriguing body. Unlike the larger icy satellites whose oceans are perched between ice layers, Europa's ocean may be in close contact with its rocky interior. The Jovian satellites exhibit strong density as well as activity gradients from Io to Callisto. It is not yet understood what properties of the Jovian nebula and the resulting satellite system control these gradients. Observations relevant to the compositions, geology, interiors, and evolution of the Galilean satellites will help constrain models for the origin of Europa and its evolution into a potentially habitable body.

Io presents an opportunity to study the rocky components of the system, unobscured by ice. Io's activity is also key to understanding the role of tidal heating in the Jovian system, which may be crucial for Europa's thermal history. Moreover, Io's volcanic emissions pervade the Jovian magnetosphere, eventually contaminating the surfaces of the other satellites.

Callisto represents the opposite extreme to Io; it is apparently undifferentiated and is nearly an undisturbed relic from the earliest days of the Jovian system. Improving our understanding of Callisto's interior structure and surface composition will provide better constraints on the conditions in the early Jovian nebula.

Ganymede is intermediate in surface activity, sharing many tectonic features with Europa. Ganymede's interior activity powers a dynamo that generates its own magnetic field. Probing this magnetosphere within the Jovian magnetosphere helps us to understand the evolution of icy satellite interiors. Additionally, Ganymede's magnetosphere provides visible contrasts on its surface between regions protected from the Jovian radiation environment and those exposed, forming its polar caps [*Khurana et al. 2007*].

Characterization of the composition of the Galilean satellite surfaces will improve our understanding of the compositional gradients in the Jovian nebula and their differing evolutionary paths as well as the physical properties of the surface and the effects of radiation. Each icy satellite has a thin atmosphere, resulting largely from sputtering, and reflecting the surface composition. These atmospheres provide a measure of the influence of radiation on surface chemistry. Any recent activity would also be revealed by changes in the density or distribution of the tenuous atmosphere. Finally, the smaller satellites of Jupiter and the rings are components of the Jovian system that reflect those bodies that formed in the vicinity of Jupiter.

#### 2.2.6.2 Jupiter Observations

Most of the mass of the Jovian system is contained in Jupiter, and thus Jupiter's composition reflects the processes by which its nebula formed and evolved. Considerable processing has occurred since Jupiter's formation; therefore, its present composition and the processes that drive the chemistry and dynamics must be understood.

Observations of atmospheric winds (**Figure 2.2-8**) and energy fluxes offer the opportunity to understand the dynamics of the Solar System's largest planet, while spectral observations reveal the active chemistry. Combined with the new understanding of the deep interior structure anticipated from the Juno mission, scheduled to arrive at Jupiter in 2016, more comprehensive models of Jupiter's origin and evolution can be constructed.

#### 2.2.6.3 Magnetosphere Observations

The magnetosphere of Jupiter is the largest "object" in the Solar System. Europa orbits within this radiation belt, bombarded by energetic particles accelerated by the flowing magnetic field lines that rotate with the planet. This arrangement is not unusual for satellites of giant planets, and it has already led to the discovery of an induced magnetic field in Europa, most likely generated in a liquid ocean beneath the ice.

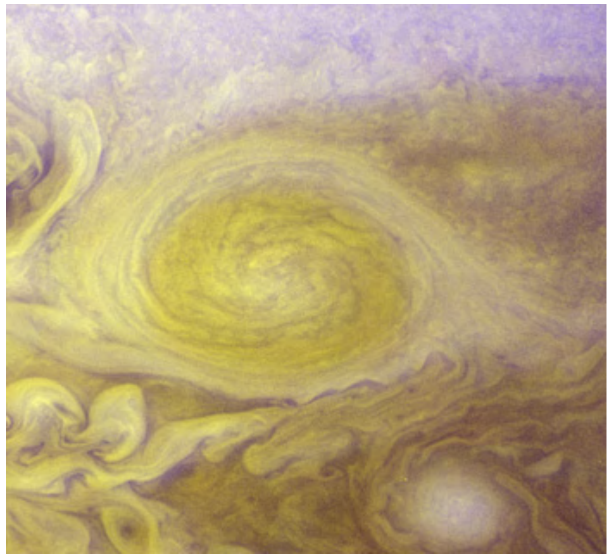


***Figure 2.2-8.*** *Image of Jupiter's "Little Red Spot" from the New Horizons spacecraft, colorized using Hubble Space Telescope images. Imaging resolution is about 15 km/pixel, which is about 10 times better than Hubble's. Images such as these permit an understanding of the development and dynamics of Jupiter's atmospheric storms.*

Understanding the sources and dynamics of the fields and plasma in the Jovian magnetosphere is essential for interpreting chemical measurements made at Europa. Observations of the magnetic field itself, the Io torus, Jupiter's aurorae, the magnetopause and plasma sheet, and the radiation energy spectrum provide the background for understanding Europa's surface chemistry.

## 2.3 Science Goal, Objectives, and Investigations

### 2.3.1 Heritage of Europa Science Objectives

Prior to the present study, several key advisory groups have considered and recommended sets of science objectives for the exploration of Europa (**Table 2.3-1**). The lineage of Europa science objectives traces back to the Europa Orbiter SDT, whose "Group 1" (highest priority) and "Group 2"

***Table 2.3-1.*** *Heritage of Europa Science Objectives.*

| Committee | Report Title | Reference |
|---|---|---|
| Europa Orbiter Science Definition Team | Europa Orbiter Mission and Project Description | NASA AO: 99-OSS-04 |
| Committee on Planetary and Lunar Exploration (COMPLEX) | A Science Strategy for the Exploration of Europa | COMPLEX [1999] |
| NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System | Europa and Titan: Preliminary Recommendations of the Campaign Science Working Group on Prebiotic Chemistry in the Outer Solar System | Chyba et al. [1999] |
| Solar System Exploration ("Planetary Science Decadal") Survey | New Frontiers in the Solar System: An Integrated Exploration Strategy | SSES [2003] |
| Jupiter Icy Moons Orbiter (JIMO) Science Definition Team | Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) | JIMO SDT [2004] |
| Europa Focus Group of the NASA Astrobiology Institute | Europa Science Objectives | Pappalardo [2006] |
| Outer Planets Assessment Group (OPAG) | Scientific Goals and Pathways for Exploration of the Outer Solar System | OPAG [2006] |
| NASA Solar System Exploration Strategic Roadmap Committee | 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate | SSER [2006] |

(second priority) objectives were subsequently endorsed by the NASA Campaign Science Working Group on Prebiotic Chemistry in the Solar System, and then by the National Research Council's Solar System Exploration Survey ("Planetary Science Decadal Survey"). The Decadal Survey explicitly stated that a flagship-class mission should address both the Europa Orbiter Group 1 and Group 2 objectives, in addition to Jupiter system science during its Jupiter orbiting phase.

Subsequent to the recommendations of the Decadal Survey, the Jupiter Icy Moons Orbiter (JIMO) Science Definition Team expanded the scope of Europa objectives and included additional objectives relevant to the whole Jupiter system. Following NASA's indefinite postponement of the ambitious JIMO mission, the Outer Planets Assessment Group honed the objectives for Europa exploration. These objectives were iterated upon by the Europa Focus Group of the NASA Astrobiology Institute, and then codified by *OPAG* [*2006*] in its *Scientific Goals and Pathways* document. These objectives were subsequently reflected in the 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate. It is these Europa objectives which the present study has modified as its goal, objectives, and investigations for Europa, described below.

### 2.3.2 Traceability from Guiding Documents

Several guiding NRC and NASA documents have emphasized the relevance of Europa exploration to highest priority science goals. These include COMPLEX's report *A Science Strategy for the Exploration of Europa* [*COMPLEX 1999*], the Solar System Exploration ("Planetary Science Decadal") Survey [*SSES 2003*], OPAG's *Scientific Goals and Pathways* report [*OPAG 2006*], the *2006 Solar System Exploration Roadmap* [*SSER 2006*], the *2007 NASA Science Plan* [*NSP 2007*], and the *Vision for Space Exploration* document [*VSE 2004*] (see §2.1).

The Planetary Science Decadal Survey builds a hierarchical flow-down from Motivational Questions, to Scientific Goals, to Scientific Themes, to Fundamental Science Questions. The Decadal Survey's five Scientific Goals were subsequently modified to become the five Science Questions highlighted in the 2006 Solar System Exploration Roadmap, which were directly adopted by the 2007 NASA Science Plan. **Table 2.3-2** maps the five Scientific Goals of the Decadal Survey to the five Science Questions of the Roadmap and the Science Plan. In doing so, the SDT considered six themes that are common to the guiding documents. Although the mapping is not one-to-one (for example, the Decadal Survey emphasizes the Processes theme, while the Roadmap emphasizes Life), similar themes are cross-cutting. The 2007 NASA Science Plan affirms that a mission to Europa makes a major contribution to the first four Science Questions, thus to the first five themes of **Table 2.3-2** (with Hazards and Resources having minor applicability). Below these five

***Table 2.3-2. Europa Explorer themes**, based on the Scientific Goals of the Planetary Decadal Survey, and Scientific Questions of the 2006 Solar System Exploration Roadmap and the 2007 NASA Science Plan.*

| GUIDING THEMES | | |
|---|---|---|
| **Solar System Exploration ("Decadal") Survey** | **2006 SSE Roadmap and 2007 NASA Science Plan** | **Europa Explorer Theme** |
| • Learn how the Sun's retinue of planets originated and evolved. | • How did the Sun's family of planets and minor bodies originate? | **Origins** |
| | • How did the solar system evolve to its current diverse state? | **Evolution** |
| • Discover how the basic laws of physics and chemistry, acting over aeons, can lead to the diverse phenomena observed in complex systems, such as planets. • Understand how physical and chemical processes determine the main characteristics of the planets, and their environments, thereby illuminating the workings of the Earth. | | **Processes** |
| • Determine how life developed in the solar system, where it may have existed, whether extant life forms exist beyond Earth, and in what ways life modifies planetary environments. | • What are the characteristics of the solar system that led to the origin of life? | **Habitability** |
| | • How did life begin and evolve on Earth and has it evolved elsewhere in the solar system? | **Life** |
| • Explore the terrestrial space environment to discover what potential hazards to the Earth's biosphere may exist. | • What are the hazards and resources in the solar system environment that will affect the extension of human presence in space? | **Hazards & Resources** |

major guiding themes are mapped to the goal, objectives, and investigations of the EE mission.

### 2.3.3 Science Goal of the Europa Explorer Mission

The planetary Decadal Survey simply summarizes the inherent motivation for Europa exploration by its fundamental science question: "Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?" Understanding both processes and habitability are key drivers for Europa exploration, as are the themes of origin, evolution, and life. Thus, the recommended overarching goal for a Europa mission is:

***Explore Europa and investigate its habitability.***

Here "Explore Europa" implies understanding processes, origin, and evolution. This includes testing of the numerous existing scientific hypotheses described in §2.2. It also allows for discovery science—unpredicted findings of the type that have often reshaped the very foundations of planetary science, especially in the surprises uncovered in the outer solar system by the two Pioneers, the two Voyagers, Ulysses, Galileo, Cassini, and most recently, New Horizons.

"Investigate its habitability" recognizes the great significance of Europa's astrobiological potential. Investigating Europa's habitability includes confirming the existence and determining the characteristics of water in Europa's subsurface, understanding the possible sources and cycling of chemical and thermal energy, investigating the evolution and chemical composition of the surface and ocean, and evaluating the processes which have affected Europa through time.

Understanding Europa's habitability is intimately tied to investigation of the Jovian system as a whole. Both Ganymede and Callisto are believed to possess subsurface oceans, Io teaches us the fundamentals of tidal heating and interactions with the Jovian environment, and Jupiter holds clues to the initial conditions of the system. Each Galilean satellite sheds light upon the others, and each is intimately tied to their parent planet and to the Jovian magnetospheric environment. As stated in the 2006 Solar System Exploration Roadmap, "By studying the Jupiter system as a whole, we can better understand the type example for habitable planetary systems within and beyond our Solar System."

#### 2.3.4 Objectives, Investigations, and Measurements

The trace from objectives to investigations to measurements to instruments is summarized in the EE Traceability Matrix (**Foldout 1 [FO-1]**). Lettered Objectives A through E are considered Priority 1, and each is deemed by the SDT as of equal priority. Lettered Objective F is considered a Priority 2 objective according to the NASA-directed groundrules of the present study, so should not drive spacecraft or payload capabilities. Investigations are listed in priority order within each objective, and the measurements (and corresponding instruments) to address each investigation are also listed in priority order. Color-coding corresponds to the guiding theme of **Table 2.3-2** to which it most closely pertains, as traced from the Decadal Survey and 2006 Solar System Exploration Roadmap.

Each objective and its investigations are described in detail below, along with the corresponding measurements to address them. **Table 2.3-3** provides a sampling of the types of specific hypothesis questions that will be addressed by the EE mission, and how they will be addressed, keyed to the investigations of the Traceability Matrix (**FO-1**).

### A. Europa's Ocean:

***Objective:* Characterize the ocean and deeper interior**

The first step in characterizing Europa's ocean will be determining the existence and extent of the subsurface ocean. If Europa has no ocean and its ice shell is coupled to its rocky mantle, then as it orbits Jupiter its measurable radial tide will vary by less than 1 m; on the other hand, if Europa has a liquid water ocean beneath a relatively thin ice shell, the tide will vary by over 30 m. Thus, measuring Europa's tides provides a simple and definitive test of the existence of an internal ocean.

In the likely instance that an ocean exists, several different geophysical measurements will place constraints on the depth, extent, and physical state of the ocean, specifically measurements related to gravity, topography, magnetics, and rotation state. All place global constraints on the ocean in ways that are coupled to other aspects of the internal structure of Europa, especially the deeper interior (the mantle and core). The relevant investigations are strongly coupled:

*Investigations:*

A1. Determine the amplitude and phase of the gravitational tides.

A2. Determine the induction response from the ocean over multiple frequencies.

A3. Characterize surface motion over the tidal cycle.

A4. Determine the satellite's dynamical rotation state.

A5. Investigate the core and rocky mantle.

The gravitational tidal potential from Jupiter varies periodically as Europa orbits (**Figure 2.2-2**), applying stress which deforms the satellite. The amplitude and phase of the gravitational and topographic tidal responses are determined by the mechanical strength and density of the layered interior. Love numbers are the dimensionless scale factors which parameterize these effects, where $k_2$ represents effects on the gravitational potential, and $h_2$ represents radial topographic effects. A homogeneous fluid body would have values of $k_2$ = 1.5 and $h_2$ = 2.5. If present, a liquid ocean would dominate the tidal response, while the product of ice shell thickness times ice shell rigidity has a lesser but important effect (**Figure 2.3-1**). Based on simulations of plausible internal structures, measurement uncertainties of ±0.0005 for $k_2$ and ±0.01 for $h_2$ will permit the actual $k_2$ and $h_2$ of Europa to be inferred with sufficient accuracy such that the combination characterizes the depth of the ocean and constrains the thickness of the ice shell [*Wu et al. 2001*; *Wahr et al. 2006*]. In turn, ice shell thickness is an important constraint on geological processes, astrobiology, and heat flux from the silicate interior (see §2.2).

Love number $k_2$ is derived by measuring the time-variable gravitational field of Europa, in turn measured by perturbations in the trajectories of orbiting spacecraft. The component of the velocity change that is in the direction to Earth is measured by a Doppler shift in the radio-frequency communication

# EUROPA EXPLORER: TRACEABILITY MATRIX

| Goal | Science Objective | Science Investigation | Measurement | Instrument |
|---|---|---|---|---|
| **Explore Europa and investigate its habitability.** | **A Characterize the ocean and deeper interior.** | A1. Determine the amplitude and phase of the gravitational tides. | A1a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover $k_2$ to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. | A1a. Telecom system. |
| | | | A1b. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1-m vertical accuracy, to recover $h_2$ to 0.01 (at the orbital frequency). | A1b. Laser altimeter. |
| | | A2. Determine the induction response from the ocean over multiple frequencies. | A2a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for at least one month. | A2a. Magnetometer. |
| | | A3. Characterize surface motion over the tidal cycle. | A3a. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1 m vertical accuracy, to recover $h_2$ to 0.01 (at the orbital frequency). | A3a. Laser altimeter |
| | | | A3b. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover $k_2$ to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. | A3b. Telecom system. |
| | | A4. Determine the satellite's dynamical rotation state. | A4a. Doppler shift from spacecraft tracking via two-way Doppler, to determine mean spin pole direction. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. | A4a. Telecom system. |
| | | | A4b. Topographic differences at cross-over points from globally distributed topographic profiles to determine spin pole direction and libration amplitudes, with better than or equal to 1 m vertical accuracy. | A4b. Laser altimeter. |
| | | A5. Investigate the core and rocky mantle. | A5a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve high degree gravity field. Doppler velocity of 0.1 mm/s over 60s accuracy. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. | A5a. Telecom system. |
| | | | A5b. Topographic profiles to resolve coherence with gravity, with better than or equal to 1 m vertical accuracy. | A5b. Laser altimeter. |
| | | | A5c. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for several months. | A5c. Magnetometer. |
| | **B Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange.** | B1. Characterize the distribution of any shallow subsurface water. | B1a. Identify and locally characterize physical subsurface horizons related to the current or recent presence or water or brine, by obtaining sounding profiles of subsurface thermal, compositional, or structural horizons, with ≤50 km profile spacing over >80% of the surface, at depths of 100 m to 3 km at 10 m vertical resolution, and perform targeted detailed characterization of selected sites. | B1a. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth). |
| | | | B1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over >80% of the surface, co-located with sounding profiles. | B1b. Wide-angle camera (stereo) and laser altimeter. |
| | | B2. Search for an ice-ocean interface. | B2a. Identify deep dielectric subsurface horizons, by obtaining sounding profiles of subsurface thermal, compositional, or structural horizons, with ≤50 km profile spacing over >80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution. | B2a. Radar sounder (nominally ~5 or 50 MHz, with ~1 MHz bandwidth). |
| | | | B2b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over >80% of the surface, co-located with sounding data. | B2b. Wide-angle camera (stereo) and laser altimeter. |
| | | B3. Correlate surface features and subsurface structure to investigate processes governing communication among the surface, ice shell, and ocean. | B3a. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with ≤50 km spacing over >80% of the surface, plus targeted characterization of selected sites. | B3a. Radar sounder (dual-frequency, nominally ~5 & ~50 MHz, with ~1 and ~10&1 MHz bandwidth) |
| | | | B3b. Map thermal emission from the surface by measuring the albedo over >80% of the surface at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, and make targetted thermal observations at better than 250 m/pixel spatial resolution and temperature accuracy | B3b. Thermal instrument |
| | | | B3c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm. | B3c. IR imaging spectrometer. |
| | | | B3d. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over >80% of the surface, co-located with sounding data. | B3d. Wide-angle camera (stereo) and laser altimeter. |
| | | | B3e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel, and topographic sampling of targeted sites with better than 1 m vertical accuracy. | B3e. Narrow-angle camera and laser altimeter. |
| | | | B3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface. | B3f. Wide-angle camera, color. |
| | | | B3g. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterizatoin of selected sites. | B3g. UV imaging spectrometer. |
| | | | B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. | B3h. Medium-angle camera. |
| | | | B3i. Doppler velocity of 0.1 mm/s over 60 s accuracy, to identify regions of density contrast within the ice crust. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. | B3i. Telecom system. |

**Europa Explorer Themes:** Origins | Evolution | Processes | Habitability | Life

*continued*

## FOLDOUT 1 (2 OF 4)
## SCIENCE TRACEABILITY MATRIX

| Goal | Science Objective | Science Investigation | Measurement | Instrument |
|---|---|---|---|---|
| Explore Europa and investigate its habitability. | **C Determine global surface compositions and chemistry, especially as related to habitability.** | C1. Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability. | C1a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm, along profiles with ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites. | C1a. IR imaging spectrometer. |
| | | | C1b. Characterize the composition of sputtered products from energetic particle bombardment of the surface, using ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, and energy resolution of 10%. | C1b. INMS. |
| | | | C1c. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites. | C1c. UV imaging spectrometer. |
| | | C2. Relate compositions to geological processes, especially communication with the interior. | C2a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm. | C2a. IR imaging spectrometer. |
| | | | C2b. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with better than 50 km spacing, plus targeted characterization of selected sites. | C2b. Radar sounder. |
| | | | C2c. Surface reflectance measurements by ultraviolet spectroscopy of targeted features at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm. | C2c. UV imaging spectrometer. |
| | | | C2d. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. | C2d. Medium-angle camera (stereo). |
| | | | C2e. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at better than or equal to 250 m/pixel spatial resolution, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy <2 K, over >80% of the surface. | C2e. Thermal instrument |
| | | | C2f. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. | C2f. Narrow-angle camera. |
| | | | C2g. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution over >80% of the surface, and topographic characterization at better than 10 m/pixel spatial scale and better than or equal 1 m vertical resolution and accuracy for targeted features, co-located with sounding data. | C2g. Wide-angle camera (stereo), medium-angle camera (stereo), and laser altimeter. |
| | | C3. Assess the effects of radiation on surface materials, albedo, sputtering, and redox chemistry. | C3a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm. | C3a. IR imaging spectrometer. |
| | | | C3b. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites. | C3b. UV imaging spectrometer. |
| | | | C3c. Characterize the composition of sputtered products from energetic particle bombardment of the surface, through ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, and energy resolution of 10%. | C3c. INMS. |
| | | | C3d. Characterize the structure of the sputter-produced atmosphere using ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emissions, at equal to or better than 3 nm spectral resolution and 100 m/pixel scale through a spectral range of at least 0.1-0.35 μm. | C3d. UV spectrometer. |
| | | | C3e. Determine global distribution of bombarding energetic electron flux, and detect upstream impacting energetic ions, by measuring magnetospheric electrons in the energy range 100 keV to 10 MeV, with pitch angle distribution and ΔE/E ~0.1 over Europa's surface, and ion from 15 keV to 750 keV from the ram direction. | C3e. Particle and plasma instrument. |
| | | | C3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface. | C3f. Wide-angle camera, color. |
| | | | C3g. Measure the surface albedo at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, over >80% of the surface. | C3g. Thermal instrument. |
| | | | C3h. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. | C3h. Narrow-angle camera. |
| | | C4. Characterize the nature of exogenic materials. | C4a. Determine the energy spectrum of energetic jovian electrons in the energy range 100 keV to 10 MeV to ΔE/E=0.1. | C4a. Particle and plasma instrument. |
| | | | C4b. Determine the flux and composition of plasma ions impacting Europa by measuring ions from 10 eV to 10 keV with 15 degree angular resolution to ΔE/E=0.15, and ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, and energy resolution of 10%. | C4b. Particle and plasma instrument and INMS. |
| | | | C4c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm, along profiles with ≤25 km spacing over >80% of the surface, plus targeted characterizatoin of selected sites. | C4c. IR imaging spectrometer. |
| | | | C4d. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites. | C4d. UV imaging spectrometer. |
| | | | C4e. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface. | C4e. Wide-angle camera, color. |

**Europa Explorer Themes:** Origins | Evolution | Processes | Habitability | Life

*continued*

| Goal | Science Objective | Science Investigation | Measurement | Instrument |
|---|---|---|---|---|
| **Explore Europa and investigate its habitability.** | **D Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.** | D1. Characterize magmatic, tectonic, and impact features. | D1a. Determine the distributions and morphologies of surface landforms at regional and local scales, by determining surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface, and characterize surface morpphology at ~10 m/pixel over targeted sites. | D1a. Wide-angle camera (color) and Medium-angle camera. |
| | | | D1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over >80% of the surface, co-located with sounding profiles. | D1b. Wide-angle camera (stereo). |
| | | | D1c. Topographic characterization at better than 10 m/pixel scale and better than or equal to 1 m vertical resolution and accuracy for targeted features, co-located with sounding profiles. | D1c. Medium-angle camera (stereo) and laser altimeter. |
| | | | D1d. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with ≤50 km spacing over >80% of the surface, plus targeted characterization of selected sites. | D1d. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth). |
| | | | D1e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. | D1e. Narrow-angle camera. |
| | | D2. Search for areas of recent or current geological activity. | D2a. Thermal mapping better than or equal to 250 m/pixel spatial resolution and temperature accuracy < 2 K, over >80% of the surface, with the same regions observed in both the day and night. | D2a. Thermal instrument. |
| | | | D2b. Search for and identify any regions of outgassing using ultraviolet stellar occultations, and ultraviolet imaging of the surface and atmosphere, at better than or equal to 3 nm spectral resolution and 100 m/pixel scale through a range of at least 0.1-0.35 μm, using limb views, along with surface profiles of ≤25 km spacing over >80% of the surface. | D2b. UV spectrometer. |
| | | | D2c. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. | D2c. Medium-angle camera (stereo). |
| | | | D2d. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. | D2d. Narrow-angle camera. |
| | | | D2e. Identify and map any age-sensitive chemical and physical indicators (e.g. $H_2O$ frost, ice crystallinity, $SO_2$, $H_2O_2$) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeting of selected sites. | D2e. IR spectrometer and UV spectrometer. |
| | | D3. Investigate global and local heat flow. | D3a. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at spatial resolution better than or equal to 250 m/pixel, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy < 2 K, over >80% of the surface. | D3a. Thermal instrument. |
| | | D4. Assess relative surface ages. | D4a. Determine regional and global stratigraphic relationships with imaging at ~100 m/pixel scale in at least 3 colors, with near-uniform lighting conditions and solar phase angle ≤ 45 degrees, over >80% of the surface. | D4a. Wide-angle camera (color). |
| | | | D4b. Identify any regional or local areas of anomalously high heat flow, by mapping nighttime temperatures at better than or equal to 250 m/pixel spatial resolution and and temperature accuracy < 2 K. | D4b. Thermal instrument. |
| | | | D4c. Determine small-scale surface morphology, with stereo imaging at ~1 to 10 m/pixel over targeted high-priority sites, with vertical rsolution of better than or equal 1 m. | D4c. Medium-angle camera and/or Narrow-angle camera. |
| | | | D4d. Identify and map any age-sensitive chemical and physical indicators (e.g. $H_2O$ frost, ice crystallinity, $SO_2$, $H_2O_2$) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeting of selected sites. | D4d. IR spectrometer and UV spectrometer. |
| | | D5. Characterize the physical properties of the regolith, and assess processes of erosion and deposition. | D5a. Determine thermal inertia of surface materials, by thermal mapping; to better than or equal to 250 m/pixel spatial resolution and better than 2 K absolute temperature over >80% of the surface, with the same regions observed in both the day and night. | D5a. Thermal instrument. |
| | | | D5b. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. | D5b. Narrow-angle camera. |
| | | | D5c. Measure ion-cyclotron waves and relate to plasma-pickup and erosion by magnetic field sampling at 32 vectors/s and a sensitivity of 0.1 nT. | D5c. Magnetometer. |

**Europa Explorer Themes:** Origins | Evolution | Processes | Habitability | Life

*continued*

| Goal | Science Objective | Science Investigation | Measurement | Instrument |
|---|---|---|---|---|
| Explore Europa and investigate its habitability. | E Characterize the magnetic environment and moon-particle interactions. | E1. Characterize the magnetic environment. | E1a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously. | E1a. Magnetometer. |
| | | E2. Characterize the ionosphere and neutral atmosphere and their dynamics, with implications for surface interactions. | E2a. Understand how sputtering generates an exosphere, by measuring the ion flux from energies of 10 keV to 1 MeV to $\Delta E/E=0.1$, and measuring ions from 10 eV to 10 keV with 15 degree angular resolution to $\Delta E/E=0.15$. | E2a. Particle and plasma instrument. |
| | | | E2b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously. | E2b. Magnetometer. |
| | | | E2c. Determine the fluxes of positive ions and neutral particles, by ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, and energy resolution of 10%. | E2c. INMS. |
| | | | E2d. Identify atmospheric emissions, and characterize spatial heterogeneity and temporal variation including through the synodic cycle, by ultraviolet imaging of the atmosphere at better than or equal 3 nm spectral resolution, and sampling on time scales of hours, through a spectral range of at least 0.1-0.35 μm. | E2d. UV imaging spectrometer. |
| | | E3. Characterize relationships between the magnetic field and plasma. | E3a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously. | E3a. Magnetometer. |
| | | | E3b. Understand how plasma interaction currents affect the induction field signature, by measuring 50 eV to 10 keV ions with 15 degree angular resolution and $\Delta E/E=0.15$. | E3b. Particle and plasma instrument. |
| | | E4. Characterize the global radiation environment. | E4a. Global detection of energetic ion and electron fluxes, by measuring Jovian electrons at energies from 100 keV to 10 MeV, and Jovian ions from energy of 10 keV to 10 MeV to $\Delta E/E=0.1$. | E4a. Particle and plasma instrument. |
| | | | E4b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously. | E4b. Magnetometer. |
| | | | E4c. Determine plasma distribution function to characterize the particle environment at all pitch angles, by measuring ions from 10 eV to 10 keV with 15 degree angular resolution to $\Delta E/E=0.15$. | E4c. Particle and plasma instrument. |
| | F Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons. | F1. Determine the nature and history of the geological activity and interior evolution of the Galilean satellites. | F1a. Understand the mechanisms responsible for formation of surface features and implications for geological history, evolution, and levels of current activity, by means of: visible imaging, IR spectroscopy, and UV spectroscopy to resolve surface features; UV stellar occultations; subsurface sounding; and thermal imaging of Io. | F1a. Cameras (including color & stereo), IR spectrometer, UV spectrometer, Radar Sounder, and Thermal Instrument. |
| | | | F1b. Determine the surface compositions and implications for the origin, evolution and transport of surface materials, by means of: visible color imaging, IR spectroscopy, and UV spectroscopy to determine composition; subsurface sounding; and ion and neutral compositions near satellites. | F1b. Cameras (especially color), IR spectrometer, UV spectrometer, Radar Sounder, and INMS. |
| | | | F1c. Determine the compositions, origins, and evolution of the atmospheres, including transport of material throughout the Jovian system, by means of: UV stellar occultations; ion and neutral compositions near satellites; magnetic field, particle, and plasma measurements near satellites; and radio occultations. | F1c. UV spectrometer, INMS, Magnetometer, Particle and plasma instrument, and Telecom system. |
| | | | F1d. Determine the interior structures and processes operating in the Galilean satellites in relation to the formation and history of the Jupiter system and potential habitability of the moons, by means of: magnetic field measurements; Doppler gravity measurements. | F1d. Magnetometer and Telecom system. |
| | | | F1e. Investigate the small bodies and rings in the Jovian system, by means of: visible imaging, IR spectroscopy, and UV spectroscopy. | F1e. Cameras, IR spectrometer, and UV spectrometer. |
| | | F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a gas giant planet. | F2a. Map the distribution of condensable and trace species in the Jovian atmosphere, by means of: UV, visible, IR, and thermal imaging at high spatial, spectral, and temporal resolution; UV stellar occultations; and radio occultations. | F2a. UV spectrometer, Cameras, IR spectrometer, and Thermal instrument. |
| | | | F2b. Investigate the energy transport in the Jovian atmosphere, by means of: UV, visible, IR, and thermal imaging at high spatial, spectral, and temporal resolution; UV stellar occultations; and radio occultations. | F2b. UV spectrometer, Cameras, IR spectrometer, and Thermal instrument. |
| | | F3. Study the interactions between Jupiter's magnetosphere and its satellites. | F3a. Understand the magnetospheric and ionospheric environments of Jupiter and its moons, and their interactions, by means of: magnetic field, particle, and plasma measurements throughout the magnetosphere, especially at boundaries and near satellites; UV and visible observations of the Io torus, UV and visible observations of Jovian aurorae and satellite footprints; radio occultations. | F3a. Magnetometer, Particle and plasma instrument, UV spectrometer, and Cameras. |

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

***Table 2.3-3.*** *Example Hypothesis Questions to be Tested with Europa Explorer*

| | Example Hypothesis Questions | Example Hypothesis Tests |
|---|---|---|
| A1. | What is the mechanical strength of Europa's layered interior, including its ocean? | Use gravity and topography to constrain the constrain the rigidity and thickness of internal layers, including the ice shell and ocean. |
| A2. | What is the salinity and thickness of Europa's ocean? | Determine the magnetic induction signal over multiple frequencies to derive ocean salinity and thickness. |
| A3. | What are the kilometer-scale variations in ice shell thickness across the globe? | Use gravity and topography to constrain the relative thickness of the ice shell, to determine whether and how layer thickness varies over ~500 km horizontal scales. |
| A4. | What is Europa's obliquity, and what does this tell us about Europa's internal structure? | Use gravitational and topographic measurements of the tides to infer obliquity, which in turn constrains moments of inertia especially in combination with libration amplitude(s). |
| A5. | Determine whether large-scale topography exists on Europa's mantle. | Measure high-order gravity terms over a time scale of several months. |
| B1. | Does thermal and compositional heterogeneity implicit in Europa's dynamic ice shell support widespread water/brine production or movement at shallow depths? | Sound Europa's shallow subsurface for liquid water, and correlate to surface morphology and thermal data. |
| B2. | Does Europa have a very thin ice shell and shallow ocean interface (at a depth of a few kilometers), or a large thickness (tens of kilometers) of warm ice directly overlying a much deeper ocean interface? | Sound Europa's ice shell for a strong water reflector at shallow depth, or to observe a gradual absorption of the signal with depth. |
| B3. | Considering that habitability of Europa will be determined by the balance of exchange between its surface and oceanic chemical reservoirs, is such exchange modulated by the movement of fluid through Europa's icy shell? | Sound Europa's ice at shallow and at greater depth, correlating to surface morphology, thermal data, and compositional data. |
| C1. | Are there endogenic organic materials on Europa's surface? | Examine surface and sputtered materials for absorptions and masses consistent with organic materials, especially in regions most protected from radiation, and correlate distributions to endogenic materials. |
| C2. | Is chemical material from depth carried to the surface? | Determine whether salts and other minerals that may be indicative of a subsurface ocean are concentrated in specific geologic features, and correlate with evidence for subsurface liquid water at these locations. |
| C3. | How does irradiation alter Europa's surface materials through time? | Determine the suite of compounds observable on Europa's surface, correlating to the local radiation environment and to the relative age of associated surface features. |
| C4. | Do materials formed from exogenic ion implantation play a major role in Europa's surface chemistry? | Determine the distribution of sulfur-rich and other compounds and correlate to inferred implantation rates. |
| D1. | What is the origin of Europa's ridges, bands, chaos, and multi-ringed structures, and how are they tied to interior processes including the location of liquid water? | Combine high-resolution imaging, compositional, subsurface, and thermal data sets to determine the style of surface deformation and the links to interior structure and water. |
| D2. | Which are Europa's youngest geological events? | Investigate stratigraphic relationships, mass wasting, small-scale impacts, thermal data, and compositional data to discover the most recent surface features. |
| D3. | Is current geological activity sufficiently intense that heat flow from Europa's interior is measurable at the surface? | Regions of current activity can observed thermally, with nighttime surface temperatures expected to be elevated above nominal values based on available solar insolation alone. |
| D4. | Are there regional or global correlations of geological features and processes through time? | Use cross-cutting relationships and compositional characteristics (color, albedo, chemical, and thermal) do determine the stratigraphic relationships across Europa at regional scales, and derive local and global stratigraphic columns. |

| | Example Hypothesis Questions | Example Hypothesis Tests |
|---|---|---|
| D5. | What are the relative roles and effects of regolith-forming processes? | Use high-resolution morphological, compositional, and thermal data to identify: mass wasting deposits and their thicknesses, small impact craters to reveal gardening depth, sputter-related textures and albedo effects and particle fluxes to constrain sputtering rate, and thermal inertia and photometric data to indicate surface particle size and packing. |
| E1. | How is the magnetic field perturbed near Europa, affecting how particles are carried onto and over Europa's surface and atmosphere? | Measure the magnetic field across the globe, at a cadence sufficient to resolve sharp current sheets created by moon-plasma interactions. |
| E2. | Is Europa's sputter-produced atmosphere patchy, and how does it vary spatially and temporally? | Observe the external field and particle environment over the globe through time, while also observing variability the of atmospheric emissions. |
| E3. | How does plasma flow around Europa, and what is the relationship between plasma and the magnetic field? | Measure ions with good energy and angular resolution, to derive their fluxes in their rest frame. |
| E4. | Do energetic electrons (~1 MeV) asymmetrically bombard Europa, as predicted by calculations and suggested by Galileo data? | Obtain global measurements of 1 MeV electrons at representative pitch angles over the whole globe of Europa. |
| F1. | Has Ganymede experienced cryovolcanism, or does intense tectonism create smooth terrains; and what is the distribution and thickness of Callisto's dark component? | Sound and image regions of smooth materials to determine the subsurface structure, including the nature of any layering and/or related tectonic structure. |
| F2. | How does small-scale atmospheric convection contribute to development and maintenance of larger-scale storms? | Observe Jupiter's atmosphere at small scales while monitoring larger-scale patterns, both over time. |
| F3. | How do the sources and dynamics of the fields and plasma in the Jovian magnetosphere vary over time, especially as correlated with Io's activity? | Monitor the magnetic and plasma environment of Jupiter's magnetosphere spatially and temporally, while also monitoring Io's activity and plasma environment. |

with the satellite. Because the perturbations are measured only by a single projected component at any given time, a complete resolution of the gravity field requires multiple orbits; moreover, a single profile is difficult to interpret because the same data must be used to determine the spacecraft orbit itself.

At X-band frequencies, velocity measurement accuracies of 0.1 mm/s are typically attained for 60 s averages. **Figure 2.3-2** illustrates the estimated gravitational spectrum for Europa, with separate contributions from an ice shell and a silicate interior, along with simulated error spectra for 30 days of tracking at each of three representative orbital altitudes [cf. *Wu et al. 2001*]. The errors are smaller at lower altitudes because the spacecraft is closer to the anomalies, and thus experiences larger perturbations.

Improving accuracy in the measurements allows both better determination of long wavelength features, and initial discrimination of some shorter wavelength features. Variations in gravitational signal amplitude, and correlation with topography, are diagnostic of internal structures. For the model parameters depicted in **Figure 2.3-2**, the lowest altitude orbit errors are small enough to resolve part of the transition from the long wavelength, silicate-dominated part of the spectrum, in which correlation with topography would be poor, into the shorter wavelength, ice-dominated regime, in which topography and gravity would be spatially coherent [*Luttrell and Sandwell 2006*]. This would permit detection of isostatic anomalies in response to topographic variations (such as volcanic rises) that may exist on the silicate core. The radio frequency tracking data will provide initial spacecraft orbit estimates. As the gravity field knowledge improves during the orbital mission, near real-time orbit position knowledge will also improve. The tracking data will be used, together with spacecraft attitude and altitude information, to simultaneously estimate the static and tidal components of gravity and topography, and

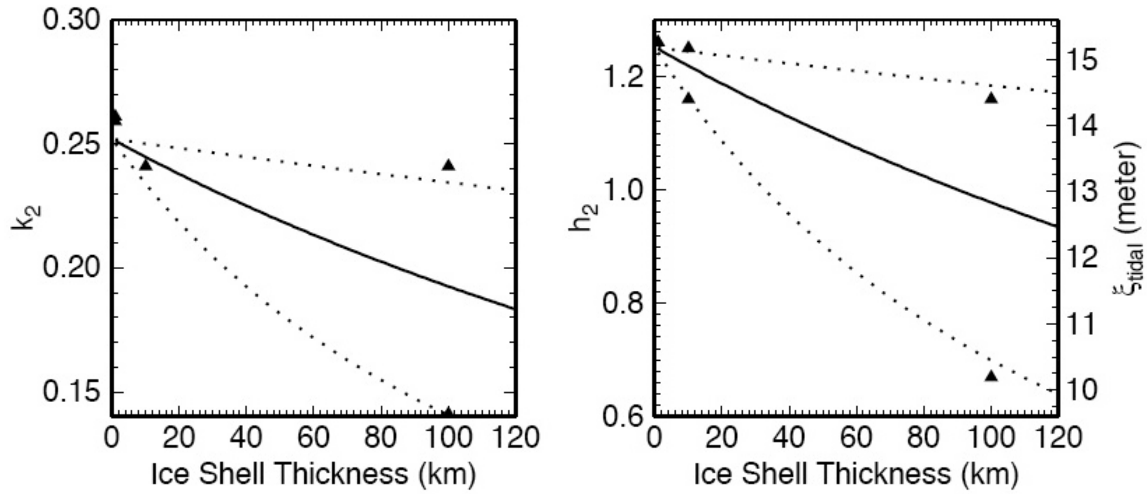



***Figure 2.3-1.*** *Sensitivity of Love numbers* $k_2$ *(left) and* $h_2$ *(right) to ice shell thickness and rigidity, with the assumption of a subsurface ocean. The right-hand plot also shows the amplitude* $\zeta_{tidal}$ *(half of the total measurable tide) as a function of ice shell thickness. Solid curves are for an ice shell rigidity of* $\mu_{ice} = 3.5 \times 10^9$ *Pa, while the dotted lines are for* $\mu = 10^9$ *Pa (above) and* $\mu = 10^{10}$ *Pa (below). A rocky core is assumed to have a radius of 1449 km and rigidity* $\mu_{rock} = 10^{11}$ *Pa, and the assumed ice + ocean thickness = 120 km. Triangles show the reported values from* Moore and Schubert *[*2000*], which did not include a core. [*Figure courtesy Amy Barr.*]*

the forced rotational variations including libration.

Love number $h_2$ is derived by measuring the time-variable topography of Europa, specifically by measuring topography cross-over points **(Figure 2.3-3)**, a technique which has been demonstrated for Earth [*Luthcke et al. 2002, 2005*] and Mars [*Rowlands et al. 1999; Neumann et al. 2001*]. At the end of the first 92 days after EOI, the sub-spacecraft track will form a reasonably dense grid, comprised of a number N (~1000) great circle segments over the surface of Europa. Each of the N arcs intersects each of the remaining N-1 arcs at two roughly antipodal locations, and at these cross-over locations, the static components of gravity and topography should agree. As illustrated in **Figure 2.3-3**, differences in the measured values at cross-over points are equal to a sum of actual change in radius caused by tides and libration, combined with the difference in orbital altitude, along with any errors in range to the center of the body or orbital position. The errors are dominated by long wavelength effects and can be represented by 4 sine and cosine terms in each orbital component (radial, along track, and cross track). The tidal effects in gravity and topography have known spatial and temporal patterns and can each be represented globally by two parameters, an amplitude and phase. The librations are effectively periodic rigid rotations with specified axes and periods, and again an amplitude and phase parameter suffices to describe each axis. Thus, there are 12N + 10 parameters to be estimated (12N orbital, 4 tidal, and 6 librational), from 2N*(N-1) cross-over points. The accuracy with which the altimetric profiles can be interpolated to the cross-over locations depends on range accuracy, surface spot size over which altitude is sampled, and along-track sampling rate. In an ideal case, the surface spots would be small (to minimize topographic variation within spots), and near-contiguous or even overlapping. Those considerations need to be assessed against power and data-rate constraints of an instrument, and the desire to topographically interrogate as much of the surface as possible.

As discussed in §2.2.2.4, the magnetic induction signal from an ocean within Europa is sensitive to the product of the electrical conductivity and thickness of the ocean (**Figure 2.2-3**). Determining the induction response at both the synodic frequency with respect to Jupiter's rotation ($T = 11.1$ hr) and the orbital frequency of Europa ($T = 85.2$ hr)

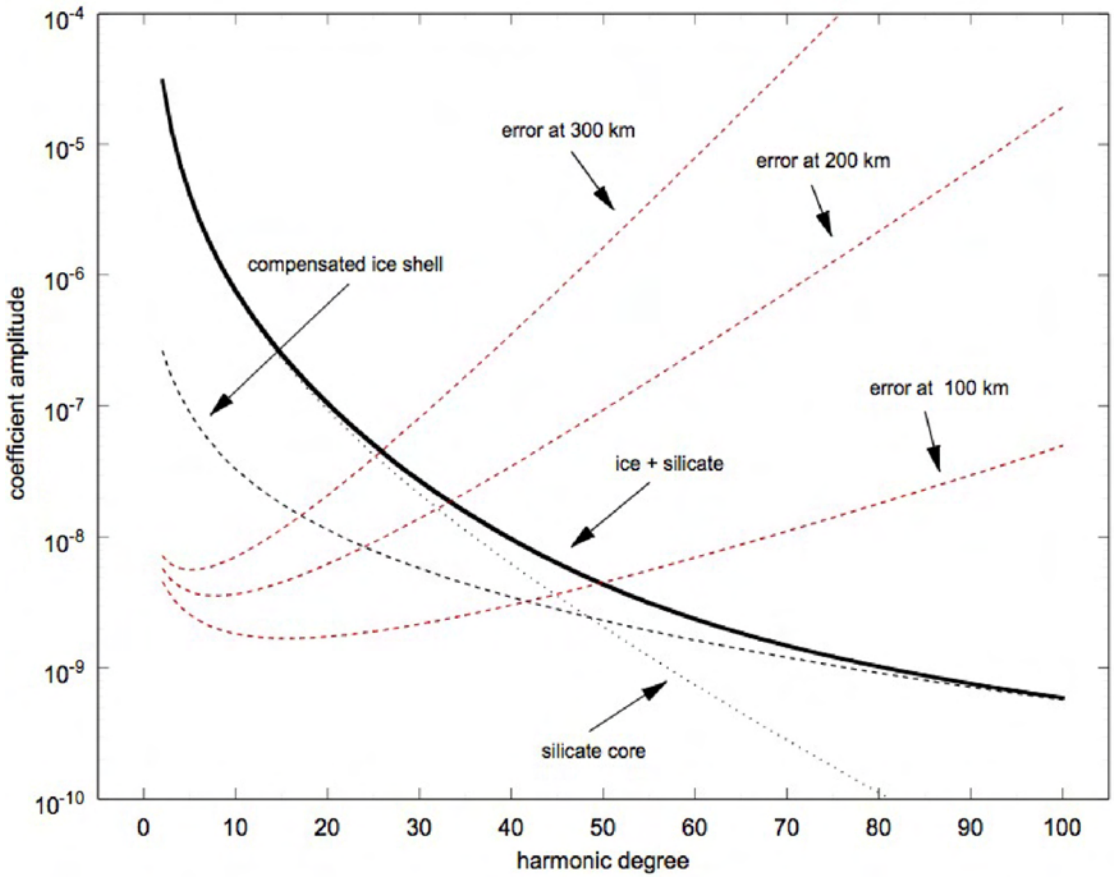



*Figure 2.3-2. **Models of Europa's gravity spectrum**, assuming an ice shell 10 km thick with isostatically compensated topography above an ocean, and a silicate interior with mean surface 100 km below the ice surface. The variance spectra of the ice topography and silicate gravity are assumed similar to those seen on terrestrial planets [*Bills and Lemoine 1995*]. The signal has contributions the silicate mantle and ice shell. The error spectra represent 30 days at fixed altitude, and reflect variations in sensitivity with altitude. The error spectra at different orbital altitudes do not have the same shape because the longer wavelength anomalies are attenuated less at higher altitudes. During a few days at these altitudes, the improvement is linear with time; for longer times, repeat sampling leads to improvement proportional to square root of time.*

can allow for ocean thickness and conductivity to be uniquely determined. In turn, ocean conductivity constrains its salinity. It is possible that additional longer frequencies caused by the background fluctuations of the magnetic field (e.g. associated with Io's torus reorganizations) could be used to sound the ocean. This drives the required sensitivity of the magnetometery measurements to 0.1 nT. Magnetometry requires near-continuous observations from Europa orbit, for at least 8–10 eurosols, i.e. at least one month. A high cadence of 8 vectors/s is required in order to remove the effects of moon-plasma interactions from the data, and knowledge of spacecraft orientation is required to 0.1°.

The primary sources of information concerning the deeper interior structure (the mantle and core) will be derived from the gravitational and magnetic fields, and the dynamical rotational state (including rotation rate, obliquity, and libration). The amplitude of forced librations in longitude, which are gravitationally forced periodic variations in rotation rate, constrains the combination (B-A)/C for the principal moments of inertia A < B < C. There may be two librational signals, one from the ice shell, and another from the deeper interior. The shell's signal

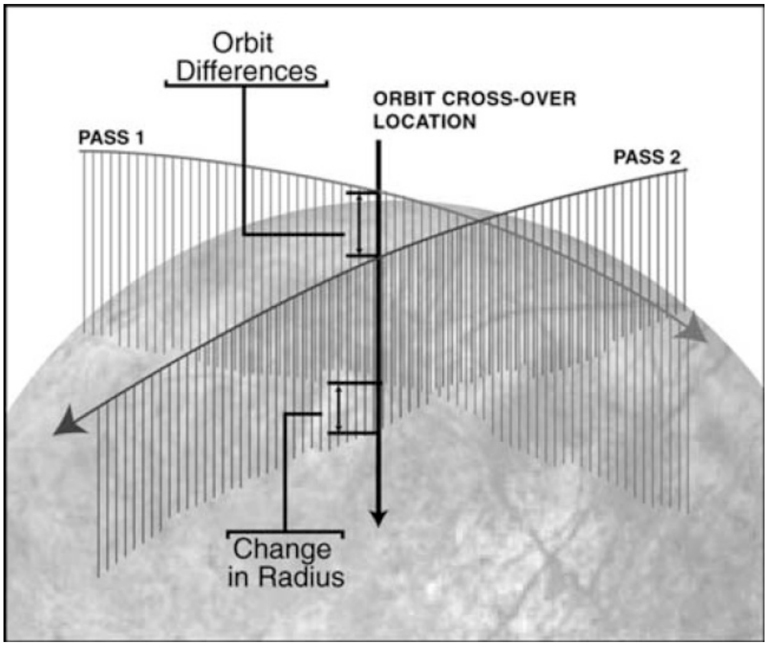



***Figure 2.3-3. Illustration of the cross-over technique.*** *Actual change in radius of Europa due to tidal and librational motions is determined by measuring altitude from the spacecraft to the surface, and by accounting for the distance of the spacecraft from the center of mass by means of Doppler tracking [*Wahr et al. 2006*].*

would be revealed in both gravity and topography data, whereas the deeper signal would appear only in the gravity. Moreover, the tidally damped obliquity, or angular separation between spin and orbit poles, provides a constraint on the polar moment of inertia C, which in turn constrains radial density variations. The dynamical rotational state of Europa will be determined using the Doppler tracking data and laser altimetry data. Initially assuming both steady rotation and zero obliquity, the cross-over analysis described above will be used to both adjust the spacecraft orbit estimate, and to determine the dynamical rotation and tidal flexing of Europa. Magnetometry data which measures very low-frequency magnetic variations, over time periods of several months or longer, will shed light on the magnetic properties of the deep interior, including the core.

**B. <u>Europa's Ice Shell</u>: Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange.**

There are strong scientific reasons for studying the subsurface structure of Europa's shell, especially as related to subsurface water and the nature of surface-ice-ocean exchange (see §2.2). The dielectric losses in very cold ice are low, yet highly sensitive to increasing temperature, water, and impurity content; therefore, much can be learned through orbital electromagnetic sounding of the ice shell. This is especially true when subsurface profiling is coupled to observations of both the topography and morphology of surface landforms and placed in the context of both surface composition and subsurface density distribution. Because of Jupiter's strong radio emissions and the unknown size of volume scatterers within Europa's ice shell, the range of sounding frequencies must be carefully matched to the science objectives.

*Investigations:*

B1. Characterize the distribution of any shallow subsurface water.

B2. Search for an ice-ocean interface.

B3. Correlate surface features and sub-surface structure to investigate processes governing communication among the surface, ice shell and ocean.

The subsurface signatures from near-global surveys at high depth resolution combined with surface topography of similar vertical resolution would identify regions of possible ongoing or relatively recent upwelling of liquid water or brines. Orbital subsurface profiling of the top 3 km of Europa's ice shell is recommended, at frequencies slightly above the upper end of Jupiter's radio noise spectrum (i.e., about 50 MHz), to establish the geometry of various thermal, compositional, and structural horizons to a depth resolution of about 10 m (requiring a bandwidth of about 10 MHz). This high-resolution search for shallow water will produce data analogous to that of the Shallow Subsurface Radar (SHARAD) instrument onboard the Mars

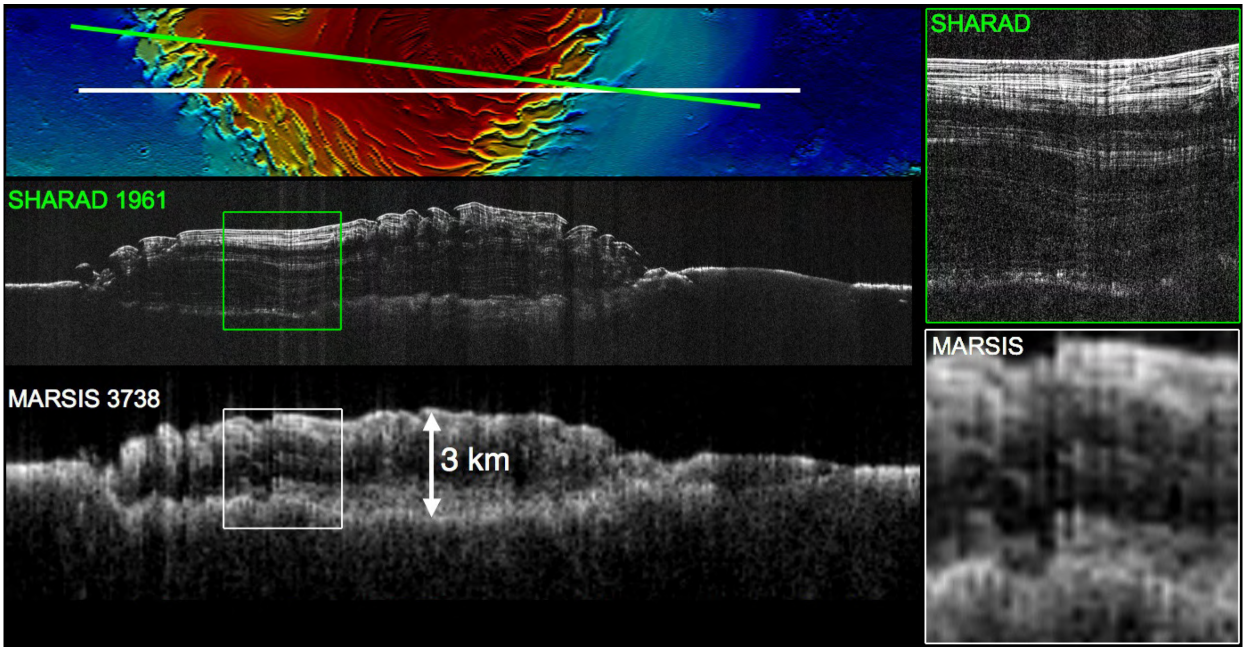



***Figure 2.3-4. Orbital Subsurface Profiling of Mars North Polar Cap.*** *These nearly co-linear profiles across the Mars North Polar Cap (MOLA data at top left) demonstrate the value of the complementary perspectives provided by the high-center frequency and high bandwidth profiling of the SHARAD instrument (20 MHz and 10 MHz, respectively), and the low-center frequency and low bandwidth profiling of MARSIS (5 MHz and 1 MHz, respectively). In particular, note the clarity of shallow horizons revealed by SHARAD (detail at top right) and the prominence of deep interfaces revealed in the MARSIS results (detail at bottom right). The value of a multi-frequency approach to subsurface profiling on Europa would be significantly enhanced in the presence of strong volume scattering. (MARSIS data courtesy of Picardi, Plaut and the MARSIS Team; SHARAD data courtesy of Seu, Phillips, and the SHARAD Team.)*

Reconnaissance Orbiter (**Figure 2.3-4**). This profiling should be done in conjunction with co-located stereo imaging and laser altimetry which can be used to register photogrammetric topography to vertical resolution of better than 10 m, permitting surface clutter effects to be removed from the radar data. Ultimately, this shallow subsurface profiling should extend over at least 80% of Europa's surface utilizing profiles with spacings no more than twice the hypothesized ice shell thicknesses (i.e., about 50 km).

Subsurface signatures from lower resolution but more deeply penetrating near-global surveys might reveal a shallow ice-ocean interface, which could be validated over a region by carefully correlating ice thickness and surface topography. An unequivocally thin ice shell, even within a limited region, would have significant implications for understanding direct exchange between the ocean and the overlying ice. Similarly, the detection of deep subsurface interfaces in these surveys and the presence or absence of shallower interfaces above them could validate hypotheses regarding the convective movement of deep ductile ice into the cold brittle shell implying indirect exchange with any ocean. Additional orbital profiling of the subsurface of Europa to depths of 30 km with a vertical resolution of about 100 m is recommended to establish the geometry of any deeper geophysical interfaces, in particular, to search for an ice-ocean interface. Although warm ice is very attenuating [*Chyba et al. 1998*], "windows" of cold downwelling material may exist within the ice shell, allowing local penetration to great depth [*McKinnon and Gurnis 1999*]. Moreover, while the presence of meter-scale voids within the ice shell would confound sounding efforts at higher frequencies (> 15 MHz) [*Eluszkiewicz 2004*], the presence of such large voids is probably unrealistic [*Lee et al. 2005*]. This deep ocean search will produce data analogous to that of the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument onboard the Mars Express spacecraft (**Figure 2.3-4**). This profiling should establish the geometry of any deeper geophysical interfaces that may correspond to an ice-ocean boundary to a vertical resolution of about 100 m (requiring a bandwidth of about 1 MHz). In particular, frequencies significantly less sensitive to any volume scattering that may be present in the shallow subsurface profiling detailed above (i.e., about 5 MHz) should be used on the antijovian side of Europa, which is shadowed from Jupiter's radio emissions. This low-frequency low-resolution profiling should be complemented by high-frequency low-resolution profiling over Europa's subjovian surface (where Jupiter's radio noise is an issue for low-frequency sounding). Combined, this deep low-resolution profiling should also cover at least 80% of Europa's surface with a minimum profile separation of about 50 km. Profiling should be performed along with co-located stereo imaging and laser altimetry of better than 100 m topographic resolution, permitting surface clutter effects to be removed from the radar data.

Ultimately, targeted surveys will be required to understand the processes controlling the distribution of any shallow subsurface water and either the direct or indirect exchange of materials between the ice shell and its underlying ocean. The presence of major cracks and faults as well as topographic and compositional anomalies, when correlated with subsurface structures within a particular targeted region, can provide critical information on tidal response and its role in subsurface fluid migration. Important factors include localized heating, the magnitude of tectonic stress, and associated strain release. Similarly, variations of the physical and compositional properties of the near-surface ice may arise due to relative age differences, tectonic deformation, mass wasting, or impact gardening. An intimate knowledge of these surface properties gained from spectroscopy and high resolution topographic characterization will be essential for integrated interpretation of observed subsurface structure, in order to understand liquid water or ductile ice migration within Europa's ice shell. Gravity data may also provide insight into anomalous regions within the ice shell. Because of the complex geometries expected for subsurface structures, full unprocessed subsurface imaging should be obtained along profiles in any region of targeted study, either to a depth of 3 km for high resolution imaging of shallow targets or to a depth of 30 km for lower resolution imaging of deeper processes, in conjunction with co-located topographic measurements. These targeted subsurface studies should be considered a necessary prerequisite for any future *in situ* astrobiological exploration.

**C. <u>Europa's Chemistry</u>: Determine global surface compositions and chemistry, especially as related to habitability.**

Composition and chemistry are the linkages between geologic processes and understanding Europa's potential for life and habitability (§2.2.1, 2.2.3). Surface composition is the result of materials generated during the evolution of Europa's surface undergoing modification by external processes. The EE investigations thus focus on determining composition then unraveling the roles of chemistry, geology, radiation, and exogenic materials by making measurement over specific locations. Thus, what is measured and where it is measured it work in tandem to address this objective.

*Investigations:*

C1. Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability.

C2. Relate compositions to geological processes, especially communication with the interior.

C3. Assess the effects of radiation on surface composition, albedo, sputtering, and redox chemistry.

C4. Characterize the nature of exogenic materials.

The first priority in investigation of Europa's surface composition and chemistry is to identify the surface organic and inorganic constituents, with emphasis on materials that could tell of Europa's habitability, and then map their distribution and association with geologic features. The search for organic materials is especially relevant to understanding Europa's potential to harbor life, including compounds with CH, CO, and CN; moreover, learning and understanding the composition of salts may indicate the composition of Europa's ocean. Other compounds of interest include water ice (crystalline and amorphous phases), and products of irradiation, such as $H_2O_2$, and compounds formed by implantation of sulfur and other ions. Other as yet unknown materials may also be present.

To accomplish this, infra-red spectroscopy measurements are required at a spectral resolution of better than 6 nm through a spectral range of at least 0.9–2.5 μm and better than 10 nm through a spectral range of at least 2.5–5 μm (**Figure 2.3-5**). Moreover, measurements through the visible wavelengths of 0.4–0.9 μm at better than 6 nm spectral resolution are desirable. Observations should at least include spectral profiles to sample across at least 80% of the globe with spacings of no more than 25 km (on the order of the nominal ice shell thickness), along with targeted imaging observations at better than or equal to 25 m/pixel spatial resolution (fine enough to resolve most small-scale geologic features and their transitions, while being a tractable requirement considering likely mission resources). Signal-to-noise ratios of greater than 100 are desirable to detect materials in relatively low abundance or mixed with dark material which lowers the contrast of absorption. An ion and neutral mass spectrometer (INMS) provides a means to directly measure species sputtered off the surface, which may include organic fragments. An INMS should operate in the mass range from 1 to > 300 amu, with a mass resolution

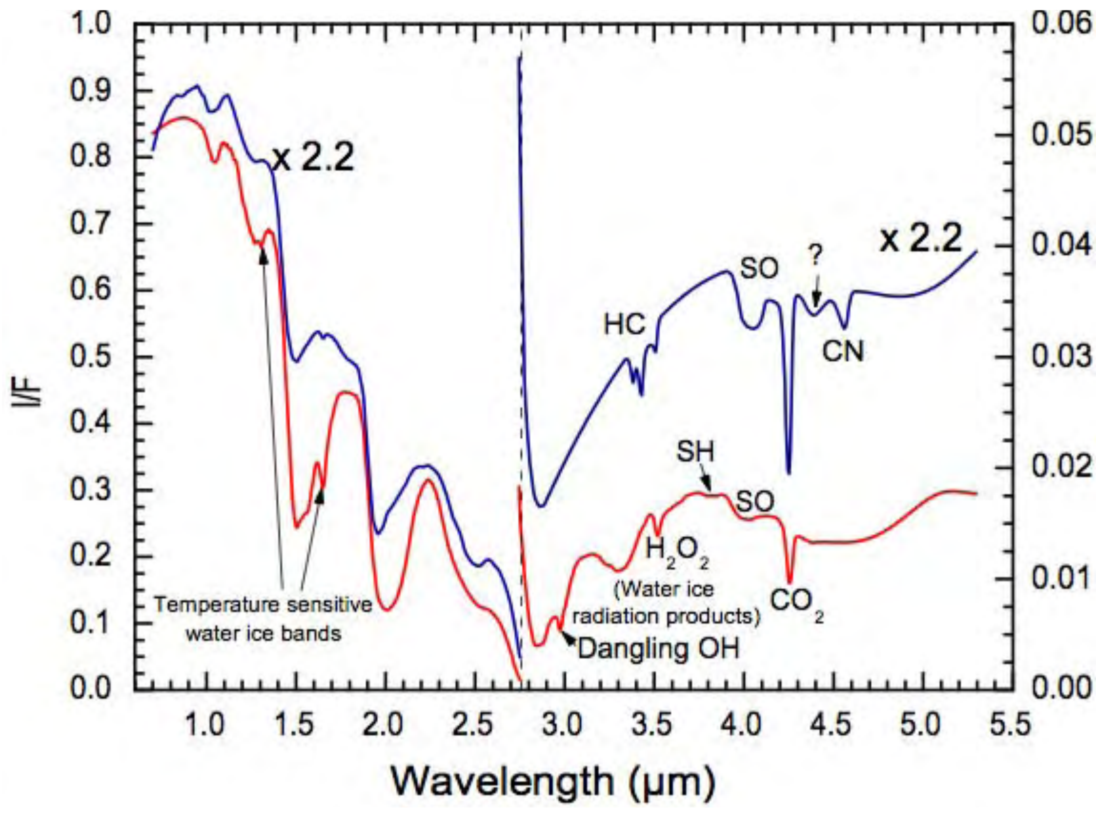



***Figure 2.3-5. Notional reflectance spectra** for icy (lower) and non-ice (upper) regions on Europa at 6 nm spectral resolution in the 1–5 μm spectral range. A variety of materials and molecules have been identified or inferred from the Galileo results. The spectra shown here are composites to show the types and variety of features found or expected, calculated based on laboratory spectra. The non-ice spectrum is scaled by 2.2 from the ice spectrum, and the 2.8–5 μm range spectra are scaled by 10 over the shorter wavelength range. [*Figure courtesy Tom McCord.*]*

($m/\Delta m$) of $\geq 500$, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, and should make continuous measurements throughout the EE mission. Ultraviolet spectroscopy from 0.10 to 0.35 µm at a spectral resolution of 3 nm enhances the ability to map non-ice species, including radiolytic compounds. Required are signal-to-noise ratios of greater than 100, profiling observations of over at least 80% of the surface with spacing no more than 25 km and spatial resolution of better than or equal to 100 m (able to resolve narrow troughs), and targeted observations over areas of interest at similar spatial resolution.

Compositional measurements provide the foundation to relate chemistry and composition to geological processes, especially as related to communication with the interior, to elucidate Europa's potential habitability. This requires synergistic coordinated observations of targeted geological features, along with the synoptic near-global remotely sensed data sets, which are discussed under the Ice Shell and Geology objectives, specifically imaging and stereo, radar sounding, and thermal data sets. The spatial resolution of targeted spectroscopic observations is determined by the scale of critical landforms such as bands, lenticulae, chaos, and craters. Visible imaging shows albedo and morphological differences on the scale of 25–100 m, implying that compositional variations also exist at this scale. Targeted spectral imaging of many examples of key landforms allows compositional information to be placed into a broader framework and related with geologic processes. A global sampling approach is recommended where profiles sample at least 80% of Europa with at most 25-km spacing, to map compositional indicators and search for locations on Europa that could have distinctive compositions.

To understand the evolution of surface materials, the effects of radiation on surface materials, albedo, sputtering, and redox chemistry must be understood. Radiolytic processes may alter the chemical and compositional signature over time. Assessing these relationships requires a detailed sampling of the surface with infra-red and ultraviolet spectroscopy, using global and targeted observations with the parameters described above. Characterization of the sputter-produced atmosphere with an INMS will allow the chemistry of sputtered constituents to be better understood. Moreover, ultraviolet stellar occultations by Europa's atmosphere will allow for the measurement of species, abundances, and ion implantation rates. This requires far-ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emissions, through a range of at least 0.10-0.35 µm at equal to or better than 3 nm spectral resolution and 100 m/pixel spatial scale. Simultaneously, it is important to measure particles, specifically electrons from about 100 keV to 10 MeV with pitch angle distribution and $\Delta E/E$ ~0.1 over Europa's surface, and ions from 15 keV to 750 keV from the ram direction. Combined with imaging data and geological stratigraphic maps, these synergistic observations will allow determination of how Europa's surface materials evolve in the radiation environment.

Finally, the nature of exogenic material must be characterized. The nature of implanted materials is elucidated by measuring ions. Each ion energy and species has a specific penetration depth in ice (**Figure 2.2-6**). The lowest energy ("cold") ions are probably deposited in the most processed layer of surface, and for this part of the discussion, may not be interesting. The 100 keV to few MeV ions penetrate slightly deeper and could be incorporated into the ice to form new molecules. Since they penetrate slightly deeper, they will not be removed from the surface as easily by processes such as sublimation and sputtering. Electrons of the same energies go much deeper into the ice and affect a deeper layer, where the ions would not reach. For this layer, the electrons deposit energy directly, or through their secondaries, and create other changes in the ice. Both species are interesting for making physical and chemical changes in the ice, typically at different depths. For both species, an energy resolution $\Delta E/E$ of 0.1 is sufficient over the energy ranges noted above. Moreover, plasma should be characterized, by measuring ions from 10 eV to 10 keV with 15 degree angular resolution to $\Delta E/E$=0.15, and with ion mass spectrometry over a mass range of 300 Daltons, mass resolution of $\geq$500, and pressure range for ions of $10^{-6}$ to $10^{-17}$ mbar, and energy resolution of 10%. Measurements over time can constrain the surface source and dynamics of sputtered species. These measurements should be synthesized with globally distributed and targeted infra-red and ultraviolet measurements as described above, along with global 3-color images at ~100 m/pixel. These data will allow materials to be traced from their magnetospheric sources, to the surface, and into the sputter-produced atmosphere.

**D. Europa's Geology: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**

Europa's landforms are enigmatic. A number of hypotheses have been proposed based on existing spacecraft data, but the genesis of its variety of surface features is not well understood. The search for recent or current geologic activity is important to understanding the origin of landforms, and most important, to understanding Europa's habitability. Identification and characterization of the most astrobiologically promising locations will determine their suitability as candidate sites for future *in situ* exploration.

*Investigations:*

- D1. Characterize magmatic, tectonic, and impact features.
- D2. Search for areas of recent or current geological activity.
- D3. Investigate global and local heat flow.
- D4. Assess relative surface ages.
- D5. Characterize the physical properties of the regolith, and assess processes of erosion and deposition.

Of first order importance is characterization of surface features—their distribution, morphologies, and topography—at regional and local scales, in order to understand the processes which formed them (**Figure 2.3-6**). Galileo imaging demonstrated that regional-scale imaging at ~100 m/pixel, especially as aided by 3-color coverage, is excellent for recognizing and characterizing the distribution of Europa's landforms, yet less than 10% of the surface was imaged at better than 250 m/pixel by Galileo. Near-global coverage (> 80% of the surface) in at least 3 colors at 100 m/pixel will ensure characterization of landforms across the satellite. Galileo imaging also showed the great value of targeted high-resolution (~10 m/pixel) monochromatic imaging for detailed characterization of selected landforms permitting inference of formational processes, and targeted imaging at this resolution is recommended.

Topographic mapping through stereo imaging at regional scale, with vertical resolution ~10 m, will greatly aid morphological characterization and geological interpretation. Stereo imaging can be achieved through horizontal overlap of adjacent wide-angle camera image tracks, resulting in approximately 10 m vertical height accuracy with 100 m/pixel images. Height accuracy further improves by $\approx\sqrt{N}$ upon averaging of $N$ overlapping stereo pairs, and each equatorial patch of Europa would be imaged about 16 times during a 1 year mission, improving height accuracy by ~4 times. High latitudes are sampled much more, so height accuracy improves even further by approximately the cosine of latitude.

It is also important to determine

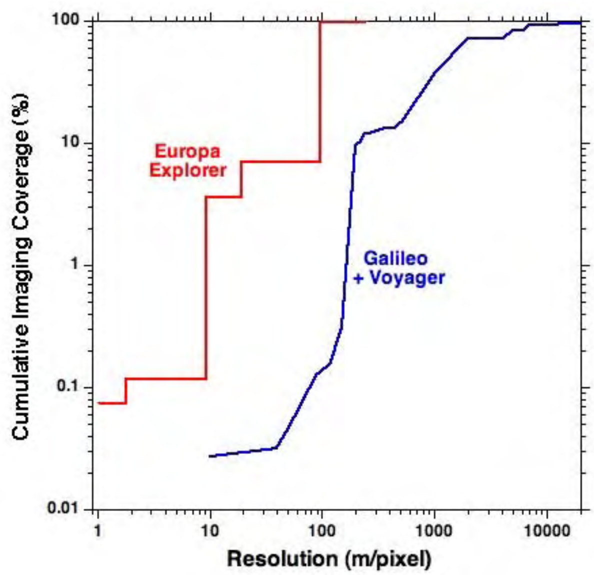



***Figure 2.3-6. Cumulative imaging coverage of Europa's surface** as a function of imaging resolution, illustrating the 1–2 orders of magnitude improvement of planned EE imaging coverage relative to that from Voyager and Galileo combined. Unlike the opportunistic coverage obtained from earlier fly-bys, EE's deliberate imaging coverage from orbit will be in discrete resolution steps.*

topographic character at high resolution through stereo imaging and altimetric profiling across targeted representative features, with vertical accuracy of 1 m or better. Subsurface profiling (discussed in §2.3.4B, above) will greatly illuminate subsurface structure and the role of liquid water. Europa's surface is quite heterogeneous and rough at the decameter scales of Galileo's highest resolution imaging (**Figure 2.3-7**), and the same may be true at smaller scales. Very high resolution monochromatic imaging (1 m/pixel) will reveal the detailed character of landforms, the properties of the regolith, and erosion and deposition processes. Moreover, imaging at this scale will be critical in characterizing potential future landing sites.

Geologically active sites will be the most promising astrobiologically, and therefore will be important to identify and characterize as possible future landing sites. Active processes typically involve elevated heat flow, and are the most likely locations to find shallow liquid water. Recently or currently active regions also best illustrate the processes involved in feature formation, showing pristine morphologies and geological relationships. Modeling shows that liquid water brought to the surface of Europa can maintain > 5 K nighttime thermal anomaly over hundreds of years, with younger spots being warmer [*van Cleve et al. 1999*]. Additionally, variations in daytime temperatures seen by the Galileo Photopolarimeter Radiometer show 5 K temperature variations that could have been caused by variations in thermal inertia when corrected for albedo [*Spencer et al. 1999*]. Regions of anomalously high heat flow should be identified through thermal mapping, with a 2 K measurement temperature accuracy permitting the search for both elevated temperatures due to thermal anomalies and derivation of thermal inertia when combined with albedo information. Such requires observing the same features in the day and at night, ideally near maximum and minimum temperatures, but with no strict requirement on the relative times between the measurements. A resolution of 250 m/pixel is sufficient to resolve Europa's larger cracks and ridge axial valleys, and observations should be made over at least 80% of the surface.

Searching for regions of outgassing is a

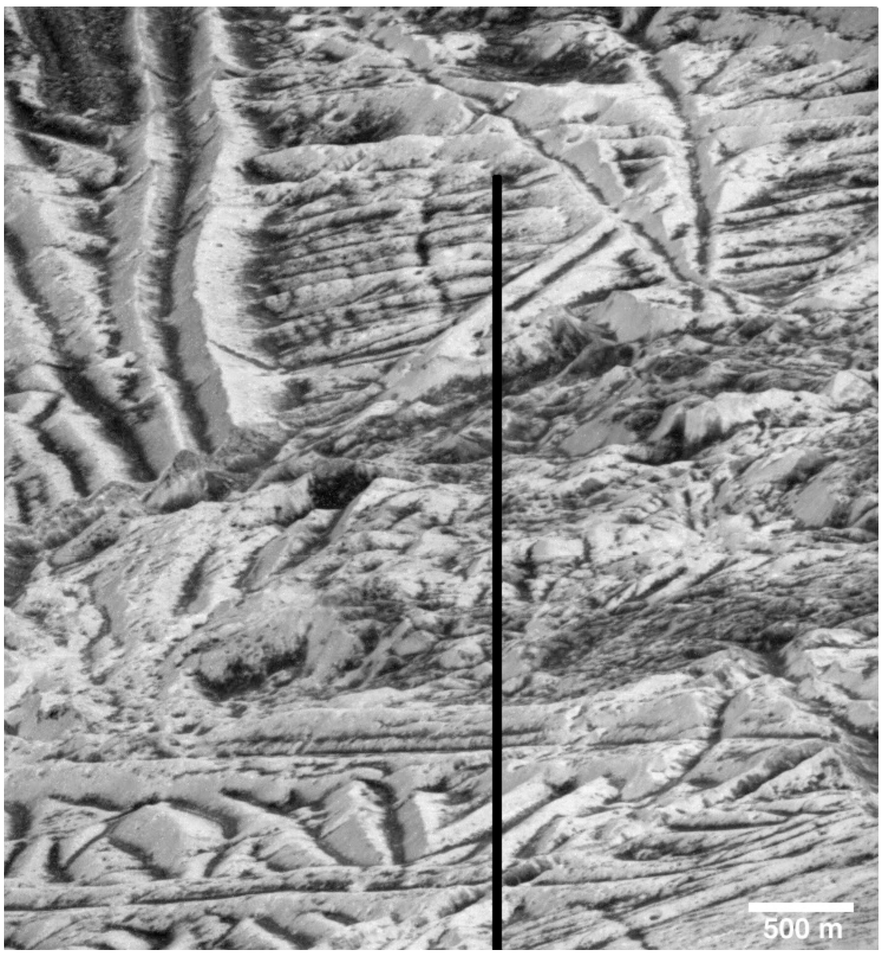



***Figure 2.3-7. Highest resolution Galileo image of Europa,*** *an oblique view at 6 m/pixel in the horizontal direction. Europa's surface is extremely rough at small scales, consistent with recent or current activity. It will be important to identify and characterize at very small scales promising sites for future* in situ *investigation, feeding forward to future landed missions.*

powerful method of locating currently active regions, best accomplished by observing stellar occultations in the ultraviolet, since vented water vapor and other gases will absorb starlight. Ultraviolet stellar occultation experiments were fundamental to discovery of plumes on Enceladus [*Hansen et al. 2006*] (**Figure 2.3-8**). Moreover, observing the surface and the tenuous atmosphere at ultraviolet wavelengths could reveal patchy regions of absorption that might be related to recent venting or other internal activity. An ultraviolet wavelength range of 0.1–0.35 µm and spatial resolution of better than 100 m/pixel are recommended, with capability to observe the sunlit surface, stellar occultations over Europa's limb, and atmospheric emissions.

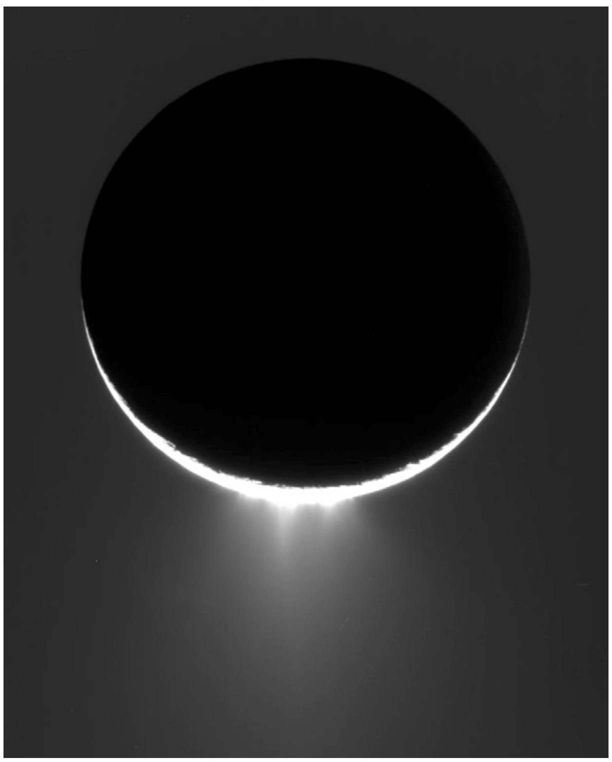


***Figure 2.3-8. The plumes of Enceladus*** *dramatically illustrate that satellite to be geologically active today, as revealed by a combination of Cassini high-phase imaging (as shown above), plus thermal, UV, and fields and particles observations [*Porco et al. 2006*]. Analogous plumes would be ~70 km tall when scaled to Europa's gravity, so similar activity could be plentiful yet undiscovered on Europa, and might contribute to Europa's recently discovered torus [*Mauk et al. 2003*]. A combination of thermal and ultraviolet observations would permit a thorough search and characterization of active regions on Europa.*

Discoveries of any active regions would be followed up by visible and other remote sensing investigations of the inferred source locations. It may be possible to observe surface changes within the time scale of the EE mapping mission; moreover, the most recently active landforms are expected to show the freshest morphologies (i.e., the least degree of mass wasting), and should display the fewest superposed small impact craters. Imaging at high resolution (10 m/pixel) in stereo, along with very high resolution (~1 m/pixel), will be used to characterize features that are suspected candidates for recent activity based on other data sets. If age-sensitive chemical or physical indicators can be identified, such as $H_2O$ frost, ice crystallinity, $SO_2$, or $H_2O_2$, then mapping their distribution may reveal currently or recently active regions; a search can be conducted with infrared and ultraviolet imaging of the surface at 100 m/pixel or better spatial scales.

Constraining the global and local heat flow of Europa would be of great importance, though high heat fluxes (~1 W/m$^2$) would be necessary for detection [*Spencer et al. 1999*]. Such a detection could indicate that significant tidal heating is occurring in the mantle. This would have important implications for the possible development of life on Europa, and potentially for understanding the development of life on Earth, where it is hypothesized that life may have developed at hot hydrothermal vents on the ocean floor. Constraints on global heat flow will also come from limitations on ice shell thickness from gravity or radar data, since a very thin (several kilometers) ice shell would imply a hot tidally heated mantle [*Moore 2006*]. Local heat flow is more plausibly detected [*van Cleve et al. 1999*], for example, if water or warm ice has been extruded onto the surface in the past century, especially at higher latitudes where background temperatures are low. Thermal emission from the surface can be appropriately mapped by measuring albedo to 10% radiometric accuracy at spatial resolution better than or equal to 250 m/pixel, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy < 2 K, over > 80% of the surface.

Understanding the relative ages of Europa's features allows the evolution of the surface to be unraveled. Indication of relative age comes from investigating the stratigraphy, derived from cross-cutting and embayment relationships, and the relative density of small primary impact craters. These types of relationships allow a time history to be assembled within individual region, and then contiguous global imaging is necessary to understand relationships globally. Galileo 3-color imaging at low phase angle showed the great advantage of color imaging in aiding stratigraphic interpretation, because features generally brighten and become less red with age [*Geissler et al. 1998*]. Without a global map, the relative ages of different regions cannot be determined, because they cannot be linked; this is the current problem in understanding Europa's stratigraphy based on Galileo imaging. Global color imaging (> 80% of the surface) at resolution better than about 100 m/pixel, with near-uniform lighting conditions and phase angle ≤ 45°, will allow Europa's global stratigraphic sequence to be derived. Similar to searching for recently or currently active regions, relative surface ages also can be derived by identifying regions of anomalously high heat flow, by determining small-scale surface morphology and topography, and by mapping any age-sensitive chemical and physical indicators.

Europa's regolith provides information about modification processes occurring on very small scales. Modification occurs by mass wasting, sputtering, impact gardening, and thermal redistribution of material across the surface. Investigation of regolith characteristics and processes will be important in characterizing high-priority sites for future landed missions, and in understanding means of communication between the oxidant-rich upper meter of the surface, and the subsurface. Regolith processes can be investigated by deriving the thermal inertia of surface materials near-globally (over > 80% of the surface), determined from thermal observations of the same regions observed in both the day and night at better than 2 K absolute temperature and ~250 m spatial resolution. Imaging at ~1 m/pixel resolution will reveal the small-scale morphology of targeted sites, shedding light on erosional processes and material redeposition. Meter-scale imaging is critical to understanding the nature and safety of potential future landing sites. Magnetometry measurements are also important to understanding sputtering; thus, it is valuable to measure ion-cyclotron waves, which can be related to plasma-pickup and erosional processes. Measuring these high-frequency waves requires magnetic field sampling at 32 vectors/s at a sensitivity of 0.1 nT, knowledge of spacecraft orientation to 0.1°.

### E. Europa's External Environment: Characterize the magnetic environment and moon-particle interactions.

The rapidly rotating magnetosphere of Jupiter is continuously overtaking Europa in its orbit. Charged particles impact the surface and atmosphere and can liberate and redistribute material. Energetic particles can deliver energy deep into the ice, and can form radiolytic products such as oxidants. Because surface, atmospheric, ionospheric, and field and particle environments are intimately connected, an integrated set of magnetic field, plasma, energetic particle and neutral atmosphere investigations are required to unravel the several processes which affect Europa's external environment, and its relationship to the surface.

*Investigations:*

- E1. Characterize the magnetic environment.
- E2. Characterize the ionosphere and neutral atmosphere and their dynamics, with implications for surface interactions.
- E3. Characterize relationships between the magnetic field and plasma.
- E4. Characterize the global radiation environment.

Jupiter's magnetic field at Europa's orbit has been modeled fairly successfully to date, but how that field is perturbed near the satellite is of great importance to Europa studies. The field perturbations relate to a number of different issues of interest. The electromagnetic fields guide how particles are carried onto and over Europa's surface and atmosphere, and also how pick up ions are accelerated into the surrounding environment. Magnetic field measurements complement direct particle measurements by other instruments. Furthermore, observations of an electromagnetic induction signature at the synodic rotation period of Jupiter provide the primary evidence of a current-day ocean within Europa; as detailed in §2.2.4, characterization of the magnetic field and induction signal at multiple frequencies will constrain the salinity and thickness of the ocean, and perhaps properties of the core. The shielding of the electric field around Europa is affected by the strength and configuration of the local magnetic field and the scale height of the atmosphere. The magnetic field must be measured with an accuracy of at least 0.1 nT and requires near-continuous measurements with a cadence of 8 vectors/s to resolve sharp current sheets created by moon-plasma interactions.

The surface of Europa continuously exchanges material with the atmosphere, and direct measurements of the atmosphere are a prime concern. The measurement of major and minor constituents of the neutral atmosphere would greatly aid geological, compositional, and exospheric studies. In addition to water ice, heavy molecules and molecular fragments can be sputtered and subsequently detected. The sputtering agents are energetic ions (in the tens of keV to hundreds of keV energy range), and their fluxes need to be directly detected over Europa's surface. Sufficient angular coverage is required to remove the effects of plasma flow (the Compton-Getting effect), with sufficient resolution to determine the energy spectrum. Ion flux should be measured from energies of 10 keV to 1 MeV to $\Delta E/E=0.1$, and ions from 10 eV to 10 keV with 15° angular resolution to $\Delta E/E=0.15$. Simultaneous magnetic field measurements similar to those described above are also required. Synergistic and highly desirable are INMS measurements of species in the mass range from 1 to > 300 amu, a mass resolution ($m/\Delta m$) of $\geq 500$, and pressure range of $10^{-6}$ to $10^{-17}$ mbar, with data collected continuously. Because sputtering is highly variable over Europa's surface, a patchy atmosphere is anticipated and can be examined with ultraviolet imaging of the atmosphere at equal to or better than 3 nm spectral resolution, through a range of at least 0.1–0.35 µm; sampling on time scales of hours will reveal variations over time.

The magnetic environment is profoundly affected by the local production of charged particles and by currents generated when plasma interacts with Europa; thus, plasma ions (tens of eV to few keV range) are linked to perturbations in the magnetic field near the satellite. Because the corotational flow velocity is ~100 km/s, the fluxes of ions up to about 100 keV are extremely anisotropic as detected by a spacecraft, and greatest in the ram direction. To determine the plasma flow around the body and the relationship between plasma and the magnetic field, ions with energies 50 eV to 10 keV need to be detected with good energy resolution ($\Delta E/E=0.15$) and angular resolution (~15°) to properly understand their fluxes in their rest frame. This investigation will assemble a consistent scenario of plasma flow and currents near the body, and magnetic field observations.

Particle bombardment, in addition to carrying energy to depth, also determines which radiolytic species are expected. Thus, understanding heavy electron doses into the surface as a function of surface position is relevant to habitability. Direct measurement of energetic ion fluxes (tens of keV to few MeV) and electron fluxes (hundreds of keV to many MeV) over the whole globe is then considered to determine surface bombardment rates, which tell of the production of oxidants and other radiolytic species. Plasma ions (tens of eV to few keV) flowing near the surface reveal how electromagnetic fields behave near Europa's surface. Their fluxes and angular distributions provide information about fields and therefore how energetic ions and electrons gain direct access to the surface and deposit their energy. Both magnetic field and ion plasma measurements are required, with parameters described above.

**F. Europa's Neighborhood: Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons.**

Understanding the Jupiter system as a whole is critical for placing Europa in its context as a member of the Jovian satellite system and for understanding the origin and evolution of the system, including Jupiter. The investigations are broader than those for Europa science, reflecting the EE study guideline that this objective must receive Priority 2 characterization. The investigations fall into three categories:.

*Investigations:*

F1. Determine the nature and history of the geological activity and interior evolution of the Galilean satellites.

F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a gas giant planet.

F3. Study the interactions between Jupiter's magnetosphere and its satellites.

These three categories emphasize the Galilean satellites, Jupiter, and the magnetosphere, respectively. The Jovian system will be the principal focus of the Jovian Tour phase of the EE mission, which has a duration of two years prior to Europa Orbit Insertion.

*Satellites:* Understanding the nature and history of the geological activity on the other Galilean satellites provides constraints on the interior and surface activity of Europa. Observations of Io in the thermal infrared directly provide the heat flow through Io’s surface and the mechanisms of volcanic heat transport. Measurements of the chemistry of Io’s voluminous volcanic deposits by infrared and ultraviolet spectroscopy reveal the interior processes in a tidally heated silicate body. Such processes may occur inside Europa, greatly contributing to its habitability. Measurements of Callisto’s surface chemistry by infrared and ultraviolet spectroscopy determine the more primitive components of the Jovian nebula, and coincident imaging, spectroscopy, subsurface sounding and stereo topography during flybys reveal the geological processes operating even on the least active Galilean satellite. The geology of Ganymede is closely related to that on Europa, and the satellites share many characteristics. Coincident imaging, infrared and ultraviolet spectroscopy, subsurface sounding, and stereo topography sufficient to resolve individual geologic features would connect the dynamic geology of Ganymede’s ice shell to the morphology and chemistry of its surface. Measurements of the properties and dynamics of Ganymede’s magnetic field constrain models of the internal heat transport processes that drive the dynamo. The magnetic field influences Ganymede’s response to Jovian magnetospheric processes, including differential radiation processing as a function of latitude. The atmospheres of the Jovian satellites can be studied by plasma and neutral gas measurements made near the moons and remotely by ultraviolet emission and stellar occultation observations. Imaging, infrared, and ultraviolet spectroscopic measurements of the shapes, surface features, and compositions of the minor bodies in the Jovian system provide a window into Jupiter’s neighborhood and the primitive components of the Jovian subnebula.

*Jupiter:* There are many opportunities for observations of Jupiter during the nearly two years that the EE will spend in Jupiter orbit prior to insertion into Europa orbit. Observations at spatial resolutions of 10s of km are better than attainable from the Hubble Space Telescope, and combined with multispectral observations can be used to characterize the local dynamics and chemistry of Jupiter’s atmosphere. The dynamics of Jupiter’s atmosphere can be inferred from imaging over time scales of minutes to days, and longer-period monitoring of months to years is needed to understand slow dynamical processes including seasonal changes. Desirable are ultraviolet, visible and infrared spectroscopy sufficient to resolve key atmospheric constituents, and imaging sufficient to resolve individual thunderstorms, as are thermal infrared images capable of resolving major eddies. Stellar occultation measurements in the ultraviolet and infrared, along with radio occultation measurements, will provide depth dependent chemistry and physical properties.

*Magnetosphere:* Investigation of Jupiter’s magnetosphere requires near-continuous temporal observations, with spatial sampling throughout the magnetosphere, especially in special regions including internal boundaries and near satellites. Nearly continuous measurements of the magnetic field, and of the energy spectrum of the plasma over a broad energy range, are required while in Jupiter orbit. Near satellites, plasma observations should be made at a variety of altitudes and orientations with respect to the plasma flow direction. Elucidating the links between Io's volcanic activity and the dynamics of the Jovian magnetosphere requires ultraviolet and visible observations of the Io torus, Jovian auroral oval, and the satellite auroral footprints at high time and spectral resolution, combined with monitoring of Io activity in the visible and infrared. The Jovian ionosphere can be probed at a range of latitudes through radio occultations at multiple frequencies, accomplished using precisely time-referenced Ka- and X-band transmissions.

## 2.4 Science Implementation

### 2.4.1 Payload Considerations

Since the first return of spacecraft data of the Jupiter system from the Pioneer and Voyager flybys, the scientific study of Europa has evolved from addressing first-order questions on its characteristics, such as assessing the fundamental processes shaping its surface, to a wide variety of sophisticated investigations based mostly on the Galileo data set. In the late 1990s, most studies of Europa were performed by Galileo science instrument teams which focused on data validation. Through venues such as the Jupiter System Data Analysis Program and the Outer Planets Research Program, data sets were merged and synthesized by the full scientific community. In the ten years since the first return of Galileo Europa data, the scientific understanding of Europa has greatly matured, leading to the formulation of sophisticated questions to be addressed through new data.

The former Europa Orbiter mission concept was developed in the late 1990s, when the focus was on basic aspects of Europa science. Since then, the Decadal Survey explicitly endorsed expansion of the science scope of a Europa mission (§2.3.1). Moreover, capabilities for such a mission have increased relative to the Europa Orbiter, e.g. through adopting a Venus-Earth-Earth Gravity Assist trajectory, enabling the full set of high priority scientific investigations identified to be addressed. (On the other hand, the deferred JIMO mission concept envisioned nuclear propulsion, potentially allowing a very large payload.)

Developing the payload for any mission concept requires consideration of two approaches: (1) identifying payloads that are designed to test specific hypotheses, and (2) identifying payloads that have the potential for serendipitous discovery, i.e., techniques which have the potential to address the unknown. Solar system exploration is replete with examples of the latter consideration; for example, the initial payload for the Mars Observer / Mars Global Surveyor mission included neither a camera nor a magnetometer and both were subsequently added. Few would argue that the discoveries afforded by these instruments, including the existence of young water-carved gullies and the presence of a remnant magnetic field, revolutionized our understanding of Mars, and helped to direct future exploration. In deriving the planning payload for the EE mission, the SDT has derived a robust planning payload that addresses specific measurements to test known hypotheses, while providing a broad and highly capable instrument suite that allows the flexibility to respond to new discoveries.

### 2.4.2 Planning Payload

The measurement requirements of §2.3 trace to a baseline mission planning payload of 11 instruments (exclusive of the telecom system). This planning payload was used to allow the scientists and engineers to develop a complete mission concept that addressed the identified science objectives within a reasonable set of requirements and constraints. The planning payload enables engineers to understand what requirements are imposed by different payload elements. The actual instruments would be the result of an Announcement of Opportunity (AO) selection process carried out by NASA. The planning payload instruments are listed in the EE Traceability Matrix (**FO-1**) and **Table 2.4-1**, and they are described in detail in §4.2.1.

Included in **Table 2.4-1** are comparisons of key instrument capabilities between the baseline and floor planning payloads, with gray shading indicating that three instruments (INMS, UVS, and NAC) are descoped entirely in the floor payload. The rationale and science impacts of descoping from the baseline to the floor planning payload are discussed in §2.4.6,

***Table 2.4-1.*** *Science Instruments, Including Baseline and Floor Mission Comparison*

| Science Instruments | Baseline | Floor |
|---|---|---|
| Telecom system | Ka and X bands | X band only |
| Wide-Angle Camera (WAC) | 3-color + panchromatic | 3-color + panchromatic |
| Medium-Angle Camera (MAC) | Stereo optics | Single optic |
| Narrow Angle Camera (NAC) | Operates in framing or pushbroom mode | NONE |
| IR Spectrometer (IRS) | Optimized spectral and spatial resolution | Lesser spectral and spatial resolution |
| UV Spectrometer (UVS) | Permits both nadir and limb viewing | NONE |
| Laser Altimeter (LA) | Multi-beam | Single beam |
| Ice Penetrating Radar (IPR) | Dipole & Yagi antennas | Yagi antenna replaced by a dipole |
| Thermal Instrument (TI) | Imaging instrument | Point instrument |
| Magnetometer (MAG) | Dual magnetometers; 10 m boom | Single magnetometer; 5 m boom |
| Ion & Neutral Mass Spectrometer (INMS) | Sensitive to low gas concentrations | NONE |
| Particle & Plasma Instrument (PPI) | Includes energetic particle sensors; plasma sensor that detects ion species | Less angular coverage of energetic particles; ion counts but not species. |

following discussion of the campaign-based data acquisition strategy during the Europa Science phase of the mission.

### 2.4.3 Instrument and Mission Requirements

The measurement requirements of §2.3 place requirements on the instruments and the mission. These are summarized for each objective in **Table 2.4-2**. Additional quantitative specifics are provided in the Traceability Matrix (**FO-1**), and requirements on the simultaneity of observations is discussed in §2.4.4.

Optimizing among these constraints has shaped the adopted nominal mission scenario. A high-inclination orbiter is required, with a nominal orbit duration of at least 26 eurosols ≈ 92 days ≈ 3 months. The orbit is near-circular, with a nominal orbital inclination of 95° (i.e. equivalent to 85° but retrograde, thus offering greater orbital stability; see §4.3.5). The optical remote sensing instruments are nadir-pointed and mutually boresighted. The orbital altitude begins at 200 km for several eurosols and then reduces to 100 km altitude. The orbit is near-sun-synchronous but precesses slowly, such that the orbit walks slightly with time, as to not exactly repeat the same groundtrack but to allow instrument fields of view to overlap with previous tracks. Thus, the orbit is near-repeating after several eurosols, within about 1° of longitude at the equator, rather than repeating exactly. The solar incidence angle is nominally 45° (2:30 p.m. orbit), as the best compromise to the requirements of various optical remote sensing measurements.

Investigations related to the Jovian system do not drive EE instrument or mission requirements, consistent with NASA guidelines for the present study. Nonetheless, significant Jupiter system science is enabled by the Galilean satellite tour, which lasts nearly 2 years prior to Europa Orbit Insertion. The planning payload instruments will provide strong capability for accomplishing Jupiter system science, with the deck of the flight system tracking Jupiter and the other Galilean satellites to accomplish observations during the Jovian tour phase (Appendix G).

### 2.4.4 Orbital Mission Data Acquisition Strategy

The data acquisition strategy during the Europa Science phase of the mission is designed to obtain the highest-priority observations first and quickly. Following a brief check-out period, data taking proceeds through 4 campaigns, beginning with Global Framework campaign, then focusing on Regional Processes, then concentrating on Targeted Processes to address local-scale science questions, and finally conducting the Focused Science campaign intended to follow-up on discoveries made during the earlier campaigns.

Throughout the Europa Science phase, several instruments collect data continuously, both on the day and night sides of Europa (**Table 2.4-3**). Specifically, these are: radio science - gravity (via the telecom subsystem), Magnetometer (MAG), Laser Altimeter (LA), Thermal Instrument (TI), Ultraviolet Spec-

***Table 2.4-2.*** *Instrument and Mission Requirements Imposed by Science*

| Science Objective | Architecture and Orbit Constraints | Additional Mission Constraints |
|---|---|---|
| A. OCEAN: Characterize the ocean and deeper interior. | Gravity and altimetry: Orbiter required, low altitude (~100-300 km), orbital inclination of ~40–85 degrees (or retrograde equivalent) for broad coverage and cross-overs. Groundtracks should not exactly repeat (while near-repeat is acceptable), so that different regions are measured. Requires a mission duration of at least several eurosols order to sample the time-variability of Europa's tidal cycle.<br>Magnetometry: Near-continuous measurements near Europa, globally distributed, at altitudes ≤500 km, for a duration of at least 1–3 months. | Gravity and altimetry: Knowledge of the spacecraft's orbital position to high accuracy and precision (~meters radially) via two-way Doppler.<br>Gravity: Long undisturbed data arcs are required (> 12 hr periods without spacecraft thrusting; see §4.3), and momentum wheels to maintain spacecraft stability.<br>Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month. |
| B. ICE: Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange. | Radar sounding: Low orbit (≤ 200 km) considering likely instrument power constraints. Near-repeat groundtracks are required to permit targeting of full-resolution observations of previous survey-mode locations. Close spacing of profiles requires a mission duration of months, and near-global coverage implies orbital inclination ≥80°. | Radar sounding and altimetry: Data sets need to be co-aligned and time-referenced to 1 ms accuracy.<br>Radar sounding: Raw full-resolution targeted radar data requires ≥900 Mb solid-state recorder. |
| C. CHEMISTRY: Determine global surface compositions and chemistry, especially as related to habitability. | Infra-red and ultraviolet spectroscopy: Solar incidence angles of ≤ 45°, with a orbital inclination ≥ 80° for near-global coverage. Near-circular orbit is desirable. Close spacing of profile-mode data implies a mission duration on the order of months. A near-repeat orbit is desired, to permit targeted observations to overlap previous profiling-mode observations.<br>INMS: As low an orbit as feasible is desired, for direct detection of sputtered particles. | Optical remote sensing: Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable. |
| D. GEOLOGY: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration. | Optical remote sensing: Near-repeating orbits required to permit regional-scale coverage overlap, follow-up targeting, and stereo; close spacing of profile data implies a mission duration on the order of months; ≥80° orbital inclination to provide near-global coverage.<br>Imaging: Solar incidence angles of 45–60° are best for morphological imaging, while a solar phase angle ≤ 45° is best for visible color imaging. Near sun-synchronous and near-circular orbit is highly desired to permit global coverage to be as uniform as practical. Beginning at a higher orbital altitude and reducing to a lower altitude will allow rapid areal coverage, followed by improved resolution coverage at low altitude.<br>Thermal mapping: Day-night repeat coverage required; afternoon orbit is desirable. | Optical remote sensing: Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable.<br>Radar sounding and altimetry: Data sets need to be co-aligned and time-referenced to 1 ms accuracy.<br>Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month.<br>Ultraviolet spectroscopy: Atmospheric emissions observations and stellar occultations, require a view to the satellite's limb. |
| E. EXTERNAL ENVIRONMENT: Characterize the magnetic environment and moon-particle interactions. | Magnetometry and particles: Near-continuous measurements near Europa, globally distributed, at altitudes ≤500 km, for a duration of at least 1 month. Although elliptical orbits are desirable, a circular orbit is sufficient. | Magnetometry: Magnetic cleanliness of 0.1 nT at the sensor location, and knowledge of spacecraft orientation to 0.1°. Calibration requires slow spacecraft spins around two orthogonal axes each week to month.<br>Particles and plasma: Require observing in the ram direction. |

trometer (UVS, specifically, the atmospheric observations by means of emissions and stellar occultation experiments), Particle and Plasma Instrument (PPI), and Ion and Neutral Mass Spectrometer (INMS).

For the other remote sensing instruments, a 2-orbit repeating scenario is planned, which permits power and data rate equalization. Even orbits emphasize optical remote sensing by the Wide-Angle Camera (WAC), Medium-Angle Camera (MAC), Narrow-Angle Camera (NAC), Infra-red Spectrometer (IRS), and UVS (surface observations), while odd orbits emphasize data collection by the Ice-Penetrating Radar (IPR). The IPR, IRS, and UVS typically operate in low-data-rate profiling modes, permitting a high degree of areal sampling across the globe, given the limited downlink rate. These instruments also operate in higher data-rate targeted modes, obtaining higher resolution data of high-priority features.

Targeted observations are implemented by orbital timing, when passing over a feature of interest with the nadir-pointed remote sensing instruments. These observations are commonly coordinated (**Figure 2.4-1**) among the several optical remote sensing instruments (MAC, IRS, UVS, and NAC), along with the profiling IPR mode, and the continuously operating TI and LA. Over 1000 such targeted observations of ~350 Mb each are obtained during the nominal orbital mission, and each remote sensing instrument has additional non-coordinated targeted opportunities during the Europa Science phase of the mission.

***Table 2.4-3.*** *Science-Based Europa Mapping Campaign Strategy*

| | | |
|---|---|---|
| All Campaigns, Continuous Observations: | | |
| | • Radio Science - Gravity<br>• Magnetometer<br>• Laser altimeter<br>• Thermal instrument (day and night)<br>• Ultraviolet spectrometer (emissions and stellar occultations)<br>• Particle and plasma instrument<br>• Ion and neutral mass spectrometer | |
| Campaign 1, Global Framework:<br>8 eurosols ≈ 28 days, 200 km altitude, Checkout to EOI + 28 days | | |
| 1A: | • First-order gravity field and shape<br>• Global color map (200 m/pixel)<br>• IPR first-order shallow water search<br>• Targeting of high-priority terrains and feature types | |
| 1B: | • Global stereo map (200 m/pixel)<br>• IPR first-order deep ocean search<br>• Targeting of high-priority terrains and feature types | |
| Campaign 1 science data acquired ≈ 480 Gb | | |
| Campaign 2, Regional Processes:<br>12 eurosols ≈ 43 days, 100 km altitude, EOI + 28 days to EOI + 71 days | | |
| 2A: | • Regional gravity field and shape<br>• Regional-scale color map (100 m/pixel)<br>• IPR regional-scale shallow water search<br>• Targeting emphasizes regional-scale processes | |
| 2B: | • Regional-scale stereo map (100 m/pixel)<br>• IPR regional-scale deep ocean search<br>• Targeting emphasizes regional processes | |
| Campaign 2 science data acquired ≈ 800 Gb | | |
| Campaign 3, Targeted Processes:<br>6 eurosols ≈ 21 days, 100 km orbit, EOI + 71 days to EOI + 92 days | | |
| | • Coordinated, process-oriented, targeted observations | |
| Campaign 3 science data acquired ≈ 490 Gb | | |
| Campaign 4, Focused Science:<br>74 eurosols ≈ 263 days, 100 km altitude, EOI + 92 days to EOI + 355 days | | |
| | • Coordinated, process-oriented, targeted observations | |
| Campaign 4 science data acquired ≈ 1.8 Tb | | |

Here is provided a brief description of the science-based campaign strategy, with the key aspects summarized in **Table 2.4-3**. Section 4.3 provides a complete description of the mission profile, while §4.5 fully describes the operations plan and data acquisition strategy.

*Campaign 1, Global Framework:* During the first campaign of the Europa Science phase, the flight system orbits at 200 km altitude. While the whole Global Framework Campaign lasts 8 eurosols (≈28 days), the mission's highest priority data is acquired during the 4 eurosols (≈ 2 weeks) of Campaign 1A, then data acquisition continues through the 4 additional eurosols during Campaign 1B. During Campaign 1A, gravity, altimetry, and magnetometry perform a first-order characterization of the ocean and ice shell. During Campaign 1A, the WAC attains a global color map, and the IPR searches for shallow water. The IRS, UVS, and TI operate primarily in profiling mode, with additional targeted observations. During Campaign 1B, the WAC acquires a global stereo map, the IPR performs a deep ocean search, and other remote sensing instruments continue to acquire profiling and targeted data. Targets for Campaign 1 are chosen using existing Galileo data. Through this and the following campaigns, the particle and magnetic field instruments operate continuously.

*Campaign 2, Regional Processes:* Regional-scale processes is the science emphasis of Campaign 2. Characterization of the gravity field during Campaign 1 allows a relatively stable orbit to be selected for Campaign 2, for which the flight system moves to a 100 km altitude orbit. Gravity, altimetry, and magnetometry improve their characterization of the ocean and ice shell. Campaign 2A again emphasizes production of a global color map by the WAC, and a shallow water search by the IPR, and Campaign 2B emphasizes stereo mapping by the WAC and a deep ocean search by the IPR. At lower altitude, these are now at two times better spatial resolution than obtained during Campaign 1. Optical remote sensing observations continue in profile mode to obtain a denser grid, now at higher spatial resolution. The expanded 12 eurosol (≈43 days) length of this campaign allows for the necessary areal coverage from this altitude relative to Campaign 1, and the number of targeted observations increases. The most interesting findings of Campaign 1 will be followed up by targeted observations in Campaign 2.

*Campaign 3, Targeted Processes:* The third campaign emphasizes coordinated targeted observations and high data-rate radar observations, homing in on specific features at a local scale. Observations during this campaign bring the total number of coordinated, multi-instrument observations to > 1000, each of the type illustrated in **Figure 2.4-1**. Profiling observations achieve a grid spacing of < 25 km for the optical remote sensing observations, and < 50 km for each of the shallow water search and deep ocean search modes of the IPR. The Project Science Group (PSG) will maintain a prioritized list of coordinated targets to be acquired by the remote sensing instruments. Targets can be added and priorities modified at any time. Targets will be selected on a weekly basis by the ground system based on priority and opportunity, depending upon the overflight geometry and the available data volume (§4.5).

*Campaign 4, Focused Science:* The emphasis of the fourth campaign is to focus in on science discoveries achieved earlier in the mission. Thus, its principal priority is to obtain "chains" of targeted observations that attack these new discoveries and newly found priorities based on previous observations. The specific science priorities and orbit characteristics are open to discussion, but a candidate list of science strategies has been developed by the SDT:

- Establish a finer topographic grid using remote sensing profiling observations.
- Infill profiling grids on IPR shallow subsurface observations, especially in discovery areas.
- Obtain higher-order gravity results (potentially including mantle topography).

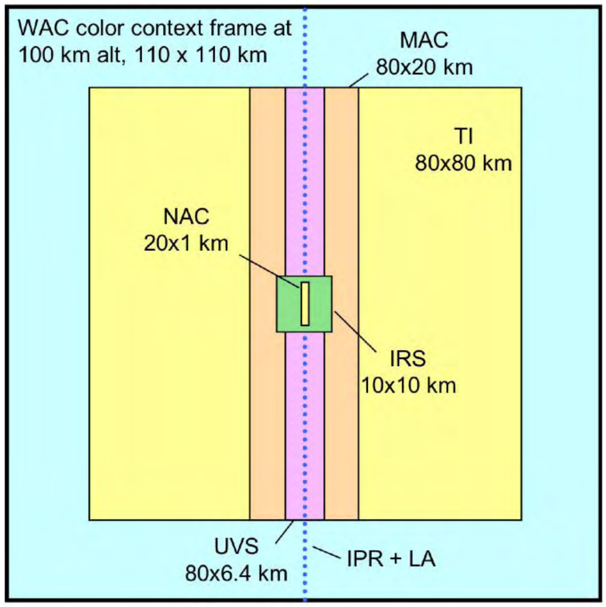



***Figure 2.4-1. Coordinated Targeted Observations****, with scales based on a 100 km altitude. Targeted observations are set within WAC color context (100 m/pixel, 3-colors plus broadband monochromatic). Coordinated targeted observations consist of: Thermal Instrument observations (large yellow, 250 m/pixel, 2 wavelengths); MAC monochromatic stereo imaging (orange, 10 m/pixel), IRS imaging (green, 25 m/pixel, 400 wavelengths), UVS imaging (violet, 100 m/pixel), NAC imaging (small yellow, 1 m/pixel), and a low-data rate IPR profile (blue, 30 seconds of data at 30 Mbps). The laser altimeter operates continuously, as do the fields and particles instruments (MAG, PPI, and INMS).*

- Measure secular changes in rotational parameters with gravity and altimetry.
- Address the properties of the core with magnetometry.
- Achieve narrow-angle camera stereo observations, using off-nadir flight system pointing.
- Investigate the time-variability of the charged particle environment.
- Improve coverage and characterization of candidate future landing sites with the remote sensing instruments.
- Dip to low altitude for improved INMS, gravity, optical remote sensing, and radar observations (only if remaining spacecraft resources allow).
- Monitor activity on Io and Jupiter with the optical remote sensing instruments.
- Attempt to use Jupiter radio emission as a source to sound to the ocean using the IPR.

The Focused Science Campaign will be implemented similarly to the Targeted Processes Campaign, with the PSG maintaining a prioritized list of coordinated targets to be acquired. The ~74 eurosol (≈9 months) duration of Campaign 4 brings the total length of the Europa orbital phase to a milestone of ~100 eurosols. This mission duration will permit extremely robust gravity, fields and particles, and remote sensing to be accomplished at Europa, ensuring that the science objectives and goal are fully achieved.

### 2.4.5 Science Value

Science value is necessarily subjective, and impossible to accurately quantify. Nonetheless, the EE SDT has worked to estimate science value ratings for each measurement in the EE Traceability Matrix (**FO-1**) as they pertain to the relevant science investigation, for both the baseline and floor mission and instrument scenarios. **Table 2.4-4** summarizes the baseline mission science value ratings at the investigation level, while the full measurement-level Science Value Matrix is included as **FO-8**. These science value ratings are performed for each Campaign and sub-Campaign of the mission as described in §2.4.4. The highest priority science is accomplished early, during Campaign 1. The science value is cumulative and increases rapidly through the first three campaigns of the Europa Science phase. The assumed operational parameters for the baseline and floor mission scenarios are described in detail in §4.5 and Appendix G.

In general, higher priority measurements within each investigation are accomplished first, so in **FO-8**, these tend to receive a higher science value rating sooner than lower priority measurements. Investigations of Objective F (Jupiter system science, a.k.a. Europa's neighborhood) are rated based on the Jupiter System Tour, so their science value scores do not change through the Europa Science phase.

The total cumulative "score" achieved through each Campaign and sub-Campaign is tabulated at the bottom of each column, along with the percentage of the total possible science value score. Measurements through the Europa Science phase are each weighted evenly in determining the total, but Jupiter system science was not included in tabulating the overall science value score. (Note that the percentage scores of **FO-8** and **Table 2.4-4** do not exactly match, because integer science values are evenly weighted in **FO-8**, while higher priority measurements are given greater weight in consolidating to the investigation level for **Table 2.4-4**.) The science value of the baseline mission accumulates rapidly during the initial science campaigns. In fact, the majority of the Baseline Science Requirements (§4.1.1.1) are expected to be met during Campaign 2 of the baseline mission, when total averaged science value reaches a rating of 4 (**Table 2.4-4**). Most measurements (but not all) achieve scores of 5 by the end of the first 92 days of the Europa Science phase, leading to an overall excellent percentage score in the high 90s for the baseline mission.

### 2.4.6 Science Descope Options

During its deliberations, the SDT first developed an iteration of the floor planning payload, then developed the baseline payload, and finally scrubbed the floor payload further in order to determine the minimum possible payload necessary to achieve the science objectives of §2.3. As discussed in §3.4, the decreased mass and power of this floor planning payload, combined with a decreased a data rate of 7 Gbits/day in the floor mission architecture, permits use of a smaller launch vehicle resulting in a less costly mission overall.

| Goal | | Science Objective | Science Investigation | Floor Campaigns 1A | Floor 1B | Floor 2A | Floor 2B | Floor 3 | Baseline Campaigns 1A | Baseline 1B | Baseline 2A | Baseline 2B | Baseline 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Explore Europa and investigate its habitability. | A. Ocean | Characterize the ocean and deeper interior. | A1. Determine the amplitude and phase of the gravitational tides. | 3 | 3 | 4 | 4 | 5 | 3 | 4 | 4 | 5 | 5 |
| | | | A2. Determine the induction response from the ocean over multiple frequencies. | 2 | 4 | 4 | 4 | 4 | 2 | 4 | 4 | 4 | 5 |
| | | | A3. Characterize surface motion over the tidal cycle. | 3 | 3 | 4 | 4 | 5 | 3 | 4 | 4 | 5 | 5 |
| | | | A4. Determine the satellite's dynamical rotation state. | 2 | 2 | 3 | 4 | 4 | 2 | 3 | 4 | 5 | 5 |
| | | | A5. Investigate the core and rocky mantle. | 2 | 2 | 3 | 3 | 4 | 2 | 2 | 3 | 3 | 4 |
| | B. Ice | Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange. | B1. Characterize the distribution of any shallow subsurface water. | 2 | 2 | 3 | 3 | 4 | 2 | 3 | 4 | 4 | 5 |
| | | | B2. Search for an ice-ocean interface. | 1 | 2 | 2 | 3 | 4 | 1 | 3 | 3 | 4 | 5 |
| | | | B3. Correlate surface features and subsurface structure to investigate processes governing communication among the surface, ice shell, and ocean. | 2 | 2 | 3 | 3 | 4 | 2 | 3 | 3 | 4 | 5 |
| | C. Chemistry | Determine global surface compositions and chemistry, especially as related to habitability. | C1. Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability. | 1 | 1 | 2 | 2 | 3 | 2 | 2 | 3 | 4 | 4 |
| | | | C2. Relate compositions to geological processes, especially communication with the interior. | 2 | 2 | 3 | 3 | 4 | 2 | 3 | 3 | 4 | 5 |
| | | | C3. Assess the effects of radiation on surface composition, albedo, sputtering, and redox chemistry. | 1 | 1 | 2 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| | | | C4. Characterize the nature of exogenic materials. | 1 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 4 | 4 |
| | D. Geology | Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration. | D1. Characterize magmatic, tectonic, and impact features. | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 4 | 4 | 5 |
| | | | D2. Search for areas of recent or current geological activity. | 1 | 1 | 2 | 2 | 3 | 2 | 3 | 4 | 4 | 5 |
| | | | D3. Investigate global and local heat flow. | 2 | 2 | 3 | 3 | 4 | 2 | 3 | 3 | 4 | 5 |
| | | | D4. Assess relative surface ages. | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 4 | 4 | 5 |
| | | | D5. Characterize the physical properties of the regolith, and assess processes of erosion and deposition. | 1 | 1 | 2 | 2 | 3 | 2 | 2 | 3 | 4 | 5 |
| | E. External | Characterize the magnetic environment and moon-particle interactions. | E1. Characterize the magnetic environment. | 2 | 4 | 4 | 4 | 4 | 2 | 4 | 4 | 4 | 5 |
| | | | E2. Characterize the ionosphere and neutral atmosphere and their dynamics, with implications for surface interactions. | 1 | 2 | 3 | 3 | 3 | 2 | 3 | 4 | 4 | 5 |
| | | | E3. Characterize relationships between the magnetic field and plasma. | 2 | 3 | 4 | 4 | 5 | 2 | 3 | 4 | 4 | 5 |
| | | | E4. Characterize the global radiation environment. | 1 | 3 | 4 | 5 | 5 | 1 | 3 | 4 | 5 | 5 |
| | F. Neighbors | Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons. | F1. Determine the nature and history of the geological activity and interior evolution of the Galilean satellites. | | | | | | | | | | |
| | | | F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a gas giant planet. | | | | | | | | | | |
| | | | F3. Study the interactions between Jupiter's magnetosphere and its satellites. | | | | | | | | | | |
| | | | *Total average score:* | 1.7 | 2.1 | 3.0 | 3.2 | 3.9 | 2.0 | 3.0 | 3.6 | 4.1 | 4.9 |
| | | | *% score:* | 34% | 43% | 60% | 64% | 78% | 40% | 59% | 71% | 83% | 97% |

| | |
|---|---|
| 5 | Definitely addresses full science investigation. |
| 4 | May address full science investigation. |
| 3 | Definitely addresses partial science investigation. |
| 2 | May address partial investigation. |
| 1 | Touches on science investigation. |
| 0 | Does not address science investigation. |

***Table 2.4-4. The floor and baseline mission science value ratings****, summarized here at the investigation level, are cumulative through the mission: the highest priority science is accomplished in Campaign 1, and science value continues to increase rapidly through the first three campaigns. (For the full measurement-level Science Value Matrix, see §7.5.)*

With the floor mission planning payload, all highest priority science investigations are addressed. However, instrument capabilities are lowered to the minimum acceptable science performance. **Table 2.4-5** lists science-based descopes to the planning payload relative to the baseline planning payload, in priority order from the scientifically most acceptable descope (1) to the scientifically harshest (17). At the end of the list, the payload floor has been reached. Because the planning payload is notional, the descope list is similarly notional and necessarily limited in specificity. The prioritization order was determined by the SDT based on perceived science impact, without direct consideration of mission implementation. For example, the NAC is considered an important instrument for the geology objective, including for characterization of potential future landing sites. Therefore, full descope of the NAC is listed near the end of the science-prioritized descope list, even though the NAC is a high mass instrument whose descope may be a higher priority from the standpoint of mission implementation. In addition to the NAC, the UVS and the INMS are fully descoped in the floor planning payload: although each of these instruments addresses multiple investigations across several objectives (**FO-1**), none of these instruments addresses the highest priority investigation of any individual Europa science objective. Thus, the highest priority investigation(s) of each objective can still be addressed with the floor planning payload (albeit not as well, especially if the NAC is descoped).

The science value of the floor mission is rated by the SDT in **FO-8** at the measurement level, and consolidated at the investigation level in **Table 2.4-4**. Where a measurement relies on an instrument that has been descoped

***Table 2.4-5.** Notional Science-Based Instrument Descope List*

| Instrument Descope | Science Ramification |
|---|---|
| 1. INMS is scaled back. | Loss of ability to measure and distinguish complex (high amu) organic species. |
| 2. UVS is scaled back. | Loss of sensitivity to map impurities decreases the ability to identify materials. |
| 3. Magnetometer boom is shortened from 10 m to 5 m. | Poorer magnetic calibration means that signal from mantle and core may become undetectable in subsidiary broad-band frequencies. |
| 4. Thermal Instrument becomes a point detector. | Loss of thermal mapping ability decreases the ability to correlate thermal signatures and thermophysical properties with geological processes and the subsurface. |
| 5. INMS is removed completely. | No in situ characterization of sputtered species, including any organics. |
| 6. MAC stereo optics are removed. | High-resolution topographic characterization is significantly degraded. |
| 7. Transponder drops Ka band, and goes to X-band only. | Poorer gravity data for high-order gravity terms. |
| 8. IRS scales back in spectral and spatial resolution. | Decreased spectral sensitivity hinders identification of impurities, especially organics, and poorer spatial resolution mapping reduces correlations with geological processes and decreases the chance of identifying unique compositional endmembers. |
| 9. PPI drops 1 telescope. | Poorer angular coverage means that information on the particle pitch angle distribution, thus on the bombardment of the surface, is diminished. |
| 10. PPI drops plasma sensor time-of-flight capability. | Information about plasma moments is lost, as is information about the field-plasma coupling. |
| 11. Magnetometers drop from 2 to 1. | Poorer calibration means that signal from mantle and core may become undetectable in the two main frequencies. |
| 12. IRS wavelength range is reduced. | Decreased ability to identify specific impurities including some organics and volatiles. |
| 13. Laser altimeter goes from multi-beam to single-beam. | Weaker geodetic and topographic framework means that additional time is required to acquire necessary precision in Love number $h_2$, and much less topographic profiling is obtained for understanding surface features and radar scattering effects. |
| 14. Ice-Penetrating Radar data rate is cut in half. | Decreased ability to locate and characterize subsurface water and structure. |
| 15. UVS is removed completely. | No outgassing, atmospheric emissions or structure characterization, decreased ability to characterize surface materials and history, and significant loss of Jupiter system science. |
| 16. NAC is removed completely. | One order of magnitude degradation in imaging resolution means loss of detailed surface characterization, including recent activity and relative ages, and significant degradation of Jupiter system imaging. |
| 17. Ice-Penetrating Radar's Yagi antennas are replaced by a dipole. | Decreased ability to locate and characterize shallow subsurface water and structure. |

in the floor mission, the corresponding measurement necessarily receives a science value rating of 0 in **FO-8**. Nonetheless, where one of the synergistic instruments is descoped from a given investigation, that investigation is still addressed through other measurements with other instruments, though not as thoroughly or robustly as with the baseline planning payload. Thus, the science value of the floor mission accumulates more slowly than the baseline, but when consolidated at the investigation level (**Figure 2.4-2**), the floor mission still achieves a majority of the Baseline Science Requirements (§4.1.1.1) by the end of Campaign 3, when the averaged science value reaches a rating of 4. The individual objective impacted most in going to the floor planning payload is Objective F (Europa's Neighborhood), although this is a Priority 2 objective by the definition of the present study's guidelines.

# 3.0 MISSION ARCHITECTURE ASSESSMENT

## 3.1 Study Context

The Europa Explorer (EE) mission concept is one of four outer planet mission concepts being studied by NASA. These studies were comprised of 2 phases. Phase 1 focused on defining science objectives and analyzing various architectural options. Phase 2 focused on further refinement of an implementation option(s) to allow for costing. Common groundrules were supplied to each study team to simplify the execution and review of the results of the studies. These groundrules, summarized in **Table 3.1-1**, also included the Final Report outline and instructions for the content to be included in each section.

***Table 3.1-1.*** *Common sponsor-released groundrules provide continuity between the four study reports.*

| | |
|---|---|
| RPS options | MMRTG, ASRG, ARTG—costs supplied |
| Planetary Protection | Each team given specific requirement—EE: ≤$10^{-4}$ of contaminating the Europan ocean |
| Launch Vehicle (LV) | Delta IV-H and Atlas family—costs given including launch services and nuclear processing |
| Technology Philosophy | Limit required new technology, but include costs if necessary |
| Launch dates | No earlier than 2015, no later than 2022 |
| DSN Capability | Ka band downlink available, current 70 m equivalent capability available, current 34 m available, DSN ground system throughput of 100 Mbits/s |
| International Contributions | None |

This EE study builds upon years of work already completed for a Europa mission with similar science objectives. As a result of this existing body of work, the EE study team was instructed to go directly to Phase 2 as the science objectives and architecture assessment had a much higher level of maturity than the other study concepts. The EE study team was directed to "examine two mission architectures presented at the November 2006 OPAG meeting. Both architectures are based on the Europa Explorer 2006 mission concept study performed by JPL." These concepts are summarized in **Table 3.1-2**. **Figure 3.1-1** shows the conceptual "reference" flight system from the 2006 study. Additionally, specific 2007 study instructions were to:

- "update, as necessary, the science objectives with the traceability of the objectives down to the strawman payload,
- "create a baseline cost and schedule and perform a cost, schedule and risk assessment, and"
- "perform a more detailed assessment of the technologies and modifications required for radiation design"

## 3.2 Architectural Options

In order to perform due diligence, the SDT evaluated alternative architectures that could potentially meet the Europa science goal and objectives: a) a single flyby similar to the *Voyager* project, b) an orbiter in the Jupiter system with multiple flybys of Europa, similar to the *Galileo* orbiter, c) a dedicated orbiter around Europa, d) a stand-alone lander on the surface of Europa, or e) some combination of the above.

The single flyby option would carry modern instrumentation, improving upon *Voyager* and *Galileo* to some degree, more analogous to the *New Horizons* Pluto flyby mission. The Jupiter orbiter option is very similar to the architectures being considered by the *Jupiter System Observer* (JSO) study, being performed in parallel with the EE study, and their preliminary results were used in this analysis.

Europa orbiter missions have been studied for nearly a decade and provided substantial information on potential designs for orbiter missions dedicated to Europa [*Clark et al. 2006*]. Aspects of the *Jupiter Icy Moons Orbiter* [*JIMO SDT 2004*] were valuable as well.

Some cursory analysis has been conducted for various landers for Europa [*Balint 2004*]. Consequently, presentations were heard on simple lander concepts [*Head et al. 2005; Zimmerman et al. 2005*]. A simple soft lander was defined as carrying a small payload that might include a seismometer, imager, and the means to make a simple compositional measurement. A capable lander was modeled on the Europa Astrobiology Lander concept [*SSES 2003*], which would perform geophysical, astrobiological, and/or compositional measurements [*JIMO SDT 2004*]. Landers might ride-along from a flyby, ride-long from an orbiting spacecraft, or be a stand-alone lander.

***Table 3.1-2.*** *The 2006 JPL Europa Explorer Study resulted in two concepts which were orbiters around Europa and provided significant science capability.*

| | Reference Atlas V 551 VEEGA | Augmented Delta IV-H VEEGA |
|---|---|---|
| Flight time to Jupiter (years) | 6 | 6 |
| Europa orbital lifetime (95%/50% confidence) | 90/225 dy | 90/225 dy |
| # of Instruments | 7 | 11 |
| Power source | 6 MMRTG | 8 MMRTG |
| Data volume | 1.2 Gb/orbit | 1.6 Gb/orbit |
| Unallocated dry mass (kg) | 20 | 350 |
| Δ cost | Reference | ±$0.7B |
| | | |
| *Instruments:* | | |
| Wide-Angle Camera (WAC) | X | X |
| Medium-Angle Camera (MAC) | Stereo | Stereo |
| Narrow Angle Camera (NAC) | | X |
| UV/IR Spectrometer (UV/IRS) | Line | Line |
| Laser Altimeter (LA) | X | X |
| Ice Penetrating Radar (IPR) | X | X |
| Thermal Imager (TI) | | X |
| Magnetometer (MAG) | X | X |
| Ion and Neutral Mass Spectrometer (INMS) | X | X |
| MeV Ion Spectrometer (MIS) | | X |
| KeV Ion Spectrometer (KIS) | | X |
| | | |
| Mass CBE # (kg): | *83* | *126* |
| Peak Power CBE (W): | *139* | *173* |
| Orbital Average Power CBE (W) | *74* | *102* |

The Europa SDT also heard presentations on a simple concept modeled on *Deep Impact* [*Prockter et al. 2006*] and on a gravity sub-satellite modeled on the terrestrial Gravity Recovery and Climate Experiment (GRACE) mission [*Watkins et al. 2004*].

## 3.3 Architecture Selection

The architectural options were assessed against their ability to achieve the Priority 1 science objectives described in §2, against their technology readiness, and against a qualitative assessment of their relative cost.

**Table 3.3-1** lists the flyby, orbiter and lander options that were considered and their scoring against the five Priority 1 science objective categories for Europa. The single flyby option was easily dismissed from further consideration because it is unlikely to yield sufficient new information in any of the Priority 1 science objective categories.

The Europa orbiting mission fully addresses all of the science objectives defined by the SDT.

An orbiter around Europa coupled with a simple lander would provide even greater science return, exceeding the science objectives in all but one category. Such a mission architecture would enable global remote sensing and ground truth for at least one site on the surface. Given the likelihood of significant Europan tidal flexing, levels of seismic activity should be of sufficient magnitude that *in situ* measurements would provide unique geophysical insight into the subsurface and interior. Although costing was not conducted for any landed systems, the study group considered that the cost for an orbiter with even a simple soft lander would exceed the guidelines posed for the study. Moreover, the inferred low technology readiness of a simple lander suggests a high risk to schedule and cost.

A large stand-alone lander carrying a full suite of instruments for surface science could provide significant new results for Europa, especially if it were long-lived (> 5 eurosols ≈ 18 days). While the science return from a surface lander could be high, a capable lander would characterize only one place on Europa, which would not necessarily be representative of the satellite as a whole. At the current stage of Europa exploration, science priorities are focused on global characterization, which would not be provided by a lander at a single location. Therefore, as reflected in **Table 3.3-1**, a capable lander in the absence of an orbiter is not highly rated against the Europa science objectives of §2. Moreover, the technology readiness of such a lander is quite low, and the surface of Europa on the scale of landers is unknown at the present time posing significant problems for a safe landing; thus, a capable lander is anticipated to have a high risk and cost.

An orbiter around Jupiter with repeated flybys of Europa could provide significant

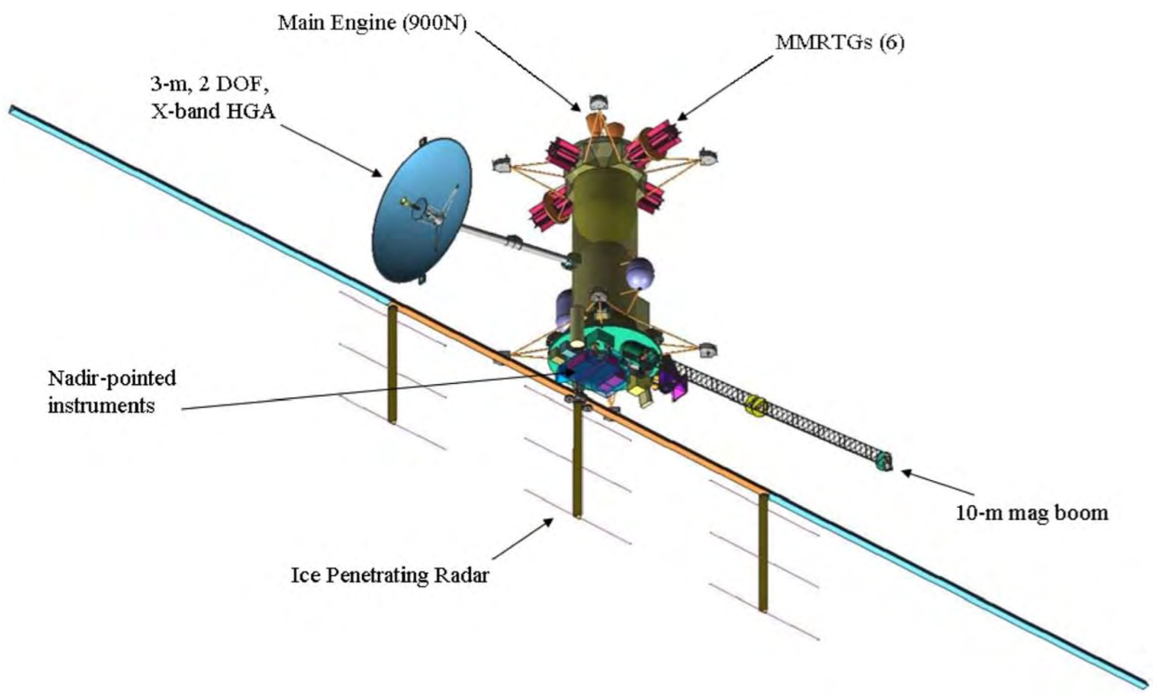



***Figure 3.1-1.*** *The 2006 reference mission concept builds upon almost a decade of concept development and utilizes both Cassini and Galileo experience for large outer planets orbital missions*

science return to address some of the key science objectives for Europa (**Table 3.3-1**). However, important measurements related to the ocean and other objectives cannot be made other than from orbit (§2.4.1). An orbiting mission is required to accomplish the ocean objective (for gravity and altimetry data measured through the tidal cycle), the ice shell objective (for significant areal coverage by ice-penetrating radar), the chemistry and geology objectives (for global and targeted coverage at high resolution), and the external environment objective (for sufficient temporal and spatial coverage).

A simple "dumb" impactor could create an impact flash to allow elemental composition to be measured remotely. Moreover, it would excavate fresh material from the shallow subsurface which has not been radiolytically processed, and which could later be analyzed remotely. However, a preliminary assessment of the impact energies for reasonable masses and velocities gained from deployment suggest that the crater formed would be too small to obtain significant compositional measurements, and might be too small to locate. Moreover, the instruments (**Tables 2.4-1** and **4.2-1**), optimized for the Europa Priority 1 science objectives are different from the specialized instrumentation to observe an impact flash and plume, implying additional cost and/or the loss of other science.

A gravity sub-satellite that would fly in formation with the main orbiter ala *GRACE* was deemed of little advantage to the Europa science objectives. Its science gain is greatest in measuring high-order (short-wavelength) gravity terms, while Europa's tidal signal is of low-order (degree 2). The potential gain over Ka- and X-band tracking of a single orbiter was deemed not worth the additional cost and complexity of a sub-satellite.

A single Europa orbiter with no lander or impactor was selected as the architecture, since it fully addresses the science objectives at the lowest risk and cost, and since it provides the information needed to enable a future Europa soft lander with acceptable risk.

## 3.4 Implementation Option Assessment

Results of previous Europa orbital mission trade studies have been used, where appropriate, for this study. A summary of previous trades is included in **Table 3.4-1**. The guidelines for this study were to assume the

| | A. Ocean | B. Ice | C. Chemistry | D. Geology | E. External Environment |
|---|---|---|---|---|---|
| **Europa Explorer** | 5 | 5 | 5 | 5 | 5 |
| **Europa Explorer + Simple Lander** | 6 | 6 | 6 | 6 | 5 |
| **Europa Multiple Fly-bys** | 2 | 2 | 2 | 3 | 3 |
| **Capable Lander (No Orbiter)** | 3 | 2 | 4 | 2 | 1 |
| **Single Flyby** | 1 | 1 | 2 | 2 | 1 |

**NOTES:**
- Multiple fly-bys means a dedicated Europa fly-by mission.
- Orbiter + lander implies a simple lander, carrying a seismometer, imager, composition experiment.
- Capable Lander is stand-alone (no orbiter), modeled after the Europa Astrobiology Lander.

| | |
|---|---|
| 6 | Exceeds science objectives. |
| 5 | Fully addresses all science objectives. |
| 4 | Addresses most science objectives. |
| 3 | Addresses some science objectives. |
| 2 | May address partial science objectives. |
| 1 | Touches on science objectives. |
| 0 | Does not address science objectives. |

***Table 3.3-1.*** *Architectures considered and rated against the Priority 1 Europa Science Objectives.*

basic configuration which resulted from JPL's 2006 Europa Explorer study. During this 2007 study, the 2006 implementation architectures were iterated with the following options:

- Launch vehicles (Delta IV-H, Atlas V)
- Launch opportunities (2015–2020)
- Launch trajectories (VEEGA, ΔV-EGA, VVMV, VMVE)
- RPS systems (MMRTG, ASRG, and ARTG)
- High Gain Antenna size/RF power

Though flight time and cost were considerations, neither were explicitly traded in this assessment. Also, a trade exists in the tour design of radiation vs. ΔV vs. tour length. This was not investigated in this study as the emphasis has been on getting to Europa with minimum radiation to lower the radiation design requirement. Work had been done on Europa Orbiter (circa 2000) to minimize ΔV and radiation. Future work would be required to optimize the tour for this mission taking into account any tour science required.

The trade of the High Gain Antenna/RF power was constrained to meet SDT identified minimum data volume required from Europa orbit (7 Gbits/day with 24-hour coverage to 70 m antenna). The trade resulted in selecting a lower risk, large diameter antenna and reducing the RF power to minimize the number of RPSs. A 3 m antenna was selected as it did not impose overly constraining pointing requirements and could easily be accommodated within the configuration and launch envelope. Larger diameter antennas would be evaluated in the future when more detail design and analysis is possible.

During the present study, the SDT synthesized and revised the science objectives based on previous Europa mission studies, and subsequently defined the planning payload that met those minimum objectives. The emphasis for the floor mission architecture was to lower the required mission resources as much as possible while meeting the minimum science objectives as defined by the SDT. The minimum payload, plus the use of the less expensive and less massive (albeit less mature) ASRGs, allows launch on the less expensive Atlas V. The science objectives for the baseline are the same as for the floor, but the baseline measurement capabilities are more robust, allowing a deeper penetration of the objectives. The baseline payload, plus the use of the more mature MMRTGs, necessitate the use of the Delta IV-H to accommodate the larger mass.

***Table 3.4-1.*** *Completed Trades from Previous Europa Studies*

| Trade Studies Performed | Disposition |
|---|---|
| Mission Architecture Options and Trades | |
| Solar electric propulsion stages | Not selected - not mass efficient |
| Solid rocket motor stages | Not necessary when using Earth gravity assists |
| Self generated magnetic radiation shield | Not selected - power prohibitive |
| Solar power vs. radioisotope power | RPS selected as is more mass efficient, supports stability reqts, and gives operational flexibility. |
| Flybys | Not selected - Can't meet science requirements |
| Landers | Not selected - Can't meet science requirements |
| Impactors | Not selected - Can't meet science requirements |
| Orbiters | Selected option |
| Distant viewers | Not selected - Can't meet science requirements |
| Telecom relay orbiter | Not selected - Not mass efficient |
| Trajectory Type (Cruise Phase) | VEEGA selected |
| Launch Year | 2015 selected |
| Launch Vehicle | Delta IV-H (Baseline) / Atlas V (Floor) selected |
| Orbital Mission Duration | 1 Year (Baseline) / 6 months (Floor) selected |
| Mission Implementation Options and Trades | |
| Power | |
| RPS Type | MMRTG (Baseline) / ASRG (Floor) selected |
| Number of RPSs | 6 (Baseline) / 5 (Floor) selected |
| Battery chemistry | Li-Ion chemistry selected |
| Battery redundancy | Single, internal redundant (at cell-level) battery |
| C&DH | |
| Integrated vs. Separate Sci/Eng Computers | Integrated Sci/Eng computer selected |
| Mass memory volume | 2.4 Gb selected |
| Mass Memory Type | CRAM selected |
| AACS | |
| Placement of ACS Thrusters vs. Plume Impingement | As per baseline/floor designs |
| Reaction Wheels vs. Thrusters | Reaction wheels selected |
| Telecom | |
| HGA vs. TWTA Power | 3m HGA and $35W_{RF}$ TWTA (Baseline) / $12W_{RF}$ (Floor) Selected |
| Deployable (ala Galileo) vs. Rigid HGA | Rigid HGA selected |
| Open vs. Closed Loop (monopulse) HGA Control | Open loop selected |
| X-band vs. Ka-band Communications | X-band selected |
| 70-m vs. 34-m DSN Antennas | 70-m DSN selected |
| Radiation | |
| Single vs. Distributed Radiation vaults | Distributed vaults selected |
| Thermal | |
| Thermal Transfer System | RPS heat with RHUs and limited heaters selected |
| Mechanical vs. electrical thermostats | Mechanical thermostats selected |
| Structural | |
| Position of IPR Antenna for structural accommodation and minimum plume impingement | Canted antenna selected |

A model was used to quickly generate point designs for implementation approaches with variations of the above options. The model assumes a minimum required mass and power margin and the unallocated dry mass and power are then calculated. The minimum margins required are 30% as defined in the JPL Design Principles. Since the minimums required are already accounted for in the model, the greater the unallocated dry mass and power levels are, the better the option. The unallocated mass is all useable dry mass since the model accounts for the propellant required to insert this mass into orbit at Europa. **Table**

**3.4-2** shows a summary of the results of those trades used to narrow down to the final architecture and implementation choice. The baseline EE architecture implementation is shown on the first line (2015 VEEGA, Delta IV-H, 6 MMRTGs).

#### 3.4.1 Launch Vehicle

The Atlas V LV has a significantly lower cost than the Delta IV-H LV. However, as shown in **Table 3.4-2**, the delivered mass capability of the Atlas V 551 is insufficient to accommodate the baseline flight system and mission design for launches between 2015 and 2018. This negative mass margin led to the decision to select the Delta IV-H as the baseline EE launch vehicle.

#### 3.4.2 Trajectory

There are many different trajectory types and launch opportunities for transfers between Earth and Jupiter between 2015 and 2020, only some of which could be evaluated within the timeframe of the study. Options other than the baseline are potentially available, and are discussed in §4.7 and Appendix E. As illustrated in **Figure 3.4-1**, the maximum allowable flight system dry mass capability varies with launch year and trajectory type. This maximum dry mass capability that can be delivered to Europa is based strictly on launch vehicle capability and required mission ΔV. In general, the VEEGA trajectory consistently provides the greatest amount of delivered dry mass capability for flight times up to ~7 years. The performance increase of the VEEGAs from 2015 to 2020 is due primarily to lower $C_3$ in the later years. The advantage of designing the mission to the 2015 VEEGA launch opportunity is that the same design can be used if the launch was deferred to 2017 or later.

Two of the other trajectory types considered, VVMV and VMVE, have maximum delivered dry mass values slightly higher than those of the ΔV-EGA but significantly lower than those of the VEEGA for equivalent launch opportunities, as shown in **Figure 3.4-1**. Since the mass of the baseline EE flight system exceeds the delivered mass capability of either of these two trajectories, neither of them was studied further.

#### 3.4.3 Power Source

Three power sources were evaluated for this study: MMRTG, ASRG and ARTG. A comparison of their major characteristics is shown in **Table 3.4-3**. All of these systems are currently in development by NASA and DOE. The MMRTG was selected over other advanced RPS technologies (ASRG and ARTG) for EE because of its heritage design as the power source for the 2009 MSL mission; thus, the expectation is that the MMRTG will have been successfully flight proven well before 2015. Six MMRTG units are required to power the baseline EE mission concept, not including a ground spare. The Department of Energy (DOE) has stated that 8 MMRTGs could be available to support missions starting in 2015, not including the MSL ground spare which could serve as the EE ground spare.

The ASRG uses a dynamic Stirling cycle to obtain dramatically higher conversion efficiencies than the thermoelectric conversion options (MMRTG and ARTG), as shown in **Table 3.4-3**. While still in development, the DOE has stated that the ASRG would be available to support missions starting in 2015. The ARTG, currently in development, is a higher efficiency version of the MMRTG technology and the DOE has stated that it would be available to support missions starting in 2017.

### 3.5 Baseline Architecture Implementation Summary

A brief summary of the architecture and associated implementation chosen for this mission concept is as follows:

- *Single orbiter:* lowest cost concept which meets science objectives
- *Low-altitude, near-circular Europa orbit*: required to meet science objectives
- *One year in Europa orbit*: addresses science hypotheses in first 3 months, allows for follow-on investigation of new discoveries
- *Delta IV-H:* significant more injected mass capability than Atlas V
- *VEEGA trajectory*: allows significant delivered mass to Europa orbit with flight times less than 7 years (self imposed requirement)
- *June 2015 launch opportunity*: Stressing case: earliest viable opportunity with engineering developments. Instrument development is pacing item. Also, has

***Table 3.4-2.*** *Europa Explorer Trade Study Options—Baseline Configuration*

| Launch Year | Trajectory | Time to Jupiter, yrs | LV Type | RPS Type | #RPSs | Unallocated Mass, kg | Unallocated Power, W |
|---|---|---|---|---|---|---|---|
| Performance for VEEGA by Launch Year and LV for MMRTG | | | | | | | |
| 2015 | VEEGA | 6.1 | Delta IV-H | MMRTG | 6 | 185 | 62 |
| 2017[1] | VEEGA | 5.7 | Delta IV-H | MMRTG | 6 | 231 | 66 |
| 2018 | VEEGA | 6.8 | Delta IV-H | MMRTG | 6 | 410 | 55 |
| 2020 | VEEGA | 6.0 | Delta IV-H | MMRTG | 6 | 647 | 63 |
| 2015 | VEEGA | 6.1 | Atlas V 551 | MMRTG | 6 | -193 | 62 |
| 2017 | VEEGA | 5.7 | Atlas V 551 | MMRTG | 6 | -166 | 66 |
| 2018 | VEEGA | 6.8 | Atlas V 551 | MMRTG | 6 | -43 | 55 |
| 2020 | VEEGA | 6.0 | Atlas V 551 | MMRTG | 6 | 117 | 63 |
| Performance for Non-VEEGA by Launch Year for MMRTG and Delta IV-H | | | | | | | |
| 2015 | ΔVEGA 2- | 4.8 | Delta IV-H | MMRTG | 6 | -233 | 75 |
| 2018 | VVMV | 6.1 | Delta IV-H | MMRTG | 6 | -123 | 62 |
| 2019 | VMVE | 6.0 | Delta IV-H | MMRTG | 6 | -140 | 63 |
| Performance for ASRG Cases by Launch Year and Trajectory Type and LV | | | | | | | |
| 2015 | VEEGA | 6.1 | Delta IV-H | ASRG | 5+1[2] | 355 | 84 |
| 2015 | ΔVEGA 2- | 4.8 | Delta IV-H | ASRG | 5+1 | -66 | 92 |
| 2017 | VEEGA | 5.7 | Delta IV-H | ASRG | 5+1 | 398 | 87 |
| 2018 | VEEGA | 6.8 | Delta IV-H | ASRG | 5+1 | 577 | 80 |
| 2018 | VVMV | 6.1 | Delta IV-H | ASRG | 5+1 | 44 | 84 |
| 2019 | VMVE | 6.0 | Delta IV-H | ASRG | 5+1 | 27 | 85 |
| 2020 | VEEGA | 6.0 | Delta IV-H | ASRG | 5+1 | 814 | 85 |
| 2015 | VEEGA | 6.1 | Atlas V 551 | ASRG | 5+1 | -26 | 84 |
| 2015 | ΔVEGA 2- | 4.8 | Atlas V 551 | ASRG | 5+1 | -292 | 92 |
| 2017 | VEEGA | 5.7 | Atlas V 551 | ASRG | 5+1 | 0.6 | 87 |
| 2018 | VEEGA | 6.8 | Atlas V 551 | ASRG | 5+1 | 124 | 80 |
| 2018 | VVMV | 6.1 | Atlas V 551 | ASRG | 5+1 | -225 | 84 |
| 2019 | VMVE | 6.0 | Atlas V 551 | ASRG | 5+1 | -245 | 85 |
| 2020 | VEEGA | 6.0 | Atlas V 551 | ASRG | 5+1 | 284 | 85 |
| Performance for ARTG Cases by Launch Year and Trajectory Type, and LV | | | | | | | |
| 2015 | VEEGA | 6.1 | Delta IV-H | ARTG | 3 | 430 | 23 |
| 2015 | ΔVEGA 2- | 4.8 | Delta IV-H | ARTG | 3 | 9 | 41 |
| 2017 | VEEGA | 5.7 | Delta IV-H | ARTG | 3 | 473 | 28 |
| 2018 | VEEGA | 6.8 | Delta IV-H | ARTG | 3 | 652 | 13 |
| 2018 | VVMV | 6.1 | Delta IV-H | ARTG | 3 | 119 | 22 |
| 2019 | VMVE | 6.0 | Delta IV-H | ARTG | 3 | 102 | 24 |
| 2020 | VEEGA | 6.0 | Delta IV-H | ARTG | 3 | 889 | 24 |
| 2015 | VEEGA | 6.1 | Atlas V 551 | ARTG | 3 | 49 | 23 |
| 2015 | ΔVEGA 2- | 4.8 | Atlas V 551 | ARTG | 3 | -217 | 41 |
| 2017 | VEEGA | 5.7 | Atlas V 551 | ARTG | 3 | 76 | 28 |
| 2018 | VEEGA | 6.8 | Atlas V 551 | ARTG | 3 | 199 | 13 |
| 2018 | VVMV | 6.1 | Atlas V 551 | ARTG | 3 | -150 | 22 |
| 2019 | VMVE | 6.0 | Atlas V 551 | ARTG | 3 | -170 | 24 |
| 2020 | VEEGA | 6.0 | Atlas V 551 | ARTG | 3 | 359 | 24 |

1. Blue text represents differences from the EE baseline configuration.
2. For ASRG, 5+1 represents five prime ASRGs used to meet baseline power requirements, and one additional unit used as an in-flight hot spare.

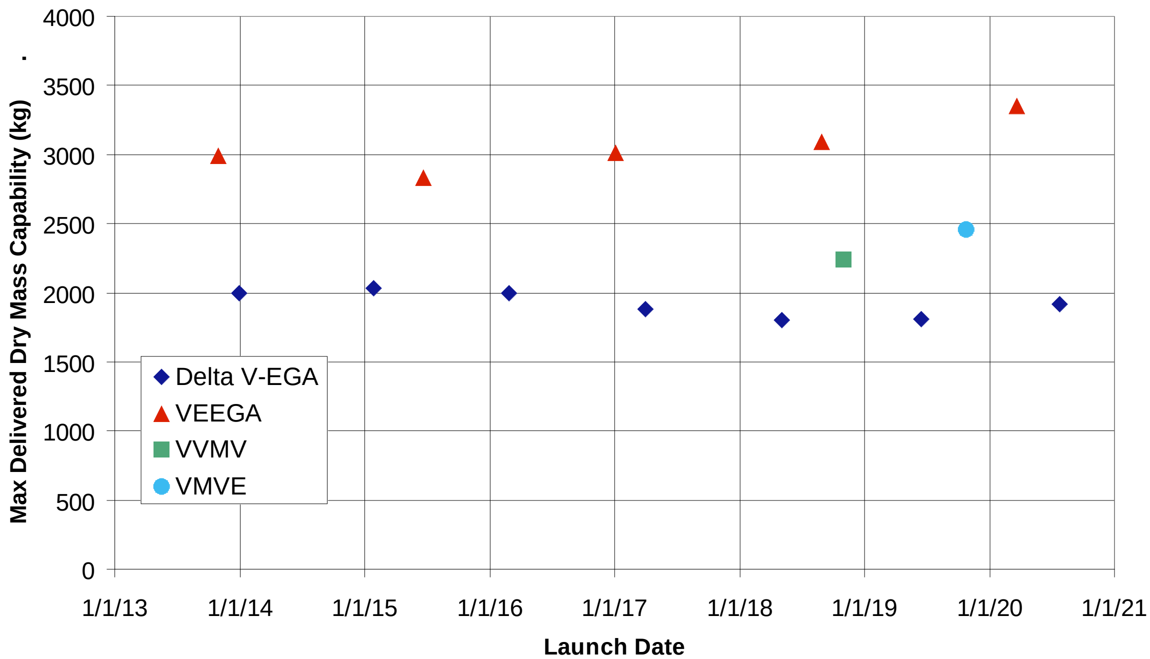



***Figure 3.4-1.*** *Maximum Flight System Dry Mass Capability vs. Launch Year for the Delta IV-H*

***Table 3.4-3.*** *Three different RPS options were evaluated for mass, power and availability.*

| RPS | Power @ BOL[1] (W) | Mass (kg) | Specific Power @ BOL (W/kg) | Converter Efficiency | Number of GPHS Modules | Estimated TRL |
|---|---|---|---|---|---|---|
| MMRTG | 125 | 44 | 2.9 | 6.3% | 8 | 6 |
| ASRG | 143 | 20.2[2] | 7.0 | 28% | 2 | 5 |
| ARTG | 250 | 40 | 7 | 8.3% | 12 | 3 |

1) BOL is defined as a time of RPS fabrication by the DOE. RPS power decreases with time due to different mechanisms including radioactive decay of the Pu-238 fuel.
2) Does not include additional mass to shield ASRG electronics for radiation environment.

lowest performance of VEEGA opportunities through 2020. Moving to later opportunity allows more development time and increases performance.

- *MMRTGs*: most mature albeit the heaviest approach. Inserting ASRGs or ARTGs at a later point would free up additional mass

## 3.6 Floor Architecture Implementation Summary

A floor mission concept was investigated with the intent to derive the lowest cost mission **Table 3.6-1** summarizes the major differences between the baseline and floor mission concepts. A brief summary of the characteristics of the floor-configured EE flight system architecture is presented in **Table 3.6-2**. The floor flight system with its baselined ASRGs can launch on the lower cost Atlas V 521; however, an Atlas 531 was

***Table 3.6-1****. The major differences between the baseline and the floor mission concepts are driven by the desire to lower the mission cost while meeting the minimum science objectives.*

| Characteristic | Baseline Mission | Floor Mission |
|---|---|---|
| Launch Vehicle | Delta IV-H | Atlas V 531 |
| RPS | 6 MMRTGs | 5 ASRGs# |
| Number of Instruments | 11 | 8 |
| Instrument Mass/power | 158 kg/ 179 W | 77 kg/106 W |
| Europa Orbital Lifetime | 12 months | 6 months |
| Data Volume** | 20 Gbits/day | 7 Gbits/days |

\# Includes spare ASRG for redundancy
** Average data volume per day during Europa orbit to 24 hour 70 m station

selected to be conservative. ASRGs were selected for the floor concept to lower cost. **Table 3.6-2** indicates that using MMRTGs would require a higher capability, and more expensive launch vehicle such as the Atlas V-541 or Delta IV-H.

Performance of the European Ariane 5 ECA was found to be potentially adequate when using ASRGs although launching nuclear material on a foreign launch vehicle would require significant effort and may not be possible.

***Table 3.6-2.*** *Europa Explorer Trade Study Options—Floor Configuration*

| Launch Year | Trajectory | Time to Jupiter, yrs | LV Type | RPS Type | #RPSs | Unallocated Mass, kg | Unallocated Power, W |
|---|---|---|---|---|---|---|---|
| 2015 | VEEGA | 6.1 | Delta IV-H | MMRTG | 5 | 583 | 87 |
| 2015 | VEEGA | 6.1 | Atlas V 531 | MMRTG | 5 | -12 | 87 |
| 2015 | VEEGA | 6.1 | Delta IV-H | ASRG | 4+1 | 723 | 82 |
| 2015 | VEEGA | 6.1 | Atlas V 531 | ASRG | 4+1 | 127 | 82 |
| 2015 | VEEGA | 5.7 | Ariane 5 ECA | ASRG | 4+1 | 8.2 | 87 |
| | | | | | | | |
| 2017 | VEEGA | 5.7 | Delta IV-H | MMRTG | 5 | 636 | 90 |
| 2017 | VEEGA | 5.7 | Atlas V 531 | MMRTG | 5 | 127 | 90 |
| 2017 | VEEGA | 5.7 | Delta IV-H | ASRG | 4+1 | 776 | 84 |
| 2017 | VEEGA | 5.7 | Atlas V 531 | ASRG | 4+1 | 155 | 84 |
| 2017 | VEEGA | 5.7 | Ariane 5 ECA | ASRG | 4+1 | 191 | 84 |

# 4.0 MISSION CONCEPT IMPLEMENTATION

*Missions to explore Europa have been considered and designed for over a decade since the Galileo mission began supplying fascinating new insights into that satellite's secrets. Earlier Europa concepts were hampered by the immaturity of the models to explain the processes at Europa, the lack of radiation hardened components, less-capable or uncertified launch vehicles, and immature power sources. Significant investment has taken place which alleviates these previous limitations. Europa Explorer has been able to leverage from these significant investments to result in a very mature conceptual design.*

## 4.1 Mission Architecture Overview

An orbital mission to Europa is identified (§3.0) as the appropriate mission architecture to satisfy the science objectives as identified in §2.0. A mission concept has been developed that performs a multi-year study of Europa and the Jupiter system, including approximately 2 years of Jupiter system science, meeting the primary Europa science goals after 92 days in orbit and expected to provide detailed Europa science for over a year in Europa orbit. This concept relies only on existing technologies, it has significantly more capability, and it returns considerably more science data than previous conventional propulsion mission concepts.

### 4.1.1 Draft Level 1 Requirements (Science only)

Level 1 requirements are negotiated between the NASA program office and the project after careful assessment of risk, allocated resources, and in consultation with JPL management, science representatives and key project staff. Preliminary level 1 requirements are required at end of Phase A with the final version approved by the end of Phase B. Notional level 1 requirements for this Europa Explorer (EE) mission study were developed to understand the driving interactions between science, implementation and risk. A draft of these requirements is outlined below.

#### 4.1.1.1 Baseline Science Requirements

The Europa Explorer Mission will achieve the science objectives of §2.0 by meeting the following requirements, which correspond to Europa Explorer science objectives A–E. [Brackets indicate specific values that are expected to be negotiated with NASA Headquarters.]

The Europa Explorer Project shall:

- Constrain the thickness of Europa's ocean and ice;
- Determine whether liquid water or thermal anomalies exist within Europa's ice shell;
- Identify key organic and inorganic chemical constituents on Europa's surface;
- Identify and characterize representative terrain types and landforms on Europa, including their topography;
- Characterize the global radiation environment near Europa.

#### 4.1.1.2 Potential Jupiter System Science Augmentations

If EE science Objective F was to be elevated to a Priority 1 objective at some time in the future, then the following augmentations to the baseline science requirements are suggested:

- Conduct long-term monitoring of Io's volcanic and atmospheric dynamics during the Jovian Tour;
- Conduct long-term Jupiter monitoring atmospheric and auroral dynamics during the Jovian Tour;
- Conduct long-term Jupiter magnetospheric observations during the Jovian Tour;
- Conduct at least [two] close < [2000] km science encounters of each of Ganymede and Callisto during the Jovian Tour.

#### 4.1.1.3 Mission Performance

The Europa Explorer Mission shall utilize a launch period that opens in [June 2015].

The Europa Explorer Mission shall achieve a Europa orbit that supports the Science Requirements in §4.1.

The nominal end of the Europa Explorer mission operations shall be [1 year] after Europa Orbit Insertion and no later than [January 2026].

### 4.1.2 Key Challenges

The primary difficulties of designing a mission to Europa are: Jupiter's radiation environment, planetary protection, high propulsive needs to get into Europa orbit and the large distance from the sun and Earth.

Radiation is the life limiting parameter for the flight system. Designing for the estimated radiation environment requires adequate knowledge of the environment, understanding of available hardware, conservative hardware and software design approaches and an approach to controlling the pervasive mission and system level impacts (including trajectory, configuration, fault protection, operational scenarios, and circuit design). Harnessing the experiences from NASA, academia, DoD, DoE, and industry is crucial to instilling the radiation-hardened-by-design concept at the mission concept level.

The high propulsive requirements to get into Jupiter orbit and subsequently into Europa orbit drives the large propellant load required and the dry mass of the propulsion subsystem to hold the propellant. Trajectory options, including gravity assists of Venus, Earth (twice), and multiple Jupiter satellites lower the propellant requirements enough to enable this mission concept.

The insolation at Europa is 3 to 4% of that at Earth. This fact, combined with Jupiter's trapped radiation and the pointing and stability required to meet the identified science requirements, strongly favors the use of radioisotope power sources over solar array power systems. Juno manages to perform its mission by strictly avoiding the most severe radiation environments, avoiding eclipses, and using its battery for relatively short high-power periods.

The distance from Earth varies from 4 to 6 AU during the course of the orbital mission at Jupiter. This large distance requires a very capable telecommunications system to return the significant data required to meet the science objectives.

#### 4.1.3 Methodology for Assessing the Mission Lifetime Duration

Europa Orbiter (2001) had a defined lifetime of 30 days in Europa orbit with an estimated 3.3 Mrad radiation dose (behind 100 mils of Al) at the end of those 30 days. No meaningful estimate of mission lifetime could be made. Over the last 6 years, Galileo data has been integrated into the Jovian radiation model, and just recently, the radiation model for the near vicinity of Europa has been updated [*Paranicas et al. 2007*]. Using these updated models and selecting a defined end of mission of 90 days in Europa orbit, the estimated radiation dose was 2.3 Mrad at the end of 90 days. Again, no meaningful prediction of mission lifetime was possible though the likelihood of surviving the 30 and 90 days, respectively, was very high.

In support of this EE mission study, a better, more systematic approach has been developed which combines fundamental parts radiation failure statistics, the current statistical environment model and a conservative simple flight system model to define the lifetime of the mission in terms of time and confidence level. This methodology removes some of the excess margin in the design process and allows the Deputy Project Manager for Radiation (DPMR) to determine the radiation design specification in terms of confidence level and mission duration. For the baseline mission, a 75% confidence level of surviving 1 year in Europa orbit resulted in a radiation design point of 2.6 Mrad, which was then used as an input to the traditional design process for the flight system.

#### 4.1.4 Mission Architecture Component Definitions

General descriptions of each component are provided in **Table 4.1-1**.

***Table 4.1-1.*** *Mission Component Definition*

| Component | Description |
|---|---|
| Launch Vehicle | 1. Delta IV 4050H-19<br>2. Support and procurement provided by Launch Planning Office at KSC<br>3. Launch mass capability of 7230 kg to $C_3$ of 14.1 $km^2/s^2$ for the June 2015 VEEGA opportunity |
| Flight System | 4. Single Orbiter<br>5. Spacecraft<br>• MMRTG Power Source supplied by the Department of Energy<br>• Chemical Propulsion—dual mode Bi-propellant system<br>• X-Band Telecommunications (Ka-Band up/down link for gravity science)<br>6. Launch Vehicle adapter<br>7. 11 individual instrument payload selected via NASA Announcement of Opportunity |
| Ground System | 8. Ground Data System<br>9. Flight Operations Team (engineering and science)<br>10. Deep Space Network and related services |

#### 4.1.5 Baseline Mission Description

The mission concept includes a single orbiter flight system which travels to Jupiter by means of a gravity assist trajectory and reaches Jupiter approximately 6 years after launch. The large main engine places the flight system into orbit around Jupiter followed by approximately 2 years of Jupiter system science while the flight system uses repeated satellite gravity assists to lower its orbit until a final burn inserts it into orbit around Europa. Once in Europa orbit, the Europa Science phase is one year; all identified Priority 1 science measurements can be addresed in the first 8 eurosols (~28 days), meaning that preliminary assessment of key hypotheses will be available. The remainder of the first year will allow for in-depth focus on strengthening the initial interpretation. Key mission parameters are shown in **Table 4.1-2**.

At a starting altitude of approximately 200 km (changing to 100 km after the initial science campaign), the flight system orbits Europa approximately 11 times in an Earth day. The science planning payload is comprised of 11 instruments and is estimated at 158 (Current Best Estimate, CBE) kg with an orbital average power of 106 watts (CBE) (see **Table 4.1-3**). The system is sized to provide a science downlink of approximately 20 Gbits per Earth day which increases as the flight system gets closer to Earth. Over the course of the first 92 days in Europan orbit, almost 2 Tbits of science data can be returned using a continuous downlink strategy which uses roughly one third of the 70 m DSN capability during the Europa Science phase. The science operations are structured to address the science objectives in priority order. Global Europa science is addressed first, followed by more localized science as the orbital mission progresses.

### 4.1.6 Floor Mission Description

An activity was undertaken with the science team to more completely understand the science drivers that form the "floor" mission. This "floor" is defined as the science complement and data return below which a mission is not worth pursuing. The SDT worked very closely with the engineering team to work through the data return strategy and flight system impacts of the instrument and science decisions. The chosen operational strategy proved to be very robust to data return and ability to meet the science objectives.

In addition to the science "floor", the engineering team investigated choices which could reduce the cost of the mission. The primary areas of concentration were to decrease the mass sufficiently to allow launch on an Atlas V launch vehicle (instead of the

***Table 4.1-2.** Key Mission Parameters*

| Parameter | Baseline Value | Notes |
|---|---|---|
| **Instruments** | | |
| Number of instruments | 11 | Does not include the on-board Ka-band uplink/downlink equipment in the baseline flight system used for gravity science. |
| Instrument mass | 158 kg | Current Best Estimate. Does not include 5.2 kg (CBE) Ka-band subsystem that is tracked in telecom, or 17 kg (CBE) for instrument shielding. |
| Instrument power | 106 W | Current Best Estimate, orbital average. This is the average power level over two consecutive science orbits (one radar orbit and one optical remote sensing orbit). Does not include power for Ka-band subsystem. |
| **Science Accommodation** | | |
| Pointing accuracy | 1 mrad (3 $\sigma$) | S/C body pointing control accuracy during nadir-oriented non-thrusting orbital period. |
| Pointing stability | 10 μrad/s (3 $\sigma$) | For body-fixed instruments in science orbit during non-thrusting periods. |
| Minimum duration between reaction wheel orbit desaturations | 24 hours | Minimum duration between desaturation thruster firings. |
| Data storage | 2.4 Gbits | Includes ~1 Gbit for science data, with balance for flight system software loads, telemetry, and margin. |
| Data volume | 20 Gb/day | Assumes 3 dB link margin, multiple data rates optimized for range, elevation, Jupiter presence, 70 m stations receiving whenever in view and 90% weather. |
| **Spacecraft** | | |
| Processor speed | 132 MHz | RAD750 flight computer |
| Available power at EOM | 618 W | Power output from 6 MMRTGs at EOM (defined as 9 years after launch) |
| Main engine thrust level | 890 N | Two 890-N engines included (one prime and one spare) |
| Delta V requirement | 2755 m/s | Assuming launch mass is equal to the launch vehicle capability (7230 kg). |
| Radiation tolerance | 2.6 Mrad | Radiation design level for flight system shielding. |
| Heliocentric operating range | 0.67 to 6.0 AU | Minimum range defined by VEEGA trajectory. |

***Table 4.1-3.*** *Baseline and Floor Mission Concept Differences*

| | Baseline Mission Concept | Floor Mission Concept |
|---|---|---|
| Launch Vehicle | Delta IV-H | Atlas V 531 |
| Power Source | 6 MMRTGs | 5 ASRGs |
| Data Volume | 20 Gbits/day | 7 Gbits/day |
| Europa Science Phase Data Volume | 3.6 Tbits | 0.9 Tbits |
| Number of Instruments | 11 | 8 |
| Instrument Mass (CBE) | 158 kg | 77 kg |
| Instrument Power (CBE, orbit average) | 106 W | 58 W |
| Estimated Mission Cost | $3.3 BFY07 | $2.4 BFY07 |

baselined Delta IV-H) and to switch to the Advanced Stirling Radioisotope Generator (ASRG) which has a predicted lower recurring cost, but is increased risk because of its lower level of design maturity. Decreasing the operations costs associated with a shorter flight time (different trajectory) was investigated but the mass would need to decrease significantly (with science instrument mass decreasing below the science floor) to enable significant savings.

The resulting floor mission concept differs from the baseline mission as shown in **Table 4.1-3**.

#### 4.1.7 Descope Decision Points and Process

See §4.10.13 for the approach to the descope plan.

## 4.2 Science Investigation

### 4.2.1 Planning Payload

The EE planning payload instruments for the baseline and floor options are summarized in §2.4.2, along with the traceability back to the science measurement requirements. This planning payload, while notional, is used to understand the engineering aspects of the mission design, spacecraft and operational scenarios associated with obtaining the data to meet the science objectives. For the purposes of this study, instruments were examined to understand the viability of an approach to meet the measurement objectives, perform in the radiation environment and meet the planetary protection requirements. Therefore, the descriptions herein are to show proof of concept and should not be taken to be final selections nor final implementations. Heritage or similarities discussed are to instrument techniques and basic design approach and are not intended to imply that specific implementations are fully viable in their detail. Physical and electrical modifications of previous designs will be required for all instruments to function within the context of the mission requirements (as included in mass and cost estimates). Alternative instrument concepts and techniques may be selected via the AO process to meet the mission objectives as stated in the final AO. Also, this planning payload is described as 11 individual instruments, though combinations of instruments may be more efficient in terms of total mass, power and cost. Individual instrument capability assumed in all estimates is meant to be conservative, but is not meant to pre-judge AO solicitation outcome.

For both the baseline and the floor cases, the payload consists of several remote sensing instruments and a set of space physics instruments. In addition, the telecommunications system provides Doppler and range data for accurate orbit reconstruction in support of geophysical objectives.

The optical remote sensing portion of the payload needs to view in the nadir direction when in orbit about Europa. The spacecraft provides an adequate mounting volume of up to ~1 × 1 × 1 m for the science payload on the nadir-facing deck. The optical remote sensing instruments will need a conical clear field of view with at least a 30° half angle centered about the nadir direction. Preliminary work with the SDT indicates that nadir pointing the instruments is adequate to meet the science objectives and therefore a scan platform is not required.

The science payload is expected to have sensors that need to be cooled to as low as 80 K for proper operation while dissipating perhaps 300 mW of heat. Cooling to this level would be accomplished via a passive radiator, mounted so as to view in a direction away from the Sun and away from Europa at all times.

The remote sensing instruments will require spacecraft pointing control to better than or equal to 1 mrad, and stability to 10 μrad/s. Pointing reconstruction to 0.1 mrad is also required.

The severe radiation environment at Europa will present challenges for the science instruments. The radiation design point is 2.6 Mrad behind 100 mils of aluminum shielding. Thus, sensors and supporting electronics will need to be shielded. The most mass-efficient approach to providing shielding is to centrally locate as much of the instrument electronics as can be distanced from the sensors to minimize volume. The payload design includes such a chassis with space for up to the equivalent of 23 6U cards. The total radiation shielding mass for the science electronics chassis is estimated to be about 17 kg.

The anticipated downlink data rate from EE at Europa will typically be 300–800 kb/s depending on the actual range to Earth, station elevation angle, etc. (see §4.5). At the mission average rate of 420 kb/s, and assuming outages of ~40% of an orbital period for occultations by Europa, the downlink data volume for science will be about 1.8 Gb per orbit. This data volume limit places severe constraints on the data return from high data rate instruments. Therefore, high data reduction factors on the raw data rates of some instruments will need to be applied through compression and/or editing, and the highest data rate instruments will have stringent duty cycle limitations. Representative data acquisition scenarios are presented in §4.5. The available data rate will support near-global visible and multispectral imaging (at a range of resolutions), altimetry, and radar mapping of Europa; continuous fields and particles data; and coverage of over 1000 selected target regions with the entire complement of remote sensing instruments (see §2.4.3) within the first 26 eurosols (~92 days) at Europa.

The baseline orbital altitude for Europa Explorer will be 200 km for Campaign 1 (Global Framework) and 100 km for Campaign 2 (Regional Processes) and Campaign 3 (Targeted Processes), and Campaign 4 (Focused Science). For these orbits, the ground tracks for successive orbits will be spaced about 250 km apart at the equator. From a 200-km altitude, views to the surface with acceptable levels of foreshortening are limited to a swath only up to ~160 km wide. Therefore, allowing for at least 10% overlap between swaths, a complete global mapping cycle would take approximately 4 eurosols (14 days) using interleaved ground tracks during Campaign 1, assuming that mapping images are acquired only every other orbit, with radar profiling taking place on the alternate orbits. For the 100-km orbit of Campaign 2, the swath width is limited to ~80 km, and a global map at the improved spatial resolution offered by this lower altitude will take approximately 8 eurosols (28 days) to complete, again assuming mapping images are alternated with radar profiling every other orbit. Proper interleaving of ground tracks for mapping implies the use of a specific chosen orbital altitude to yield the exact orbital period required.

To achieve the Europa geophysical objectives connected with characterizing the subsurface ocean and the overlying icy shell, the flight system orbit must be reconstructed to an accuracy of 1 m in the radial direction. To achieve this level of accuracy, adequate levels of Doppler tracking are required (with dual frequency preferred), and thruster firings must be restricted to not more than one per 24 hours.

As introduced in §2.4.2, the baseline planning payload selected for the Europa Explorer study consists of a notional set of 8 remote-sensing instruments, 3 fields-and-particles instruments, and a Ka-band transponder added to the X-band telecommunications system. For the science floor mission, the payload is reduced to 6 remote sensing instruments and 2 fields and particles instruments, the capabilities of most instruments are reduced, and the Ka-band transponder is eliminated. **Table 4.2-1** presents the estimated resource requirements for each instrument and for the total payload.

Radiation tolerance and planetary protection compliance is a common challenge for all instruments. Detailed design work in these areas is beyond the scope of the present study, but will be required early in the development process to enable mature instrument concepts to be proposed in

***Table 4.2-1a.*** *Europa Explorer baseline planning payload resource requirements*

| BASELINE | | | | IPR orbit w/ comm | | IPR orbit no comm | | Imaging orbit w/ comm | | Imaging orbit no comm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Instrument | Mass (kg) | Operating Power (W) | Standby Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Approximate Dimensions (cm) | Field of View |
| Wide-angle Camera (WAC) - color | 3 | 5 | 1 | 0 | 1 | 0 | 1 | 80 | 4.2 | 0 | 1 | 5 × 5 × 5 (optics)<br>5 × 15 × 20 (electronics) | 58° × 58° |
| Medium-angle Stereo Camera (MAC) | 10 | 10 | 1 | 0 | 1 | 0 | 1 | 16 | 2.44 | 0 | 1 | 10 × 5 × 5 (each optics)<br>5 × 15 × 20 (electronics) | 11.7° × 0.0057° per camera |
| Narrow-angle Camera (NAC) | 15 | 12 | 2 | 1 | 2.1 | 0 | 2 | 1 | 2.1 | 0 | 2 | 60 × 10 × 10 (optics)<br>5 × 15 × 20 (electronics) | 0.59° × 0.59° (0.59° × 1.17° desired) |
| IR Spectrometer (IRS) | 25 | 22 | 1 | 0 | 1 | 0 | 1 | 80 | 17.8 | 0 | 1 | 37 × 39 × 83 (optics)<br>20 × 25 × 13 (electronics) | 9.17° × 0.014° |
| UV Spectrometer (UVS) | 15 | 10 | 1 | 0 | 1 | 0 | 1 | 100 | 10 | 100 | 10 | 51 × 24 × 31 | 3.67° × 0.043° |
| Laser Altimeter (LA) | 15 | 21 | 5 | 100 | 21 | 100 | 21 | 100 | 21 | 100 | 21 | 75 × 60 × 60 | 0.029° diam spot 0.080° swath width for 5-spot pattern |
| Ice Penetrating Radar (IPR) | 36 | 45 | 20 (warm) 10 (stand-down) | 90 | 42.5 | 0 | 20 | 0 | 10 | 0 | 10 | 20 × 30 × 20 (electronics) + 30-m dipole + 10-m × 2.6 m Yagi (65 × 25 × 25 stowed) | 5.7° swath width |
| Thermal Instrument (TI) | 8 | 14 | 1 | 0 | 1 | 81 | 11.53 | 8 | 2.04 | 81 | 11.53 | 29 × 37 × 55 | 47° × 35° |
| Magnetometer (MAG) | 4 | 2 | 1 | 100 | 2 | 100 | 2 | 100 | 2 | 100 | 2 | 2 × 2 × 2 (2) +<br>10-m boom | |
| Ion and Neutral Mass Spectrometer (INMS) | 15 | 28 | 5 | 100 | 28 | 100 | 28 | 100 | 28 | 100 | 28 | 19 × 23 × 32 | 20° |
| Particle and Plasma Instrument (PPI) | 12 | 10 | 1 | 100 | 10 | 100 | 10 | 100 | 10 | 100 | 10 | 20 × 27 × 36 | sensor dependent |
| | | | | | | | | | | | | | |
| TOTAL ALL INSTRUMENTS | 158 | 179 | 39 | | 110.6 | | 98.53 | | 109.58 | | 97.53 | | |
| TOTAL ALL INSTRUMENTS + 30% contingency | 205 | 233 | 51 | | 144 | | 128 | | 142 | | 127 | | |

***Table 4.2-1b.*** *Europa Explorer floor planning payload resource requirements*

| FLOOR | | | | IPR orbit w/ comm | | IPR orbit no comm | | Imaging orbit w/ comm | | Imaging orbit no comm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Instrument | Mass (kg) | Operating Power (W) | Standby Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Duty Cycle % | Average Power (W) | Approximate Dimensions (cm) | Field of View |
| Wide-angle Camera (WAC) - color | 3 | 5 | 1 | 0 | 1 | 0 | 1 | 80 | 4.2 | 0 | 1 | 5 × 5 × 5 (optics)<br>5 × 15 × 20 (electronics) | 58° × 58° |
| Medium-angle Camera (MAC) | 7 | 7 | 1 | 0 | 1 | 0 | 1 | 16 | 1.96 | 0 | 1 | 10 × 5 × 5 (each optics)<br>5 × 15 × 20 (electronics) | 11.7° × 0.0057° |
| IR Spectrometer (IRS) | 12 | 20 | 1 | 0 | 1 | 0 | 1 | 80 | 16.2 | 0 | 1 | 37 × 39 × 83 (optics)<br>20 × 25 × 13 (electronics) | 9.17° × 0.014° |
| Laser Altimeter (LA) | 7 | 15 | 5 | 100 | 15 | 100 | 15 | 100 | 15 | 100 | 15 | 75 × 60 × 60 | 0.029° diam spot |
| Ice Penetrating Radar (IPR) | 31 | 45 | 20 (warm)<br>10 (stand-down) | 50 | 32.5 | 0 | 20 | 0 | 10 | 0 | 10 | 20 × 30 × 20 (electronics) +<br>30-m dipole<br>(65 × 25 × 25 stowed) | 5.7° swath width |
| Thermal Instrument (TI) | 5 | 5 | 1 | 100 | 5 | 100 | 5 | 100 | 5 | 100 | 5 | 29×37×55 | 47° × 35° |
| Magnetometer (MAG) | 2 | 1 | 1 | 100 | 1 | 100 | 1 | 100 | 1 | 100 | 1 | 2 × 2 × 2 +<br>10-m boom | |
| Particle and Plasma Instrument (PPI) | 10 | 8 | 1 | 100 | 8 | 100 | 8 | 100 | 8 | 100 | 8 | 20 × 27 × 36 | sensor dependent |
| | | | | | | | | | | | | | |
| TOTAL ALL INSTRUMENTS | 77 | 106 | 31 | | 64.5 | | 52 | | 61.36 | | 42 | | |
| TOTAL ALL INSTRUMENTS + 30% contingency | 100 | 138 | 40 | | 84 | | 68 | | 80 | | 55 | | |

response to an AO. Note that compromises to instrument performance may be required to enable the designs to meet the radiation and planetary protection requirements. Specific activities to support early education of potential instrument providers to the complexity of options to meeting radiation and planetary protection requirements have been identified and are a part of the estimated project cost. The allocated masses presented here are estimates based on analogous instruments on previously flown missions, with specific consideration for mass needed for radiation shielding.

The instruments are anticipated to have designs compatible with the approach to planetary protection outlined in §4.6. In the event of conflicting materials capabilities, alternative sterilization or aseptic assembly strategies will be applied to ensure planetary protection requirements are not compromised. One common challenge for the instruments is the performance and availability of sensors which can meet the radiation and planetary protection environment. Instruments which use traditional technology will need to evaluate the required performance as well as implementation options such as cooling, shielding and integration techniques, and sterilization approaches in order to select the appropriate implementation. The project will generate and disseminate special guidelines for these special developments early in the project to potential instrument providers. Additional descriptions along with specific issues or concerns for each instrument follow.

### 4.2.2 Instrument Descriptions

#### *Wide-Angle Camera*

The notional Wide-Angle Camera (WAC) has an Instantaneous Field of View (IFOV) of 1 mrad yielding a pixel footprint on the surface of 100 m from a 100 km altitude orbit. To allow completion of a global map in 8 eurosols (~28 days) using only every other orbit, the WAC must have ≥ 600 pixels across track; a standard 1024 pixel CCD or CMOS detector array is baselined to provide margin and some swath overlap side to side. A radiation shield around the detector and its co-located electronics (~1 cm of tantalum, mass of ~1 kg) will be required to ensure adequate signal-to-noise ratio (SNR) performance. This shield will also limit the radiation dose seen by the detector to about 30 krad. The rest of the electronics can be located remotely in the science electronics chassis. From the 200 km orbit, mapping swaths will overlap by 50% side to side providing stereo coverage at ~200 m resolution.

The WAC operates as a framing camera and has 4 spectral filters (violet, green, near-IR, and pan-chromatic). The filters could be implemented either via a selectable filter wheel or by superimposing the four filters directly on the detector with each one covering ¼ of the array in the along-track direction. For the orbital ground speed of 1.37 km/s at 100-km altitude, the maximum exposure time for 1 pixel of smear is 73 ms, which should give adequate signal-to-noise ratios for broad-band filters. Acquiring one frame every 16 s while cycling through the 4 filters will yield contiguous 4-color coverage along the swath. Images are read out in < 2 s into an internal frame buffer to minimize radiation noise. 12-bit data encoding is assumed. Real-time data reduction by a factor of 3 is envisioned via compression. The data are transferred to the spacecraft C&DH at 16 s/frame with an output data rate of 267 kb/s.

A generic block diagram for the WAC and the other two EE camera systems is included as **Figure 4.2-1**. Sterilization for planetary protection will be accomplished using dry heat or radiation exposure, provided a CMOS detector is used. The WAC has similarities to the MRO MARCI and the Lunar Reconnaissance Orbiter Camera (LROC). The WAC is the only EE instrument that is not changed at all in the floor mission.

#### *Medium-Angle Camera*

The notional Medium-Angle Camera (MAC) has an IFOV of 0.1 mrad yielding a pixel footprint on the surface of 10 m from a 100 km orbit. To image geological features and provide context coverage for the Narrow-Angle Camera and the imaging spectrometers, a swath width of 20 km from 100 km altitude is desired; therefore, a detector with 2048 pixels across track is warranted. Radiation shielding is similar to that described for the WAC. The MAC is limited to a single panchromatic band, consistent with the science requirements.

The baseline includes twin MAC optics viewing fore and aft along track with ~30°

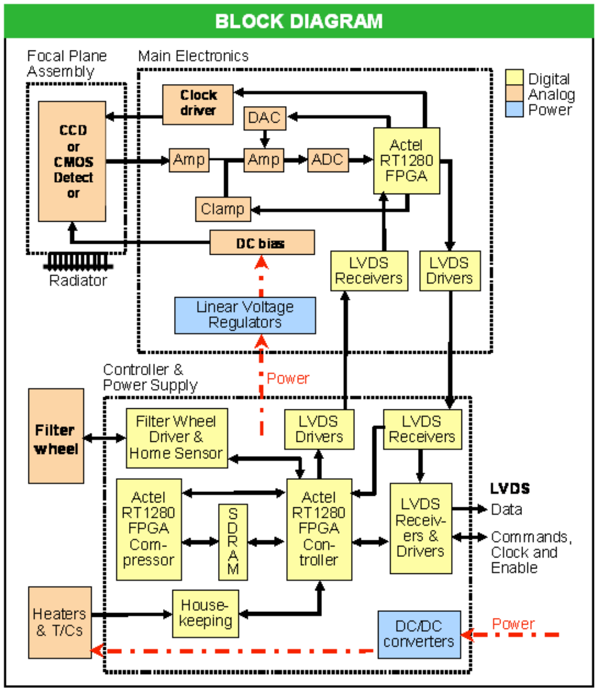



***Figure 4.2-1.*** *Camera system block diagram; the same block diagram applies to all three notional EE cameras (WAC, MAC, and NAC).*

separation angle, to obtain stereo images of a given target area on the same orbital pass, thus with the same lighting geometry. This MAC is envisioned as a pushbroom imager. Orbital motion moves a nadir pixel by its dimension in 7.3 ms at 100 km altitude. To collect enough signal for adequate SNR, at least a few lines of Time-Delay Integration (TDI) will be required. Assuming 12-bit encoding, the raw instrument output data rate is 3.37 Mb/s from each camera. Real-time data reduction by a factor of 3 is envisioned via compression. The data are then transferred to the spacecraft C&DH with an output data rate of 1.1 Mb/s from each camera.

The floor mission includes only a single MAC camera (as opposed to a stereo pair). Sterilization for planetary protection could be accomplished using dry heat or radiation exposure if a CMOS detector is used. To gain adequate SNR a detector with TDI is necessary, or it would be possible to add multiple successive frames, each offset by one pixel along track from the previous one. The MAC will have similarities to the Stardust NAVCAM and the Dawn Framing Camera (although these are not pushbroom devices), and the pushbroom Mars Express High Resolution Stereo Camera (HRSC).

*Narrow-Angle Camera*

The notional Narrow-Angle Camera (NAC) has an IFOV of 10 μrad yielding a pixel footprint on the surface of 1 m from a 100 km orbit. For imaging at this high resolution from a low circular orbit, a pushbroom imager with TDI and a wide swath is best. However, the NAC also serves as the prime imaging instrument for observing Europa and other distant objects in the Jupiter system during the Jovian Tour. In this mode, a framing camera may be more desirable thus the notional approach is a NAC system that can operate in both pushbroom and framing modes. It uses a 1024 × 2048 CCD array that can be read out in the normal way for framing camera operation, or clocked in TDI mode when in low orbit about Europa. In the 100-km orbit, the line shift time would be 0.73 ms, and the total integration time would be as much as 0.75 s. In the 100 km orbit with 12-bit encoding, the raw output data rate is 33.6 Mb/s. Real-time data reduction by a factor of 3 is envisioned internal to the instrument via compression. The data then are transferred to the spacecraft C&DH with an output data rate of 11.2 Mb/s.

Radiation shielding is as described for the WAC. Use of the required CCD detector in the NAC will require obtaining a sterile detector in order to meet planetary protection require-ments. The NAC will have similarities to the Mars Global Surveyor Mars Orbiter Camera (MOC), Lunar Reconnaissance Orbiter Camera (LROC) NAC, and the Deep Impact Medium Resolution Instrument (MRI). The NAC is not included in the floor mission.

*IR Spectrometer (IRS)*

The notional IR Spectrometer (IRS) covers a wavelength range of 0.4 to 5 μm with a spectral resolution of 6 nm below 2.5 μm, and 12 nm above 2.5 μm, yielding a total of 558 spectral channels. These two spectral ranges are covered by two separate spectrometers fed by a common fore-optic. The detectors must be shielded against radiation flux and passively cooled to ~80 K to yield acceptable signal-to-noise performance. The radiation shield for each detector is estimated to require 1.3-cm thick tantalum with a mass of 2 kg. The signal-chain electronics co-located with the detectors also require shielding of 0.5-cm thick tantalum with a mass of 0.5 kg for each. The IRS IFOV is 0.25 mrad. It has 640 pixels across track and operates with a 19 ms integration and frame repeat time from a 100 km altitude orbit. A single-axis scan mirror with a ±60° along-track range is used to increase integration time using target motion compensation or for flyby imaging during the tour. A block diagram of the IRS is shown in **Figure 4.2-2**.

At 12 bits/pixel, the raw output data rate is 226 Mb/s, and with 2.5:1 lossless data compression performed internal to the instrument, the full-resolution data rate would be 90 Mb/s. A profiling mode is included with 4 × 4 pixel summation that reduces the output compressed data rate to 5.6 Mb/s. A targeted mode is also included that uses target motion compensation to increase the integration time by 8×, yielding a full-resolution output compressed data rate of 11.3 Mb/s. For global mapping, the IRS is envisioned to be operated as a point spectrometer with a compressed output data rate of 40 kb/s in the 100 km orbit. Other spatial and spectral editing/summing modes could also be included.

Sterilization for planetary protection can be accomplished using dry heat or radiation exposure for all components except for the detector. For this point design, implementing a sterile fabrication process for producing sterile IR detectors would be required. For the science floor case, the IRS is reduced to a single spectrometer spanning the spectral range of 0.9 to 5 μm, with lesser spectral and spatial resolution. The IRS has similarities to

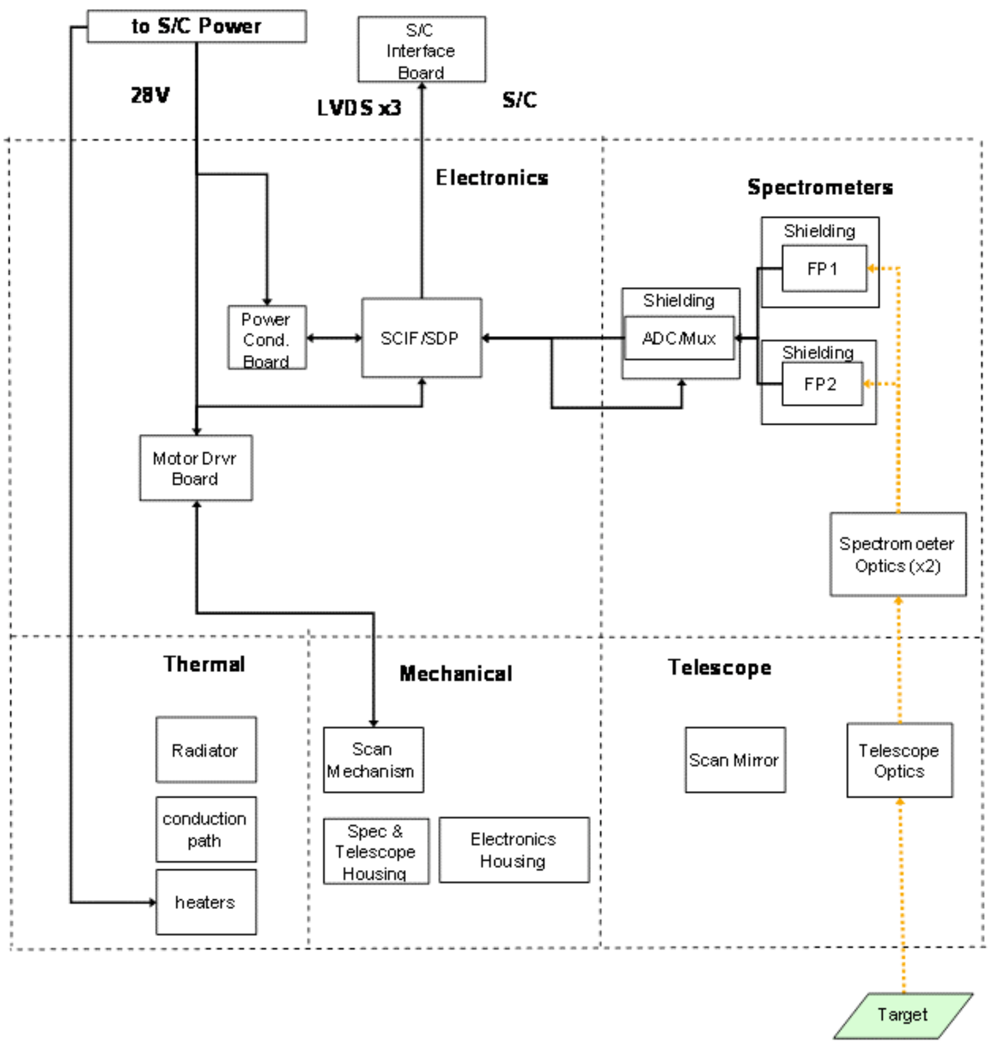



***Figure 4.2-2.*** *IRS Block Diagram*

the Cassini VIMS instrument and the Chandrayaan Moon Mineralogy Mapper ($M^3$).

### Laser Altimeter

The notional Laser Altimeter (LA) is a diode-pumped Nd-YAG laser transmitting at 1.064 μm and including a sensing telescope and time-of-flight sensing electronics. Its range precision is ~10 cm. The baseline design includes a 5-spot cross pattern of 0.25 mrad diameter spots. Each 3-ns pulse produces 200 μJ of energy. Pulses are transmitted at a rate of 30 Hz. Its output data rate is 12 kb/s, and the instrument is expected to operate continuously. Any data reduction via compression/editing/summing is expected to be done in the spacecraft computer. For the science floor case, instead of a 5-spot pattern, the LA is reduced to a single spot. Shielding is anticipated for sensitive components, including detectors and electronics (replacement of the FPGA with an ASIC is required). The fiber optics in the lasers will require an active mitigation approach such as photobleaching to anneal out radiation-induced color centers [*Ott 1998*]. The LA is similar to the Mars Global Surveyor's Mars Orbiter Laser Altimeter (MOLA) instrument, the Near Earth Asteroid Rendezvous's NEAR Laser Rangefinder (NLR; **Figures 4.2-3** and **4.2-4**), and the Lunar Orbiter Laser Altimeter (LOLA) for the Lunar Reconnaissance Orbiter.

### Ice-Penetrating Radar

The notional Ice Penetrating Radar (IPR) is a dual-frequency sounder (nominally ~5 MHz with ~1 MHz bandwidth and ~50 MHz with ~10 MHz bandwidth). The higher frequency band is designed to provide high spatial resolution (footprint and depth) for studying the subsurface above 3 km depth at high (10 m) vertical resolution. The low-frequency band is designed to search for the ice/ocean interface on Europa or the hypothesized

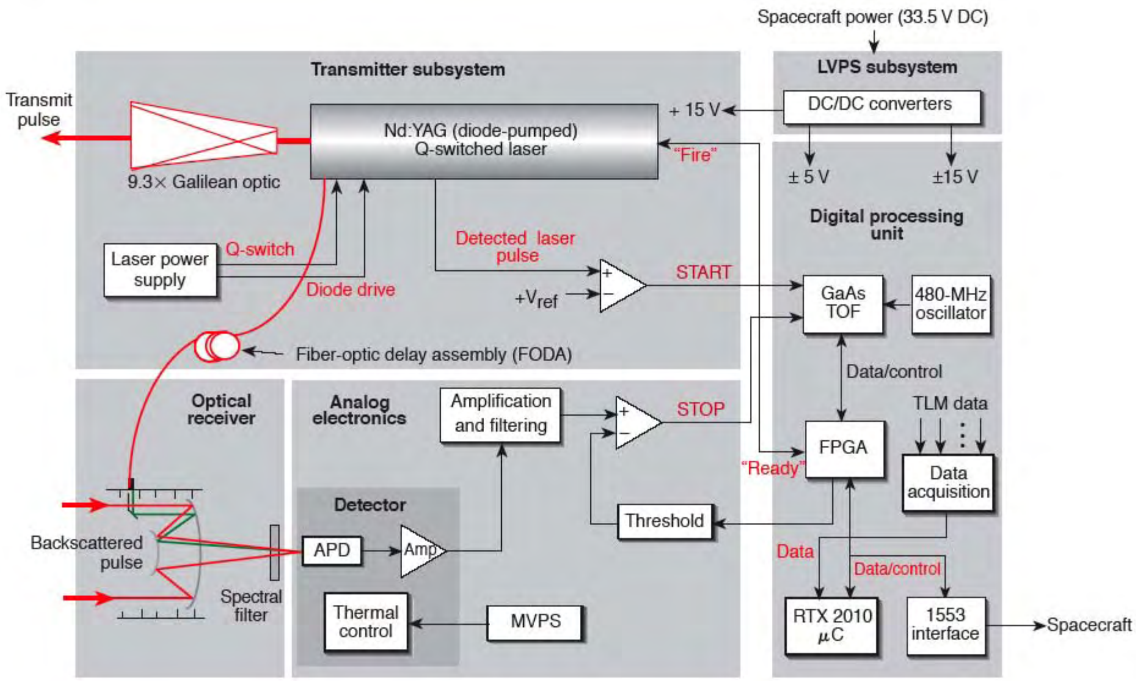



***Figure 4.2-3.*** *Block diagram of the NEAR Laser Rangefinder, a similar type of instrument to what would be flown on EE. The five subsystems of the NLR instrument consist of the transmitter subsystem, the low-voltage power supply (LVPS), the optical receiver, the analog electronics, the digital processing unit. Gray areas indicate these subsystems. Red lines indicate optical signals (laser light). Thresholding is used both to start the time-of-flight (TOF) counters (START) and to stop the same counters (STOP). APD = avalanche photodiode; μC = microcontroller; FPGA = field-programmable gate array (replacement with an ASIC is needed); MVPS = medium-voltage power supply; TLM = telemetry data [*Cole 1998*]. The physical decomposition of the subsystems is indicated by the grey boxes. The "Detector" cannot be separated from the Optical Receiver. The other subsystems may be separated for radiation shielding [*Cole 1998*].*

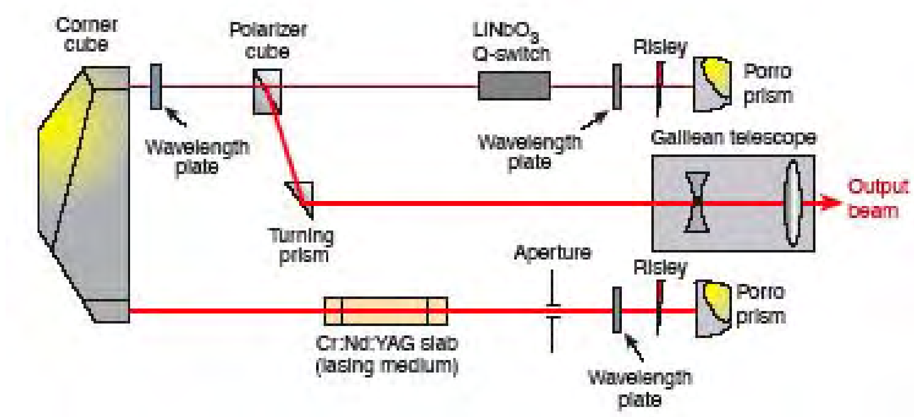



***Figure 4.2-4.*** *Optical Schematic from the NEAR Laser Rangefinder. NLR laser reasonator cavity configuration is a polarization-coupled U-shaped cavity design. The Cr,Nd:YAG zigzag slab is side-pumped by a diode laser array to optimize conversion efficiency* [Cole 1998]*.*

transition between brittle and ductile ice in the deep subsurface at a depth of up to 30 km (and a vertical resolution of 100 m). This band mitigates the risks posed by the unknown subsurface structure both in terms of unknown attenuation due to volumetric scattering in the shallow subsurface and thermal/compositional boundaries that may be characterized by brine pockets. Additionally, the low-frequency band is less affected by the surface roughness that can attenuate the reflected echo and clutter noise. However, because the low-frequency band is vulnerable to Jupiter noise when operating on the Jovian side of the moon, it is necessary to increase the radiated power compared to space-flight hardware currently deployed for subsurface studies of Mars.

For the baseline, the instrument would use a dual antenna system with a nadir-pointed 50-MHz Yagi array with a backing element that also serves as a dipole antenna for the 5-MHz system. The floor instrument would substitute a simpler and less massive dipole antenna for the Yagi array for use at high frequencies, and data rates and volumes would be decreased. Because this instrument is a depth sounder with variable vertical resolution, there is no FOV requirement.

The IPR Functional Block Diagram is shown in **Figure 4.2-5**. The transmitter matching network box (#2) is located close to the antenna. The digital electronics and receiver are located in box #1, which could be a remotely located shielded instrument electronics chassis. The two boxes can be combined to save mass if needed.

256 Mb of internal non-volatile memory is envisioned. The IPR will rely on its own processing capability. Range compression, pre-summing, Doppler filtering, data averaging, and resampling are done internal to the instrument to reduce its normal output data rate to ~280 kb/s.

Electromagnetic interference must be considered in the spacecraft design from the start. These requirements have been flowed down to all spacecraft and science subsystems. Special care must be taken in shielding cables and other subsystems. Space-qualifiable parts that are radiation hardened to 1 Mrad are currently available. Sterilization for planetary protection can be accomplished using dry heat or radiation exposure for all components.

There are essentially two operating modes for the IPR. Because the global surveying mode is achieved with onboard processing, and the deeper targets will benefit from better relative sampling along track, both the shallow

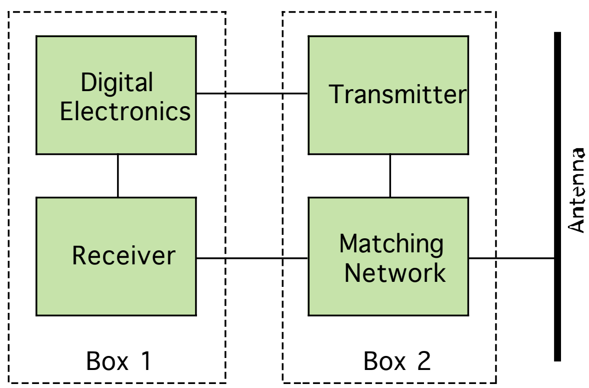



***Figure 4.2-5.*** *IPR functional block diagram.*

high-resolution and deep low-resolution surveys (i.e., < 3 km depth targets at 10 m resolution and < 30 km depth targets at 100 m resolution, respectively) will have similar power consumption and data rates of ~45 W and ~280 kb/s, respectively. In the baseline scenario, at least 90% of the portion of each radar sounding orbit will have these characteristics. Stand-by power will be ~20 W for the non-operating portion of the orbit. For non-IPR orbits, the IPR will be off and will need 10 W for heaters. A second mode capable of capturing short bursts of raw radar data (~30 seconds at 30 Mb/s, producing a post-processing swath ~20 km long) will also be available for targeted surveys, using full power for several minutes at each target, producing ~900 Mb of data.

The IPR is similar to the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on Mars Express and the Shallow Radar (SHARAD) instrument on the Mars Reconnaissance Orbiter (MRO).

*Thermal Instrument*

The notional Thermal Instrument (TI) is envisioned to use microbolometer detector arrays to determine surface temperatures from emission in at least 2 bands in the 8–26 μm range. The 320 × 240-pixel array detector does not need cooling. A detector radiation shield of 1 kg is included. The pixel IFOV is 2.5 mrad yielding a pixel scale of 250 m on the surface and a frame footprint of 80 × 60 km from a 100-km orbital altitude. The optics aperture required for adequate SNR is only ~3 cm, but improved SNR can be obtained with a faster optic. A flip mirror provides a deep space view for calibration. A block diagram of the TI is shown in **Figure 4.2-6**.

The integration time for one pixel of smear is 180 ms from a 100 km orbit. With data encoded to 16 bits/pixel, the raw data rate from two channels is 6.8 Mb/s. Data compression of 2:1 is applied internal to the instrument. Data summing can be done to improve SNR or reduce data rate. For global mapping, the cross-track data can be co-added, resulting in a compressed data rate of 43 kb/s, which is the value adopted in the science data acquisition scenario of §4.5.3. Mapping data are collected continuously for 100% of all orbits until globally distributed coverage is obtained at least twice (day and night). Radiation and

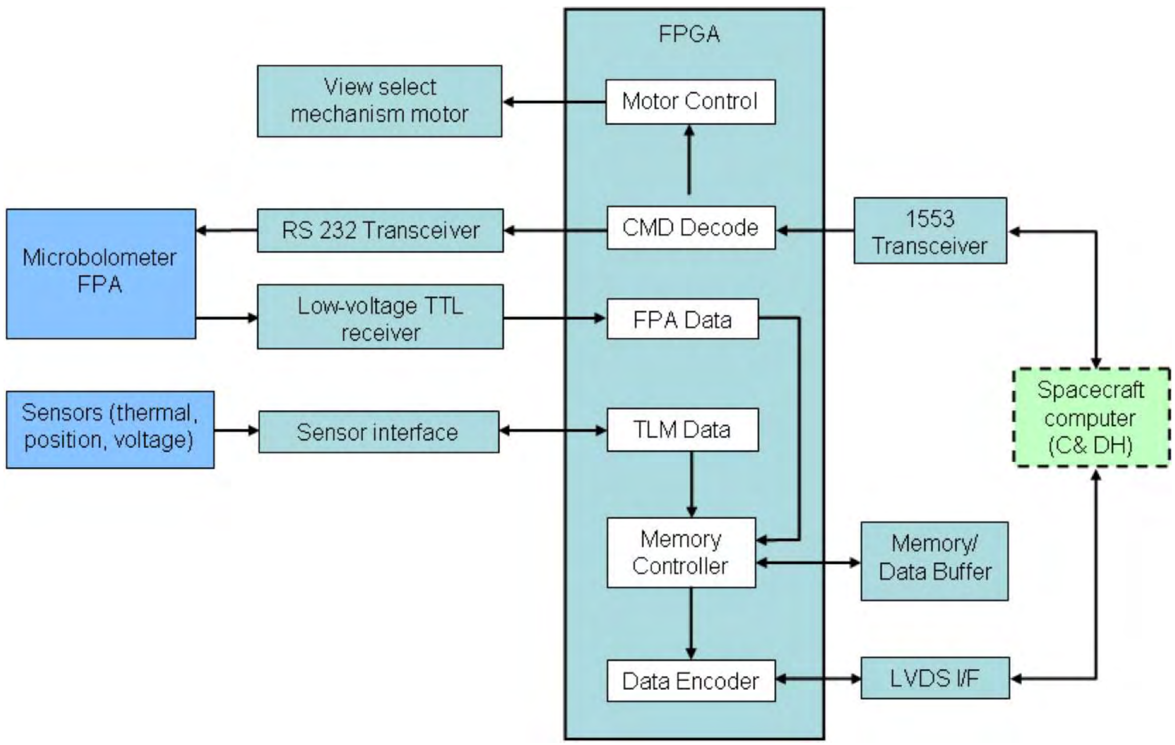



***Figure 4.2-6.*** *Thermal Instrument block diagram.*

planetary protection requirements do not pose any specific development issues for the TI, except that the FPGA will need to be converted to an ASIC. For the science floor case, the TI is a point spectrometer, with a compressed data rate of 4 kb/s, and will accept reductions in spatial resolution and SNR to save mass and power. The TI is similar to a design by Ball Aerospace [*J. van Cleve, personal communication*] and has similarities to the Thermal Emission Imaging System (THEMIS) instrument on Mars Odyssey.

### *Magnetometer*

The notional Magnetometer (MAG) is a fluxgate magnetometer similar to those flown on several other missions including Galileo at Jupiter. It comprises two DC magnetic sensors mounted on a 10-m boom, one at the tip and the other about half way out from the spacecraft. Fluxgate instruments rely on the hysteresis effect found in ferromagnets. Two solenoids with ferromagnetic cores wound in opposite directions are driven with a sufficiently high frequency (several kHz) current to drive them into saturation. The difference field between these coils is sensed by a third coil, which sees a second harmonic of the primary field. This second harmonic field is rectified and smoothed and is directly proportional to the background field. The rectified field is exceptionally linear and is digitized using A/D converters. A block diagram of the MAG is shown in **Figure 4.2-7**.

The highest cadence rate required is 32 vectors/s to measure the ion cyclotron waves near Europa. The expected field range over the whole mission is 0–1000 nT. The magnetic field of the spacecraft at 5 m distance along the boom must be < 0.1 nT with a variation of < 0.03 nT.

The sensor is mounted at the end of the boom and has no active electronics. The magnetometer electronics will be housed in the science electronics chassis. The baseline MAG is capable of data processing and requires two electronic cards. It incorporates a CPU and internal RAM memory (< 2 Mbytes) for data processing and burst mode. The baseline instrument can manage I/O and data processing and limited storage (to avoid blackouts at critical times). The output data rate is 2 kb/s per sensor (uncompressed).

The dual magnetometer design reduces two types of risks. First, the dual magnetometer is able to quantify and therefore separate the internal field from the spacecraft from the background field. Secondly, if one magnetometer were to fail, the second one

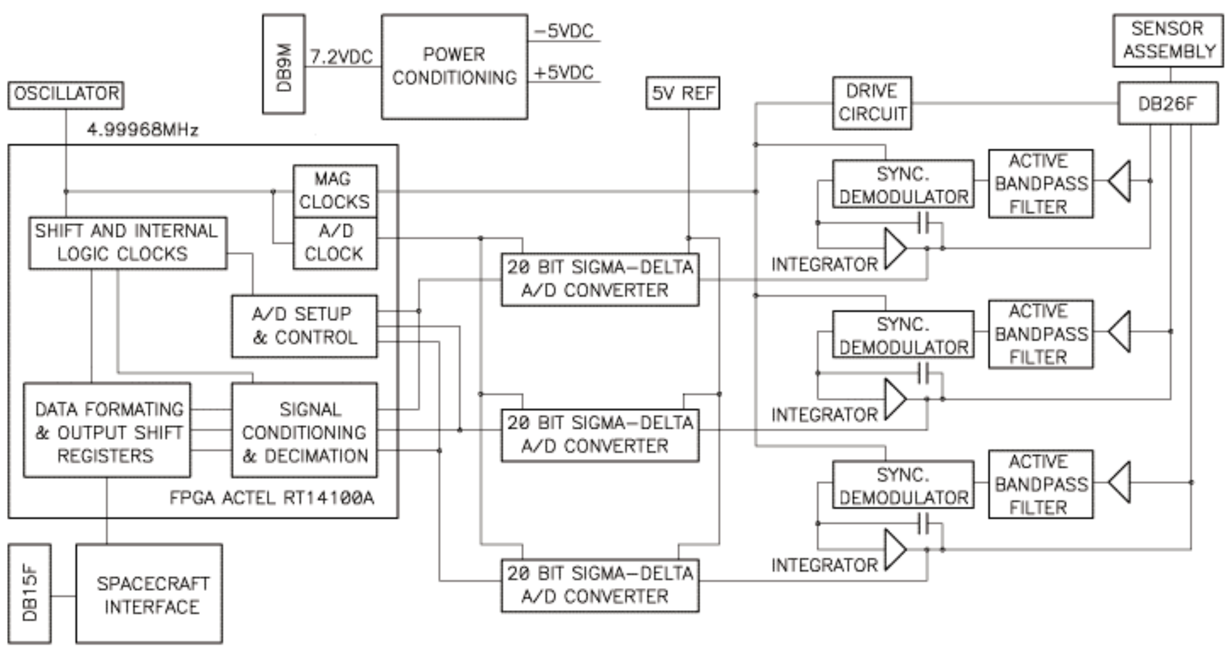



*Figure 4.2-7. Magnetometer block diagram.*

would still be able to fulfill the science role if calibrations are performed in space to assess the spacecraft generated magnetic field.

Fluxgate magnetometers can easily withstand the high radiation environment of Europa. Sensors should have no problems with radiation since they have no active parts. Radiation hardened versions of all processing parts, including ADCs, opamps, analog switches, and discrete transistors.

The fluxgate sensors suffer from small but measurable drifts in their zero levels. On a non-spinning spacecraft such as for EE, these can be measured in the solar wind by utilizing the rotational nature of the interplanetary magnetic field. Calibrations from the measured field will need to be performed once a week. Continuous data at a resolution of 1 s or better is required. Once inside Jupiter's magnetosphere, in the Jovian Tour phase, slow spacecraft spins around two orthogonal axes will be required to determine offsets. These are performed roughly once every week. In the primary Europa Science phase, spacecraft spins around the two orthogonal axes are performed once every month.

The MAG parts can be sterilized with standard procedures.

The floor science unit consists of a single sensor and electronics card on a 5 m boom. The floor science instrument is a simple state machine with the spacecraft computer lifting the measured vectors directly.

The MAG has similarities to instruments flown on Galileo, Polar, Fedsat, and Space Technology 5 (ST5).

### *Ion and Neutral Mass Spectrometer*

The notional Ion and Neutral Mass Spectrometer (INMS) determines the elemental, isotopic, and molecular composition of Europa's atmosphere and ionosphere. To accomplish this, the INMS covers a mass range of 1–300 Daltons with mass resolution greater than 500 and a pressure range of $10^{-6}$ to $10^{-17}$ mbar for neutrals and low-energy (< 100 eV) ions. A Reflection Time of Flight (RTOF) mass spectrometer was selected for the notional approach to meet the mass range, mass resolution, and sensitivity, and the mass and power allocations. Exospheric gases and ions are collected, ionized if necessary, and accelerated to sensors that determine their masses and mass-to-charge ratios. Species at densities as low as $10^{-2}$ $cm^{-3}$ can be detected. The INMS needs to view in the ram direction while making its measurements with a clear 20° FOV. The INMS includes a calibration system that can inject known gases into the instrument. A block diagram of the INMS is shown in **Figure 4.2-8**.

The output data rate is 1.5 kb/s. INMS is expected to be operated continuously at Europa. The instrument processor performs all control and data processing functions. The electronics include high voltages that will need to be isolated to avoid electromagnetic interference effects on other instruments and the spacecraft. The INMS is packaged as a single unit to retain alignment and timing characteristics that are determined during ground testing and to facilitate integration.

The RTOF has two potentially radiation-sensitive components, the detector and the TOF electronics, which are relatively fast. Other components are inherently tolerant to radiation. The detector will be shielded and will be as small as possible to reduce background counts and shielding mass. The detector will degrade slowly with total dose, so the larger risk is increased background counts, a noise source that reduces sensitivity. There are several options for radiation-hardening of the TOF electronics. A TOF integrated chip that is hardened to more than 1 Mrad has recently acquired flight heritage. These and other electronics will be shielded, and 4 kg has been allocated for shielding. Radiation analysis will determine how that mass is allocated between the detector and the electronics.

The entire INMS assembly can be heated in a vacuum to 150°C. This will meet the nominal planetary protection requirements bioburden reduction regime which is typically performed at 125°C. Some components can be heated to 300°C prior to assembly.

The INMS has similarities with the Cassini INMS and the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA). The INMS is not included in the science floor case.

### *Particles and Plasma Instrument*

The notional Plasma and Particles Instrument (PPI) is envisioned as a single instrument with three separate sensors. The first sensor is a pair of telescopes like the Proton/Electron Telescope (PET) on the Solar,

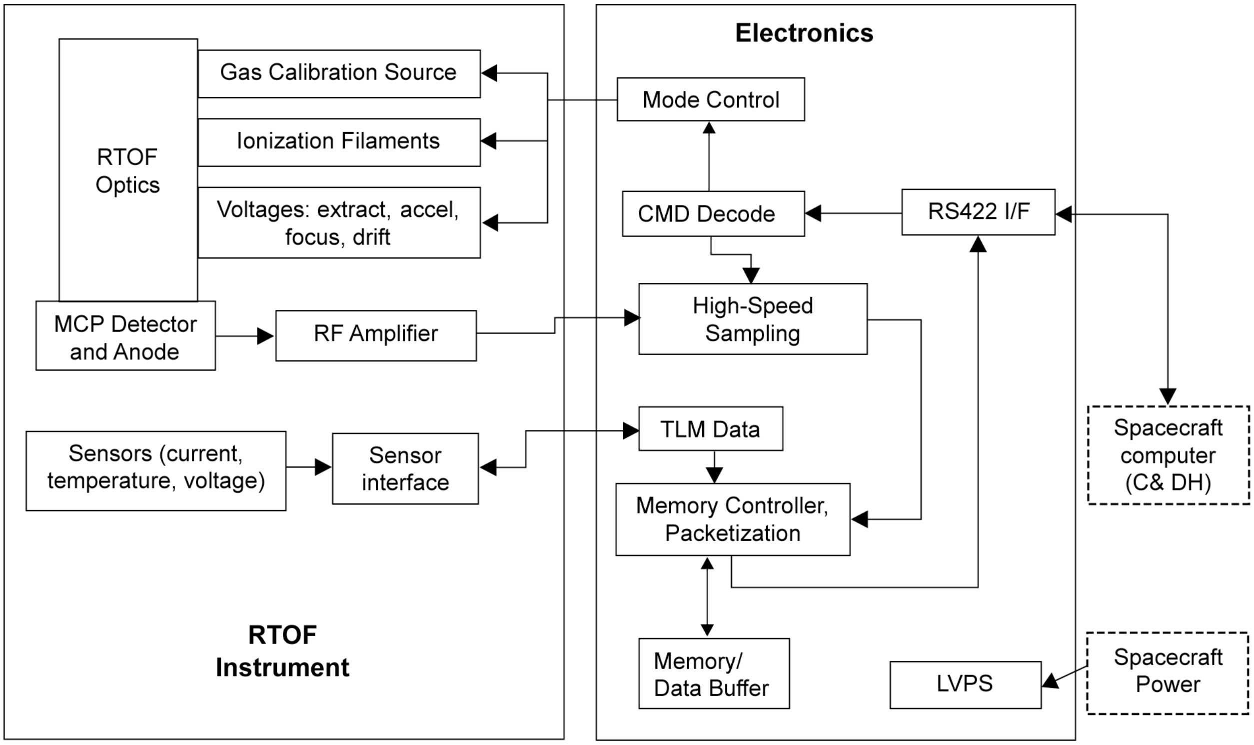



*Figure 4.2-8. INMS Block Diagram.*

Anomalous, Magnetospheric Particle Explorer (SAMPEX) or the Cassini Low Energy Magnetospheric Measurement System (LEMMS). It would typically detect few hundred keV to 10 MeV electrons and few to few hundred MeV ions. This sensor would contain a detector stack, and coincidence and anti-coincidence methods would separate energies and species. It would probe the radiation environment to understand those particles contributing to the energetics of Europa's surface. The angular resolution is ~15°. The two telescopes are mounted orthogonal to each other to provide wide angular coverage of the radiation-dose electrons.

The second sensor is a puck-like ion sensor similar to the Juno Energetic-particle Detector Instrument (JEDI) or the Pluto Particle Spectrometer Science Investigation (PEPSSI) on the New Horizons spacecraft. It measures few keV to few MeV ions with a nominal fan of 160° × 15°. Such a device provides the count rate and energy and angular coverage of ions. The energy range is chosen to include the ions that are the main sputtering agents of the surface.

The third sensor is an electron mass/charge ratio (E/Q) device such as the Fast Imaging Plasma Spectrometer (FIPS) on MESSENGER. It would detect the plasma ion count rate and velocity vector as well detect ion species. It includes TOF capability. The range of such devices is typically tens of eV/Q to 10 keV/Q, and the coverage is ~1.5π steradians (75° × 360°). Angular resolution is ~30°.

These sensors are not articulated and do not require a turntable. Instead, the instrument is mounted on the spacecraft so that the various sensors view the highest flux directions of incidence over part of the orbit. For example, it would optimally view into the ram direction over Europa's trailing hemisphere as often as possible. A block diagram of the PPI concept is shown in **Figure 4.2-9** including its FOV requirements.

All event processing and data compression are performed by the instrument processor; output is formatted as packets and sent to spacecraft C&DH. The output data rate is 2 kb/s.

The functional block diagram above is drawn to show physical units. Each box is a separate electronics board in the instrument stack, and the sensors are physically separate units. Electronics are based on those for Juno/JEDI. The electronics and the sensors are

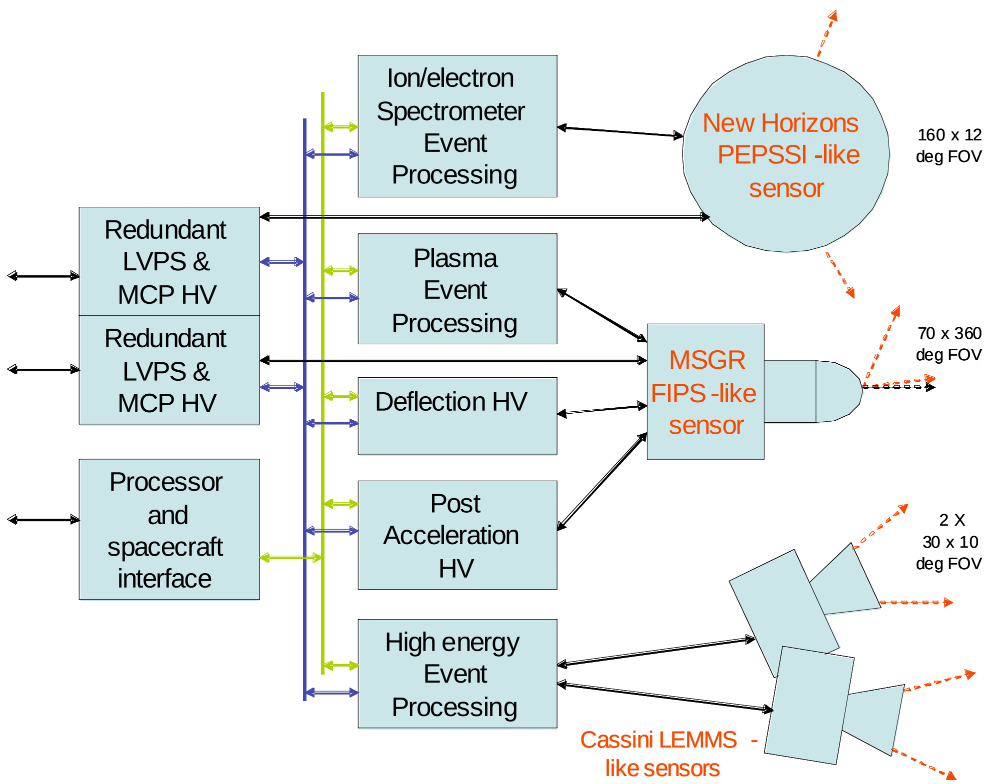



*Figure 4.2-9. Particle and Plasma Instrument (PPI) block diagram.*

surrounded with 100 mils of WCu (density 15.85 g/cm$^3$); this is the same as the Juno design, and will permit use of available parts tolerant to ~200 krad. Additional shielding may be needed around the detectors. This design assumes the electronics are not housed in the science electronics chassis. High voltages are required by this instrument.

The PPI can tolerate high heat for planetary protection sterilization, with the possible exception of the detectors. The bare unpowered detectors can tolerate high-temperature soak; however, epoxies used in the assembly of these detectors into a system must be carefully evaluated for proper characteristics at these temperatures. Therefore, high-temperature soak (or high radiation dose) is planned for most of the parts, the manufacturing process must ensure clean detectors, and then clean conditions are required to keep the instrument sterile during assembly, integration and test.

For the science floor case, the PPI is simplified by removing the second PET-type telescope and the ion composition measurement capability from the plasma E/Q sensor. The notional PPI has similarities to the Cassini LEMMS, SAMPEX/PET, Juno/JEDI, and MESSENGER/FIPS.

#### *Ultraviolet Instrument*

The notional Ultraviolet Spectrometer (UVS) comprises a 2-D CODACON detector with simultaneous spectral and 1-D spatial coverage capabilities. The UVS measures atmospheric and surface composition and atmospheric density, through stellar occultations, limb scans, and surface imaging.

The UVS has three channels, covering the Extreme Ultraviolet (EUV, 55–110 nm), Far Ultraviolet (FUV, 110–190 nm), and Near Ultraviolet (NUV, 190–350 nm) wavelength ranges. A high-speed photometer is aligned with the telescope-spectrographic channels. Images are made by scanning a slit, using the motion of the spacecraft. Stellar occultations are performed by pointing the UVS boresight at a star (via instrument articulation) and tracking the star as the flight system's motion along its trajectory causes the star to pass behind the limb of Europa. The detector format is 1024 spectral × 64 spatial pixels. Each of the 64 spatial pixels is 1 mrad (× ~0.75 mrad). A 1 min swath performed in

100 km orbit will cover an area 100 m wide × 62 km long, for one of the 64 pixels.

To obtain full spatial resolution on the surface of Europa in the 100 km orbit, frames will need to be acquired every 50 ms. Assuming 16-bit encoding, the raw uncompressed full-resolution data rate would be 21 Mb/s. Substantial editing, binning, and compression will be accomplished internal to the instrument. During global mapping at 100 km, the output data rate will be reduced to 5 kb/s by using a combination of such techniques. UVS is expected to collect data continuously day (surface and atmosphere) and night (atmosphere).

Prior to launch, the instrument is calibrated in the laboratory in manners similar to UV instruments on past missions. The post-launch Interplanetary phase will be important for performing stellar calibrations to check instrument behavior with time. Observations of objects such as the Moon and asteroids will aid calibration and testing of data processing techniques.

The UVS is similar to the Cassini Ultraviolet Imaging Spectrometer (UVIS), the exploded diagram for which is shown in **Figure 4.2-10**. The UVS is not included in the science floor.

*Radio Science - Gravity*

The planning payload includes provision of a dual-frequency (X and Ka band) transponder in the spacecraft telecommunications system, providing 2-way coherent X-/Ka-band Doppler tracking and range measurements required for orbit reconstruction in support of geophysics (and navigation). Noise in the Doppler measurements is dominated by line-of-sight plasma effects in the solar wind and the Earth's ionosphere. Having multiple frequencies (X- and Ka-band) permits the best job of removing these, yielding improvement over the 0.1 mm/s over a 30-s integration time provided by single-frequency X-band tracking.

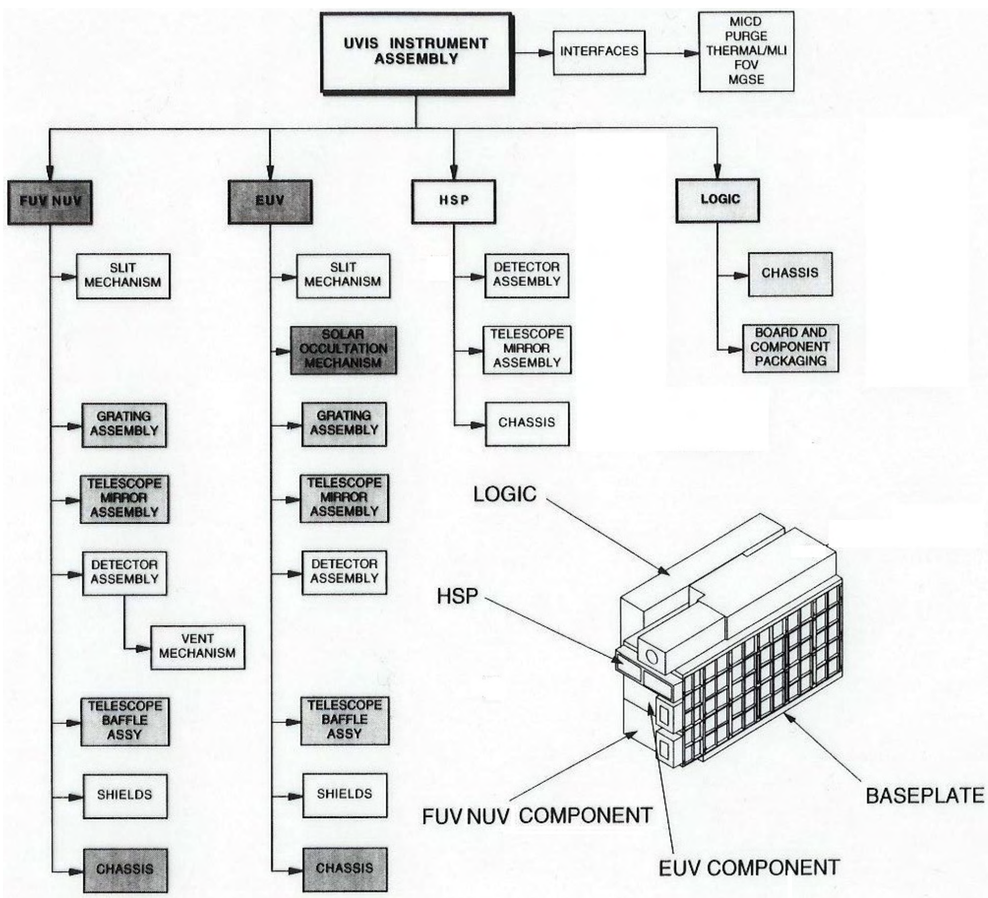



***Figure 4.2-10.*** *UVIS instrument from Cassini showing two spectrometers (a NUV channel will also be included) and the high speed photometer.*

The operations scenario for tracking is discussed in §4.5.

The floor mission includes X-band Doppler only.

## 4.3 Mission Design Overview

The flight system will be launched on a Delta IV 4050H-19 from Cape Canaveral Air Force Station on a VEEGA interplanetary trajectory. After a cruise of 6 years, the flight system will perform a large propulsive burn to capture into the Jupiter system. The flight system will then perform an approximately 2-year gravity-assist tour to lower its energy with respect to Europa. This tour provides the collateral benefit of extensive opportunities for Jovian system science. Finally, a final burn permits capture into low circular orbit at Europa. The first 8 eurosols (~28 days) of the Europa orbital mission are known as the Global Framework Campaign which is performed at an altitude of approximately 200 km. After concluding the first science campaign, the flight system will maneuver to a circular orbit of approximately 100 km to begin the Regional Processes Campaign, which lasts 12 eurosols (~43 days). The third campaign, the Targeted Processes Campaign, continues through 26 eurosols (92 days) from EOI. Campaign 4, Focused Science, comprises the rest of the prime mission at Europa and ends at one year after EOI. **Foldout 2 (FO-2)** depicts a summary of the mission design.

For discussion of data acquisition scenarios, data return strategies, and communication strategies, see §4.5 and Appendices G and H.

### 4.3.1 Mission Phase Definitions

General descriptions of each phase and the related activities are provided in **Table 4.3-1**.

### 4.3.2 Launch

A Delta IV 4050H-19 launches the flight system to a $C_3$ of 14.1 $km^2/s^2$ during a 21-day launch period opening on 12 June 2015. The launch vehicle and launch period parameters are shown on **FO-2E**. The flight system is designed to launch on any given day in the launch period without re-configuration or modification.

### 4.3.3 Interplanetary Trajectory

The baseline trajectory used for the EE mission is a VEEGA departing Earth in June 2015 (**FO-2A–2D**). Cruise navigation uses Doppler, range, and ΔDOR observations from the Deep Space Network (DSN).

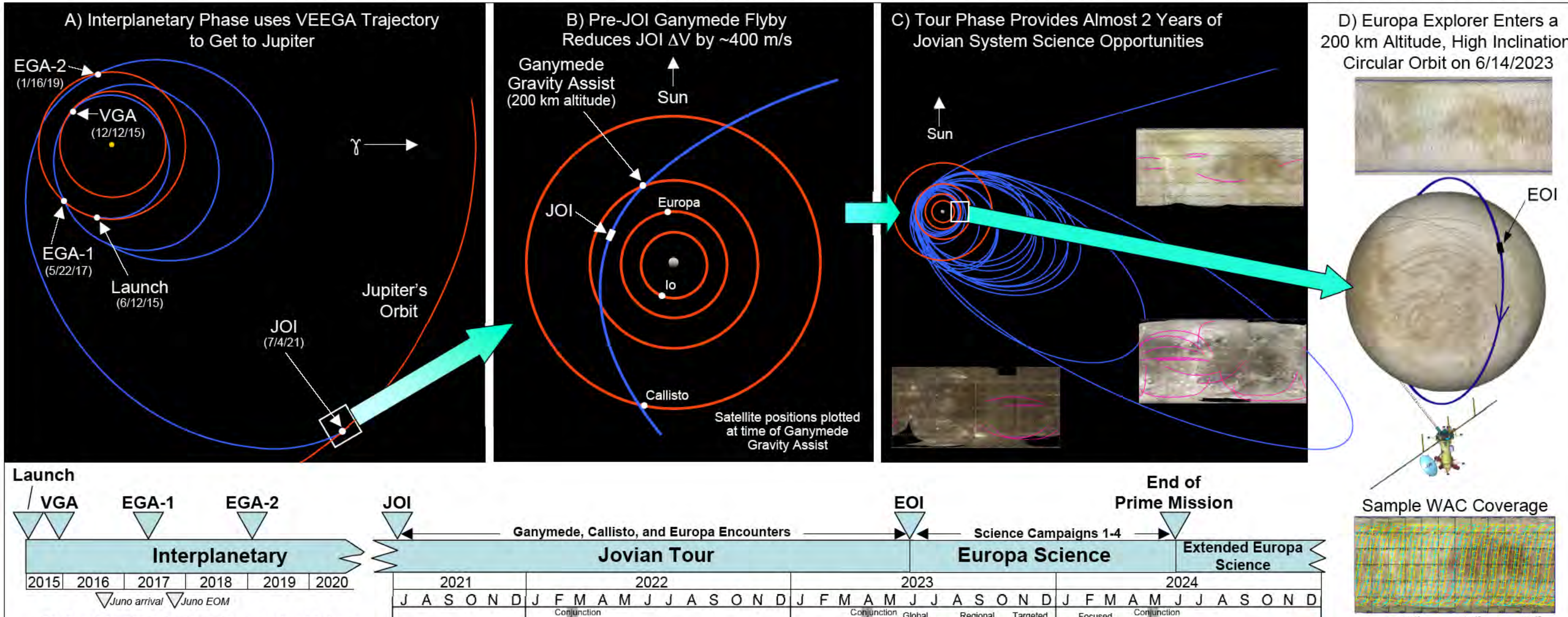
### 4.3.4 Trajectory at Jupiter

On the initial approach to Jupiter, the trajectory flies by Ganymede for a gravity assist prior to Jupiter orbit insertion (JOI). A Ganymede gravity assist is preferred over the slightly more effective Io gravity assist because it results in much lower radiation exposure for the flight system. JOI occurs near perijove of 12.5 Jovian radii and results in an orbit period of about 200 days. Near apojove

***Table 4.3-1.*** *Mission Phase Definition and Description*

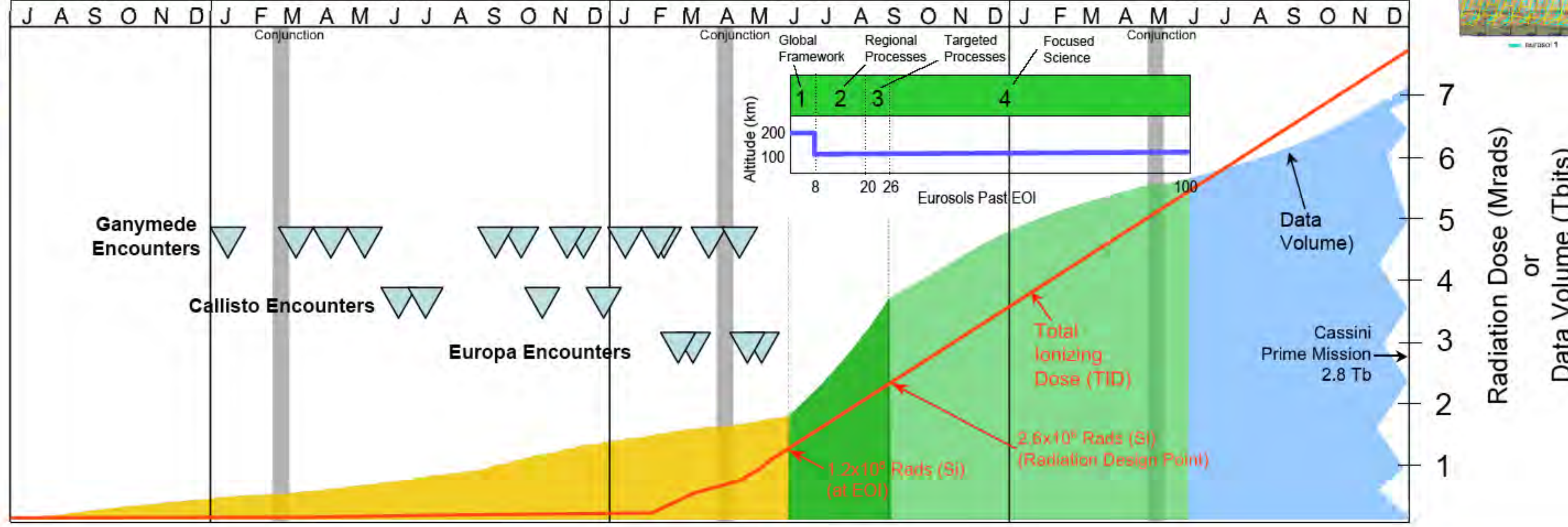
| Phase | Activity | Start/End |
|---|---|---|
| Interplanetary | Launch and Early Operations: Begins with the launch countdown. Activities include initial acquisition by the DSN, checkout and deployment of all critical flight system systems and a major maneuver to clean-up trajectory errors from launch vehicle injection | Jun/Jul 2015<br>30 day duration |
| | Cruise: Activities include science instrument calibrations, Venus and Earth gravity assist flyby science operations, potential asteroid flyby target of opportunities, annual spacecraft health checks, trajectory correction maneuvers, and operations readiness testing. | Jul/Aug 2015 to Dec 2018 |
| | Jupiter Approach: Activities include final preparations, training, and ORTs for all mission elements in preparation for JOI and Jovian moon flybys, and an optical navigation campaign to improve satellite ephemerides prior to pre-JOI Ganymede flyby. | Jan 2019 to JOI (July 2021) |
| Jovian Tour | The phase is characterized by multiple (20+) flybys of the outer three Galilean satellites to shape the trajectory for the purpose of getting to Europa with as little propulsive ΔV as possible. The final month of the phase includes large deterministic maneuvers aimed at setting up the final approach to Europa and EOI itself. The tour allows for significant science observations of the Jovian system | JOI to EOI<br>(July 2021 – June 2023) |
| Europa Science | Begins after achieving the orbit around Europa and continues for one year. Consists of four science campaigns, preceded by a short checkout period:<br>Campaign 1: Global Framework<br>Campaign 2: Regional Processes<br>Campaign 3: Targeted Processes<br>Campaign 4: Focused Science | Jun 2023 – Jun 2024 |
| Extended Europa Science | Begins after the Europa Science phase ends. End date is dependent on negotiated funding period, flight system health, and remaining propellants. | June 2024 + |

## Europa Explorer Mission Design Delivers 11 Rad-Hard Instruments to Low-Altitude Europa Orbit to Explore Europa and Investigate Its Habitability




### E) Key Mission Design Parameter Values

| Parameter | Value |
|---|---|
| Launch Vehicle | Delta IV 4050H-19 |
| Earth to Jupiter Trajectory | VEEGA |
| Earth Launch Period | 6/12/2015 to 7/2/15 |
| C3 ($km^2/s^2$) | 14.1 (maximum) |
| Jupiter Arrival Date | 7/4/21 |
| Declination of Launch Asymptote (deg) | –25.9 (maximum) |
| Jupiter Arrival $V_\infty$ (km/s) | 6.2 (maximum) |
| JOI Earth Range (AU) | 4.3 |
| JOI Periapsis Altitude ($R_J$) | 12.5 |
| Jupiter Capture Orbit Period (days) | 184 |
| Tour | 7/4/2021 to 6/14/2023 |
| EOI | 6/14/2023 |
| Primary Europa Science | 6/14/2023 to 6/14/2024 |
| Orbit Altitude, Average (km) | 200, then 100 |
| Orbit Period (min) | 138, then 126 |
| Ground Speed (km/s) | 1.2, then 1.3 |
| Orbits/day | 10.4, then 11.4 |
| Europa Initial Orbit Inclination | 95 deg |



of the first orbit, a perijove raise maneuver is performed to set up the first Ganymede encounters of what is to be a low radiation tour. The 23-month tour takes advantage of the gravity assists from Jupiter's moons to decrease the ΔV (and associated propellant), required to get into Europa orbit by roughly 3 km/s.

Many possible tour designs exist. A tour typically lasts 1–2 years and requires ΔV of roughly 10 m/s per satellite flyby. The baseline tour design is only one possible design, to illustrate feasibility. The radiation dose as a function of mission time (**FO-2**) for the baseline tour is slightly higher than that of the archetype low-radiation tour developed by Europa Orbiter, called 99-35 (the 35th tour designed in 1999). Experience on Europa Orbiter indicates that further refinement is very likely, given more detailed analyses than were possible as part of this study. Future analyses will also take planetary protection into consideration, similar to the reliability-based probability of impact approach used for Juno. Therefore, the radiation design dose from tour 99-35 is a realistic nominal case assumed in the flight system design. The baseline tour, which follows guidelines for tour development originally generated for Europa Orbiter includes 13 close Ganymede flybys, 4 at Callisto and 4 at Europa prior to EOI as shown in **Table 4.3-2**. In addition, science observations of the Jovian magnetosphere and atmosphere, and monitoring of Io, will be possible between encounters during the Jovian Tour phase.

The final Ganymede gravity assist sets up a near-Hohman (minimum energy) transfer to Europa. This transfer is followed by three consecutive Europa flybys that reduce the orbital period from a 2:3 resonance (meaning that EE goes around Jupiter two times in the time it takes Europa to go around three times) to a 3:4 resonance to finally a 5:6 resonance prior to EOI. Propulsive maneuvers are performed near apojove following the flybys to efficiently reduce arrival speeds at Europa. This final approach phase requires about 63

***Table 4.3-2.*** *Encounter dates for close encounters of Galilean satellites during the representative Jovian Tour phase*

| Enc | Body | Date | Altitude [km] | $V_\infty$ [km/s] | Period* [d] | Inclination* [deg] | $R_p$* [$R_J$] |
|---|---|---|---|---|---|---|---|
| G0 | Ganymede | 4-July -21 | 500 | 7.79 | - | 2.2 | 12.5 |
| G1 | Ganymede | 6-Jan-22 | 1500 | 6.65 | 71.4 | 0.6 | 11.8 |
| G2 | Ganymede | 18-Mar-22 | 120 | 6.48 | 28.6 | 0.1 | 11.1 |
| G3 | Ganymede | 16-Apr-22 | 100 | 6.46 | 21.5 | 4.6 | 10.7 |
| G4 | Ganymede | 7-May-22 | 100 | 6.40 | 24.9 | 0.4 | 10.9 |
| C1 | Callisto | 4-Jun-22 | 400 | 6.20 | 33.4 | 4.5 | 12.7 |
| C2 | Callisto | 8-Jul-22 | 1909 | 6.18 | 37.7 | 0.2 | 13.3 |
| G5 | Ganymede | 14-Sep-22 | 100 | 5.04 | 21.5 | 4.5 | 12.5 |
| G6 | Ganymede | 5-Oct-22 | 1190 | 4.92 | 19.5 | 0.3 | 12.4 |
| C3 | Callisto | 23-Oct-22 | 3095 | 5.02 | 23.9 | 0.4 | 14.1 |
| G7 | Ganymede | 19-Nov-22 | 958 | 3.66 | 14.3 | 1.6 | 13.2 |
| G8 | Ganymede | 3-Dec-22 | 100 | 3.67 | 13.9 | 8.4 | 13.6 |
| C4 | Callisto | 27-Dec-22 | 1159 | 3.47 | 15.1 | 0.9 | 14.4 |
| G9 | Ganymede | 14-Jan-23 | 2695 | 2.64 | 10.7 | 0.8 | 13.5 |
| G10 | Ganymede | 5-Feb-23 | 1312 | 2.65 | 7.2 | 0.4 | 11.3 |
| G11 | Ganymede | 12-Feb-23 | 2594 | 2.63 | 5.6 | 0.1 | 9.0 |
| E1 | Europa | 27-Feb-23 | 6069 | 2.36 | 5.3 | 0.8 | 8.9 |
| E2 | Europa | 10-Mar-23 | 8773 | 2.29 | 5.1 | 1.2 | 8.8 |
| G12 | Ganymede | 28-Mar-23 | 1139 | 1.76 | 5.7 | 8.6 | 11.0 |
| G13 | Ganymede | 25-Apr-23 | 200 | 1.76 | 5.3 | 0.7 | 9.3 |
| E3 | Europa | 28-Apr-23 | 1451 | 1.62 | 5.3 | 0.4 | 9.3 |
| E4 | Europa | 9-May-23 | 1500 | 1.42 | 4.7 | 0.4 | 9.3 |
| EOI | Europa | 14-Jun-23 | 669.5 | 0.57 | - | - | - |

**Post-encounter, Jupiter-relative*

days following the last Ganymede flyby.

Other types of Europa approaches, some promising lower overall ΔV, were initially investigated by Jupiter Icy Moons Orbiter (JIMO) and should be explored more fully. This final approach takes place within a high radiation environment, so flight time for this phase is a key characteristic that can be traded with ΔV (propellant mass) to result in an optimal combination for the mission. Several innovative techniques for designing captures at Europa were developed as part of the JIMO work and should be analyzed for applicability to a relatively high-thrust mission as conceived for the current study.

#### 4.3.5 Orbits at Europa

As described in §2.4.1, to satisfy the science objectives, the science orbit at Europa needs to be low altitude (~100–200 km), near circular, high inclination, with solar incidence angle near 45° (i.e., a 2:30 p.m. orbit). (An example is shown in **FO-2D**.) If left uncontrolled, arbitrary orbits with these characteristics become more eccentric, due to Jupiter's gravitational perturbations, and generally impact Europa within about a month. These orbits need to be maintained on a regular basis.

Special cases of "frozen orbits" have been demonstrated to increase orbital lifetimes several fold. These near-circular long-lifetime orbits provide an efficient mechanism for minimizing station-keeping ΔV and maximizing time between required maneuvers. The exact "frozen" orbital conditions depend on the details of the gravity field (especially $J_3$) which cannot be known *a priori*. The gravity field will be determined from a near-circular orbit at an altitude of 200 km during the Global Framework Campaign, the first 8 eurosols (28 days) of the orbital mission. Based on estimates of the dominant gravity field terms from Galileo measurements, the expected average eccentricities of the frozen orbits are < 0.01. Due to the third-body perturbation, the semi-major axis and inclination have periodic variations of a few km and a couple degrees, respectively.

During Campaign 1, the parameters for the second orbit will be chosen after determining the gravity field terms. Then the flight system will transfer from the initial 200 km orbit to a 100 km orbit where the Regional Processes and Targeted Processes Campaigns will occur.

At 200 km altitude, the orbit period is 2.3 hr and the maximum occultation durations by Europa are 33% of the time. For a 100-km altitude orbit, the orbit period is 2.1 hr, and occultations by Europa can last up to 37% of the time depending on the orientation of the orbit. The primary constraints on the orbit orientation are the required inclination and nodal phase angle. The chosen orbital parameters are shown in **FO-2E**. With every Europa orbit around Jupiter (3.551 days), there is also an occultation by Jupiter that lasts 2.5 hr.

The frequency of thruster activity, whether for momentum wheel desaturation or for science orbit maintenance, directly impacts the orbit determination and associated gravity science. A trade exists between the frequency and total ΔV required for the maintenance maneuvers, with smaller, more frequent maneuvers potentially resulting in less ΔV overall. However the more frequent maneuvers may significantly degrade the ability to accurately reconstruct the orbit and gravity field signatures. Preliminary analysis shows that orbit maintenance maneuvers would not be required any more often than once every week and momentum wheel desaturations no more than once per day. The precise elements for the science orbits and the orbit maintenance strategy have not been determined, but these represent a detailed optimization and are not a fundamental mission feasibility concern.

The nominal science mission ends with the flight system in the science orbit at Europa. Due to the Europa orbit instabilities, the ultimate disposition of the flight system will be eventual impact on the surface of Europa. It is this ultimate fate which drives the planetary protection requirement for sterilization.

#### 4.3.6 Mission ΔV

A summary of the ΔV for the mission is provided in **Table 4.3-3**, and **Figure 4.3-3** shows how the ΔV is spread throughout the mission timeline.

The ΔV listed for deep space maneuvers (DSMs) is the largest value needed over the 21-day launch period for the trajectory shown in **FO-2A**. Other types of trajectories, and

***Table 4.3-3.** ΔV Summary for the End-to-End Trajectory*

| Activity | ΔV [m/s] | Description |
|---|---|---|
| Launch Injection Correction | 30 | Correct S/C injection errors from LV. |
| Earth Biasing | 50 | Extra DV to bias aim-point of both Earth flybys away from planet. May be integrated with other TCMs or performed separately. |
| DSM | 215 | Largest DSM for start of 21 day launch period of June 12, 2015. This corresponds to launch $C_3$ of 13 $km^2/s^2$. |
| Interplanetary TCMs | 20 | Many small statistical maneuvers |
| JOI | 1050 | Jupiter orbit insertion (including minimal gravity losses) |
| PJR | 70 | Perijove raise maneuver. Required to set up low radiation start to Jovian Tour. |
| Tour Deterministic | 100 | Deterministic maneuvers needed during tour with Ganymede, Callisto, and Europa gravity-assists, designed to reduce energy at Europa |
| Tour Statistical | 50 | Many small statistical maneuvers during the tour. |
| Large Maneuver Cleanups | 20 | Estimate of large maneuver clean-up DV, 1% of JOI+PJR+Europa Approach+EOI. |
| Europa Approach | 145 | Phase of large maneuvers and Europa resonant orbits designed to further reduce Europa-relative energy beyond what is possible from the tour alone. |
| EOI | 665 | Europa orbit insertion (including gravity losses) |
| Europa Altitude Change | 40 | Hohmann transfer from 200 km circular to 100 km circular orbit |
| Orbit Maintenance | 200 | DV required to maintain circular orbit for 1 year |
| Reserves (Bi-Prop) | 50 | Reserved DV for any required trajectory changes in flight |
| Reserves (Mono-Prop) | 50 | Reserved DV for any required trajectory changes in flight |
| TOTAL | 2755 | |

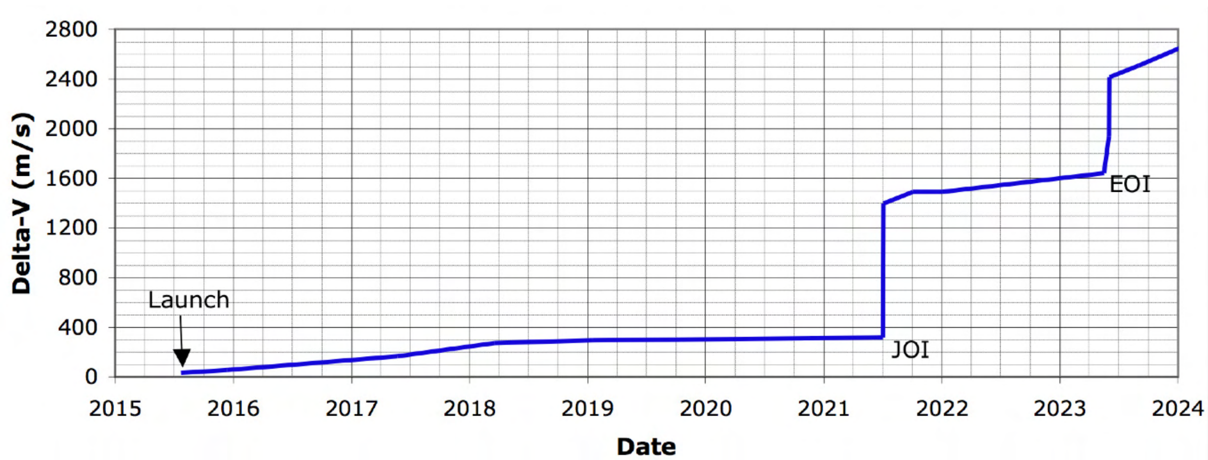



***Figure 4.3-3.** Distribution of ΔV as a function of mission timeline.*

even VEEGA trajectories at other launch opportunities, can have significantly different amounts for DSMs, ranging from zero to several hundred m/s.

As discussed previously, the exact strategies for achieving the final science orbit and maintaining that orbit are still open. Therefore, the ΔV values in the table were selected to conservatively encompass the possible strategies.

#### 4.3.7 Mission DSN Coverage

The planned usage of the DSN is shown in **Table 4.3-4**. It should be noted that the 2015 equivalent capability of the indicated subnet is intended here.

## 4.4 Flight System Design and Development

### 4.4.1 Flight System Overview

The EE flight system design is derived directly from the *Europa Explorer Design Team Report 2006* which in turn had been derived from previous Europa Orbiter (2001), Europa Geophysical Explorer (2005) and numerous trade studies conducted over the past decade. As the science objectives have been modified by the science community (§2) and advancements in technologies, models and

***Table 4.3-4.** Planned DSN coverage as a function of Mission Phase*

| DSN Coverage | | | | | |
|---|---|---|---|---|---|
| **Description** | **Subnet** | **Year** | **Hours/ track** | **Tracks/ week** | **Duration (weeks)** |
| Interplanetary Phase Jun 2015 to Jul 2021 | | | | | |
| Launch to L+30 | 34BWG | 2015 | 8 | 21 | 4 |
| Maneuvers & VEEGA | 34BWG | 2015–2019 | 8 | 10 | 11 |
| Annual health checks | 34BWG | 2015–2019 | 8 | 7 | 5 |
| Eng telemetry + Nav (through VEGA) | 34BWG | 2015–2016 | 8 | 3 | 41 |
| Eng telemetry + Nav (till JOI – 18m) | 34BWG | 2016–2019 | 8 | 2 | 176 |
| Eng telemetry + Nav (till JOI – 2m) | 34BWG | 2020–2021 | 8 | 3 | 71 |
| JOI Approach Hvy tracking** | 34BWG | 2021 | 8 | 21 | 3 |
| JOI Approach Lt tracking** | 34BWG | 2021 | 8 | 14 | 3 |
| JOI | 34BWG | 2021 | 8 | 20 | 2* |
| | 70 | 2021 | 8 | 1.5 | |
| Jovian System Tour Jul 2021 to Jun 2023 | | | | | |
| Jupiter System Science | 34BWG | 2021–2023 | 8 | 7 | 55 |
| Fly-by Prep & Science | 34BWG | 2022–2023 | 8 | 14 | 44* |
| (22 fly-bys) | 70 | | 8 | 3 | |
| Europa Science Jun 2023 to Jun 2024 | | | | | |
| EOI | 34BWG | 2023 | 8 | 20 | 2* |
| | 70 | | 8 | 1.5 | |
| Campaigns 1,2,3 | 70 | 2023 | 8 | 21 | 13* |
| Ka-band Radio Science | 34BWG | | 8 | 7 | |
| Campaign 4 | 70 | 2023–2024 | 8 | 7 | 39+ |

*Coverage by both 34m and 70m antennas during this time span.
**ΔDOR tracking would be used during approach and as needed during cruise, not called out separately.

knowledge have evolved, the mission architecture has been explored and refined finally resulting in the approach described herein.

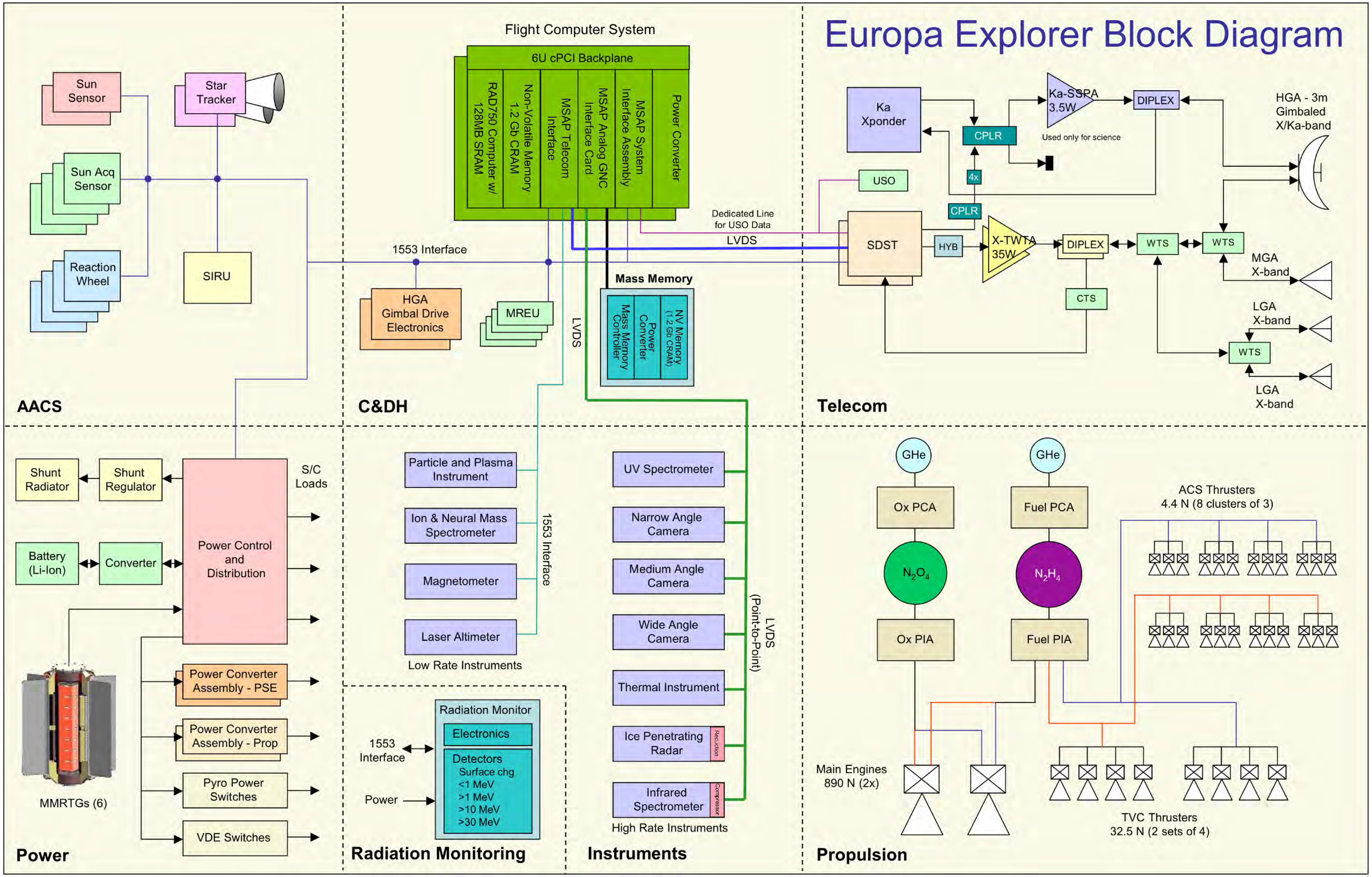
The EE flight system is a redundant, 3-axis stabilized flight system powered by Radioisotope Power Systems (RPSs). The conceptual block diagram is shown in **FO-3**. The flight system includes an articulated 3-m high-gain antenna (HGA), using X-band, for high rate science downlink. The baseline flight system has 11 instruments and a Ka-band system for gravity science investigations. Six Multi-Mission RTGs (MMRTGs) would power the flight system, providing about 618 watts of electrical power at End of Mission (EOM, defined as 9 years after launch). A lithium-ion (Li-ion) battery provides for power demands that exceed the MMRTG capability during orbit and other times during the mission. The Maximum Expected Value (MEV) of the flight system mass at launch, including contingency, is 7045 kg with respect to the currently quoted Delta-IV capability of 7230 kg.

The data processing and handling architecture includes a dual-string RAD750 computer that is capable of performing all science and engineering functions including identified science data compression. Data storage is implemented using 2.4 Gb of non-volatile chalcogenide random access memory (CRAM) with 1 Gb currently allocated for science use, and the remaining 1.4 Gb allocated for engineering and science FSW, engineering telemetry, processing space, and margin.

The flight system attitude is controlled primarily with reaction wheels during science operations. Small thrusters, 4.4 N (1 lbf) each, are used to reduce post-launch separation rates, to provide attitude control during cruise, and to desaturate the reaction wheels during the Jupiter Tour and Europa orbit phases. Because the detection of the tidal signature requires an orbit reconstruction with a radial error of about 1 m, residual ΔV must be minimized during the Europa Science phase and so the 4.4 N thrusters are coupled and redundant.

The propulsion system has a dual mode architecture, which includes redundant, fixed, 890 N (200 lbf) bipropellant main engines plus smaller monopropellant thrusters. Orbit

**FOLDOUT 3**
**SYSTEM FUNCTIONAL BLOCK DIAGRAM FOR EE FLIGHT SYSTEM**



maintenance ΔV maneuvers are performed using the same 4.4 N monopropellant thrusters that are used for attitude control. The total capability of the propulsion system, using the main engine and the smaller thrusters, is 2755 m/s.

Waste heat from the MMRTGs is used for thermal control to the maximum extent practical, in order to reduce the use of electrical power for heaters. Radioisotope Heater Units (RHUs) and Variable RHUs are also used for the same reason.

*Configuration*

The conceptual configuration of the baseline flight system is shown in **Figures 4.4-1** to **4.4-3**. The major configuration drivers were as follows:

- Nadir fields-of-view for the remote sensing instruments;
- Usage of propellant tanks with existing diameter sizes
- Delta IV-H fairing envelope and access door size and number (3 doors, each at 1.22 m × 1.83 m or 4 feet by 6 feet each)
- Accommodation of 6 MMRTGs and the HGA within the fairing
- MMRTGs view of each other and to space
- RCS thrusters (24 thrusters, each 4.4 N) with placement driven by the coupling requirement and plume impingement considerations on instruments and MMRTGs

### 4.4.2 Systems Engineering

Four specific, cross-cutting areas are especially challenging for this mission: radiation, planetary protection, long-life and fault protection. As the EE design evolves,

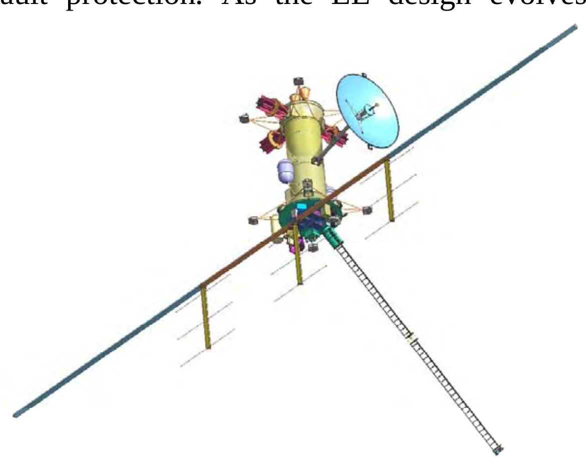


***Figure 4.4-1.*** *Deployed Configuration of the EE Flight System*

system engineering trades across these areas will represent an ongoing effort that will keep the team focused on producing an efficient, robust design. Additional discussion regarding these efforts appears in the following subsections.

EE has considered use of very limited heritage hardware and software designs from JPL's institutional avionics product line (Multi-mission System Architectural Platform, MSAP), the Cassini Propulsion System, Europa Orbiter and JIMO developments, and the MMRTG. Due to the long life, planetary protection requirements and harsh radiation environment, it is envisioned that all circuits will be new (with new parts and analyses) but the basic approaches can be inherited.

#### 4.4.2.1 Radiation

The Jovian radiation environment provides unique design challenges for missions that spend a significant time in the Jupiter radiation belts as radiation damage to electronic parts is anticipated to be the life-limiting factor for most such missions. Prior Europa concept studies have used conventional techniques to design missions having a high confidence of mission durations of 30 and 90 days, but they are inadequate to predict actual mission lifetimes. Advances in tools, design techniques, parts and material capabilities and processes now available can be used to more accurately understand the radiation design for EE. These approaches have been scrutinized by experts in their fields and have been found to be sound. [Reference Appendix C] It is recommended that such reviews continue throughout the project's development to ensure an ongoing, independent assessment of the overall radiation design. Based on these advances, the EE mission has a high confidence of completing a one-year mission in orbit around Europa. Using these technical advances, radiation dose, and consequently mission lifetime at Europa can also be traded with other resources such as mass and propellant to optimize the mission return.

*Radiation Model*

The radiation environment model used is based on data from Pioneers 10 and 11, Voyagers 1 and 2, and Galileo. These data (> 35 data sets) are combined to predict a statistical radiation environment. Most recently, Galileo data was evaluated

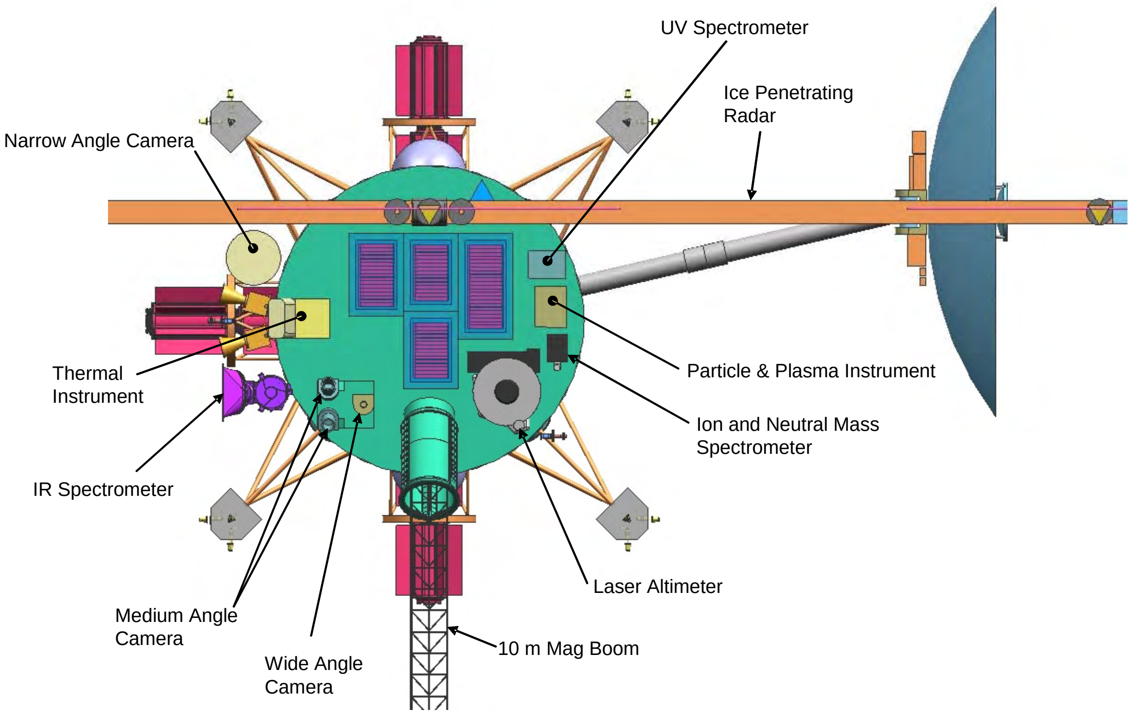



***Figure 4.4-2.*** *Science Instrument Configuration of the EE Flight System*

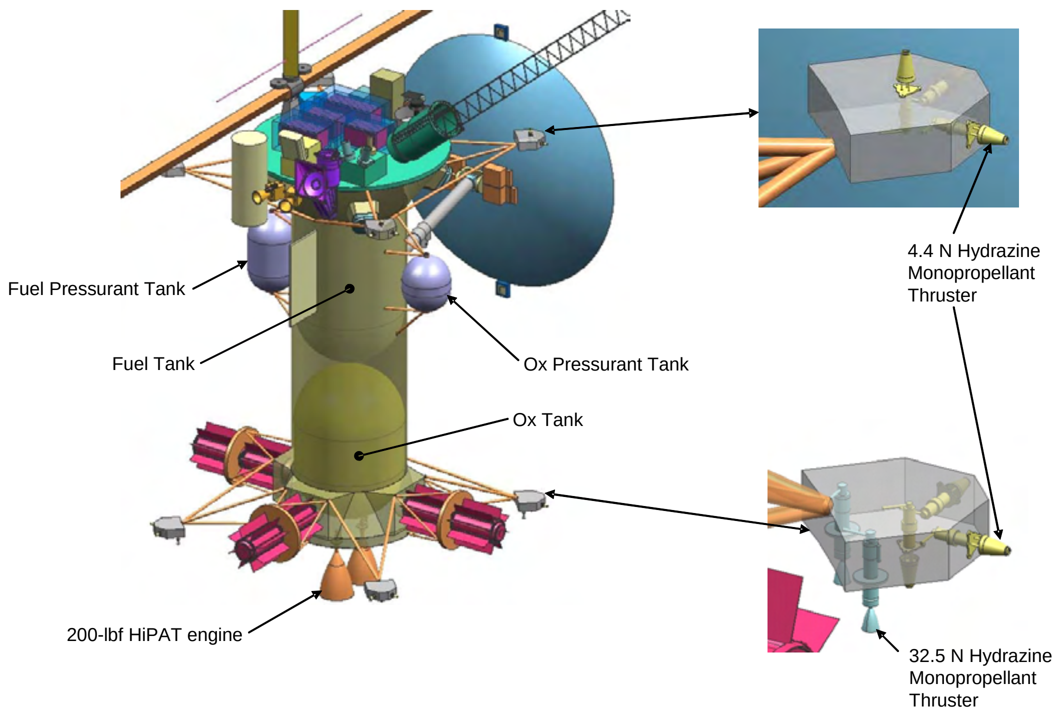



***Figure 4.4-3.*** *Propulsion System Configuration of the EE Flight System*

specifically to characterize the environment in the near vicinity of Europa [*Paranicas et al. 2007*]. In addition, EE has included a radiation monitoring subsystem that will monitor the actual radiation exposure to allow correlation to the predictive modeling effort.

*Approach to Predicting Mission Lifetimes*

NASA has typically designed missions that have vastly exceeded their radiation design lifetimes (including Pioneer, Voyager, and Galileo, to name just a few). For example, Galileo's mission was extended three times, and the spacecraft accumulated a radiation dose at least 8 times its design level. At the end of its mission, after almost 8 years at Jupiter, the spacecraft was still functioning. There was no meaningful way to predict mission lifetime beyond the baseline mission.

The conventional radiation design approach uses a conservative method to accommodate the life-limiting effects of radiation but cannot predict mission lifetime. This conventional approach predicts the radiation environment via the environment model and multiplies that by a Radiation Design Factor (RDF) = 2. This method is excessively conservative and results in hidden margin throughout the flight system. This method was used to define a Europa Orbiter mission life of 30 days (3.3 Mrad Si) in 2001; and a mission life of 90 days (2.3 Mrad Si) in the 2006 EE study [Europa Explorer, 2006]. The 2007 EE studies use the greatly updated environment model.

A new systems approach for relating the radiation tolerance of electronic parts to resulting spacecraft lifetime was developed in recent months by collecting newly available statistical failure data on electronic parts, developing a spacecraft model that extends parts reliability to system reliability, and incorporating the statistical environment model. **FO-4 (1 of 2)** illustrates the radiation design process whereby a designer can choose the desired mission length and probability of survival and consequently derive the required radiation design point. The chosen mission lifetime of 75% confidence of a 1 year mission led to the design point of 2.6 Mrad Si dose behind 100 mils of Al (see **Figure 4.4-4**). This estimate is still conservative due to the lifetime model's bounding assumptions.

This new lifetime model can also be used to determine a mission lifetime for a given radiation design point and confidence level. Mission lifetime will be traded with other design factors such as science data return, mass and radiation exposure in order to minimize mission risk and reduce excessive margins. This work has been favorably peer-reviewed by a joint panel of experts from JPL and APL. Review involving a broader community is planned in the near future.

*Detailed Design Approach*

All circuits, materials and sensors will

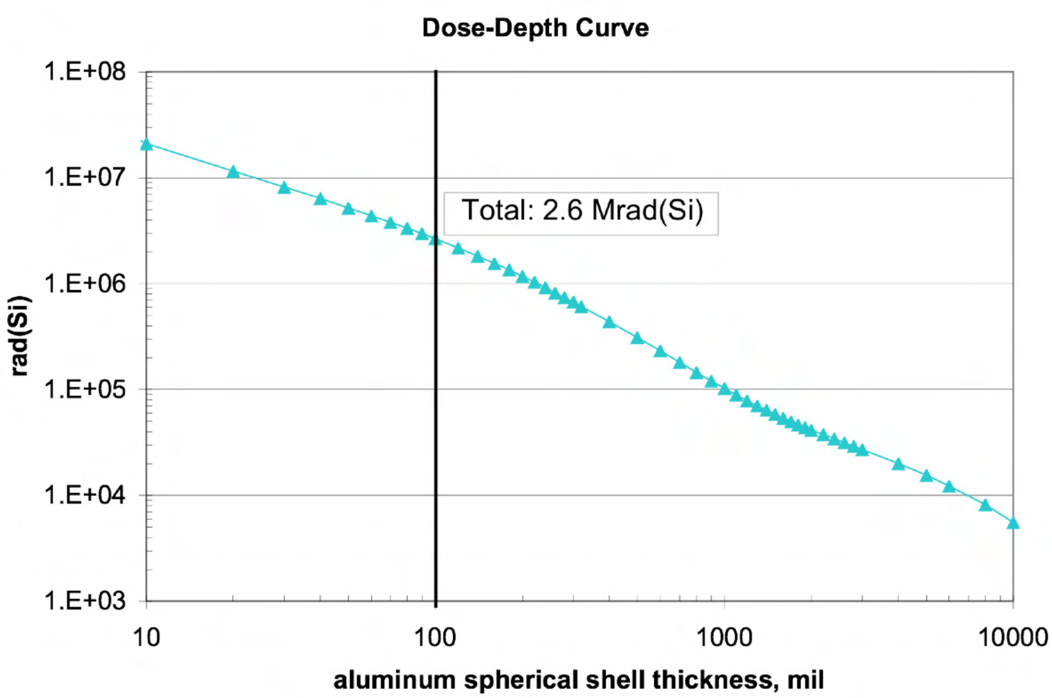



***Figure 4.4-4.*** *EE Radiation Dose Depth Curve*

require evaluation for operation in a radiation environment. Parameters such as timing, thermal conductivity, Signal-to-Noise Ratio, parasitic power draw, band gap width and many others are affected by choosing radiation hardened components. The use of highly radiation tolerant parts and electronic design architectures will be strongly encouraged; it is expected that parts will have from 100 krad to 1 Mrad tolerance. Implementations will preferentially use radiation tolerant hardware. For example, mechanical thermostats are preferred over electronic controllers. More basic approaches which do not incorporate as many design features may be required to design within the available components (e.g., less precision on Analog-to-Digital Conversion).

Other radiation hardened techniques for designing and manufacturing are becoming available but are not yet qualified. Radiation-hardened-by-design techniques are used for commercial applications but are not yet qualified for this environment; those techniques will be further examined in Phase A and B to provide as many qualified design approaches as possible. Similarly, Field Programmable Gate Arrays (FPGAs) are available but not yet qualified for this use and thus Application Specific Integrated Circuits (ASICs) are baselined for use. Work to qualify FPGAs will continue. Sensors and materials will require evaluation on a case-by-case basis and may need to be replaced or customized. Software mitigation approaches such as Time-Delay Integration (TDI) and Error Detection and Correction (EDAC) can be used in some cases to mitigate in-flight radiation effects. Techniques that minimize the vulnerability of less hard electronics will be implemented, e.g. quickly transferring science data acquired by radiation vulnerable sensors to radiation tolerant processing/storage devices. Budget and schedule have been set aside to address these parts qualification and design issues.

Design analysis and testing will ensure that the designs will function using available rad-hard parts within the required parameters. Early identification, documentation and dissemination of available parts, materials and design techniques will help mitigate the risk associated with this extensive development effort. Note that designing for the planetary protection requirements will require similar efforts.

*Shielding Approach*

The design incorporates a combination of shielded chasses and enclosures to protect the electronics and detectors. This approach minimizes mass when compared to a single centralized vault (Juno approach) when assemblies with drastically varying radiation tolerances are used (Juno has most electronics less than 50 krad tolerance). The selected EE approach allows flexibility due to different part tolerance levels for each subsystem element (100 krad to 1 Mrad), and prevents having to shield everything down to the "lowest common denominator" part tolerance level. Additionally, physical location of some sensitive parts precludes an enclosure-type shielding approach (e.g. pressure transducers for propulsion, controller boxes for ASRGs if used). As the design matures and the part radiation tolerance becomes better known, this trade will be periodically re-evaluated to take advantage of the most mass efficient approach.

For the current EE design, all electronics packaged on standard 6U cards are assumed to use a shielded chassis to reduce the radiation dose to one half the part-level tolerance value (to allow for the RDF of 2). For pre-packaged electronics or sensors/detectors, shielded enclosures are used instead. As shown in **Table 4.4-1**, the minimum part tolerance level of subsystem components (before factoring in the RDF) is typically 300 krads, with the exception of the propulsion system pressure transducers that are rated for 75 krads, and the SIRU which is rated for 200 krads. For some subsystems (e.g., Telecom-SDST) some individual assemblies may require additional localized shielding to reach the tolerance listed in the tables. The power electronics and mass memory are both rated for a 1 Mrad dose, and the MMRTGs are capable of withstanding multi-Mrads of dose.

The total spacecraft shield mass is ~122 kg (CBE), comprised of 17 kg for payload instruments and detectors, and 105 kg for bus subsystems. The thermal and structures & mechanisms subsystems include no radiation sensitive components, and thus do not require any additional shielding. The shield modeling to date only assumes spherical shell models.

***Table 4.4-1.*** *Radiation Tolerance of EE Units Suggests a Distributed Shielding Approach*

| Subsystem / #Units | Part Tolerance, krad | Shielding Approach | # Cards or Enclosures | Shield Mass (CBE), kg |
|---|---|---|---|---|
| Payload | | | | 17.3 |
| Instruments | 300 | Chassis | 23 × 6U Cards | 13.4 |
| Detectors | 300 | Enclosures | Enclosures | 3.9 |
| Bus | | | | 105.2 |
| AACS | Varies | Varies | 10 Enclosures | 25.7 |
| SIRU (1) | 200 | Enclosure | 1 Enclosure | 9.5 |
| Star Trackers (2) | 300 | Enclosure | 2 Enclosures | 7.3 |
| Sun Sensors (2) | 300 | Enclosure | 2 Enclosures | 4.7 |
| Sun Acq. Sensors (4) | 300 | Enclosure | 4 Enclosures | 0.2 |
| Rxn Wheel Electronics (4 controllers in 1 box) | 300 | Enclosure | 1 Enclosure | 4.0 |
| C&DH | 300 | Chassis | 24 x 6U cards | 13.2 |
| Avionics | 300 | Chassis | 20 x 6U cards | 12.0 |
| Science Mass Memory | 1000 | Chassis | 4 x 6U cards | 1.2 |
| Power | Varies | Varies | 30 x 6U cards | 5.0 |
| Chassis #1 | 1000 | Chassis | 15 x 6U cards | 2.5 |
| Chassis #2 | 1000 | Chassis | 15 x 6U cards | 2.5 |
| MMRTGs | Multi Mrads | None | None | None |
| Propulsion | 75 | Enclosure | 12 Enclosures | 23.7 |
| Pressure Trans. (12) | 75 | Enclosure | 12 Enclosures | 23.7 |
| Struct. & Mech. | Nothing Radiation Sensitive | | | 0 |
| Telecom | 300 | Enclosure | 2 Enclosures | 37.6 |
| Telecom Enclosure | 300 | Enclosure | 2 Enclosures | 37.6 |
| Thermal | Nothing Radiation Sensitive | | | 0 |
| Total Shield Mass, kg (CBE) | 122.5 | | | |

There are several planned approaches to reducing shield mass:

- placement of components within an enclosure (e.g., sensitive components on cards in center of stack of 6U chassis)
- incorporating structural mass (e.g., propellant tanks) into shield model
- using less sensitive components (e.g., batteries) to shield more sensitive devices
- physically locating assemblies of similar rad-tolerance and using single enclosure (e.g., Telecom equipment)
- Layering of shield materials (High Z and Low Z)

*Role of System Engineering and Management for Radiation Design*

Radiation requires a system-level response. System engineering the radiation design involves defining the environment, designing for that environment and mitigating residual risk due to uncertainties as shown in **FO-4 (2 of 2)**. Defining the environment includes defining the lifetime requirements, modeling the environment, and designing the trajectory to lessen radiation. Designing for the environment encompasses parts capability and testing, configuration and layout, and modeling for radiation transport mechanism and shielding. Mitigating residual risk covers prioritizing science collection, designing fault protection, and developing contingency plans to ensure graceful system degradation and margin adequacy. All these must be done concurrently by performing trade studies and risk analysis to optimize the design and manage margins. The purplish-blue boxes in **FO-4 (2 of 2)** are activities emphasized by the conventional design approach. The maroon highlights are activities that received new emphasis from a system approach to radiation design by EE. The design approach, for the activities with asterisks, has recently been favorably peer reviewed by external review boards.

EE will establish processes and products, and provide assistance by radiation experts to enable a good radiation design. The specific approach is to:

- appoint a Deputy Project Manager for Radiation (DPMR) reporting to the Project Manager to lead all radiation activities for the project. The DPMR has the authority to trade technical and programmatic resources in order to manage project risk. The DPMR will work closely with the PM and the entire project team on radiation issues;
- appoint a Deputy Project System Engineer for Radiation (DPSER) reporting to the Project System Engineer (PSE) to lead the Radiation Systems Team comprised of system engineers, configuration and shielding engineers, parts and materials specialists, and mission designers;
- add trained radiation system engineers at the Project, Spacecraft, Payload, instrument and subsystem levels, to address system issues related to environment, parts, material, shielding, fault protection and operations, with access to area experts supporting all aspects of developments including science instruments and vendor activities;
- engage the Mission Assurance organization early in the Project lifecycle (Pre-phase A) to document and communicate the radiation requirements and design guidelines and to understand the systems trades;
- utilize radiation technical working groups to work day-to-day issues such as requirements, trades, modeling and plans;
- initiate a Radiation Advisory Board early in the Project lifecycle consisting of scientists and practitioners independent of the project who will periodically review the project's approach to radiation tolerant design, risks and mitigation strategies, and advise Project Management;
- provide frequent communication of new issues and insights about radiation to all staff;
- develop new engineering processes to handle radiation issues to enable a highly reliable system such as interfaces between structural models and shielding models and radiation-hard by design techniques; and
- develop and distribute Radiation Design Guidelines, an Approved Parts and Materials List and a formal Radiation Control Plan to all staff (including potential instrument providers prior to instrument AO release) early;
- develop a training program to indoctrinate and train engineers and scientists on the radiation issues. It will be available to all project staff, partners and suppliers. The program is based on the documents stated above. It will include classroom training, online tutorial and extensive documentation.

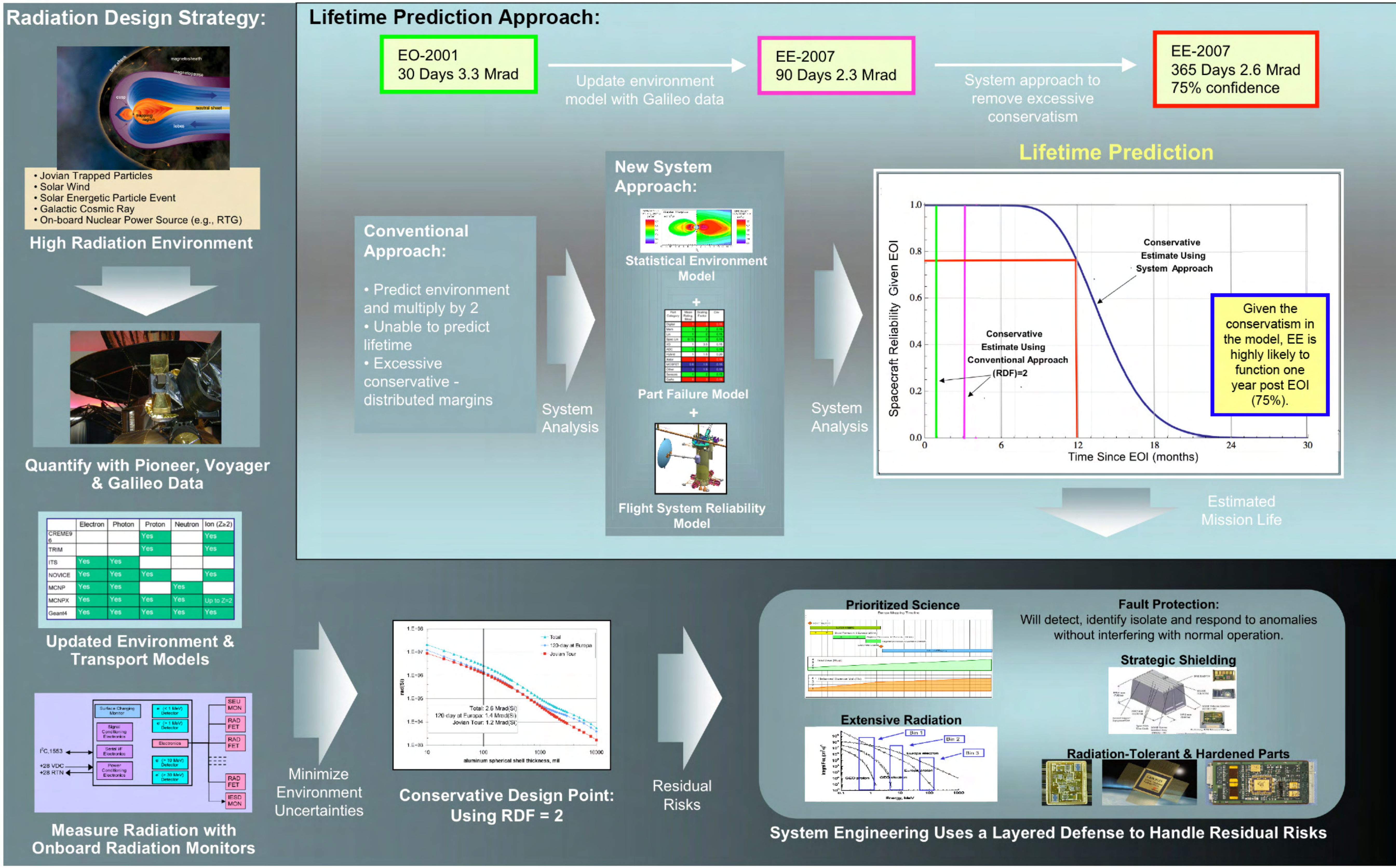
Radiation system engineering is an ongoing process that emphasizes system optimization; trading implementation options with performance risk and reduce unnecessary margins.

Project management has ultimate responsibility for all radiation aspects of the mission and delegates the day-to-day activities to the DPMR. The DPMR will work closely with the PSE, the DPSER, the MAM, Payload System Engineer, PS (as the representative of the science teams) and the PM in trading off between technical and programmatic margins such as consumables, budget and schedule. The Radiation Advisory Board will interact and report to the DPMR as an advisory panel regularly.

Designing for the Jupiter/Europa radiation environment requires significant time for a system level design approach, circuit design and analysis, parts procurement and testing, and verification and validation. These and other approaches need to be adequately planned and assessed during the early phases of the project. The project has elected to provide a more conservative estimate of the mission cost and schedule without these time/cost saving approaches to ensure that adequate time and money would be available if these approaches cannot be justified for this mission.

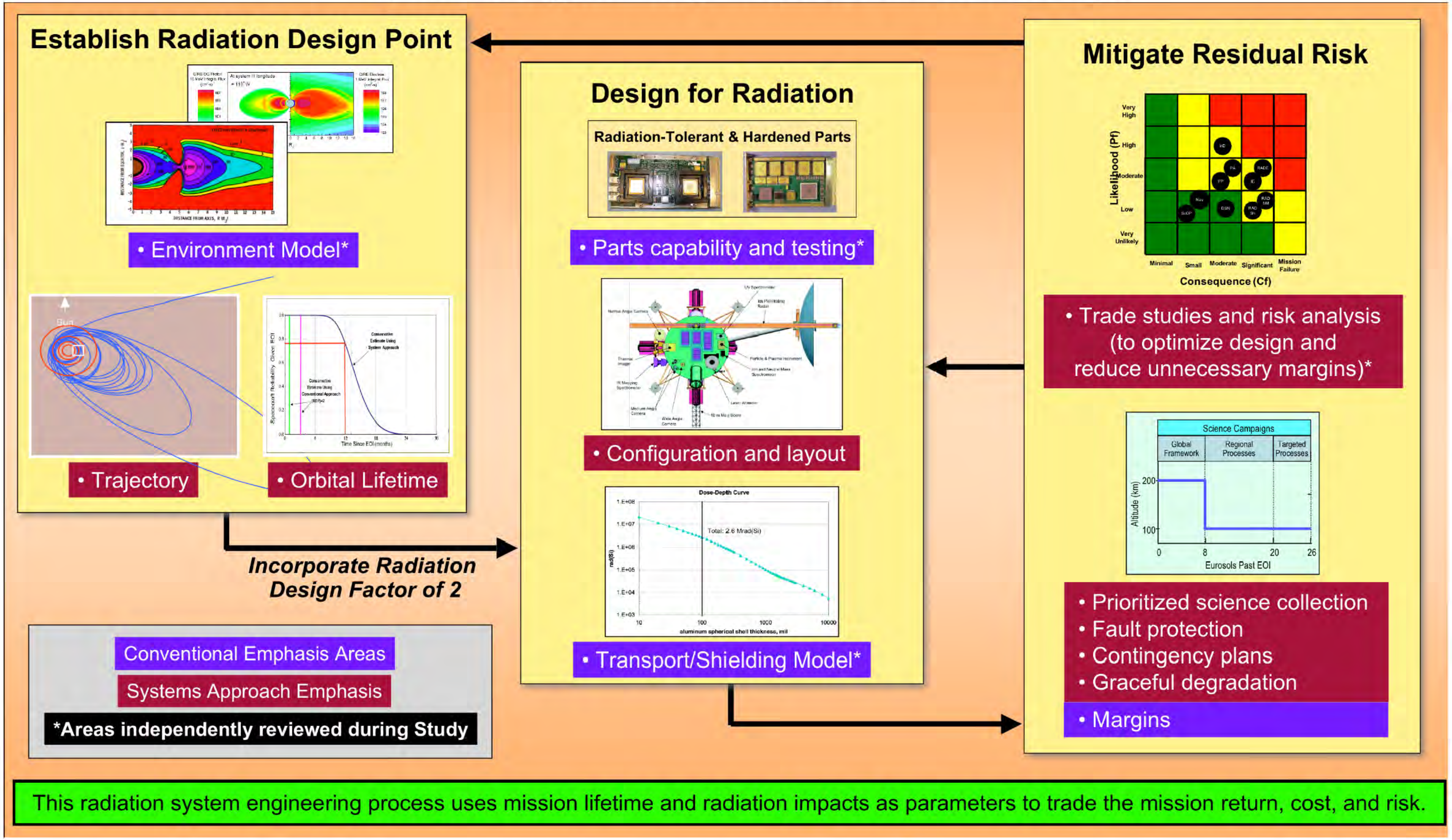
There will be many trade studies performed in Phases A and B to determine the best radiation mitigation design aspects. Technical trades between trajectory design, shielding design, component rad-hardness, fault protection design and autonomy will need consideration. All of these intricate trades involve significant schedule, cost and risk implications and therefore must be considered early and across the project. These near term tasks, enabling a sound development schedule, are outlined in §4.7.8.

# High Likelihood of a 12-month Mission at Europa




| | Electron | Photon | Proton | Neutron | Ion (Z≥2) |
|---|---|---|---|---|---|
| CREME96 | | | Yes | | Yes |
| TRIM | | | Yes | | Yes |
| ITS | Yes | Yes | | | |
| NOVICE | Yes | Yes | Yes | | Yes |
| MCNP | Yes | Yes | | Yes | |
| MCNPX | Yes | Yes | Yes | Yes | Up to Z=2 |
| Geant4 | Yes | Yes | Yes | Yes | Yes |

# System Engineering of the Radiation Design



#### 4.4.2.2 Planetary Protection

As described in more detail in §4.6, the approach to planetary protection compliance for the EE flight system will involve a combination of both the control of bioburden material and sterilization of the flight system from the radiation doses in the Jovian environment. Trade studies will need to be performed that compare dry heat sterilization approaches to the radiation resistance of various components of the flight system.

Two significant assessments have also been performed by senior JPL engineering teams in the last 18 months for the Mars Program related to sterilization capability for parts and materials for a potential Mars astrobiological Lander [*Mars System Sterilization Study 2006*], based on MER and MSL heritage equipment. Neither study identified any commonly used parts and materials that could not be qualified for EE use based on the proposed planetary protection approach.

#### 4.4.2.3 Long Life—High Reliability

Long life, highly reliable, deep space missions are founded in NASA's institutional design practices and processes. These systems are required to operate over long periods of time and over great distances with limited human interaction. Lessons learned from Voyager, Galileo, Cassini, and others, are incorporated into practices and designs including Extreme Value Worst Case Analysis, Parts Stress Analysis, block redundancy, autonomous fault recovery, cross-strapping, internal redundancy and functional redundancy in appropriate combinations to eliminate all non-exempt single point failures (SPFs). All redundancy, fault-protection logic and cross-strapping circuitry is validated in the system testbeds or in integration and test prior to launch. For any remaining SPFs, a risk evaluation will be performed. As a result, the SPF will be eliminated or a waiver to the Single Point Failure policy will be generated (requiring institutional approval).

In parts selection and qualification, the Project is governed by the JPL Institutional Part Program Requirements as tailored for the EE mission. In compliance with these requirements, all critical electronics are subjected to destructive physical analysis (DPA), residual gas analysis (RGA) and particle impact noise detection (PIND), as appropriate. All parts will require certification for radiation either by vendor guarantee or additional Radiation Lot Acceptance testing (RLAT).

#### 4.4.2.4 Fault Protection

Given the duration of the mission and the one-way light time from the Jovian system, autonomy is needed to handle the flight system safety issues. As such, a system of monitors and responses will mitigate, isolate, and recover from off-nominal behaviors if encountered during the mission. It is common design practice for onboard fault protection algorithms to halt normal operations and place the flight system into a safe configuration, awaiting ground response, when they detect a potentially unsafe condition. An exception to this is when a flight system is executing a time critical operation, such as an orbit insertion. The Europa fault protection design will use an approach that places emphasis on continuing the mission, or fail-operational, rather than placing the flight system in a safe configuration and waiting for ground response. This design philosophy has been used in more limited cases for several Mars missions. The Europa mission will adopt this philosophy as the norm with exceptions evaluated on a case-by-case basis.

In line with this philosophy, the fault protection design will include transient recovery. In many fault situations it can be assumed initially that an anomaly is a radiation induced transient, and the response could be to reset the affected equipment and continue the mission. A hardware reset could be attempted first, followed by a power cycle if necessary. An anomaly that does not clear after resetting will be treated as a hard failure. Hard failures could result in hardware swapping, with continuation of the mission where possible and prudent. Flight system safing will still be used for the most serious anomalies.

EE's fault protection design is based on an underlying architecture consisting of:

- Lower-level fault protection that is built into the hardware-control software modules
- Performance-level fault protection that consists of a series of performance monitors that examine and respond to specific subsystems for performance deviations or fault indications

- System-level fault protection that is made up of system-level utilities and contingency mode executives

All fault monitors and responses can be individually enabled or disabled by command or configuration file.

#### 4.4.2.5 Assumptions, Requirements, and Constraints

The list below summarizes the key constraints that have driven the EE flight system design.

- The flight system design shall employ technology that either exists already or is under development and is planned for qualification early in the EE project lifecycle. An exception would allow use of the Advanced Stirling Thermoelectric Generators (ASRGs) in the event that they are deemed the appropriate design choice.
- Do not preclude the use of ASRGs in place of the baseline MMRTGs.
- The mission radiation design dose (referenced to 100 mil aluminum shell) is 2.6 Mrad, which must be tolerated with a RDF of at least 2.
- The required total ΔV is 2755 m/s.
- The flight system must be capable of providing orbit maintenance ΔV in any direction while in the science data acquisition attitude (but not during science observations).
- Approximately 20 Gbits of science data is returned per Earth-day during the first 92 days of the Europa Science phase, 8 Gbits per day afterwards.
- Retransmission of downlinked data is not required.
- Jupiter tour science acquisition is assumed but shall not drive the flight system design.
- The mission is to be compatible with the anticipated DSN capabilities as of 2015.
- Minimum heliocentric range is 0.67 AU.

#### 4.4.2.6 Payload Interfaces

As described in §4.2, the spacecraft will accommodate the payload by providing for a view in the nadir direction for the remote sensing instruments when in orbit around Europa. The spacecraft will maintain pointing control to 1 mrad and stability to 10 μrad over 1 s. Payload accommodation for all electrical, thermal and mechanical interfaces will be developed between the spacecraft development team and the payload teams. The system functional block diagram in **FO-3** shows the data interfaces for the instruments. Instrument fields of view and volumes are shown in **Table 4.2-1**. Instrument data rates and compression factors are noted in **Table 4.5-2**.

#### 4.4.2.7 Launch Vehicle Interface

In the launch configuration, the EE flight system is mounted to the Delta IV-H launch vehicle (LV) as shown in the **Figure 4.4-5**. The flight system's LV adapter is mounted to the LV via a permanently bolted field joint. The separation of the flight system from its LV adapter and the launch vehicle is assumed to be via a linear separation device (Superzip).

In order to fit within the Delta IV fairing envelope, there are three assemblies that are in a folded/stowed configuration. The HGA, Ice Penetrating Radar (IPR) antennas, and Magnetometer boom are stowed and deployed after launch.

#### 4.4.2.8 Resource Margin Summary

The EE design contains robust margins. A major difference exists in the margin calculation between that specified in the Study Guidelines and JPL Design Principles and Practices (JPL DPP). Below is a discussion of the major difference which can be used to interpret the information in the mass and power tables later in the section, **Tables 4.4-4** and **4.4-5**. Conservative margins have been used which provide significant room for mission concept modifications without large impacts on the primary resource constraints (number of RPS units and launch vehicle injected mass capability).

JPL DPP states a minimum of 30% JPL-Margin should be held for dry mass and power

***Table 4.4-2.*** *Examples of Calculating Contingencies and Margins*

| Value | | |
|---|---|---|
| Current Best Estimate | 100 kg | Example value |
| Contingency | 25 kg | = MEV–CBE |
| Contingency | 25% | = Cont/(MEV-Cont) |
| Maximum Expected Value (MEV) | 125 kg | = CBE + Contingency |
| Maximum Possible Value (MPV) | 175 kg | Example value |
| Study Guidelines Margin | 50 kg | = MPV–MEV |
| Study Guidelines Margin | 40% | = SG-Margin/MEV |
| JPL-Margin | 75 kg | = MPV–CBE |
| JPL-Margin | 43% | = (MPV-CBE)/MPV |

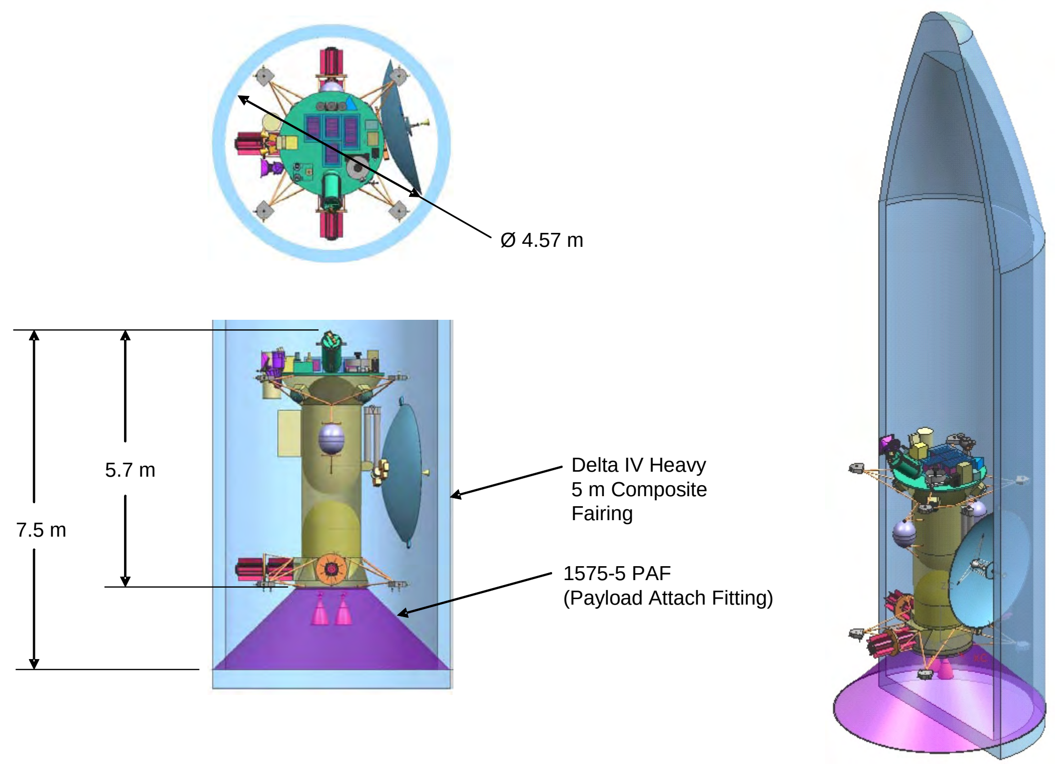



***Figure 4.4-5.*** *Stowed Configuration of EE Flight System in Delta IV-H LV Fairing*

at the Missions Concept Review (MCR, end of Phase A). JPL-Margin is calculated differently than either the Contingency or Margin as defined in the Study Guidelines (SG-Margin). A JPL-Margin of 30% would be the equivalent of the Study Guidelines (Contingency+SG-Margin) equal to 43% of the CBE, as shown in the example (**Table 4.4-2**).

JPL-Margin requirements are based in historical planetary mission experience and are deemed as the minimum acceptable for a mission of this complexity.

JPL-Margins of 30% are considered minimum to hold at this time which still allows for significant trade space and ensures that JPL-Margin of 30% can still be held at MCR. Any mass or power available above a JPL-Margin of 30% is described herein as "unallocated" and can be thought of as additional flexibility above that deemed minimally acceptable.

A summary of the Mass and Power resources is shown in **Table 4.4-3**.

***Table 4.4-3.*** *Summary of EE Mass and Power Margins*

| | Dry Mass | Wet Mass | Power, W |
|---|---|---|---|
| Flight System CBE | 1855 kg | 6215 kg | 428 W |
| Flight System MEV | 2345 kg | 6705 kg | 555 W |
| Flight System MPV | 2837 kg | 7198 kg | 618 W |
| SG-Contingency | 26.5% | | 29.9% |
| SG-Margin | 20.6% | | 11.2% |
| JPL-Margin | 34.5% | | 30.7% |
| Unallocated | 185 kg | | 62.1 W |

*System-Level Mass Summary*

The EE flight system has a total launched wet mass of 6215 kg (CBE), and is comprised of an 1855 kg dry flight system and 4360 kg of propellant (**Table 4.4-4**). The propellant mass of the baseline flight system is sized for the entire injected mass capability of the Delta IV-H launch vehicle (7230 kg) minus the LV-side launch vehicle adapter. There is currently 185 kg of unallocated mass that is potentially available for future flight system growth, additional radiation shielding, and/or upgrades.

With the exception of structures and mechanisms (S&M) and cabling, all mass estimates were provided by the owners of their respective subsystem. The MEV S&M and Harness mass estimates (CBE plus contingency) were computed as percentages of other flight system masses. This approach uses as-built percentages of S&M and harness mass from Cassini and assumes it provides reasonable estimates for EE. The MEV cabling mass was estimated as 7% of the MEV flight system dry mass minus radiation shielding.

*System-Level Power Summary*

The power estimates for each subsystem are identified in **Table 4.4-5**. With the exception of cabling and telecom, all power levels were provided by the subsystem owners. The cabling power loss was computed as 3.5% of the total CBE flight system power use; the telecom power level was computed based on the required orbital downlink data volume.

The current best estimate (CBE) for the EE flight system power required is 428 W averaged over two successive Europa science orbits (one IPR orbit and one imaging orbit), **Figure 4.4-6**. This 2-orbit average power level with 30% subsystem contingency (555W total) represents the RPS sizing case for the EE mission (**Table 4.4-5**) and results in the need for 6 MMRTGs, and one small battery to cover any short duration periods when instantaneous power demands temporarily exceeds the available RPS power. The power demands in the other modes such as launch, cruise, JOI, and EOI are then easily met. The power profile over the course of 2 orbits is shown in **Figure 4.4-7**. The profile assumes the baseline science 2-orbit observing scenario with 2 target sets per orbit (power spikes occur when targeting instruments are powered on). The power profile assumes 30% subsystem contingency and an additional 13% system contingency to balance the energy, including battery recharge. The battery depth of discharge (DOD) is limited to no more than 40%. Assuming a 28 V bus, the energy demands are readily met with a commonly available 25 A-hr battery. The battery is charged when excess RPS power is available in the non-communications modes. The profile shows a maximum battery DOD of 13%.

### 4.4.3 Subsystem Descriptions

#### 4.4.3.1 Structures and Mechanisms

The EE S&M approach was based on analogy to prior concepts and missions, specifically Europa Orbiter and Cassini. As the subsystems become better defined, the structures and mechanism approach will change from analogy to a bottoms-up concept. The major drivers on the structures design were the propulsion tanks and the large amount of propellant. For cost reasons, existing propellant tank sizes that were flight qualified were baselined. Given this and the volume of propellant (~4360 kg), two tanks of Cassini heritage of 1.24 m diameter, 1.7 m (oxidizer) and 2.7 m (fuel) in height were used

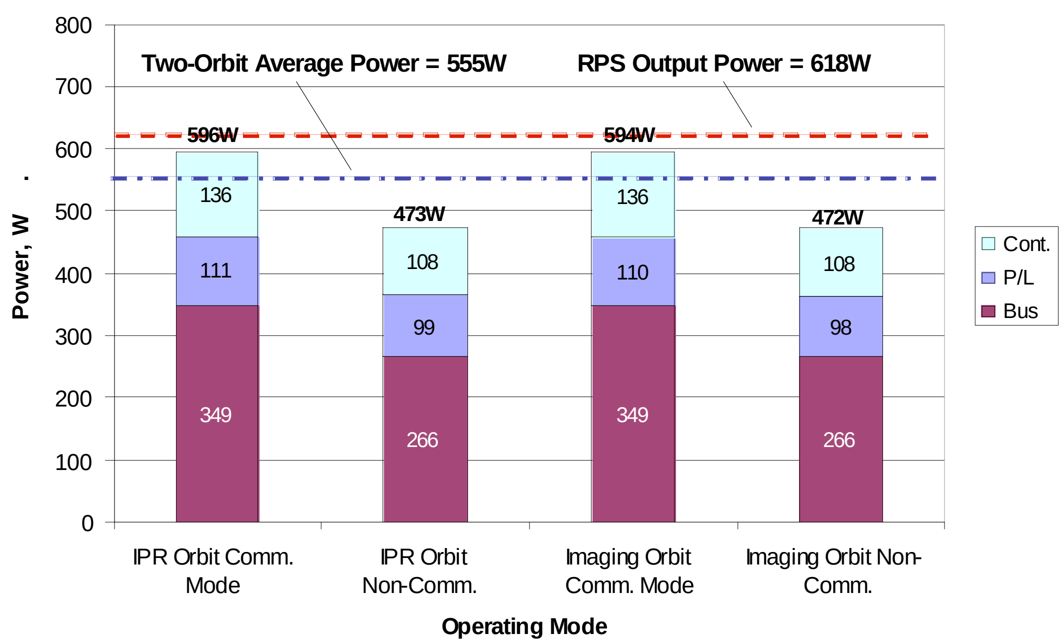



***Figure 4.4-6.*** *Europa Explorer Power Modes and Average Power Level (30% Subsystem Power Contingency Shown).*

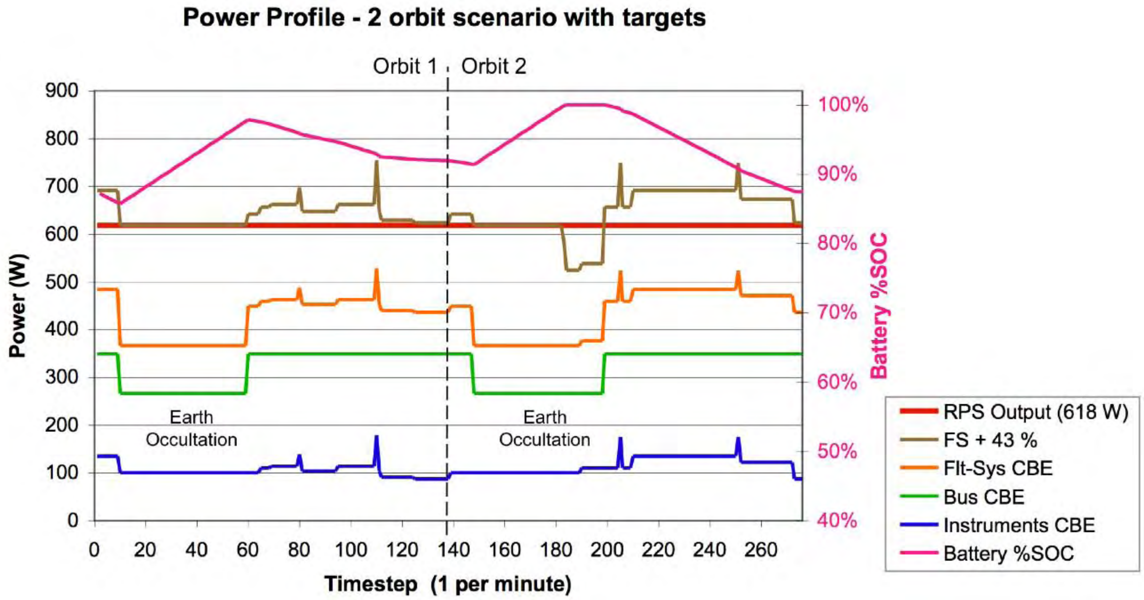



***Figure 4.4-7.*** *Power Profile for Two Orbit Scenario*

which drove the flight system stack height of 7 m as seen in **Figure 4.4-2**.

The 3-meter HGA is boom-deployed. The HGA boom axis is positioned such that the HGA is directly behind the IPR antenna, in order to center the times of IPR antenna obscuration of the HGA within the earth occultation periods during Europa orbit. Thus, the total duration of IPR antenna interference is minimized. The HGA configuration is shown in **Figures 4.4-2** through **4.4-4**. One of the gimbaled axes is parallel to the IPR antenna boom and the other is perpendicular to the first, i.e. about the yoke axis.

The MMRTGs are mounted in 3 stacks of two units (6 total) attached near to the launch vehicle adaptor. This configuration was chosen to limit the number of doors required in the launch vehicle fairing to 3, which eases integration issues and has been vetted by the Launch Planning Office at KSC. Each outer MMRTG mounts directly to the flight system via a milk-stool truss structure since the inner MMRTG cannot support the outer one.

The flight system S&M mass estimate was based on a percentage of the launch mass capability of the Delta IV for this mission (7230 kg). Based on the Cassini flight system actual launch mass distribution, a 12.5% factor on the wet launched mass was used to derive the estimated 738 kg (with 30% contingency) S&M subsystem mass. The Cassini flight system was used as it had a similar mass (5711 kg) and had a similar proportion of propellant mass to EE.

The Structure separated after LV separation (LVA and lower portion of the separation band), HGA Boom & gimbal, and MMRTG support structures were estimated using newly developed estimates as well as using other available data. The EE LVA was estimated using its current geometry as well as the as-built Cassini LV adapter mass. The linear separation device (Superzip) was estimated using the Cassini data and scaling to the current EE LV interface diameter. The MMRTG support structure mass estimate was based on a new estimate as well as the Cassini and Mars Science Laboratory data. The HGA boom mass estimate was also based on a new independent estimate using a 5 Hz frequency goal. The two-axis gimbal estimate was based on the JIMO telecom platform gimbal, a similar mass item.

Note that all structure and mechanism CBE design mass estimates assume growth of other subsystems to their maximum allocations. If one or more subsystems grow to more than their allocation, the S&M subsystems could require a portion of the flight system mass margin.

***Table 4.4-4.*** *Mass Estimates for EE Flight System*

| Subsystem | Flight System Mass, kg | | | Notes |
|---|---|---|---|---|
| | CBE | Cont. | CBE + Cont. | |
| **Payload** | **158** | **30%** | **205** | **Excludes radiation shielding mass.** |
| Instruments | 158.0 | 30% | 205.4 | 11 instruments. Does not include Ka-band system for gravity science and USO (both tracked in telecom) |
| **Bus** | **1574** | **26%** | **1980** | **Excludes radiation shielding mass.** |
| AACS | 50.8 | 37% | 69.8 | Includes SIRU, star trackers, and sun sensors |
| CDH | 42.3 | 32% | 55.9 | Includes redundant Rad 750 flight computer and 2.4 Gb NVM |
| Power (w/o RPSs) | 50.4 | 27% | 64.0 | Includes power distribution, switches, and power converters |
| RPS System w/ Adapters | 291.0 | 5% | 305.6 | Six MMRTGs and associated struts and adapters |
| Cabling | 129.7 | 30% | 168.6 | CBE value equals 7% of CBE Spacecraft Total Dry mass (including radiation shielding mass) |
| Propulsion | 296.9 | 31% | 389.8 | Includes 900N main engines, ACS and RCS thrusters, tanks and associated plumbing. |
| Structures & Mechanisms | 567.9 | 30% | 738.2 | Includes S/C structure, HGA gimbals and motors, magnetometer boom, and SC side LVA. Worst case value equals 12.5% of LV injected mass capability minus RPS & LV struts/adapters and LV-side LVA and augmented to account for a different LV-side LVA. |
| Telecom | 58.9 | 29% | 75.8 | Includes 3m HGA, MGA, LGAs, Ka-band system used for gravity science experiments and USO. |
| Radiation Monitoring System | 8.0 | 30% | 10.4 | Allocation |
| Thermal | 78.4 | 30% | 101.8 | Includes MLI, heaters, and RHUs. Assumes temp sensors feed into C&DH for processing, and heaters use thermostats or S/W control. |
| **Radiation Shielding** | **122.5** | **30%** | **159.2** | |
| **Spacecraft Total Dry** | **1855** | **0** | **2345** | **Includes Payload, Bus, Shielding, and System Contingency.** |
| **Additional System Margin** | - | **16%** | **307** | Additional contingency added to obtain specified 30% margin (43% contingency) at system level for the S/C bus and PL. |
| **Spacecraft Total Dry** | **1855** | **0** | **2652** | **Includes Payload, Bus, Shielding, and System Contingency.** |
| Propellant | 4360 | | 4360 | Worst case prop mass based on Injected Mass Capability minus LV adapter (LV side) using CBE+Cont. values. Uses 21d worst case DSM Delta V value and includes allocation for uncertainties. Accounts for LV adapter (LV-side) that stays behind with LV |
| **Spacecraft Total Wet (e.g., Separated Wet Mass)** | **6215** | | **7012** | **Includes Payload, Bus, Shielding, System Contingency, and Propellant.** |
| LV Adapter (LV Side) | 25 | 30% | 33 | Mass delta between 1575-5 PAF (baselined) versus 1194-5 (stock). LVA stay behind with launch vehicle |
| **Launch Mass Wet** | **6240** | | **7045** | **Includes entire wet spacecraft, all adapters, and contingencies.** |
| Injected Mass Capability | | | 7230 | For Delta IV-Heavy with $C_3$=14.1 km $^2$/s$^2$. |
| **Remaining LV Capability** | | | **185** | **Accounts for mass contingencies and additional system margins as indicated above.** |
| **Flight System Dry Mass Contingency per Study Guidelines** | | **26.5%** | | (MEV-CBE)/CBE |
| **Flight System Dry Mass Margin per Study Guidelines** | | **20.6%** | | (MPV-MEV)/MEV |
| **Flight System Dry Mass Margin per JPL Design Principles** | | **34.5%** | | (MPV-CBE)/MPV |

***Table 4.4-5.*** *Power Estimates for the EE Flight System. Power levels for each mode (Comm. and Non-Comm.) are averaged over two orbits (one IPR and one Imaging)*

| Subsystem | Flight System Power, W | | Notes |
|---|---|---|---|
| | Comm. Mode | Non-Comm. Mode | |
| **Payload** | **110.1** | **98.0** | **Average over two consecutive science orbits** |
| Instruments | 110.1 | 98.0 | Two-orbit average orbital power of 106.1W (CBE). . |
| **Bus** | **348.8** | **266.4** | **Average over two consecutive science orbits** |
| AACS | 95.0 | 95.0 | Includes star tracker, star sensor, and SIRU. |
| CDH | 67.5 | 67.5 | Includes RAD750 and 2.4 Gb of NVM |
| Power | 25.9 | 25.9 | Power for switches and power converters |
| Propulsion | 13.0 | 13.0 | Average thruster power calculation including catbed heaters, valve power, and pressure transducers |
| Structures and Mechanisms | 11.0 | 0.0 | Includes power for gimbal motors and resolvers |
| Cabling | 16.1 | 12.8 | Equals 3.5% of total spacecraft power (CBE) |
| Telecom | 98.4 | 30.3 | Avg telecom power estimate for X and Ka-band. Assumes 11.5 hr Goldstone pass for Ka link. |
| Thermal | 18.0 | 18.0 | Power for electrical heaters |
| Radiation Monitoring | 4.0 | 4.0 | Allocation |
| **Total Power Level (CBE), W** | **458.9** | **364.4** | |
| **Contingency%** | **30%** | | |
| **Total Power Level w/ Contingency, W** | **596** | **473** | |
| Orbit Period, hrs | 2.3 | | Based on 200km altitude circular orbit. |
| Mode Duration per Orbit, hrs | 1.54 | 0.76 | |
| Energy Used per Mode, W-hr | 918 | 360 | |
| **Energy Used/Orbit, W-hr** | **1277** | | Does not account for battery charge/discharge losses. |
| RPS Type | MMRTG | | Baseline configuration |
| RPS Unit Output at EOM, W | 102.9 | | Value based on age of fuel and generators at EOM (12 years from BOL, 9 years from BOM). |
| **Avg Total Power Used per Orbit w/o cont., W** | **428** | | **CBE Value** |
| **Avg Total Power Used per Orbit w/ cont., W** | **555** | | **Max Expected Value (MEV)** |
| **Required # of RPSs (w/o redundancy)** | **6** | | |
| **Total RPS Power Produced at EOM, W** | **618** | | **Max Possible Value (MPV)** |
| **Excess RPS power available** | **62.1** | | **Unused RPS power after accounting contingency** |

| | | |
|---|---|---|
| **Flight System Power Contingency per Study Guidelines** | **29.9%** | (MEV-CBE)/CBE |
| **Flight System Power Margin per Study Guidelines** | **11.2%** | (MPV-MEV)/MEV |
| **Flight System Power Margin per JPL Design Principles** | **30.7%** | (MPV-CBE)/MPV |

#### 4.4.3.2 Thermal Control Subsystem

The Thermal Control Subsystem (TCS) maintains the flight system within specified temperature limits for all flight phases from launch to end of mission. The TCS provides this thru the utilization of waste heat from the RPSs, RHUs, and passive thermal designs such that very little electrical power is required.

The TCS driving requirements are:

- The external environmental incident energy due to changes in range between the flight system and the Sun, particularly during cruise.
- The Venus gravity assist will take the flight system to ~0.67 AU, which will have an incident solar flux over 2 times that at 1 AU.
- The solar range at Jupiter for this mission is 6.0 AU, which reduces the incident solar flux to 3.3 % of that at 1 AU.
- Minimize the electrical power required.

The TCS uses flight proven thermal control elements to minimize risk and the design elements require as little electrical power as is possible.

To account for the wide range of solar distances inherent to the VEEGA trajectory, an external element such as a solar shade over some or all of the flight system elements may be necessary for the inner solar system phase of flight. An estimate for this shield mass (10 kg, CBE) is included in the TCS mass. For the Jupiter and Europa phases, thermal isolation provided by Multi-layer Insulation (MLI), thermal surfaces, and thermal conduction isolation will be used. These elements have been used in numerous previous missions and were used on the Galileo mission, which orbited Jupiter.

To lessen the electrical power required, two thermal control technologies (MMRTG waste heat and RHUs) will be used. The MMRTG base operates at ~140 C and the flight system operates at 20 C, so thermal energy from MMRTG waste heat could be transferred to cooler flight system elements. In particular, the 6 MMRTGs are mounted on the propulsion subsystem, and with the use of internal thermal louvers and infrared (IR) channels, thermal energy will be transferred to the propulsion subsystem and to the base of the electronics mounting surface. This technology was used on the Cassini flight system successfully.

For areas where MMRTG waste heat cannot be used, RHUs and Variable RHUs will be used where practical instead of electrical heaters. RHUs will be used to heat assemblies where constant thermal energy is required. Variable RHUs will be used in areas where more control is necessary. Examples of this requirement are the thruster clusters, ΔV engine control valves, batteries, etc. Detail locations of RHUs and Variable RHUs will be determined in the design process. RHUs and Variable RHUs have been used extensively in previous missions (e.g., Cassini, Mars Exploration Rovers).

Electrical heaters with thermostats are required and used only in locations where use of MMRTG waste heat or RHUs is not viable. Mechanical thermostats will be used to minimize radiation shielding requirements. The electric heaters and thermostats used have extensive flight experience. The only other electronic components in the TCS are temperature sensors, and they have an extensive experience base and were successfully used on the Galileo flight system.

#### 4.4.3.3 Power Subsystem

The Power Subsystem provides power using 6 MMRTGs with a predicted end of mission power capability of 618 W. An internally redundant 25-Ahr Li-Ion battery is used for energy storage to handle transient demands power during the mission. The design utilizes an unregulated power bus with the operating point adjusted to track the peak power point of the MMRTGs throughout the life of the mission. The power bus (22–36 Vdc) is capable of delivering 1440 W under peak load conditions. The power subsystem concept is illustrated in **Figure 4.4-8**. The bi-directional converter will provide individual cell monitoring, over-voltage protection and direct access to comply with the latest range safety requirements for Li-Ion batteries.

Each MMRTG can deliver 125 W each at beginning of life (BOL), and 103 W at end of mission (EOM) 12 years later. The 12 year interval is divided into the following periods:

- Three years between when DOE manufactures the RPSs (defined as BOL) and when they are launched (termed Beginning of Mission, or BOM), and

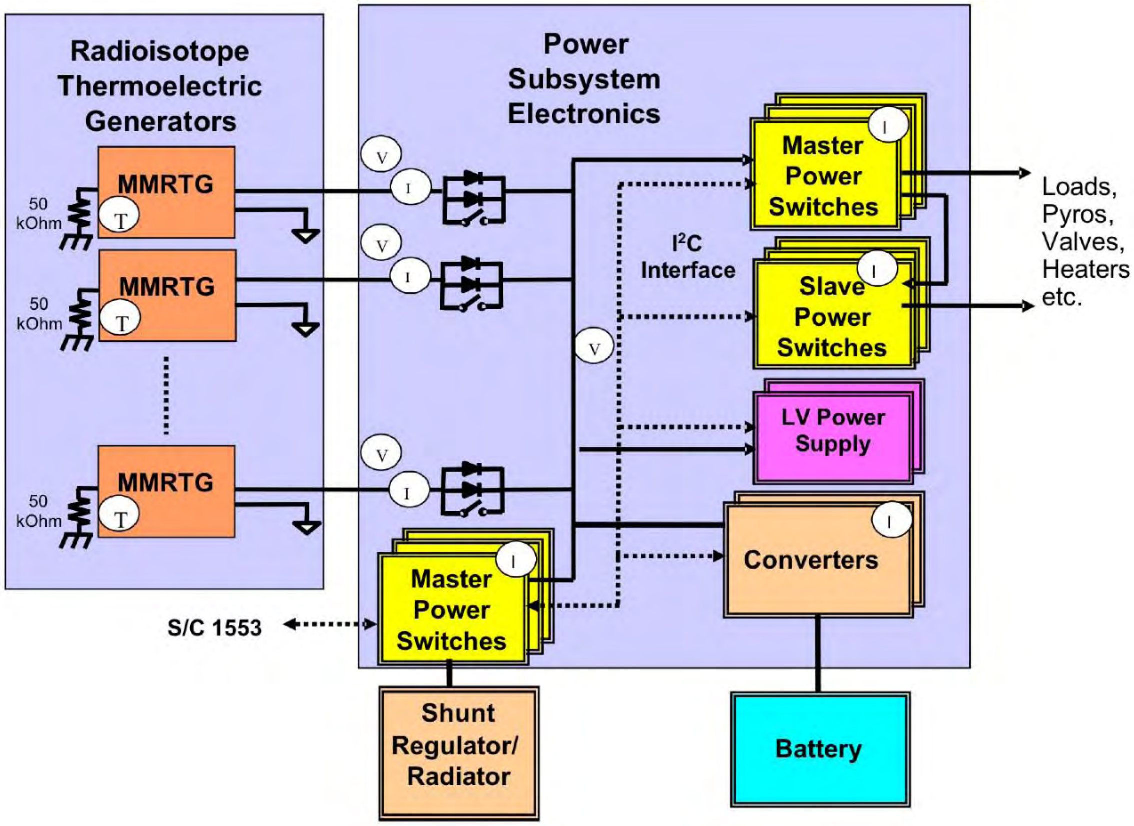



*Figure 4.4-8. Power System Block Diagram*

- Nine years between launch (BOM) and the end of the 1 year orbital period at Europa (EOM).

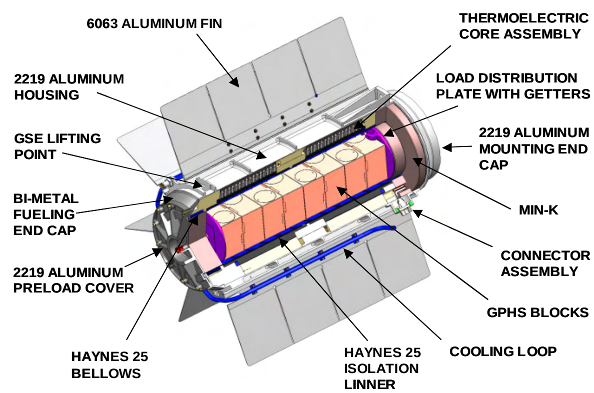
The MMRTG is currently under development and is the baseline power source for the Mars Science Laboratory due to launch in 2009. The MMRTG has a degradation rate of approximately 1.6% per year leaving approximately 618 W at the end of the 9-year mission for all 6 units. A performance summary and illustration of the MMRTG is shown in **Figure 4.4-9**.

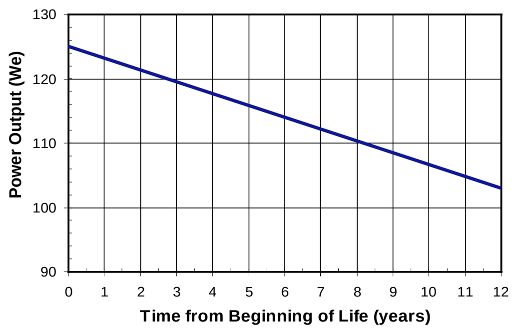
A 25-Ahr Li-Ion battery was selected due to the high energy density (~100 W-hr/kg) and the relatively benign radiation degradation. Both Li-Ion and Super Ni-Cd batteries have been radiation tested and are shown to perform well in this radiation environment. The depth-of-discharge for the battery is limited to 40%, whereas the currently predicted DOD level in Europa orbit is ~13%, (assumes 43% total power contingency), leaving significant margin for operational flexibility.

The power subsystem electronics are based on radiation hardened, X2000 technology that has been verified to the 1 Mrad total dose level. MMRTG power is provided through a fault tolerant interface to a single, power bus similar to the Cassini design. The power bus will combine the use of the shunt regulator—sized for the BOM power from the MMRTGs—with the bi-directional power converter used to control the charge and discharge of the battery. The bi-directional converter will provide individual cell monitoring, over-voltage protection and direct access to comply with the latest range safety requirements for Li-Ion batteries. Power is distributed using a combination of fault tolerant master and slave switches to the electrical loads, valves and pyrotechnic devices.

Power converters in this radiation environment are problematic. There are some current manufacturers of 1 MRad power converters, thought they have not yet been qualified for this type of long-life, high radiation environment. The approach would be for the project to qualify a few power converters or vendors which could be utilized across the

| MMRTG Characteristics | |
|---|---|
| Power/unit, W (BOL) | 125 |
| Duration from BOL to EOM, yrs | 12 |
| Power Degradation Rate/year | 1.6% |
| Power/unit, W (EOM) | 103 |
| Mass, kg | 44 |
| #GPHS Modules | 8 |
| Thermal Power, Wth | 2000 |
| Specific Power, W/kg (BOL) | 2.8 |
| Conversion Efficiency, % | 6.3% |
| $T_{hot}$, °C | 635 |
| $T_{cold}$, °C | 208 |
| Rad. Sink Temperature, K | 4 |
| Redundancy | Built-in |



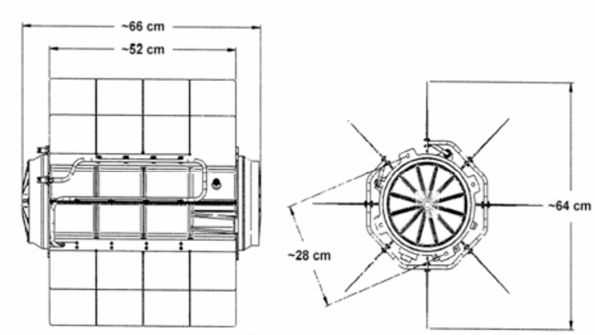




*Figure 4.4-9. Performance and Configuration of the MMRTG*

flight system. Special function converters may need to be specifically designed.

#### 4.4.3.4 Telecom Subsystem

Based on science and mission requirements and constraints, the EE telecom subsystem must provide: 1) reliable and robust low rate engineering command and telemetry links for critical events (launch, JOI, EOI) and safemode; 2) Dual frequency Doppler measurements (X and Ka bands) of the Europa gravity field; and 3) High downlink rates for science data in the Europa science phases, during Cruise calibrations, and during Earth, Venus, and Galilean satellite encounters.

A block diagram of the telecom subsystem is shown in **Figure 4.4-10**. Significant features of the telecom design include the following:

- Redundant cross-strapped X/Ka Small Deep Space Transponders (SDSTs),
- Redundant cross-strapped 35-W X-band traveling wave-tube amplifiers (TWTAs),
- One Ka carrier-only transponder (similar to the Juno design Ka-band translator),
- One 3.5-W Ka-band solid-state power amplifier (SSPA) (similar to Juno design),
- One 3-m X/Ka high gain antenna (HGA),
- One X-band medium gain antenna (MGA),
- Two X-band low-gain antennas (LGAs)
- One Ultra Stable Oscillator (USO)

The subsystem power and mass performance meets the required science data rates and mission geometry. For a detailed discussion of mission geometry, see §4.3 and **FO-2**. The range to Earth varies from 4-6 AU at Jupiter. Sun-Earth-Jupiter angles must be greater than ~50 degrees at EOI to reduce solar plasma noise constraining the maximum Earth range for the telecom design to 5.5 AU. Orbit period and occultation determine available downlink time. This is 55% to 60% depending on orbit altitude and includes losses for DSN lockup time.

The selected design for this study is an X band high and low rate system with a low power, carrier-only Ka-band system. The Ka band low power system is analogous to the Juno Ka-band translator. The use of Ka-band or X-band was considered for high rate telemetry links but ultimately, X-band was selected because 1) data retransmission is not planned, 2) system mass and power limits favor X-band, 3) pointing accuracy for X-band fits within that needed for science pointing,

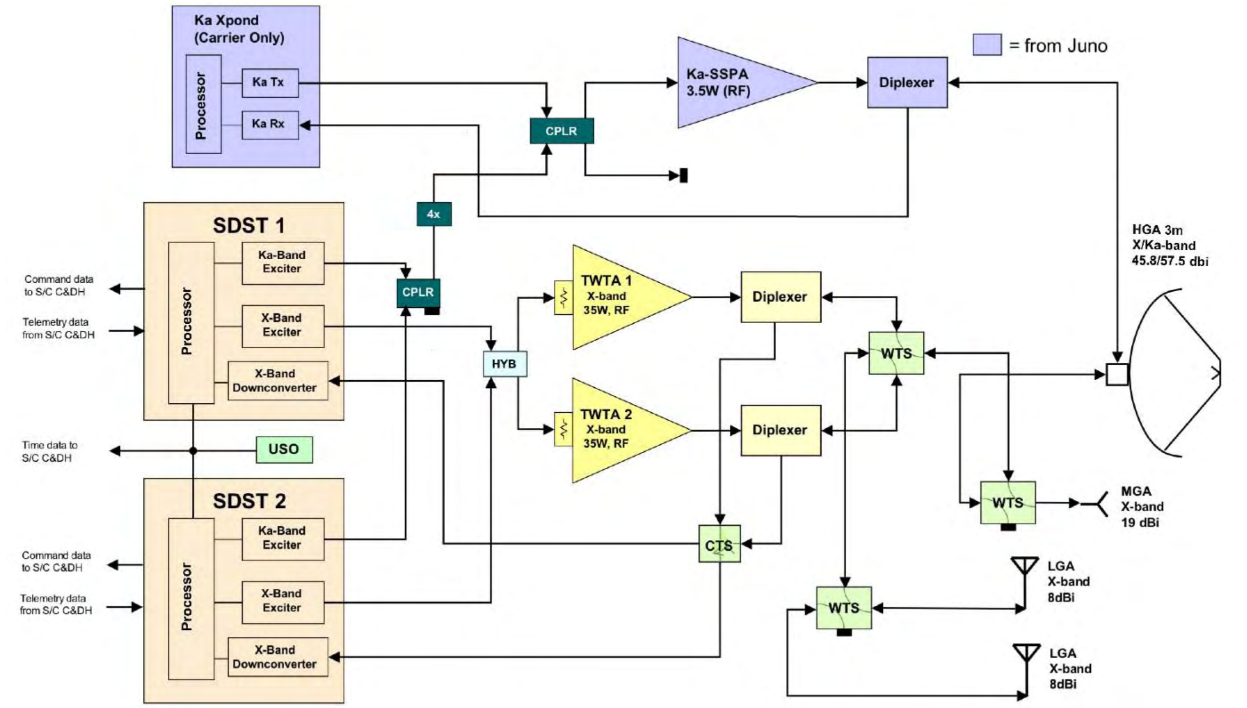



***Figure 4.4-10.*** *Telecom Subsystem Block Diagram*

and 4) X-band data return meets the science requirements. Future trade studies on the DSN, SSR, and Telecom design tradeoffs are described in §4.7.4.

The telecom hardware is mounted on the back of the HGA reducing the circuit loss between the output of the high-power amplifiers and the HGA. The Ka-band transponder provides carrier-only, coherent, Ka up, Ka down Doppler data. The SDSTs receive X-band uplinks, and provide X-band Doppler, range, and telemetry. The SDSTs are also cross-strapped using Ka-band exciter slices to provide Ka band Doppler, range, and, as a contingency, low-rate telemetry via the Ka-band SSPA. The USO is used both for a stable frequency reference for the SDST and for a timing reference signal to the C&DH subsystem for high accuracy commanding and telemetry time tags.

The telecom subsystem provides link performance of 200 kb/s to a DSN 70 m antenna from a range of 5.5 AU. The link assumes 90% weather, 20 deg station elevation, Turbo coding (8920, 1/6) with frame error rates (FER) of $10^{-4}$, and suppressed carrier QPSK modulation. Selected link design control tables can be found in Appendix H of this report.

Traditional link designs assume worst case station elevation angles and other system noise sources (monthly weather, Jupiter hot body noise, etc.). By taking advantage of actual elevation angles and Jupiter noise conditions for each orbit lockup at occultation exit, average data rates can be increased from 200 kb/s to 320 kb/s. §4.5.4 contains detailed analysis and discussion of this technique and other data return strategies.

The subsystem power and mass performance meet the required science data rates and mission geometry parameters. Driving geometry parameters include range to Earth, Sun-Earth-Jupiter angle, orbit period, and occultation durations (for Europa and Jupiter). For a detailed discussion of mission geometry, see §4.3 and **FO-2**. The range to Earth varies from 4–6 AU at Jupiter. Sun-Earth-Jupiter angles must be greater than 50 degrees at EOI to reduce solar plasma noise, constraining the maximum Earth range for the telecom design to 5.5 AU. Orbit period and occultation duration determine the available downlink time. This is 55% to 60% depending on orbit altitude and includes losses for DSN lockup time.

The selected design for this study is an X-band high and low rate system with a low power carrier-only Ka-band system. The Ka-band low power system is analogous to the Juno Ka-band translator. The X-band high rate design was selected based largely on low on-board mass memory, weather reliability and pointing accuracy issues. Because X-band is more robust to clouds and rainy weather at DSN stations and has lower losses due to spaceraft pointing control accuracy, an X-band system was deemed more reliable for the short Europa Explorer mission lifetime. The availability of the DSN 70 m network or its equivalent allowed the telecom system to use.

#### 4.4.3.5 Command and Data Handling Subsystem

The Command and Data Handling (C&DH) Subsystem is based on the Multi-Mission System Architectural Platform (MSAP) architecture (**Figure 4.4-11**) and uses a block-redundant flight computer to perform science data processing (e.g., data compression) and flight system processing and control. The C&DH is required to provide downlink data rates to the SDST from 10 bps to 32 kb/s for safing and engineering telemetry and from 32 kb/s to 1.6 Mb/s for science telemetry. Most of the Europa Science mission phase will need science rates between 160 and 800 kb/s and the C&DH should be built to accommodate the unused portions of the 3 dB telecom design margin.

The science data of all instruments can be compressed by the flight computer with software except for the IRS which is assumed to have its own data compressor and the IPR who internal processor reduces data rates for each observation mode. The aggregate data collection rate from the instrument suite is 7.8 Mb/s. The actual implementation of the data compression will be decided by each instrument developer.

The dual-string configuration includes:

- Flight proven RAD750 Processors with 128 MB of rad-hard SRAM,
- Non-Volatile Memory (NVM) card with 1.2 Gb of chalcogenide RAM (CRAM),
- MSAP Telecommunication Interface (MTIF) board,
- MSAP System Interface Assembly board (MSIA),
- MSAP Analog GNC Interface Card (MAGIC), and,
- MSAP Remote Engineering Unit (MREU).

The MTIF has interfaces to the SDST as well as being the Bus Controller (BC) of the 1553 Bus. The MSIA is the interface between the Compact PCI Bus and the 1553 Remote Terminal protocol engine, plus it provides

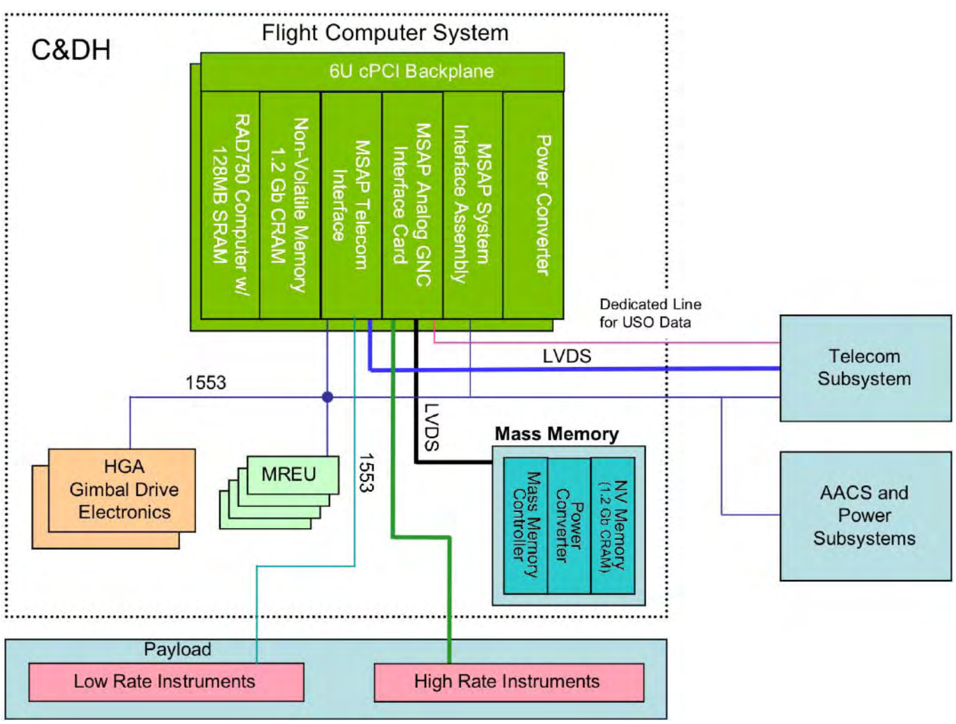



*Figure 4.4-11. C&DH Block Diagram*

fault detection unit support for use in a dual string system configuration. The MAGIC card is the interface to the ACS subsystem and the stand-alone sold-state mass memory device.

A radiation evaluation has been done on a board-by-board basis for the MSAP C&DH subsystem as well as the Cassini as-built parts list and the assessment is that the modifications are understood and within the experience base of JPL and others.

The flight computer interfaces with the low-speed instruments via the 1553 bus. The 1553 bus carries both commands to and data from the low-speed instruments. The high-speed instruments have point-to-point Low-Voltage Differential Signaling (LVDS) interfaces to the mass memory. These LVDS interfaces carry both the commands to the instruments and the data from the instruments. The protocol of *Mars Science Laboratory Project Instrument Standard Electrical and Interface Specification* will be adopted for the LVDS interface.

The project requirements for the mass memory are 1 Gbits for science data storage and 1.4 Gbits for flight software, engineering telemetry and margin (**Figure 4.4-12**). Boot code for the RAD750, flight software and engineering TM are stored on a block redundant 1.2 Gb non-volatile memory (NVM) memory card, located on the C&DH backplane.

Science data is stored on a single, internally redundant 1.2 Gb solid state recorder located in its own enclosure and connected to both C&DH strings via an LVDS interface. This allows the science mass memory data to be shared between the primary and backup computers without the need for cross-strapping.

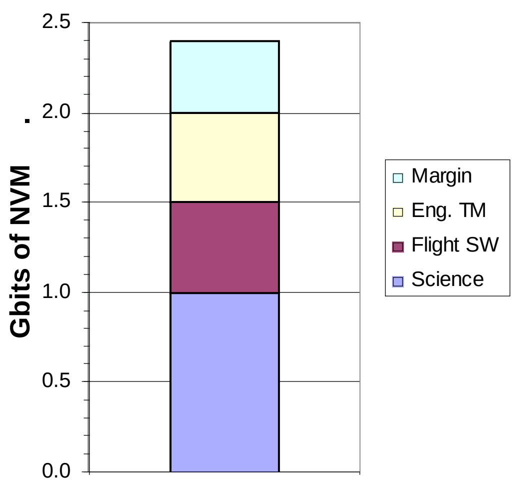



***Figure 4.4-12.*** *Non-Volatile Memory (NVM) Allocation to Science and Engineering*

The conceptual design of solid state recorder and NVM card are based on:

- Device Selection: Chalcogenide RAM (CRAM), Phase Change
- 16 Mb-stacked devices from BAE
- Radiation tolerance > 1 Mrad; << 1E-11 upsets/bit-day
- 50 nS read, 500 nS write
- 20 mW/MHz active power
- < 10 mW/device standby/sleep
- Endurance >> 1E10 cycles, Retention > 10 years
- Hi-Rel, "Class S" product off BAE RH Manassas fab
- 6U Eurocard format

#### 4.4.3.6 Attitude & Articulation Control Subsystem

The Attitude & Articulation Control Subsystem (AACS) is a fully redundant three-axis stabilized zero momentum system that controls the flight system orientation or attitude, and provides stable platform for remote observation pointing of a suite of science instruments.

The AACS driving requirements are:

- Provide for a stable, nadir-pointed platform for science investigations
- Pointing knowledge of 0.1 mrad or better
- Pointing accuracy of 1 mrad or better
- Pointing reconstruction of 0.1 mrad or better
- Pointing stability of 10 μrad/s or better (driven by the NAC instrument)

These requirements are satisfied using an array of 24 4.4 N hydrazine thrusters and four reaction wheels (RW). Preliminary analysis shows that the reaction control system (RCS) thruster array needs both attitude and translation control in all six degrees-of-freedom in the Europa science orbit without having to change the gravity gradient stable orientation of the flight system. This results in the redundant set of 24 thrusters. Additional analysis is planned to assess whether this can be reduced. The wheels, with ±25 Nms momentum storage, are employed only during the Jovian Tour and Europa Science phases of the mission, and are de-saturated periodically (no more than once a day) by firing the 4.4 N thrusters.

The articulation function is primarily for the two-axis gimbaled HGA pointing and tracking of the Earth for telecommunications. In addition, the AACS controls the thrust vector during ΔV burns of the 890 N bi-propellant main engine. Thrust vector control (TVC) of the fixed main engine is accomplished by pulse-on control of four 32.5 N hydrazine thrusters on booms outboard of the main engine. All these control functions are supported by a precision attitude determination (AD) capability provided by a combination of attitude sensors and the AACS flight software executing on the flight system computer.

For sensing the flight system's orientation, AACS uses an internally redundant inertial measuring unit (IMU), two star trackers (ST), and acquisition sun detectors (ASD) located on the spacecraft main body. Additionally, two fine sun sensors (FSS) are mounted on the HGA. The IMU attitude information and bias drift are periodically estimated and updated with accurate ST measurements. The STs are arranged non-co-aligned to further improve measurement accuracy and provide adequate redundancy.

For improved downlink pointing, the FSSs are mounted on the HGA and are boresighted and calibrated with the HGA X-band beam pattern in order to circumvent the predictive pointing limitations caused by alignment uncertainties and instabilities due to the ST mounting, the deployed boom-mounted HGA, gimbal drives, and the RF mechanical-electrical boresight alignment. This enables the Earthline to be directly determined by the precisely known Sun-Earth ephemeris and offset pointed from the solar intensity centroid.

Typical AACS functions unfold in post launch/trans-Jupiter injection and flight system deployment from the LV with the IMU gyros, ASD, FSS, and RCS enabled in order to cancel LV upper stage tip-off rates, reduce residual body rates, and acquire the Sun reference. Following this, the star pattern identification and tracking for three-axis precision attitude determination is accomplished. With the Interplanetary phase of the mission underway, the AACS maintains vehicle three-axis stabilization via commanding of the RCS thrusters and determines attitude by star pattern observations. The HGA is deployed soon after injection and is calibrated for beam pattern and boresight knowledge.

Upon arrival at Europa, the flight system is inserted into a science orbit and gravity-gradient stabilized by a commanded turn maneuver that aligns the science instrument's line-of-sight (LOS) to nadir. This attitude is long term stable, but subject to perturbations and secular momentum accumulation due to gravity harmonics, orbit altitude variation, orbit eccentricity, and environmental effects. The set of four RWs provides autonomous maintenance of this attitude without the need for frequent use of RCS thrusters, which would violate the constraints for science data collection. Non-thrusting "quiet" periods for science will be at least 24 hours long.

**Figure 4.4-13** shows the hardware and software general functions of the AACS. The light blue color indicates the sensor signal processing, attitude determination, algorithmic controllers, and commander software functions. The sensor and actuator hardware is shown in gold. AACS flight software is hosted and executed by the flight computer in a real-time interrupt (RTI) driven operating system. The RTI rate needs to be sufficiently high to enable the most demanding bandwidths for the AACS control functions such as HGA pointing and TVC during Main Engine burns. An RTI of as high as 100 Hz may be needed to satisfy these needs.

The X-band downlink data rate and SNR, require a 3-m HGA given the distance from Earth of Europa. The HGA diameter determines the beam pattern and its spatial power roll-off function. The required pointing precision is governed by the RF link analysis of pointing offset error vs. signal power loss. To constrain the pointing loss for an acceptable data rate at Europa requires a total vector pointing error of 3 mrad (3-sigma) or less. This includes all sources of calibrated alignment uncertainty and stability errors from body-mounted STs to the deployed boom-mounted HGA gimbal drives and the RF mechanical-electrical boresight.

The 4.4 N RCS thrusters are chosen for an impulse bit of sufficient magnitude for attitude control authority during commanded turns and small ΔV burns, while fine enough to

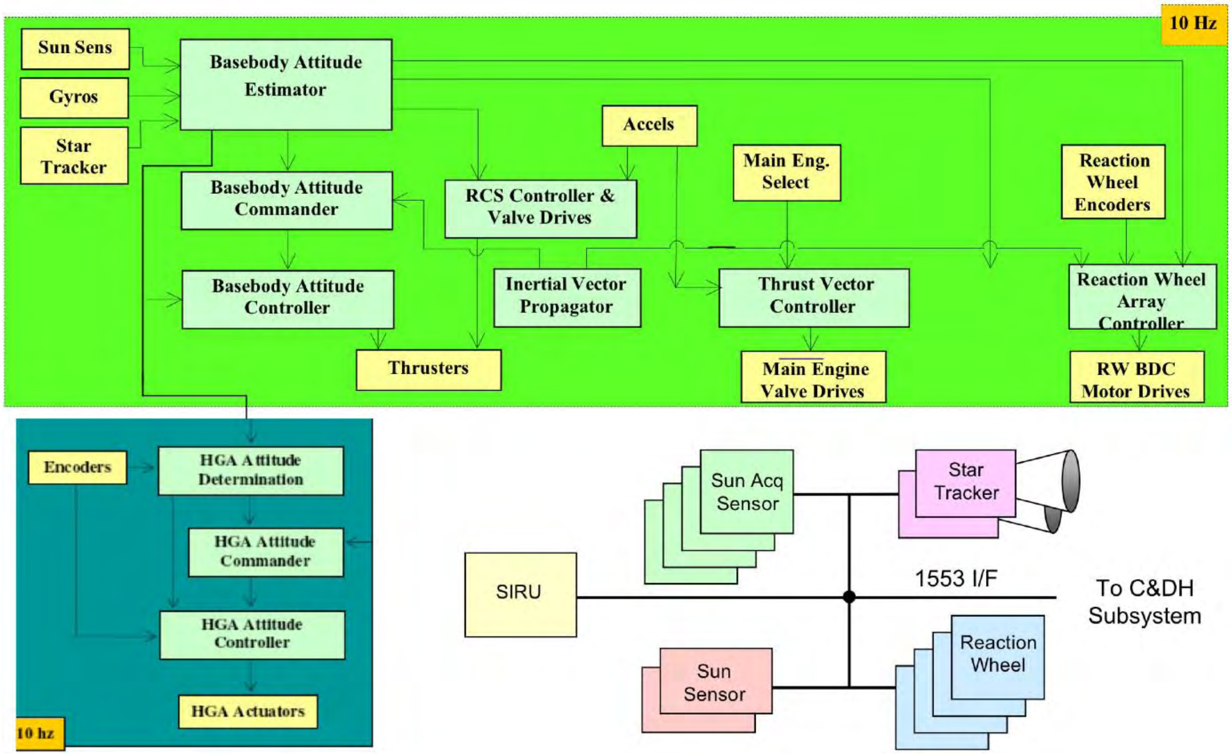



*Figure 4.4-13. AACS Functional Block Diagram*

minimize the propellant expended in 3-axis limit-cycle stabilization. The RCS thrusters are used during the long Interplanetary phase, and the reaction wheels are used during the Jovian Tour and Europa orbital operations.

The RCS propellant required for 4.4 N, $N_2H_4$ thrusters during cruise is determined by 3-axis attitude limit cycle control with selectable deadbands (db), and commmanded attitude turns for Trajectory Correction Maneuvers (TCM) burns from LV injection dispersion clean-up to JOI burn. Propellant estimates assume best estimate nominal values for flight system mass properties and operational parameters. (Note: certain second-order factors have not been addressed, nor have maneuvers for HGA and/or instrument calibrations been included.)

#### 4.4.3.7 Propulsion Subsystem

The leading design drivers for the propulsion system are the mission duration and the required ΔV to get to Jupiter and into orbit around Europa. The mission duration leads to the necessity for a fully redundant propulsion system, able to accommodate a failed component and leaking valves. The high ΔV requirement results in high engine throughput, many engine start-ups, and associated valve cycle usage. This, in turn leads to the selection of robust, long-life engines and thrusters with good qualification margins and an extensive test history.

Radiation primarily affects two propulsion components; pressure transducer electronics and soft goods within electrical valves. Current state-of-the-art flight pressure transducers are not particularly rad-hard, nor are they designed to be rad-hard. Upgrading of such electrical components as op amps will be needed. Further research into pressure transducers used in the nuclear power industry is still required. The primary soft goods in valves are the sealing materials, such as Teflon, AF-E-411 (rubber), Vespel, etc. Better characterization of the properties and performance of these materials in high radiation environments is required.

The primary thruster configuration requirement is the need to minimize residual ΔV during momentum wheel desaturations. When combined with a redundancy requirement, this led to a configuration of 24 thrusters located on the eight "corners" of the flight system as illustrated in **Figure 4.4-14**.

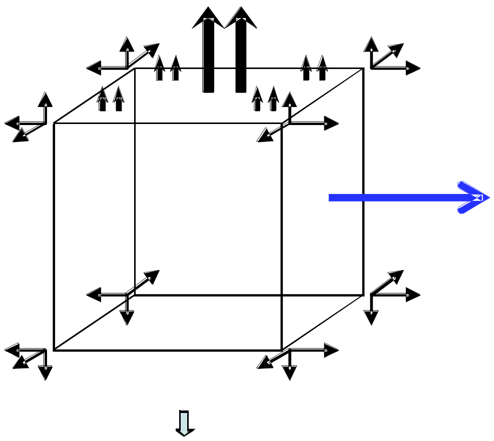


***Figure 4.4-14.*** *Engine and thruster Configuration (Main engines (2) and TVC thrusters (8) shown on +Z deck. Remaining thrusters (24) are configured in 8 clusters of 3 thrusters each.)*

The propulsion system design is based on that developed for the Europa Orbiter study, with modifications made to accommodate EE specific requirements, **Figure 4.4-15**. It is a dual mode, bipropellant system using hydrazine ($N_2H_4$) fuel and nitrogen tetroxide ($N_2O_4$ or NTO) oxidizer. Approximately 4460 kg of propellant is carried. The $N_2H_4$ and $N_2O_4$ are used by the 890-N (200-lbf) bipropellant main engine. The hydrazine is also used by the monopropellant thrusters, both for TVC and the RCS.

The baseline for the main engine is a 890-N (200-lbf) thrust NTO/$N_2H_4$ bipropellant engine currently being developed by Aerojet, Redmond, for an Air Force program called Advanced EHF. The engine is a scaled up version of their 450-N (100-lbf) class HiPAT engine. A second engine is included in the design for redundancy.

Eight Aerojet 32.5-N (7.32-lbf) MR-106L thrusters (4 primary and 4 redundant) are baselined to provide TVC for the main engine, as well as provide ΔV for small maneuvers. Twenty four Aerojet 4.5-N (1-lbf) MR-111 thrusters (12 primary and 12 redundant) are baselined to provide attitude control (e.g., 3-axis limit cycle control, reaction wheel de-saturations, flight system turns, etc.) for the flight system. In addition, the thrusters may be used for very small ΔV maneuvers.

#### 4.4.3.8 Flight Software

Highly reliable software for mission-critical applications is essential for this long-life, highly visible mission. JPL has established a set of institutional software development and acquisition practices as well as design principles that apply to mission-critical and mission-support software. These practices conform to the NASA Procedural Requirements for Software (NPR 7150.2) and are an integral part of the JPL FPP and DPP. In addition, the JPL organizations that will be responsible for the management and development of the EE mission critical software are certified at CMMI Level 2 (or greater) which has been shown to correlate strongly with reduced defects and improved cost and schedule performance.

Written in “C” using the VxWorks operating system, the EE flight software:

- Allocates and manages onboard computational resources for all engineering and science processing needs
- Performs memory management of command sequences and science data
- Executes command receipt verification and validation
- Performs self-test
- Gathers and reports health/safety status at the subsystem and flight system level
- Hosts onboard autonomy necessary to recover the flight system from anomalies encountered during all phases of the mission, including EOI.

There is a large portion of the EE software that is inherited from MSAP development activity. This flight-proven software design provides high test and operational flexibility to accommodate science and engineering needs, autonomous fault recovery, and in-flight software updates for unforeseen situation resolution. In addition to the flight software itself, other inherited products reduce development cost and risk includes: documentation, the development environment (config management, test harnesses and scripts) for delivered functionality. Further, the MSAP simulation test environment includes the simulation for the MSAP supported hardware. The Operating System and sequencing machine will be the same as for MSAP.

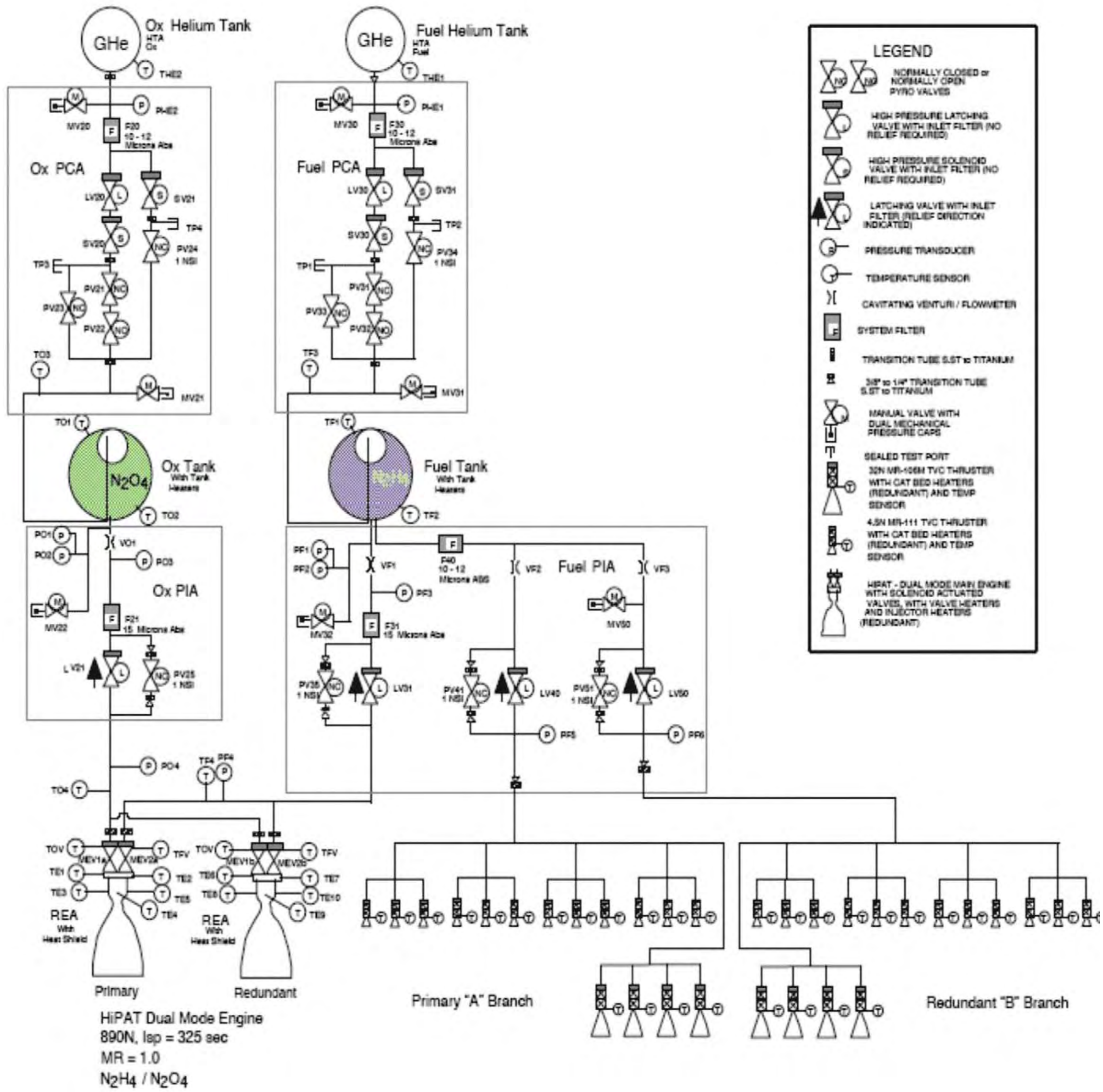



***Figure 4.4-15.*** *Propulsion System Schematic for EE*

Minimal effort is assumed for the adaptation of these specific MSAP products for EE.

The Boot (initial program load) and the flight software initialization modules are inherited from MSAP but will require some level of re-engineering and full re-testing to work for the EE mission. A moderate re-engineering effort will be required for those MSAP modules that interface with the radiation-hardened avionics set.

#### 4.4.3.9 Radiation Monitoring Subsystem

The Radiation Monitoring Subsystem (RMS) provides continuous monitoring of real-time radiation environments at multiple key locations and has three driving requirements: measure the actual radiation and surface charging environment, collect data to determine the effectiveness of the shielding design, collect data to understand anomalies in the computer system due to Internal Electrostatic Discharge (IESD) and Single

Event Upsets (SEUs). A main electronics and sensor box is located on the electronics deck and contains surface charging sensors, energy sensitive dosimeters and Total Ionizing Dose (TID) dosimeters. This box will be a variation of the previously flown Compact Environmental Anomaly SEnsor (CEASE) design. Small individual flight-proven "RADFET" dosimeters are distributed across the flight system to measure the TID behind and within the various shielding. Additionally, IESD and SEU sensors will be placed in the computer system. Signals from the distributed dosimeters, IESD and SEU sensors will be collected via the main electronics box and sent to the C&DH at very low rates (~10 kb/day) via the 1553 data bus. The block diagram is shown in **Figure 4.4-16**.

### 4.4.4 Verification and Validation

EE will verify and validate the mission system to ensure it meets specifications and is capable of accomplishing the science objectives. A combination of system analysis, modeling and simulation tools, engineering development unit hardware and testbeds, flight software testbeds utilizing simulations and engineering model (EM) hardware, flight system functional/environmental testing (Assembly, Test and Launch Operations, ATLO) and readiness tests will be used.

*Simulation Capability*

A high fidelity model-based simulation capability (S-Sim) is baselined for flight software test and verification. The first S-Sim version will be available to support the first flight software release and continue on with expanded capability in support of testing of subsequent flight software builds. The

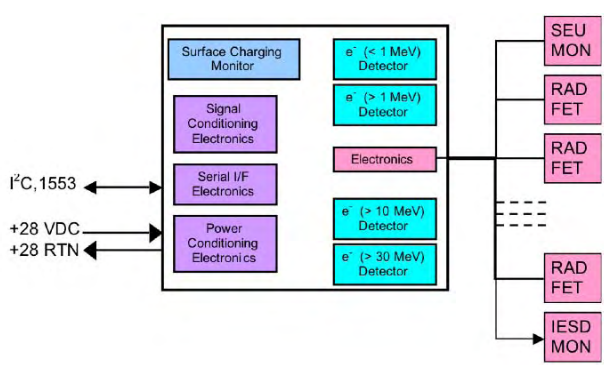



***Figure 4.4-16.** Radiation Monitoring Subsystem measures actual radiation dose throughout the flight system*

simulation environment will be available on all software developers & testers workstations (full software simulators). These simulators will be built to allow for interchangeability between software models and hardware EMs later in the "hardware-in-the-loop" testbeds in such a way that is transparent to the flight software. This will enable the ability to use the same test scripts whenever the testbed models are interchanged with EMs.

In addition to the simulation capability described above, EE will have 3 primary system testbeds: 1 single-string and 2 dual-string. The Mission System Testbed (MSTB) is a dual-string high-fidelity testbed that is dedicated to system V&V, Flight Software fault tests, mission system tests, and ATLO support.

The Flight Software Testbed (FSWTB) is a single-string "hardware-in-the-loop" testbed that is dedicated to Flight Software and Flight Hardware integration. Additionally, there is one GSE development station called the Realtime Development Environment (RDE) that is dedicated to Ground Support Equipment (GSE) hardware and software development and test. Multiple Workstation Testbeds will also be available to all software developers & testers during development.

These testbeds will include the C&DH, AACS, power, telecom and harness subsystems. Only the MSTB will have hardware versions of the engineering subsystems; they will be simulated on the other testbeds.

The testbeds will include the Ground Data System (GDS) hardware and software as well. The EM versions of all flight system engineering subsystems and instruments pass through the testbeds for integration and interface verification. No flight units are required to flow through the testbeds unless there are major modifications from the EM, however, the testbeds can support flight hardware integrations if needed. There will be a simulation environment for Verification and Validation (V&V) that can off-load the hardware-in-the-loop testbeds as well as using the EM integration effort to help enhance evaluation of model fidelity. The simulation environment interfaces and procedures will be compatible with those of the hardware testbeds. The testbeds will also be used to train test analysts to support ATLO testing as well as to support ATLO procedure development and anomaly investigation. All flight software versions will be verified on the testbeds prior to being loaded onto the Flight System in ATLO or in operations.

*ATLO and I&T Approach*

The EE system integration and test (I&T) approach is modeled after the Cassini ATLO effort as these two missions share a great deal of similarity in complexity and design. The JPL 25-foot thermal vacuum chamber will be utilized for system thermal vacuum testing with two planned tests, one using the solar simulator and one without the solar simulator. All testing will be performed by ATLO system engineers, with extensive support from subsystem and instrument engineers and the actual operations team. The EE GDS will be used in all the functional and performance tests to allow for end-to-end data flow testing and tools suites validation. Operational Readiness Tests (ORTs) will be performed to assess the infrastructure and team's ability to execute the operational phases of the mission.

A Developmental Test Model (DTM) will be built that will effectively be the EM for the flight system structure. The DTM is used to alleviate the schedule impact of the flight unit. The DTM will be used to do static and modal testing which allows the flight unit to be integrated in parallel. In addition, the DTM is used to do fit checks and cable or mass mock ups. Further, the DTM will be used to validate the sterilization philosophy for planetary protection. This model will also be used as a fit check "trailblazer" at the launch site to ensure that the procedures and processes for integration of the RPS to the flight system are compatible and streamlined during the launch preparations.

A trailblazer activity is required to plan and execute the integration activities of the RPS with the flight system and launch vehicle. Planning begins early in Phase B where requirements and storyboards are put together to understand the constraints imposed at the launch site. Mock ups of the hardware and facilities are created to physically simulate the integration. Ultimately, the ground support equipment, RPS simulators and DTM meet at the cape to walk thru the simulated installation process to ensure adequate clearances, procedures and safeguards.

The ATLO schedule and I&T plan are summarized in **FO-5**. This process is designed to provide verification of the flight system design and workmanship by subjecting the flight system to a demanding series of functional, operational, and environmental tests, while also maintaining the integrity of the planetary protection approach. Initial assembly begins with delivery of the flight system primary structure, the propulsion subsystem and the electrical cable harness. Each electrical subsystem undergoes vibration, thermal, pyroshock, Electromagnetic Compatibility/Interference (EMC/EMI) and magnetics testing/characterization, and potentially, sterilization processing prior to delivery to ATLO. Each subsystem with electrical functionality is integrated using assembly plans and test procedures that ensure mechanical and electrical safety and which have been verified in the testbed. Once all of the engineering subsystems are safely integrated and fully functional at the system level, the instrument payloads are integrated with the spacecraft to complete the flight system. A preliminary Incompressible Test List is generated by Project Critical Design Review (CDR) and approved by ATLO Readiness Review (ARR) to identify and assure that all critical testing is performed on the flight system prior to launch. To ensure that a complete and comprehensive system-level test program is provided, ATLO V&V is augmented with payload simulators, engineering models and the DTM.

The EE team will maintain a rigorous formal program for testing flight hardware at all levels of assembly ("Test as you fly and Fly as you test"). Electrical testing includes component interface tests, flight system functional tests, DSN compatibility tests, instrument interface verifications, performance tests and environmental tests. All electrical test procedures are verified on the testbed prior to being run on the flight system. Similarly, all flight software versions are run through the testbeds before being uploaded onto the flight system in ATLO.

The EE environmental test program consists of a comprehensive system level test program that ensures that the flight system has been verified to operate in the expected environments of the mission. At the subsystem or assembly level, all flight hardware will be tested to acceptance levels and durations if there has been a preceding qualification test or to protoflight levels and durations if no qualification unit was available. System level environmental tests include system level acoustics, vibration and shock, thermal balance, and thermal vacuum. The system level EMC/EMI, and magnetic cleanliness verification is performed via modeling of the assembly and subsystem level testing performed prior to ATLO. Modal surveys are also preformed to validate the flight system structural model. Functional tests are repeated after each environmental test to ensure that the test effects have not degraded system performance. Post-environmental tests also facilitate verification of any modification to flight software or flight sequences (see **FO-5**).

All flight engineering subsystems are required to track powered-on time. Flight engineering subsystems other than instruments are required to accumulate 200 hours prior to integration and 500 hours (with a goal of 1000 hours) at the system level prior to launch. Instrument electronics are required to accumulate 300 hours prior to integration and 200 hours prior to launch.

The flight system is enclosed in a non-flight biobarrier and trucked intact to the launch site. Functional testing is performed prior to and immediately after shipment to verify that the shipment did not adversely effect its performance. The RPSs will be delivered separately to the launch site by the DoE. The RPSs will be test fitted to the flight system to ensure adequate mechanical and electrical functionality. They will then be removed and stored until final integration on the launch pad.

Final testing, propellant loading, and launch vehicle, RHU and RPS integration is completed and the flight system is ready for launch.

## 4.5 Operational Scenarios

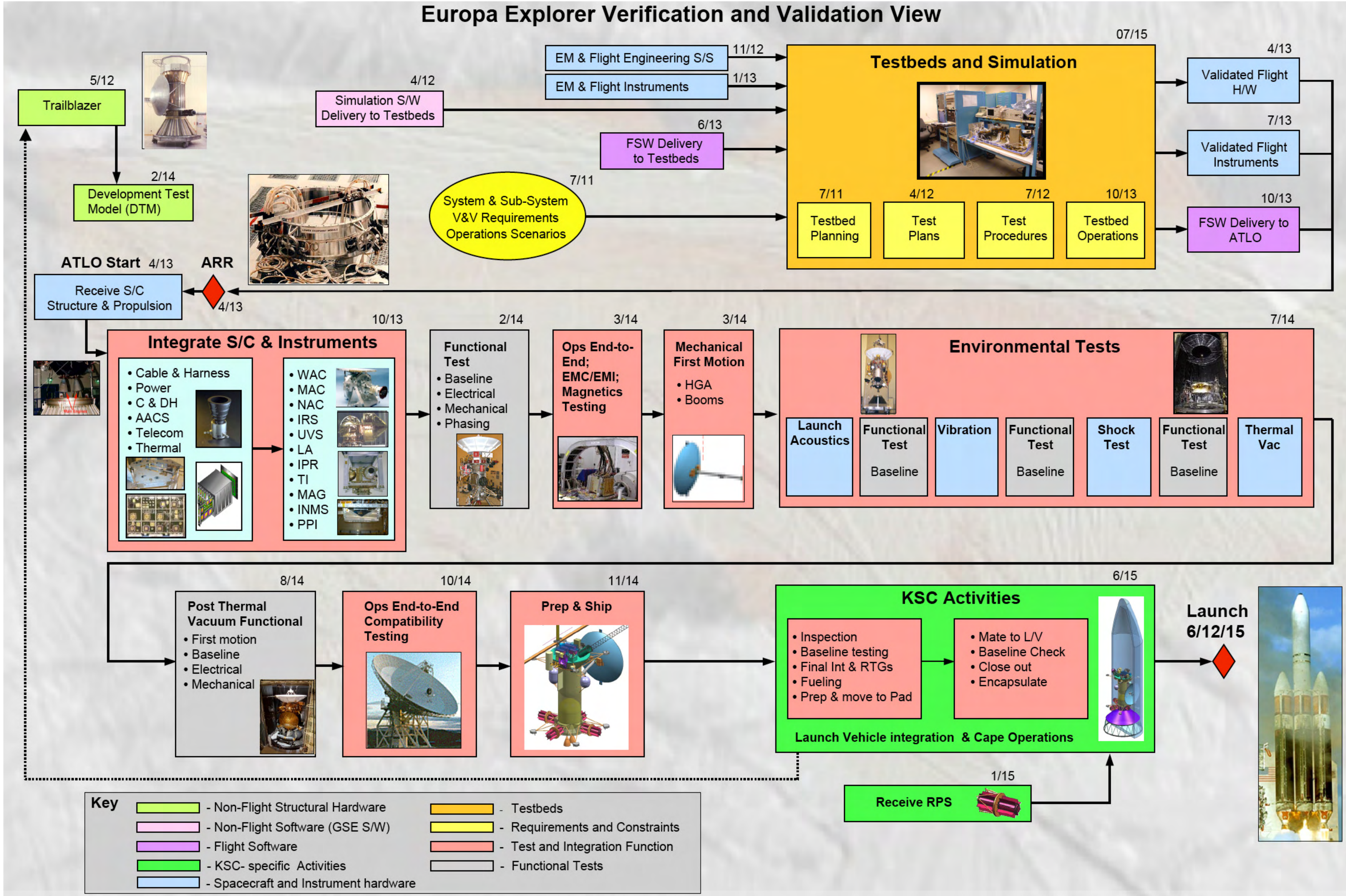
### 4.5.1 Overcoming the Challenges of Operating in Europa Orbit

Europa and its vicinity is a challenging and hazardous environment for operating any science mission. Mapping Europa requires a large and complex payload that collects large volumes of science data. The largely unknown Europa gravity field represents both a high priority science goal to help characterize its ice shell, oceans and rocky core, but also a challenge to finding and maintaining good quality mapping orbits. These challenges have been considered in depth and have been answered by spacecraft and payload hardware and software concepts and operational strategies. The operational scenarios resulting from these design concepts and strategies provide a means to collect and return the science data needed to meet all of EE's science objectives.

The radiation environment limits the amount of on-board data storage available. Mass memories of 1–2 Gb can be reasonably accommodated in the EE flight system design. Given a few operational constraints commonly encountered in past missions, they can support daily data volumes of an order of magnitude greater than their capacity. These constraints include: near real time data compression and downlink encoding, downlinking all data on the orbit collected, collecting data only during downlink sessions, assuming no data retransmission, and scheduling continuous DSN tracking.

Short term radiation effects such as SEUs and gradual degradation due to displacement damage can cause frequent fault protection intervention. In most missions the system's reaction to faults, whether major or minor, prevent normal flight system operations while ground operations personnel resolve causes and ensure safe return to operations. Because of EE's relatively short mission duration and the desire for nearly continuous data acquisition, fault containment and response designs will be needed to keep the flight system operating in the presence of minor faults, and to help return the flight system to normal operations quickly when more serious faults occur.

Due to limited knowledge of the Europa gravity field and Jupiter's gravitational perturbations, initial orbits will likely need maintenance every week to few weeks. In the first weeks in Europa's orbit, Doppler data will increase knowledge of the Europa gravity field rapidly and initial orbit parameters will be adjusted for additional stability. A more stable lower orbit will be designed for later mapping activities. Because of increasing knowledge of


Europa Explorer Verification and Validation View
5/12
Trailblazer
2/14
Development Test Model (DTM)
4/12
Simulation S/W Delivery to Testbeds
EM & Flight Engineering S/S
11/12
EM & Flight Instruments
1/13
6/13
FSW Delivery to Testbeds
7/11
System & Sub-System V&V Requirements Operations Scenarios
07/15
Testbeds and Simulation
7/11
Testbed Planning
4/12
Test Plans
7/12
Test Procedures
10/13
Testbed Operations
4/13
Validated Flight H/W
7/13
Validated Flight Instruments
10/13
FSW Delivery to ATLO
ATLO Start 4/13
Receive S/C Structure & Propulsion
ARR
4/13
10/13
Integrate S/C & Instruments
• Cable & Harness
• Power
• C & DH
• AACS
• Telecom
• Thermal
• WAC
• MAC
• NAC
• IRS
• UVS
• LA
• IPR
• TI
• MAG
• INMS
• PPI
2/14
Functional Test
• Baseline
• Electrical
• Mechanical
• Phasing
3/14
Ops End-to-End; EMC/EMI; Magnetics Testing
3/14
Mechanical First Motion
• HGA
• Booms
7/14
Environmental Tests
Launch Acoustics
Functional Test Baseline
Vibration
Functional Test Baseline
Shock Test
Functional Test Baseline
Thermal Vac
8/14
Post Thermal Vacuum Functional
• First motion
• Baseline
• Electrical
• Mechanical
10/14
Ops End-to-End Compatibility Testing
11/14
Prep & Ship
6/15
KSC Activities
• Inspection
• Baseline testing
• Final Int & RTGs
• Fueling
• Prep & move to Pad
• Mate to L/V
• Baseline Check
• Close out
• Encapsulate
Launch Vehicle integration & Cape Operations
Launch 6/12/15
1/15
Receive RPS
Key
- Non-Flight Structural Hardware
- Non-Flight Software (GSE S/W)
- Flight Software
- KSC- specific Activities
- Spacecraft and Instrument hardware
- Testbeds
- Requirements and Constraints
- Test and Integration Function
- Functional Tests

the Europa gravity field and the change in orbit from 200 km to 100 km, it is expected that orbit maintenance interruptions to science operations should decrease in frequency over the course of the Europa Science phase.

The EE science scenario is designed to obtain the highest-priority observations early in the Europa Science phase. The earliest and highest priority goals, to be accomplished in the first 4 weeks, include 2 global maps, 1–2 degree global grids from the 5 profiling instruments, and several hundred coordinated targets of high interest sites. After the initial campaign, the orbit altitude will be lowered and higher resolution global maps, additional profile grids and hundreds more coordinated target observations will be collected to answer regional process questions. The third month of the Europa Science phase will be devoted almost entirely to acquiring coordinated targets to answer local-scale science questions. To meet these science objectives, the flight system will need to acquire and return an average 20 Gbits per day. To balance power, mass, and data volume, continuous tracking by DSN 70 m stations (or equivalent) will be needed to return these data volumes. The final portion of the Europa Science phase, lasting 9 months will be devoted to addressing new questions discovered in the initial observations.

In the first 26 eurosols of the Europa Science phase, complete color and stereo maps of the surface are obtained, profiling observations cover the globe such that their spacing density is 25 km for optical remote sensing and 50 km for each IPR mode, and more than 1000 synergistic multi-instrument targeted observations are obtained of high priority sites.

Several previous planetary missions have met similarly aggressive science goals in challenging environments with similar operations scenarios. **Table 4.5-1** shows a comparison of operational mission characteristics for other in-family previous planetary missions.

#### 4.5.2 Mission Scenarios Overview

Operational scenarios have been devised for each EE mission phase based on mission priorities. The primary mission duration is about 9 years. The first 6 years are needed to deliver the flight system to Jupiter and are devoted to launch, cruise, and preparation for JOI and Jupiter system science operations. Following JOI, the mission will undertake a series of gravity assist flybys of the Galilean satellites Ganymede, Calisto, and Europa to reduce the propellant requirements to enter orbit at Europa. The gravity assist flybys and other aspects of the Jovian Tour trajectory represent opportunities for close and far observations of the Galilean satellites and Jupiter. The EOI begins a one-year Europa Science phase which completes the primary mission. Following the Europa Science phase, given funding approval, an Extended Europa Science phase will commence, lasting for the remainder of the useful life of the flight system. When the flight system becomes non-operational or when it runs out of propellant for orbit maintenance, the flight system will ultimately crash into Europa within weeks to months, which is the driver for the stringent planetary protection requirements on the mission.

*Summary of Operations Scenarios By Mission Phase*

After launching in June of 2015, the

***Table 4.5-1.** Comparison of Operational Mission Characteristics*

| Mission Comparison | Europa Explorer | Cassini | MRO | MGN | MER |
|---|---|---|---|---|---|
| Mission Phase Durations<br>Interplanetary Cruise<br>Primary Science | <br>72 months<br>12 months | <br>84 months<br>48 months | <br>7 months<br>26 months | <br>14 months<br>9 months | <br>7 months<br>3 months |
| Number of Instruments | 11 | 12 | 8 | 4 | 6 |
| On-board Data Storage | 1 Gb | 3.5 Gb | 160 Gb | 2 Gb | 2 Gb |
| Data Rate | 200–600 kb/s | 14–165 kb/s | 550–6000 kb/s | 270 kb/s | 128 kb/s |
| Daily Data Volume | 20 Gb | 2 Gb | 70 Gb (avg) | 13 Gb | 0.04 Gb |
| Primary Mission Data Volume | 3.6 Tb | 2.5 Tb | 50 Tb | 3.5 Tb | 0.04 Tb |
| DSN Tracking | 28 tracks/wk (92 d)<br>14 tracks/wk (270 d) | 8 tracks/week | 19 tracks/week | 21 tracks/week | 2 ODY relays/day |
| Science Planning:Execution Cycle | 1 wk: 1wk | 26 wk: 4 wks | 2 wk: 2 wks | 2 wk: 1 wk | 1 day: 1 day |

mission focus will be on the checkout and deployment of all critical flight systems. For the first month of operations, the mission will rely on continuous tracking with 34 m DSN stations. Operations teams will characterize the flight system post-launch. A major maneuver will be needed to remove launch injection errors in the interplanetary trajectory. Real-time initiated commanding predominates during this early period to provide flexibility to respond to unknowns. A transition to sequence-initiated commanding will occur as the transition to cruise completes.

The cruise sub-phase encompasses the gravity assist flybys of Venus and Earth, which are needed to add the necessary energy to the trajectory to reach Jupiter. Each gravity assist will be used to check-out and characterize all instruments and fly-by operating processes and tools. During quiet periods of cruise the operations and supporting teams will be testing and training on the tools and processes to be used for the Jupiter system science and Europa science operations. Cruise sequences will last one to two months during quieter periods, and will last one to two weeks near the Venus and Earth flybys. DSN tracking will be normally twice per week with 8-hour 34 m passes. Tracking will increase to nearly continuous levels in the weeks surrounding major maneuvers and gravity assist flybys.

After the final gravity assist flyby of the Earth in January 2019, the mission operations and science teams and operations centers will begin staffing up in preparation for JOI and science in the Jupiter system and will deploy and test final flight and ground software. While all critical activities for JOI and science operations at Jupiter will have been tested pre-launch, final updates based on post-launch experience and new capabilities will be deployed, and testing and training will be performed to assure mission readiness. DSN Tracking will increase to nearly continuous levels in the two months prior to JOI to support final navigation targeting and to prepare for Jupiter observations and the first Ganymede encounter.

In the Jovian Tour phase, the flight system will make routine and frequent observations of Jupiter and its environment. More detailed discussion of the Jupiter system science scenarios are contained in §4.5.8. There will be opportunities to observe Ganymede, Callisto, and Europa during more than 20 close flybys in this phase. In addition, many more opportunities exist as well to observe Jupiter from less than 1 million kilometers, and Io, Europa, Ganymede, and Callisto from less than 500,000 km. Fly-bys are 1 to 2 months apart early in the phase, becoming a week or less apart as the tour ends. Operations team sizes increase by the end of the tour to support activities in the reduced time between fly-bys and to prepare for Europa operations. The final month prior to EOI will focus on the end-game, the closely timed flybys of Europa setting up the geometry for EOI. Science operations in the end-game will be reduced in complexity in favor of navigation and maneuver activities. Early Jovian Tour sequences will last one to two months with special short term sequences developed for encounters. DSN tracking will be normally one 8-hour 34 m pass per day with 70 m passes near flybys at closest approach. Tracking will increase to nearly continuous levels in the month prior to EOI to support final navigation targeting and prepare for Europa science operations.

The Europa Science phase is one year long. Data acquisition and return scenarios are detailed in §4.5.3 and §4.5.4. This phase represents the accomplishment of all of the high priority science goals of the mission. Data collection spans 4 major campaigns:

- Campaign 1, Global Framework at 200 km orbit for 8 eurosols (~28 days),
- Campaign 2, Regional Processes at 100 km orbit for 12 eurosols (~43 days),
- Campaign 3, Targeted Processes at 100 km for 6 eurosols (~21 days), and
- Campaign 4, Focused Science at 100 km for 74 eurosols (~273 days).

Science data collection is continuous and repetitive with continuous fields and particles, altimetry, thermal imaging, ultra-violet and infra-red spectroscopy profile data collection, along with alternating orbit global imaging and radar sounding. This repetitive data collection represents about 2/3 of the daily average downlink data volume. On orbits when additional data volume is available, targeted data acquisitions comprising IPR profiles, MAC, NAC, UVS and IRS images will be collected. Except for the low rate instruments, all observations will be taken when Earth (and the DSN) is in view, enabling rapid downlink of high rate science data. Sequences for repetitive mapping activities will be uplinked once per week. Lists of targets to be acquired via on-board targeting software, will be developed and uplinked to the flight system every few days. Quick look data processing, mapping assessment, and target selection processes will all be rapid, needing about one day each. Data return will be via continuous 70 m tracking. Data rates will be determined every orbit based on the conditions for DSN elevation angle and Jupiter radio (hot body) noise for that orbit. These variable data rates increase the average data volume returned by nearly 50% over traditional methods. One additional 34 m DSN station will be scheduled each day to allow 2-way Ka-band Doppler tracking for gravity science.

The latter 3/4 of the Europa Science phase will focus on addressing new questions arising from data collected in the first 26 eurosols (92 days) and on characterizing potential landing sites for future missions. Science data collection will be planned for daily 8-hour passes to DSN 70 m stations. The specifics of this approach are to be worked out in greater detail in future studies. The Ka-band gravity science over daily 34 m stations will continue through the entire Europa Science phase. Sequence durations will be increased to 2–4 weeks. Target updates will be uplinked once per week

Extended Europa science could start after the end of the Europa Science phase though it is currently not planned or costed. This phase could focus on localized data acquisition for detailed analysis of questions raised by previous mission results and on additional characterization of potential landing sites.

#### *Flight System Operability Features*

The EE flight system is comprised of a spacecraft and a payload of 11 science instruments. The payload list, operational needs, and data rates are shown in **Table 4.5-2**. The details of the flight system design are in §4.4. The operations scenario trade studies and sensitivities leading to the current design are noted in Appendix G.

The flight system will be continuously nadir pointed while in Europa orbit. This allows the payload to observe the surface continuously and monitor the local environment from a consistent attitude. The HGA will be pointed to Earth continuously via a 2-axis gimbal.

#### *Mission Design*

The cruise, Jovian Tour trajectories and Europa science orbits are described in §4.3 and shown in **FO-2.**

To satisfy the science objectives, the science orbit at Europa will be low altitude (~100–200 km), near circular, high inclination, and have consistent day-to-day lighting. Depending on altitude, there will be 10–11 orbits per day and ground-track speeds will be between 1.2 and 1.3 km per second.

#### *Mission Operations System*

The Mission Operation System (MOS) is comprised of all hardware, software, networks, facilities, people, and processes used to operate the flight system. The MOS includes project specific elements, i.e., GDS and flight teams, elements shared with other projects, i.e., DSN and related services, and those parts of the science teams that are used in the operations of the flight system. A high level data flow diagram showing elements of the flight system and MOS elements is shown in **Figure 4.5-1**.

The MOS functional elements include mission and science planning, sequencing and command processing, telemetry and tracking data processing, data management and archiving, science data processing, navigation, mission monitoring and flight system analysis, and infrastructure support.

Most of the MOS functions planned for the EE use standard implementations and practices and have no unusual issues. The DSN is of concern because of the necessity for 70 m coverage and the recognition that 70 m equivalent downlink capabilities are asserted via guidelines to support this mission, but no detailed, funded implementation plans are in place. Another MOS issue that deserves special attention is that of long-term experience retention. The most challenging activities requiring the highest degree of technical flexibility occur 8 years after launch. While several methods for retaining domain and test knowledge will be needed, one method planned is that of regular and intensive training. Training activities will be planned at

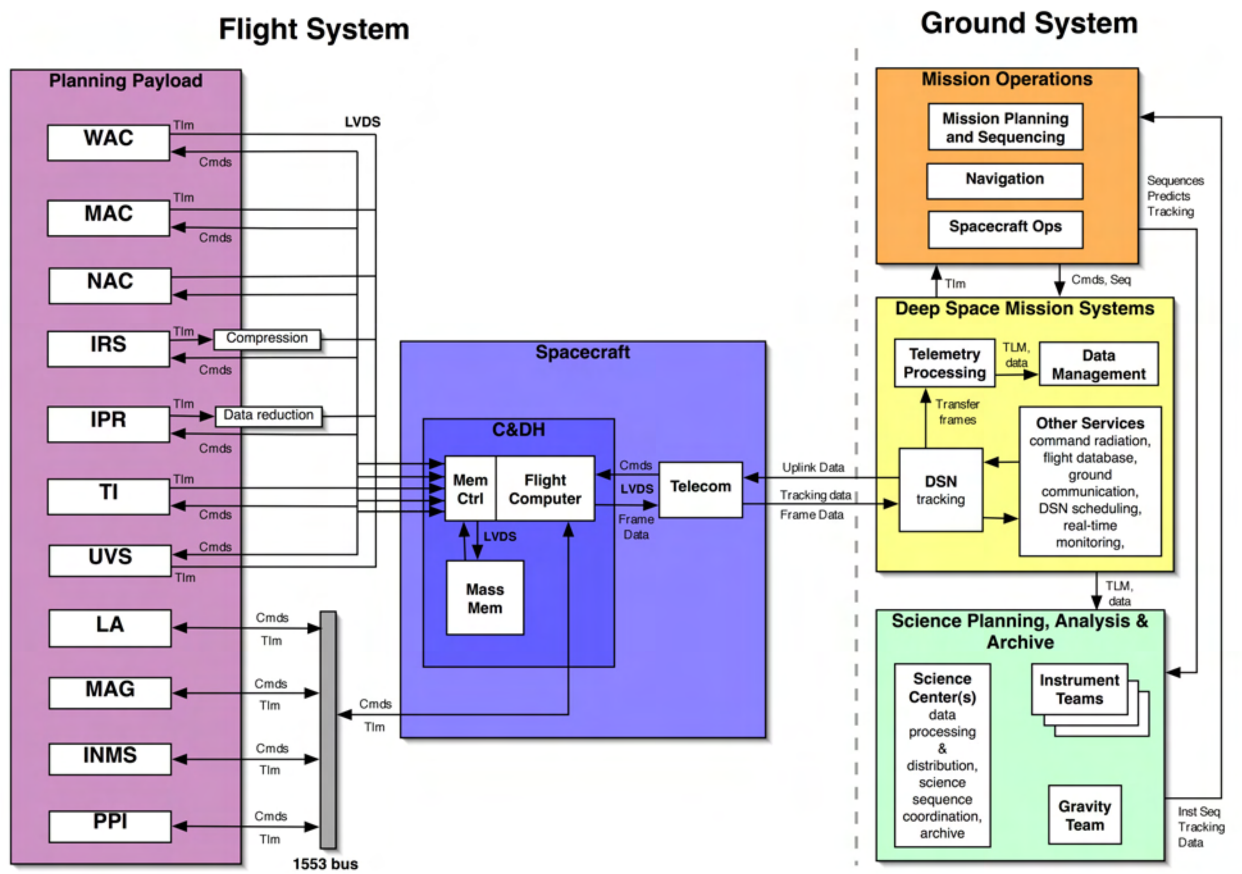



*Figure 4.5-1. End-to-End Data Flow Diagram*

regular intervals and will include post launch training activities and ORTs for each gravity assist encounter, the first Ganymede flyby, JOI, EOI, and Europa science campaigns. Specially designed challenges and flight system anomaly resolution exercises will be needed to keep specialize knowledge fresh and accessible.

### 4.5.3 Science Data Acquisition Scenario

The most challenging issues driving the design and operation of the EE mission arise from the Europa science operations scenarios. This section will focus on describing the science data acquisition strategies and operations scenarios for the Europa Science phase.

During Campaign 1, the flight system orbits at 200 km altitude for 8 eurosols (28 days), and the mission's highest priority data is acquired. During the first 4 eurosols (Phase A), gravity, altimetry, and magnetometry perform a first-order characterization of the ocean. The WAC attains a global color map, and the IPR searches for shallow water. During the next 4 eurosols (Phase B), the WAC acquires a stereo map, and the IPR performs a deep ocean search. Profile-mode observations are performed by the infrared and ultraviolet spectrometers and the thermal instrument. Coordinated targeted observations are performed by the multiple optical remote sensing instruments, and will be targeted using existing Galileo data. Global maps obtained during this campaign will be used to select target observations in later campaigns.

Regional-scale processes are the science emphasis of Campaign 2. Characterization of the gravity field during Campaign 1 allows a relatively stable orbit to be selected for Campaign 2, where the flight system moves to a 100 km altitude orbit for the remainder of the mission. From this distance, optical remote sensing instruments provide 2 times better spatial resolution but only half the longitudinal area coverage. The duration of the campaign is expanded to 12 eurosols (43 days) to accomplish the global mapping and profile distribution goals. Gravity, altimetry, and magnetometry improve their characterization of the ocean. The first 6 eurosols (Phase A) again emphasizes a shallow water search by the IPR and production of a global color map by the WAC, and the second 6 eurosols (Phase B) emphasizes a deep ocean search by the IPR and stereo mapping by the WAC. Profile-mode observations continue by the infrared and ultraviolet spectrometers and the thermal instrument, also now at higher spatial resolution. Global mapping at higher resolutions generates higher data rates. This leaves slightly less data volume per day for coordinated targeted observations.

Campaign 3 emphasizes Targeted Processes. Targets of these synergistic observations are specific high-priority features and terrains recognized from data obtained earlier in the mission. Most of the downlink resource goes to targeted observations that occur during this campaign, bringing the mission's total of acquired targets to more than 1000.

The emphasis of Campaign 4 is to focus in on science discoveries achieved earlier in the mission. The principal priority is to obtain "chains" of targeted observations that attack these new discoveries and newly found priorities based on previous observations. A list of potential observation scenarios includes:

- Create a finer global and regional grid of profiling observations (IPR, IRS, UVS), particularly in discovery areas. This would be routine mapping data collected on particular orbits.
- Continue dual frequency gravity and continuous laser altimetry and fields and particles measurements.
- Collect additional coordinated target sets to investigate new discoveries and priorities and to improve coverage and characterization of candidate future landing sites.
- Collect off-nadir NAC stereo images using left/right roll-only pointing.
- Propellant permitting, plan a campaign of lower altitude operations for improved measurements (altitude depends on propellant allocation and orbit stability analysis through campaign 3).
- Monitor Io and Jupiter for several orbits, 1 to 2 times per week. Date selection gives range of resolution, phase and longitude.

Except for coordinated targeted observations, most science data collection is continuous and repetitive. Particles and magnetic field investigations (MAG, PPI and INMS) operate continuously. The LA and the UVIS profile the surface continuously and the TI, nearly continuously. The IRS, in point mode, profiles the dayside of every orbit. Every other orbit the WAC collects a swath of moderately compressed imaging data over 80% of the dayside. On alternate orbits, the IPR collects a data reduced sounding profile over 90% of the dayside surface.

The WAC images in two modes, full color (3 colors + panchromatic) and panchromatic only modes for stereo mapping coverage (with a factor of 4 difference in data rate). From the early 200 km orbits, the WAC data will be compressed with a slightly lossy factor of 4. From 100 km, a lossless data reduction factor of 3 will be used. At 100 km WAC data rates are twice the rates from 200 km. The early portions of campaigns 1 and 2 will collect global color images from the WAC. After completing the global map, stereo coverage at lower rates will be collected until the end of the campaign. Multiple images allow improved stereo processing.

IPR data are collected in two different modes. The shallow water search mode will be used in the first half of campaigns 1 and 2. The deep ocean search mode will be used in the second half of campaigns 1 and 2. Each mode collects data at 280 kb/s.

The data volumes for the 2-orbit repetitive cycle are allocated based on coverage extent needed. Precise timing is not specified, however. This allows adjustment of the image or sounding start times to allow coverage of both polar regions. These allocations allow close spacing at high latitudes in both hemispheres providing planning margin for the WAC or for radar data processing advantages for the IPR.

The continuous and alternating orbit data collection activities represent about 2/3 of the daily average downlink data volume. The data are collected at low enough rates that most of the data are downlinked in near real-time, requiring very little of the 1 Gb SSR storage capacity. The continuously operating instruments fill the SSR by about 15% during Earth occultations and that is rapidly downlinked after occultation exit. This strategy allows the remaining 1/3 of the daily data volume to be used for coordinated target observations over selected sites at Europa. Either imaging or IPR targets can be acquired at nearly any time in either orbit type.

Figure 4.5-2 shows the 2-orbit cumulative data volume usage for the instruments and the downlink. The SSR state and limits are shown to highlight minute-by-minute usage. The simulation is per minute and does not account for latencies in data transfer, compression or encoding, which are assumed to be small. Estimates are included for orbit period, occultation durations, DSN lockup times and ephemeris timing errors for occultation start/end times. The example is for the beginning of campaign 1 when average downlink rates are lowest. A power profile for the same two orbit scenario can be found in Figure 4.4-7.

There are two types of target data sets, Coordinated Targeted Observations, and Full Resolution IPR. Targeted observations are: MAC monochromatic stereo imaging (orange, 10 m/pixel), IRS imaging (green, 25 m/pixel, 400 wavelengths), UVS imaging (violet, 100 m/pixel), NAC imaging (yellow, 1 m/pixel), and a low-data rate IPR profile (blue, 30 seconds of data at 280 kb/s). The laser altimeter is simultaneously operating in profiling mode. Full resolution IPR data sets are based on 30 sec of data at 30 Mb/s, approaching the 1 Gb capacity of the SSR, and cannot be taken at the same time as coordinated target observations.

Figure 4.5-3 shows a view of the coordinated target observations, with scales based on a 100 km flight system altitude. Each coordinated image represents about 370 Mb of data collected in about 1 minutes' time. The SSR holds this data until it can be downlinked (along with the other data collected). On average, about one target per orbit will fit in the data stream. Two targets can be collected at a time for delayed downlink. The IPR full resolution targets take 900 Mb at a time. Only one of these can be collected at a time. More than 1000 targets (both types) will be returned during the Europa Science phase.

Target acquisition will be via on-board, ephemeris driven software. The flight system will have a shape model of Europa and an orbit ephemeris. Targeting software will calculate the precise time to image a selected site (lat, lon, alt) as it passes into the instrument field of view. Updated ephemeris files will be uplinked to the flight system as needed to maintain the desired accuracy. Lists of targets to be acquired and corresponding imaging parameters will be developed and uplinked to the flight system every few days. To speed up

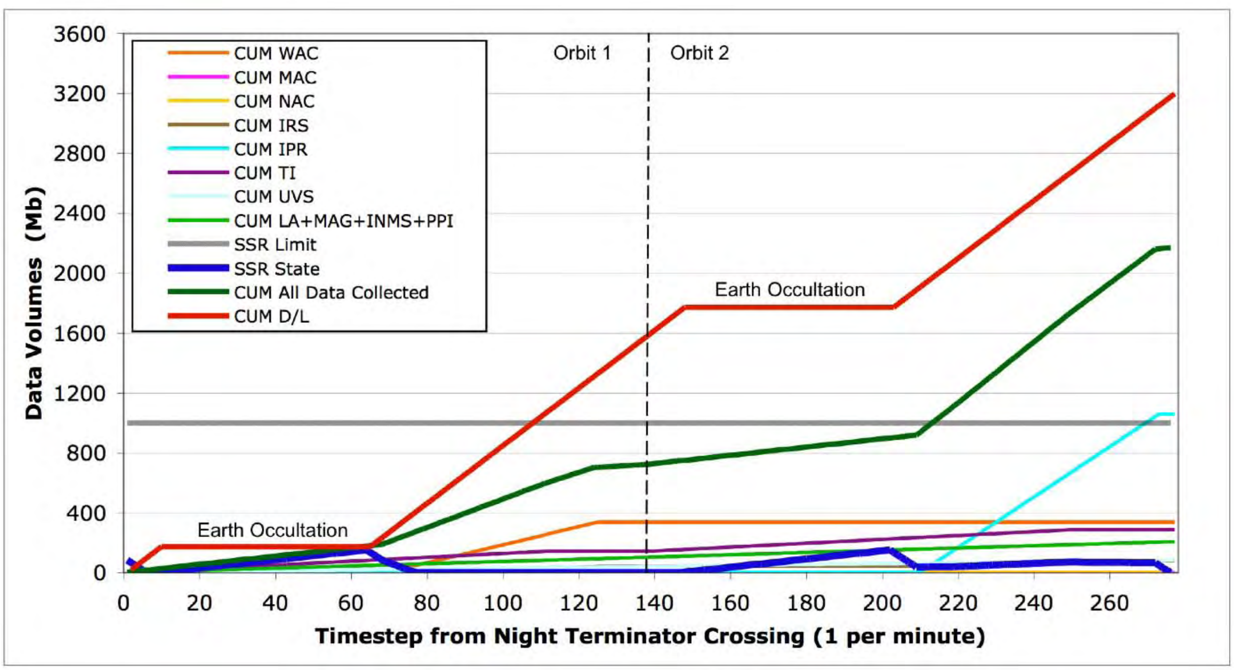
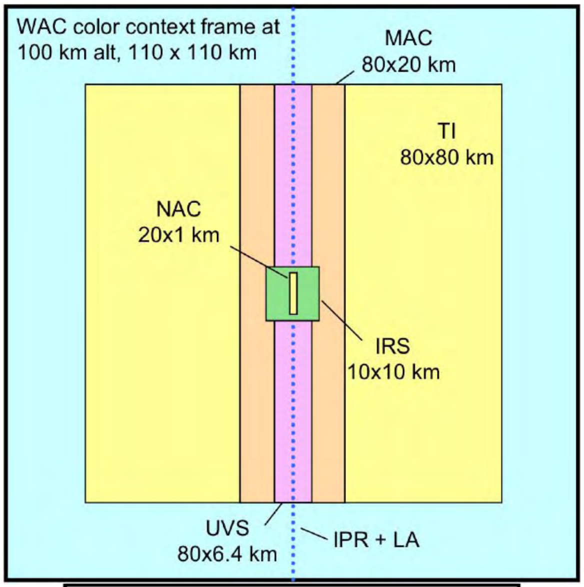



*Figure 4.5-2. Cumulative data volume for a 2-orbit repeating cycle*




**Data Volume for Coordinated Images**

| | | |
|---|---|---|
| WAC 110x110 km* | 15 | Mb |
| MAC 80x20 km | 45 | Mb |
| NAC 20x1 km | 60 | Mb |
| IRS 10x10 km | 128 | Mb |
| UVS 80x6.4 km | 120 | Mb |
| TI 80x80 km | 3 | Mb |
| IPR+LA Profile* | 17 | Mb |
| Total | 358 | Mb |

* Data collected in routine mapping

*Figure 4.5-3. Coordinated Target Images*

the selection and file development process, targets can be selected by ground software using data volume modeling and priority based selection criteria. Similar to MER and MRO science prioritization processes, targets and priorities will be selected by a subset of the PSG and placed in the target data base. New targets can be added at any time and software target lists will be reviewed by science teams before uplink.

Data reduction and compression strategies vary by instrument and by campaign. **Table 4.5-2** shows payload operational characteristics including the data rates, data reduction factors, and instrument duty cycles and data volume collected for the 2-orbit repetitive cycle and for the 200 km and 100 km orbits.

Mapping sequences will be updated and uplink products built and tested once per week. The data collection profiles and patterns (orbit repeat intervals, collection lengths, start locations, etc.) will be based on previous week's planning reflecting the adjustment of pre-arrival plans. The collection profiles will be developed from activity template menus to reduce development and verification schedules. The short planning duration is needed to accommodate large ephemeris errors based on poor gravity field knowledge early in the orbiting mission. As mapping progresses, the short planning cycle enables the adjustment of data collection profiles to avoid redundant coverage or recover observation opportunities lost due to telecom link outages, spacecraft engineering events (e.g., OTMs), or safing events. Routine engineering activities such as OTMs, reaction wheel momentum desaturation, and health and safety activities will be planned and uplinked to the orbiter on a weekly basis, coinciding with mapping sequence uploads.

Coordinated target observations are planned several times per week based on the remaining data volume resources from the weekly mapping sequences. A target data base will be maintained with prioritized target locations (lat, lon, alt, extent). Based on available data volume, SSR state, DSN schedule, ground track locations, and target priority, targets will be selected, by ground software, for one to two day planning cycles. Only targets predicted to pass under the nadir track of the orbiter will be considered for selection. Target lists will be sent to the orbiter and will be executed via ephemeris driven on-board sequencing software. The short planning duration is needed to accommodate large ephemeris errors based on poor gravity field knowledge early in the orbiting mission. The number of targets will vary with available data volume but will average one to two targets per orbit.

#### 4.5.4. Data Return Strategy

Data acquired by the science instruments will either be stored on the SSR or transferred directly to Earth in the downlink stream. The C&DH will prepare and/or process the science data (compression and frame encoding) then route through the SDST for downlink. All acquired data will be transmitted to the DSN. For each week during the mission, data volume estimates will be provided to the ops teams based on the scheduled DSN tracking for the period. The data volume estimates will be used to verify the science activity plans and

***Table 4.5-2.*** *Payload Operational Characteristics*

| Science Instruments | Operational Characteristics | | 200 km Rate (Mb/s) | 200 km Duty Cycle | 200 km Comp Factor | 100 km Rate (Mb/s) | 100 km Duty Cycle | 100 km Comp Factor |
|---|---|---|---|---|---|---|---|---|
| Telecom system | Ka-band, 8 hours/day<br>X-band, 24 hours/day | | 2-way Doppler | | | 2-way Doppler | | |
| WAC | Provides global color and stereo maps. | Color | 0.4 | 40% | 4 | 0.8 | 40% | 3 |
| | Operates every other orbit. | Panchromatic | 0.1 | 40% | 4 | 0.2 | 40% | 3 |
| MAC | Used for targeted modes. | | 3 | - | 4 | 6 | - | 3 |
| NAC | Used for targeted modes in framing or pushbroom modes. | | 15 | - | 4 | 30 | - | 3 |
| IRS | Point mode, every orbit, for distributed global profiles. | Point Mode | 0.03 | 40% | 2.5 | 0.1 | 40% | 2.5 |
| | Target mode for 10km x 10 km full spectrum images. | Target Mode | 30 | - | 2.5 | 30 | - | 2.5 |
| UVS | Permits both nadir and limb viewing. Point mode, every orbit, for distributed global profiles. | Point Mode | 0.005 | 40% | 1 | 0.005 | 40% | 1 |
| | Target mode for full spectrum images. | Target Mode | 4 | - | 2 | 4 | - | 2 |
| LA | Continuous Operation | | 0.012 | 100% | 1 | 0.012 | 100% | 1 |
| IPR | Alternating orbits for distributed global profiles. Modes for shallow water and deep ocean searches. | Profile Mode | 0.1 | 40% | 2.5 | 0.1 | 40% | 2.5 |
| | Full resolution target mode | Target Mode | 30.0 | - | 1 | 30.0 | - | 1 |
| TI | Point mode, every orbit, for distributed global profiles. | | 0.043 | 100% | 2 | 0.043 | 100% | 2 |
| MAG | Dual magnetometers; 10 m boom. | | 0.004 | 100% | 1 | 0.004 | 100% | 1 |
| INMS | Sensitive to low gas concentrations. | | 0.0015 | 100% | 1 | 0.0015 | 100% | 1 |
| PPI | Includes ion species. | | 0.002 | 100% | 1 | 0.002 | 100% | 1 |

to determine data volume availability for target selection in the coming one week period.

The SSR will function as a short term buffer for data acquired while the flight system communications are occulted by the Earth or when data is collected at aggregate rates exceeding the downlink rate. For most orbits, 10–15% of the SSR will be needed for storing data from the continuously operating instruments while in occultation. Once or twice per orbit, a coordinated target observation will be collected and stored in the SSR. The target observation sizes are constrained to fit, with margin, into the SSR. The data will be queued with all other data for subsequent downlink. Buffer architectures and queuing schemes have not been considered. The small SSR can be used for longer term storage of very small amounts of high priority data. For the most part, data collected will be downlinked in the order it was collected. No facility for re-transmission, data editing, or for accommodating long DSN gaps is possible. It is assumed that all data transfers, compression, encoding, and other process steps will not cause significant latencies in the data flow and therefore congestion in the SSR.

The current telecom design provides 200 kb/s to a 70 m DSN antenna at a range of 5.5 AU (at 20 deg elevation and 90% weather). Using an operational technique to transmit at the best achievable rate after each orbit occultation, the system takes advantage of increased elevation angles at DSN sites during a tracking pass as well as increasing rates when Europa is farthest away from Jupiter's hot body noise. These advantages increase the average data rate to 320 kb/s at 5.5 AU with an orbit-to-orbit variation from 160 kb/s to 410 kb/s. **Figure 4.5-4** shows the orbit-to-orbit variations of data rates for the first week of operations at Europa. Subsequent weeks will have a similar pattern but the decreasing Earth range will increase the average rates. **Figure 4.5-5** shows the data rates for the Jovian and Europa Science phases. **Figure 4.5-6** shows the daily data volumes available from the 34 m and 70 m stations.

*DSN Scheduling Rationale*

Similar to other deep space missions with long cruises, EE uses economical DSN tracking in the Interplanetary phase. The planned DSN coverage is shown in **Table 4.3-4**. Semi-weekly tracking is used to perform navigation and maintain the health of the flight system. Additional tracking will be scheduled to support spacecraft and instrument calibration activities, science operations at the gravity assist flybys of Earth and Venus, and maneuvers to refine trajectory targeting before and after each flyby.

About 18 months before JOI, tracking is increased to provide additional navigation analysis and allow early Jovian system science and commanding support for the final preparation for JOI and the Jovian Tour. JOI approach is accompanied with significantly increased tracking and Delta DOR tracks to ensure accurate JOI entry targeting. 70 m tracking support for the JOI burn activities will be scheduled to augment the 34 m tracking to provide the best telemetry reception available at Jovian ranges.

Once in Jupiter orbit, tracking consists of daily 34 m passes, intended to support science data collection and navigation. This routine is augmented around fly-bys to support the final navigation analysis and fly-by science. During and right after each fly-by, tracking is augmented with several tracks of DSN 70 m antennas to maximize science return.

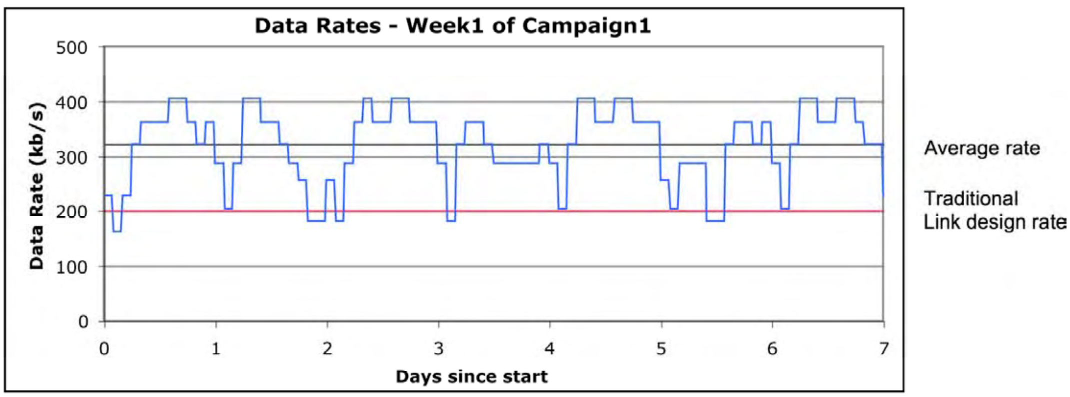



*Figure 4.5-4. Data Rates Variations After Each Occultation*

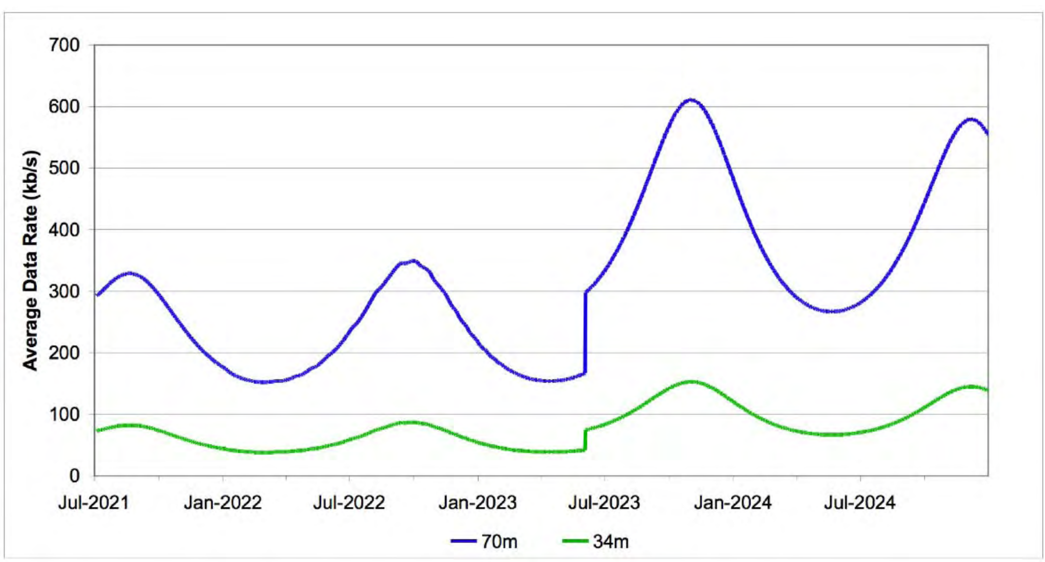



*Figure 4.5-5. Average Data Rates for 34 m and 70 m Stations*

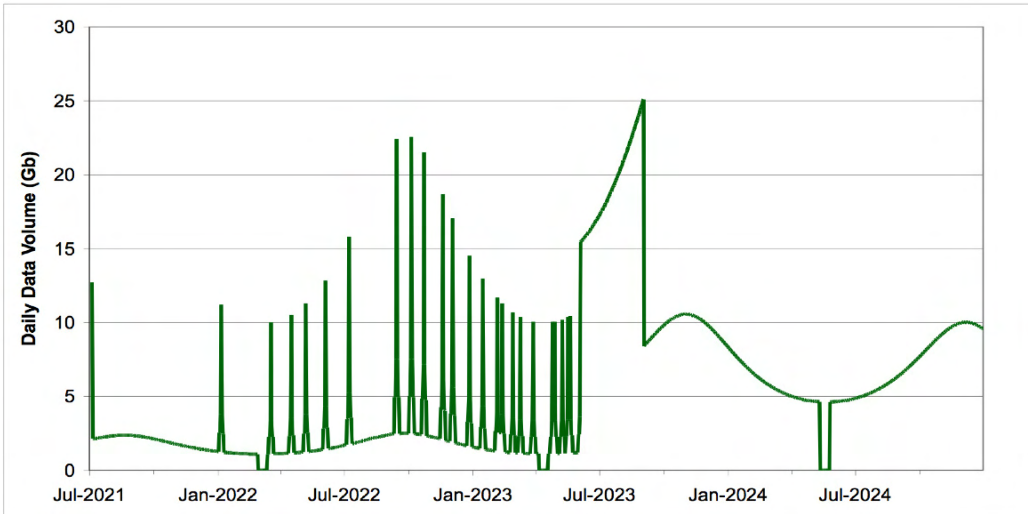



***Figure 4.5-6.*** *Daily Data Volumes*

One month prior to and after EOI, 70 m continuous tracking will be scheduled to support critical trajectory activities. 70 m continuous coverage will be scheduled for the remainder of the first 92-days to meet science coverage and targeting goals. In addition to the 70 m tracking, after EOI there will also be 8 hours per day of 34 m Ka-band 2-way tracking to support Europa radio science activities. X- and Ka-band transponders are operated independently of each other and use independently scheduled DSN resources. Ka-band uplink and downlink signals are not modulated for commands or telemetry so no command interference is possible during simultaneous operations.

After 92 days, daily 8-hour 70 m passes will be used to support continued observations, return additional science data and support the navigation activities needed to maintain a stable orbit around Europa. This daily coverage will be continued into an extended mission should that be approved.

#### 4.5.5 Data Processing and Science Planning

Because of the short mission, uncertainties in the gravity field (and therefore uncertain predictions for the flight system location one week in the future), and the potential for reactions to radiation induced events and degraded performance, the rapid assessment of science data products, and rapid planning and replanning of science data collection will be needed over time spans of about 1 week.

Recent experience from MRO and MER has shown that rapid data delivery and quick look processing as well as rapid decision making and activity planning are possible for the planning schedules needed by the Europa Explorer mission. MRO has demonstrated the long term processes for delivering ~100 Gb per day to distributed science centers. Those science centers have shown that they can quickly produce planning quality data products in one or a few days. MRO target selection processes take 3 days for nadir based targets and 1 week for complicated off-nadir coordinated targets. MRO acquires 10 times more targets per day than EE is currently considering. MER has shown that one day turn around of science products to next day activity plans is possible over mission lifetimes as long as or longer than EE's.

EE science activity planning and replanning flexibility will be needed to respond to flight system anomalies, timing errors, and non-deterministic processes. It will be needed to respond to short term science discoveries as well, such as detected plumes and hot spots. For the most part, response to science discoveries will take the form of re-allocating target data priorities in future days to observe previously unconsidered sites.

#### 4.5.6 Mission Performance

The allocation of data volume resources and targets acquired are shown in **Table 4.5-3**. A preliminary discussion of the margin (data rates, data volumes, schedule) with respect to science goals is included.

**Figure 4.5-7** shows the coverage of Europa during campaign 1 from the 200 km orbit. Complete color WAC coverage is obtained in the first 3 eurosols. Another complete WAC map (in pan-chromatic mode) to be used for stereo topography takes another 3 eurosols. Additional stereo coverage would be acquired during the two remaining eurosols to improve stereo products.

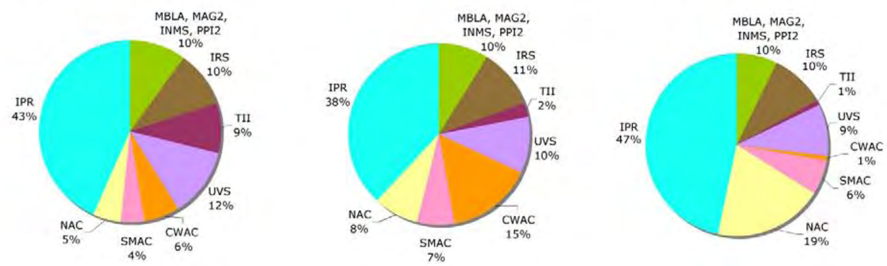
**Figure 4.5-8** shows the coverage of Europa during campaign 2 from the 100 km orbit. Complete color coverage is obtained in the first 7 eurosols. Because of the significant overlap in the first 7 eurosols, stereo coverage will be complete in another 4–5 eurosols.

Ground track coverage can be used as a proxy for the coverage of the profiling instruments. **Figures 4.5-9** and **4.5-10** show the buildup of ground tracks in campaign 1 and campaigns 1, 2 and 3, respectively. The white box overlay is a 10 × 10 degree square with 1 degree tick marks to show that ground track coverage will be better than the 25 km spacing requirement at the equator by about a

***Table 4.5-3.*** *Summary of Data Volumes and Targets Acquired by Phase and Instrument*

| | Campaign 1: Global Framework | | | | | | Campaign 2: Regional Processes | | | | | | Campaign 3: Targeted Processes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference S/C (Baseline) | Glob data per day (Gb) | Targ data per day (Gb) | % tot vol | Avg Targ per day | Cam Tot Targ | Cam Tot Vol (Gb) | Glob data per day (Gb) | Targ data per day (Gb) | % tot vol | Avg Targ per day | Cam Tot Targ | Cam Tot Vol (Gb) | Glob data per day (Gb) | Targ data per day (Gb) | % tot vol | Avg Targ per day | Cam Tot Targ | Cam Tot Vol (Gb) | Total Targets | % total vol | Total Vol (Gb) |
| **Data Volume** | 10.7 | 6.6 | | | | **483** | 11.7 | 7.5 | | | | **804** | 3.1 | 20.0 | | | | **486** | | | **1773** |
| **WAC** | 1.1 | | 6% | | | **31** | 2.9 | | 15% | | | **122** | 0.2 | | 1% | | | **3** | | 9% | **156** |
| **MAC[1]** | 0.0 | 0.7 | 4% | 12 T | **333** | **15** | 0.0 | 1.3 | 7% | 11 T | **441** | **53** | 0.0 | 1.5 | 6% | 12 T | **254** | **30** | **1028 T** | 6% | **98** |
| **NAC[2]** | 0.0 | 0.9 | 5% | 12 T | **329** | **18** | 0.0 | 1.6 | 8% | 11 T | **441** | **66** | 0.0 | 4.5 | 19% | 30 T | **630** | **95** | **1400 T** | 10% | **179** |
| **IRS[3]** | 0.4 | 1.3 | 10% | 12 T | **328** | **54** | 0.7 | 1.3 | 11% | 11 T | **441** | **86** | 0.7 | 1.6 | 10% | 12 T | **254** | **47** | **1024 T** | 11% | **187** |
| **IPR[4]** | 5.5 | 1.8 | 43% | 3 T | **70** | **218** | 5.5 | 1.8 | 38% | 2 T | **84** | **306** | 0.0 | 10.8 | 47% | 12 T | **252** | **227** | **406 T** | 42% | **750** |
| **TI** | 1.5 | | 9% | | | **42** | 0.5 | | 2% | | | **19** | 0.2 | | 1% | | | **4** | | 4% | **65** |
| **UVS** | 0.4 | 1.6 | 12% | 14 T | **383** | **58** | 0.4 | 1.5 | 10% | 13 T | **525** | **81** | 0.4 | 1.7 | 9% | 14 T | **298** | **45** | **1205 T** | 10% | **184** |
| **LA** | 1.0 | | 6% | | | **29** | 1.0 | | 5% | | | **44** | 1.0 | | 4% | | | **22** | | 5% | **94** |
| **MAG** | 0.3 | | 2% | | | **10** | 0.3 | | 2% | | | **15** | 0.3 | | 1% | | | **7** | | 2% | **31** |
| **INMS** | 0.1 | | 1% | | | **4** | 0.1 | | 1% | | | **5** | 0.1 | | 1% | | | **3** | | 1% | **12** |
| **PPI2** | 0.2 | | 1% | | | **5** | 0.2 | | 1% | | | **7** | 0.2 | | 1% | | | **4** | | 1% | **16** |

[1] MAC targets are 1 minute duration (71 km @200 km, 78 km @100 km)
[2] NAC targets are 15 seconds duration
[3] IRS targets are each 400x400 pixels, 128 Mb
[4] IPR targets are each 30 Mb/s x 30 s, 900 Mb



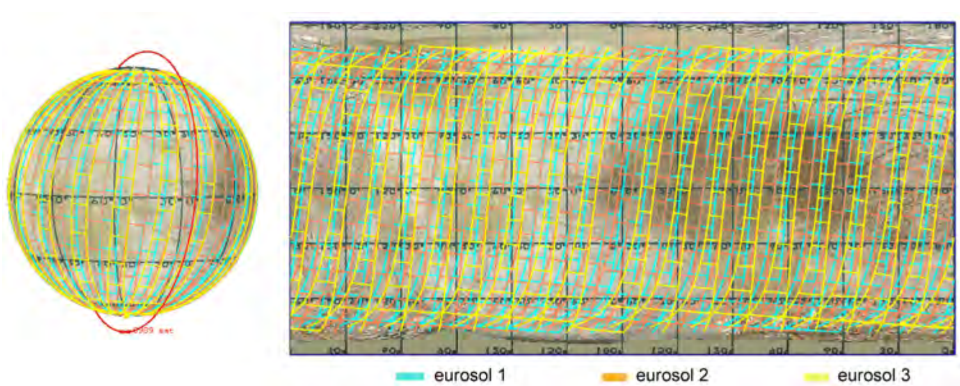




***Figure 4.5-7.*** *WAC coverage in Campaign 1*

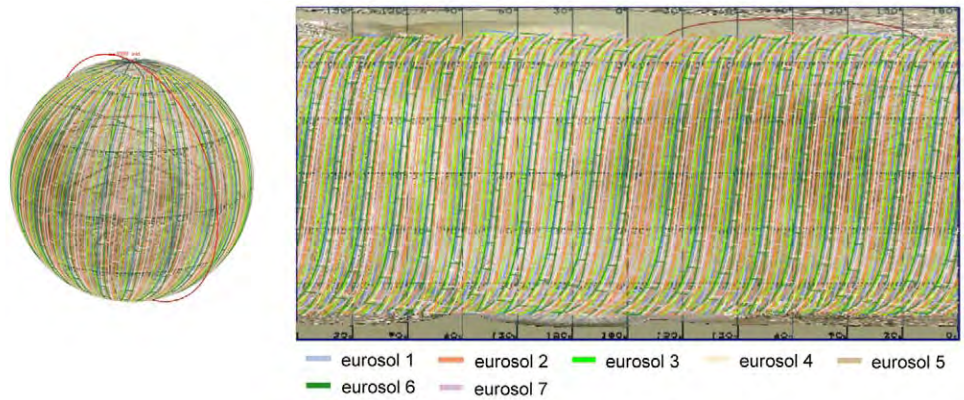



***Figure 4.5-8.*** *WAC coverage in Campaign 2*

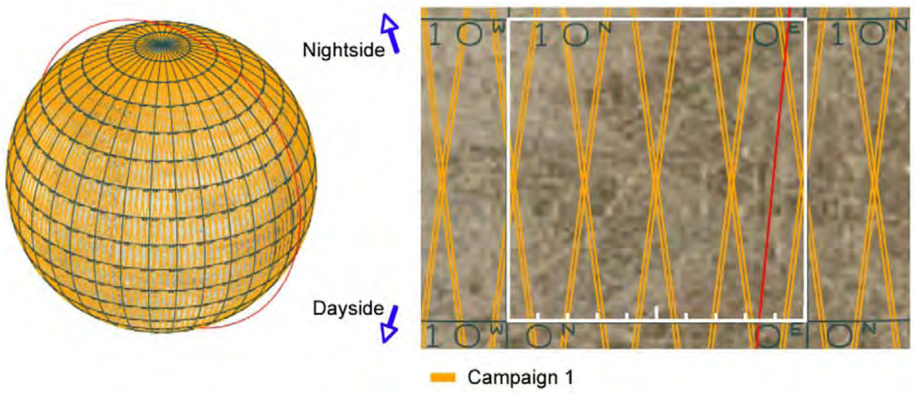



***Figure 4.5-9.*** *Ground Track coverage in Campaign 1*

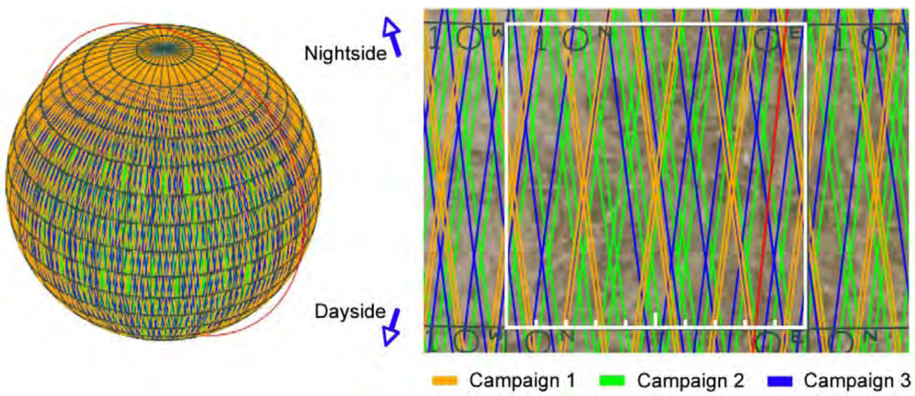



***Figure 4.5-10.*** *Ground Track coverage in Campaigns 1,2,3*

factor of 4 (1 deg = 27 km at Equator). IPR profiles will have half the number of ground tracks due to the alternating orbit data collection strategy. IPR tracks will exceed requirements by a factor of 4 also.

**Figure 4.5-11** shows the cumulative data volume for the Jovian and Europa phases of the mission. The primary Europa Science phase is highlighted.

#### 4.5.7 Trade Studies

Summaries of the results of key trade studies and analyses are provided here. For more details see Appendix G.

*Floor vs Baseline Science Scenario*

The science scenario development process started with a smaller payload and simpler science goals (than the baseline) to define a reasonable floor mission scenario. A simple

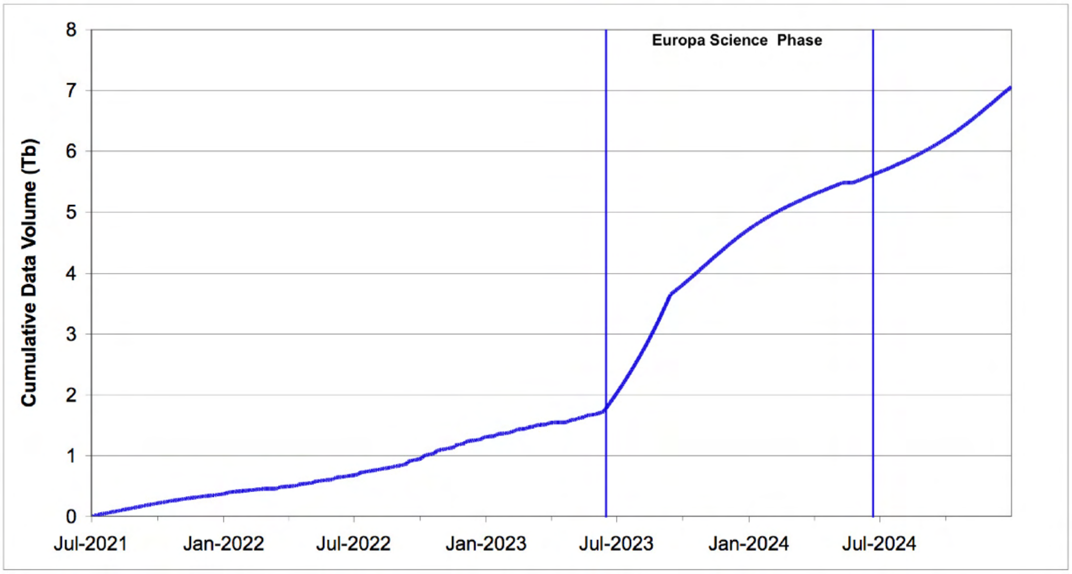



***Figure 4.5-11.*** *Cumulative Data Volume Returned*

data acquisition simulator was developed to measure the performance of the operations scenarios. The flight system requirements for telecom data rates and data storage needs were defined to meet floor data volume requirements. Concurrently with scenario development, the SDT developed the traceability and value matrices. Initial versions of these products were developed using early versions of science scenarios.

With basic floor scenarios in place, the performance estimator was updated with the baseline payload and initial science collection scenarios were evaluated. Operations scenario trades were then used to define the telecommunications and data storage needs of the baseline flight system.

Targeting strategies evolved with the maturing of the operations scenarios to include a strategy for obtaining coordinated targets. After the baseline data acquisition scenario was determined, the floor scenario was re-evaluated and the flight system requirements were balanced to meet the science goals. The flight system mass, power and data rate requirements were significantly reduced.

*Data Collection Strategies*

For global mapping and global distribution of IPR profiles, considerable competition for data storage and downlink resources was an issue. Each instrument could build up global coverage in a single eurosol. A trade study was performed to simulate different options to share the downlink data volume between the WAC, the IPR and the other profiling and continuous operation instruments to meet the high priority science goals. Options included increased data reduction to lower data volume per orbit, time sharing via sequential campaigns (one or two eurosols per campaign) for each investigation, and interleaving data takes on alternating orbits. Based on analysis, both investigations were able to build up global coverage at constant and acceptable rates without compromising data quality or campaign goals using the alternating orbit strategy. Other investigations were improved by the lower average consumption of data volume by the WAC and IPR. Specifically IRS, and later UVS, were able to collect profiles more frequently and the thermal instrument data rate was increased. The strategy ultimately consumed roughly 2/3 of the daily data volume, enabling a gradual accumulation of coordinated targets, with an average of one per orbit, at all stages of the science phase.

*DSN Sensitivity Study*

The DSN sensitivity study examined the trades among DSN resources and the impacts to the flight system and operations scenarios to maintain the science mission goals. The study considered the Europa Science phase with particular emphasis on the goals for the first 92 days. Primary consideration was given to options to reduce 70 m tracking needs.

Cases studied were: Baseline–Continuous tracking with 70 m stations plus a 34 m station for Ka-band radio science; 2 cases with two 70 m tracks per day with a 34 m station for both radio science and telemetry; and 2 cases with one 70 m track and one 34 m track per day. In each tracking scenario, the 2 cases examined improvements to the flight system or increases to the mission duration.

The study showed that the results are unaffected by short term scheduling interruptions. Onboard downlink priorities can be used to reduce targeting activities, then IPR swaths, then mapping data collection. There is no need to reduce Laser Altimeter or fields and particles data collection if tracking gaps are less than a day or two.

A small increase in mission duration could occur if tracking gaps are chronic (> 1 per week). Larger SSR capacities are needed for significant, routine, and scheduled DSN tracking gaps: 3 times larger if two 70 m tracks per day (with one 34 m for radio science and data) are used; 5 times larger if only one 70 m track per day (+ one 34 m) is scheduled.

For Campaign 4 with one 70 m and one 34 m track per day, 5–15 targets per day are achievable depending on SSR capacity.

If the 70 m or equivalent capability is not available and is known prior to CDR, the flight system power could be increased by 1 RPS and the HGA diameter could be increased to preserve the science data acquisition scenario. The Ka-band system could be improved to send telemetry (slight power increase) and the mission increased to 6 months.

If the 70 m or equivalent capability is not available and is not known until after CDR, the science operational scenarios will be redesigned and the 34 m meter network will be used, with some use of arrays, and the mission would need to increase duration to 9–12 months. In this case the highest priority goals would be achieved after 4–6 months

*Mass memory size*

The mass memory trade study examined the breakpoints in the mission operations scenarios where increased SSR capacity enabled useful capabilities. The study considered additions to the SSR design concept as units at the card level. The cards in the design concept have 1 Gb of useful mass memory per side for a total of 2 Gb per card.

The breakpoints examined were the mass memory needed to enable large gaps in DSN tracking coverage, science data collection opportunities, and operability improvements.

Tracking gaps of 2 hours, 4 hours, and increments of 8 hours were considered as representing 1 orbit, 2 orbits and whole tracking passes respectively.

Science opportunities were limited to the size of coordinated targets. In the baseline mission, imaging targets are less than 400 Mb whereas radar targets are 900 Mb and the baseline SSR cannot store both at the same time. The next useful breakpoint is the ability to collect and store both target types simultaneously.

The operability improvements are generally considered to be retransmission of data lost in downlink, and the capability to post process data on-board for data editing or prioritization. Latency for retransmission was assumed to be 8 hours.

The trade study concludes that for the addition of a single card (3 Gb science data allocation), the simultaneous collection of imaging and radar targets and the accommodation of 2-hour tracking gaps is enabled. With 2 added cards (5 Gb), the mission can perform routine mapping and accommodate a planned DSN gap of 8 hours. With 3 added cards (7 Gb), routine mapping and full target data acquisition are enabled in the presence of an 8-hour tracking gap. The retransmission of data is enabled with the addition of 4 cards to the SSR giving a 9 Gb science allocation. This is also the SSR size deemed useful for Jupiter system tour science.

#### 4.5.8 Jupiter System Scenarios

While the flight system is in Jupiter orbit during the tour, each Jupiter closest approach typically happens within a day or two of a satellite gravity assist flyby or encounter. Orbits with gravity assist flybys have additional DSN tracking coverage scheduled. During weeks with satellite encounters, the tracking coverage supports collection of approximately 30 Gb per day. During closest approach the SSR can support collection and return of around 2–3 Gb at ranges less than 10,000 km. The remaining downlink data volume capacity can be divided between far encounter observations (between 10,000 and 100,000 km), Jupiter observation opportunities, and non-targeted opportunities to observe other satellites at ranges of between 100,000 and 500,000 km. Non-targeted means they are geometrically opportunistic and have no impact on the vehicle flight path. Standard DSN coverage during weeks without gravity assist flybys gives downlink capacity between 5 and 10 Gb per day. The Jupiter opportunities are well distributed across the tour, facilitating observation of changing phenomena that span the length of the 23-month tour. **Table 4.5-4** summarizes the number and characteristics of the Jupiter observing, gravity assist encounter, and not-targeted observing opportunities during the tour.

Several feasibility level analyses were conducted to explore the usefulness of EE payloads during gravity assist encounters. An example of the ground tracks for the tour encounters with Ganymede is shown in **Figure 4.5-12**. The EE payload is intended to collect data in a close near-circular orbit of Europa. Ground speeds, altitudes, and lighting conditions are consistent in Europa orbit but vary drastically for flybys. Furthermore, to effectively use some of the instruments, flight system slews may be needed. Two flyby examples were studied to determine how, generally, the observations might be acquired. **Figure 4.5-13** shows a representative timeline of a coordinated target observation set (similar to those used in Europa orbit) that could be obtained during a flyby. The example is a low altitude, fast flyby with ranges less than 100,000 km for over 20 hours. For the encounters examined, slew rates to maintain tracking were within reasonable limits compared to conditions in Europa orbit. An alternating imaging vs IPR strategy was employed because of data volume constraints. SSR capacity was the primary constraint to encounter data collection but was less so for non-targeted encounters and Jupiter observations. In all cases, flybys will be conducted within the relevant PoI requirements for planetary protection (e.g. $10^{-4}$ for Europa), by agreement with the NASA PPO.

## 4.6 Planetary Protection

### 4.6.1 Overview of Planetary Protection

Planetary protection (PP) requirements for Europa are a significant challenge. The final fate of the EE, impacting on the Europan surface, means that the mission will be classified as category IV under current COSPAR and NASA policy [*COSPAR 2002*].

The approach to planetary protection compliance for the EE mission concept can be summarized as follows:

- control bioburden (by sterilization processing before launch) for those areas not receiving a sterilizing radiation dose in the Jovian environment (principally shielded radiation sensitive flight system hardware)
- allow radiation from the Jovian environment to sterilize the remainder of the flight system during the mission, prior to Europa orbit insertion (EOI).

This approach is in contrast to those for current projects with significant PP requirements, Juno and MSL. In summary, for the Juno case, the PP requirement is met by i) impact with Jupiter (nominal) or ii) avoidance of (accidental) impact on Europa until after the spacecraft will have received a sterilizing dose of radiation in the jovian environment (non-nominal). In comparison with MSL, the EE bioburden requirement is more stringent than for Mars, but EE can take credit for bioburden reduction on spacecraft surfaces following launch, due to sterilizing effect of the jovian radiation environment. As

***Table 4.5-4.** System Science Observing Opportunities*

| | Opportunities | Ranges (km) | Phase angles (deg) | Ground Speeds (km/s) |
|---|---|---|---|---|
| Jupiter | 40 | 560,000 – 1,000,000 | 10 – 100 | |
| Encounters | | | | |
| *Callisto* | 4 | 370 – 3600 | 80 – 120 | 2.8 – 4.7 |
| *Europa* | 5 | 100 – 2800 | 60 – 100 | 0.4 – 1.9 |
| *Ganymede* | 14 | 450 – 8050 | 70 – 170 | 1.2 – 6.9 |
| Non-Targeted Encounters | | | | |
| *Callisto* | 1 | 325,000 | 70 | |
| *Europa* | 13 | 107,000 – 460,000 | 5 – 135 | |
| *Ganymede* | 7 | 28,000 – 430,000 | 55 – 114 | |
| *Io* | 17 | 276,000 – 490,000 | 8 – 174 | |

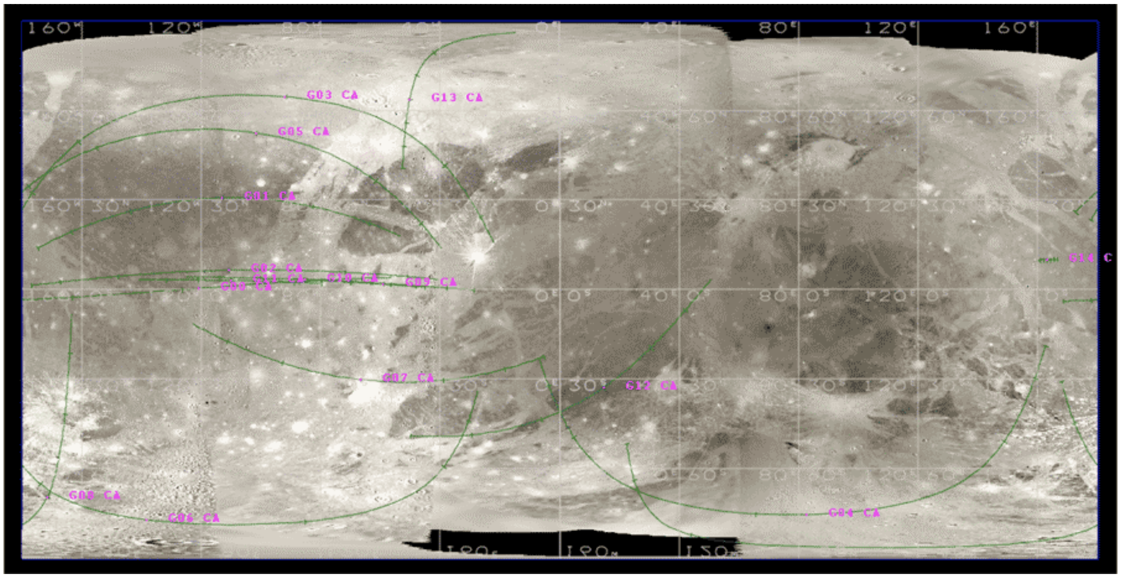


***Figure 4.5-12.*** *Ganymede Flyby encounters*

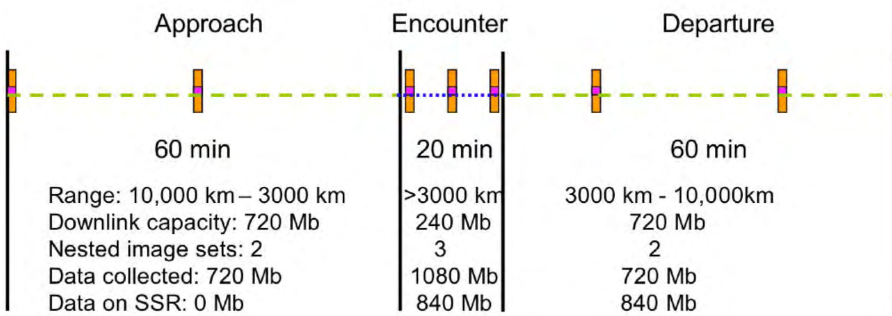



***Figure 4.5-13.*** *Example encounter timeline with coordinated target observation data sets*

a result, the EE PP implementation is an activity of similar complexity to MSL, but requiring a different approach.

However, the study team has specifically sought and gained the support of the NASA PPO for the approach presented, given that the specific requirements for Europa can be met [*Conley 2006*].

#### 4.6.2 PP Requirements

Current PP policy (NPR8020.12C, 2005) specifies requirements for Europa flyby, orbiter, or lander missions as follows:

> *Methods…including microbial reduction, shall be applied in order to reduce the probability of inadvertent contamination of an Europan ocean to less than 1 × 10$^{-4}$ per mission. These requirements will be refined in future years, but the calculation of this probability should include a conservative estimate of poorly known parameters and address the following factors, at a minimum:*
>
> a. *Microbial burden at launch.*
>
> b. *Cruise survival for contaminating organisms.*
>
> c. *Organism survival in the radiation environment adjacent to Europa.*
>
> d. *Probability of landing on Europa.*
>
> e. *The mechanisms of transport to the Europan subsurface.*
>
> f. *Organism survival and proliferation before, during, and after subsurface transfer.*

In addition, there are requirements to avoid harmful contamination of any other of the Jovian satellites.

#### 4.6.3 PP Technical Approach

The probability of contamination, $P_c$, for a Europan mission, is dependent on the following terms [*Space Studies Board 2000*]:

- Microbial bioburden at launch (N, measurable by classical bioassay)
- Probability of cruise survival ($P_{cs}$, estimable, but typically a small reduction factor)
- Probability of Jovian Tour survival ($P_{rad}$, estimable based on flight system design and radiation dose effects)
- Probability of landing on Europa ($P_e$, =1 for EE)
- Probability of transport to the Europan sub-surface ($P_t$, an item difficult to estimate)
- Probability of organisms' survival, dispersion and proliferation ($P_g$, an item difficult to estimate)

This will be interpreted for EE as:

$$P_c = N \times P_{cs} \times P_{rad} \times P_e \times P_t \times P_g \leq 1 \times 10^{-4}$$

Based on guidance from the PPO, the $1 \times 10^{-4}$ requirement highlighted in the groundrules is acceptably met by ensuring that the flight system has zero survivor organisms at the earliest credible encounter point for Europa, which is EOI. This approach removes many of the poorly defined/debatable factors in the probability relationship, which simplifies to a probability of a single survivor contaminant organism at EOI requirement $P_{c[EOI]}$:

$$P_{cEOI} = N \times P_{cs} \times P_{rad} \leq 1$$

Suitably conservative figures will be adopted for $P_{cs}$ and $P_{rad}$, based on the actual organisms present, whereas N will be obtained from direct biological measurement and subsequent application of sterilization processing, and conservative radiation exposures. For initial analysis purposes, and based on the radiation study for this report (Appendix C), the following values are obtained: > 60 Mrad at the flight system surfaces (inside thermal blankets, taken to be equivalent to 1 mil aluminum), and ~6.1 Mrad inside 15 mils aluminum at the end of the jovian tour (prior to EOI).

Using these values, together with a estimate start bioload of ~1 × 109 (based on the 2× MRO estimate, since EE is a comparably larger spacecraft), the use of the DHMR method (4 orders of magnitude reduction—NASA standard) and the radiation exposure at 6 Mrad of up to 10 orders of magnitude reduction (Space Studies Board 2000 suggestion), the feasibility of this approach in achieving PcEOI < 1 can be seen.

However, the implementation will require analysis at a detailed level.

Each hardware element will be required to demonstrate compliance with the overall flight system $P_c < 1$ requirement at EOI, by demonstrating compatibility with dry heat microbial reduction or environmental radiation sterilization or another sterilization approach agreed and accepted by the PP subject matter expert. This $P_c < 1$ at EOI approach eliminates the concern of the RPS as a heat source to support propagation of terrestrial biological contamination.

The requirement to avoid contamination of (impact with) other Jovian satellites will be met through trajectory analysis. This includes the $10^{-4}$ requirement to avoid impact with Europa prior to EOI.

Early (Phase A) formalization of the mission categorization and approach will be sought through the NASA PPO and the relevant peer review process. This needs to be early enough so that project can switch to an alternative (e.g. system probability analysis) method and/or evaluate descope options early in the project at low cost penalty; this is carried within the overall project risk.

### 4.6.4 PP Implementation Overview

#### 4.6.4.1 Flight System Design and Fabrication

In order to achieve compatibility for the flight system, it is necessary to consider dry heat sterilization compatibility in the trade studies alongside the radiation resistance. Both aspects will be considered in the generation of an approved parts list.

For some hardware where there is conflict between radiation and DHMR compatibility for individual components, it may mean that the instrument is actually "distributed"—electronics and sensors physically separated on the flight system. It may influence the choice of sensor technology for some instruments, if one sensor choice is much more robust than another in this context (for example ASICs may be preferred to FPGAs).

In the specific case of the instrument payload, it is not possible to determine final planetary protection implementation ahead of the instrument selection process. However, it is anticipated that instrument proposers will be required to address planetary protection compatibility in their proposals and that it will be given significant weighting in the selection process. In addition, a mid-Phase B Planetary Protection review will be held, so that costs and implications of developing mitigation strategies can be factored into the mission early.

At the current stage of maturity (see also §4.4.2.2, 4.7.6, 4.8.2.5, 4.9.4), no planetary protection roadblocks have been identified with this "box level sterilize then assemble" approach.

#### 4.6.4.2 Assembly and Test

In the current approach, it is assumed that the option exists to maintain spore density at $300/m^2$ as performed for the MER spacecraft

It is assumed that RPSs self sterilize, propellant is filtered etc. and that other marginal cost approaches beneficial to PP mitigation are followed (for example modification of contamination control bake-out parameters to allow bioburden reduction credit to be taken).

No specialized PP facility costs or LV costs have been assumed in this approach. It is assumed ATLO will be in standard class 100 k conditions. Requirement to work cleaner than this (e.g. in tented class 10 k or better with personnel controls and monitoring, to accommodate lower than anticipated sterilization effects from the irradiation in the jovian environment) will be carried as a technical risk. The detailed integration of the ATLO/PP flow will be an output from Phase A.

#### 4.6.4.3 Flight System Launch Configuration

It is necessary that areas of the flight system not experiencing adequate levels of Jovian radiation to achieve sterility will be sterilized during before or during ATLO and cleanliness maintained by protecting from recontamination prior to launch with HEPA filters.

The program for each subsystem will be developed during Phase A (spacecraft)/B (instrument) activities, when detailed radiation models will be available to determine, at the box-level, whether a sterilizing radiation dose is received by the hardware item before EOI.

#### 4.6.4.4 Mission Operations

Data from the RMS obtained during the operational phase of the mission, particularly during the Jovian Tour, will inform the true irradiation environment experienced by the hardware. This will give confidence that the required level of sterilization is achieved prior to EOI. Extending the pre-EOI tour to achieve a given irradiation dose for PP purposes remains a possible option.

## 4.7 Major Open Issues or Trades

### 4.7.1 Trajectory Opportunities

The VEEGA opportunity selected for the baseline mission is only one of a number of launch opportunities in 2015. In any given year, there are many opportunities which result in different flight times, fly-bys, delivered mass, etc. (See Appendix E). This particular opportunity was selected as it was fairly well characterized and earlier opportunities would have compressed the development schedule too much. Later launch opportunities are available with trajectory characteristics which would be acceptable. The later opportunities could be assessed with input from the SDT and HQ to optimize the mission technically, scientifically and programmatically by trading flight time, delivered mass, and launch date.

### 4.7.2 Tour Optimization

The baseline Jupiter system tour is designed to reduce the propellant load required to get into Europa orbit, to reduce the radiation dose prior to EOI, and to allow additional time for tour encounters. Minimizing radiation fluence, minimizing $\Delta V$ required (translates into propellant), setting up satellite encounters for science observations, or phasing satellite encounter arrival times (avoiding solar conjunction, minimizing Earth distance, etc.) are all considerations when designing the tour. Particular "loose moon" orbits could be designed to loosely capture into satellite orbits [*Ross et al. 2003*]. Designing the tour portion of the trajectory must be performed with the full science, engineering and programmatic team to ensure the optimal mission solution.

### 4.7.3 Main Engine

Alternatives to having 2 fixed main engines were identified during the course of the study, but a tradeoff among them was not conducted. The issue is that the flight system center of mass migrates during the course of the mission as the propellant load is used up, but the main engines' thrust vector remains fixed to the flight system body. The simple solution, implemented in this design, is to use TVC thrusters to counter the resultant torque. Since the TVC thrusters point in the same general direction as the main engine, their thrust is also contribute to achieving the desired ΔV. However, being monopropellant thrusters, the TVC thrusters are not as efficient in their use of fuel. Cost, complexity, and mass benefits of alternative implementations (e.g. using a single main engine, gimbaling the engines, or using bipropellant TVC thrusters) need to be assessed in trading off other options. Configuring four smaller main engines in a square pattern, then off-pulsing them to avoid a net torque, is also an alternative.

#### 4.7.4 On-Board Science Data Storage and Ka vs. X Band

The EE design for data storage and return was chosen as the best response to the limitations of radiation-hardened memory technology. While the baseline mission meets the data requirements, additional SSR capacity would enable the system to be more flexible and to better tolerate unplanned ground and flight system mishaps (i.e., safing and tracking outages) as well as planned tracking gaps. The CRAM technology currently baselined for the SSR will continue to improve. As the technology and characterization knowledge base improves, refinements and possible dramatic improvements in SSR capability may be reasonable. Current analysis (Appendix G) indicates that SSR volumes of 5 Gbit or 10 Gbits are stepwise significant increases in mission flexibility. The increased capability and the additional lifetime leads to a desire to re-evaluate Ka-band vs. X-band downlink (when ground station weather outages can be tolerated efficiently). The impact of the evolution of the SSR is significant and therefore will be monitored closely in the next study phase. SSR designs will be evaluated and traded against other resources and impacts on science operations will be captured.

#### 4.7.5 Upper Stage

During Europa Orbiter studies, a Star 48V upper stage was envisioned to provide additional injected mass launch capability since the available lunch vehicles at the time could not provide enough capability to inject Europa Orbiter on a direct-to-Jupiter trajectory. This option has not been explored for EE as the current launch vehicles are able to provide adequate capability using indirect trajectories. This option could be re-evaluated in conjunction with other in-direct trajectories (e.g., ΔV-EGAs) or to augment the Atlas 5 capability without incurring the full cost of a Delta IVH.

#### 4.7.6 Planetary Protection Options: Pre-launch vs. Post-launch Sterilization

The planetary protection requirement to take advantage of the Jovian system radiation to effect sterilization is in conflict with the desire to minimize the dose delivered to the flight system hardware. This trade will be an early output of a Phase B analysis modeling the flight system design, mission design and expected radiation environment. The outcome of this modeling activity may affect the planetary protection implementation. A Planetary Protection Review is scheduled in mid-Phase B to re-assess the approach and validate that the adopted methodology will meet the requirements.

#### 4.7.7 Radiation Related Effort

It is essential to start as early as possible to address issues related to radiation design and risk mitigation. Many efforts have been identified and pursued to date and much progress has been made. Efforts like these must be continually addressed throughout the formulation, implementation and even operations phases of the project. There will be many trade studies performed in Phases A and B to determine the optimal decomposition of the radiation mitigation aspects of the design, including trajectory design, shielding and enclosure design, component rad-hardness, fault protection design and autonomy. All of these intricate trades involve significant schedule, cost and risk implications and therefore must be considered early and across all disciplines of the project.

In addition to the technical trade studies, groundwork must be laid to provide the tools and information to effectively design and operate the mission. Previous work had already identified areas requiring additional effort and the recently concluded technical peer reviews have identified additional work that augments the previously defined effort.

The key focus for the next phase of the study is to prepare for the instrument AO and the Phase A effort. Obtaining and documenting radiation and planetary protection information necessary to prepare credible and mature instrument proposals is critical to lowering the development risk for the project. This information is also required for spacecraft designers but on a slightly later schedule.

1. *Identify and qualify parts and processes for radiation and planetary protection.*

   The parts investigated will include FPGAs, power converters, memories, ADC/DACs, sensors such as CCD/CID/APS, optoelectronics, muxes, and DSPs. Strategies for ASIC procurement will be investigated including examining commercial rad-hard by design foundries and structured-ASIC approaches.

2. *Identify radiation testing requirements for parts and materials.*

   Testing facilities and approaches will be investigated to provide proposers and designers adequate information to adequately scope their effort. This effort will include investigating radiation facilities and their cost, irradiation and measurement conditions and approaches, types of radiation effects to be examined in parts (i.e., the numerous single-event effects (upset, latchup, burn-out, gate rupture, transients), total ionizing dose effects (including ELDRS), displacement damage effects, and workforce estimates for testing.

3. *Define radiation and ESD design guidelines for Instrument and assembly providers.*

   Develop a set of radiation design guidelines for designers, including considerations for planetary protection, which cover issues such as shielding, parts and materials, qualification, testing, worst case analysis, rad hard-by-design techniques, and surface charging mitigation approaches. Follow and tailor, as necessary, JPL's rigorous design guidelines for ESD and grounding for EE. Provide early testing of materials to define acceptable use. Develop mission design guidelines early in the design cycle. Develop a plan to conduct design workshops to train designers on the environment and charging issues.

4. *Plan radiation model upgrades*

   The Jovian radiation environment model will be updated starting in Phase A to include the following issues: local shielding effects due to Europa; information for energy range above 30 MeV using Pioneer and Galileo data; secure an up to date version of the Khurana magnetic field model to compare the predictions with the currently used VIP4 model; and update the model coordinate system using the first adiabatic invariant and Rj. Planning and scoping this upgrade and the sustaining engineering associated with keeping the model current, will be planned during the next study phase.

   A new radiation systems reliability analysis tool has been developed during this study. This tool, based on 1st principles, predicts mission lifetime using statistical reliability data from EEE parts and spacecraft models. This tool needs to be further vetted and refined as more information on parts (from testing) and flight system design information become mature. A plan will be developed to keep this powerful mission reliability analysis tool current for the life of the mission.

5. *Document fault protection and autonomy approach.*

   The required fault protection and autonomous operations approach for EE is an extension of previous mission experience. The proposed approach needs to be further refined and documented through the Systems Engineering process and exposed to all stakeholders including: ground system, mission operations, science, flight system hardware and software designers, and system engineers. A number of trade studies will be done in support of this work.

6. *Plan management and systems engineering for radiation issues.*

The management and systems engineering approach must support the challenging technical work in a high radiation environment. The identification and staffing of the DPMR and DPSER is essential to the early project. Early planning will include documention of the radiation system engineering roles, the working group charter and the operational approach. The Mission Assurance organization is key to documenting and communicating the radiation requirements and must take a central role in the early systems engineering effort to understand the systems trades and to optimize the design. Implementation decisions are needed early in the project planning for EEE parts common buys approach, centralized vs de-centralized radiation testing, approved parts lists, and interface definition between mechanical model of flight system and radiation model.

7. *Establish Radiation Advisory Board*

   It is essential to establish the Radiation Advisory Board early in the project. The charter for this independent board is to give independent advice to enhance mission success. Early input on decisions and approaches is most effective and allows the project to leverage the experiences of external people and organizations.

There are many other activities which will be pursued as the Project enters Phase A. Those listed above are considered the most crucial and time critical for the next study phase.

#### 4.7.8 Potential Europa Ensuing Science Candidates

This study focused almost exclusively on understanding the operational scenarios and limitations of the first 92 days in orbit at Europa while meeting all the science objectives. Very little attention was paid to additional science operations past this first 92 days. The SDT brainstormed candidate science strategies for the remainder of the Europa Science phase; see §2.4.4 for the list of candidates.

#### 4.7.9 RPS Development

The Department of Energy (DoE) has provided information on the development, cost and schedule for 3 different types of Radioisotope Power Sources for consideration in this study. A summary of the technical parameters is given in **Table 3.4-2**. Due to the desire to launch as early as practical, the ARTG was considered too high a risk for launches evaluated in this study (through early 2017) due to its estimated longer development schedule and higher development risk. If the progress on the ARTG continues and the development risk declines, the option to use ARTGs would become available. The substitution of ARTGs in place of MMRTGs is relatively simple as they are similar implementations. If ASRGs were to be baselined, an analysis would need to be performed to understand the implications of the substitution, as discussed below.

The most significant advantages of the ASRG are its higher conversion efficiency and higher specific power compared with the MMRTG. The higher ASRG conversion efficiency translates into roughly four times less required Plutonium fuel (GPHS Modules) for an equivalent power level as for the MMRTG. The higher ASRG specific power appears to result in significantly lower RPS power system mass compared with the MMRTG. Unfortunately, there are still many unknowns associated with the final implementation of the ASRG and thus, the final system mass advantage is unclear.

Though the decrease in Plutonium required is significant (from 8 to 2 GPHS Modules per unit), the DoE has committed that enough fuel would be available to support 8 MMRTGs by 2015 if the decision was made soon. Thus, it would be highly desirable to lower the fuel required, but not critical. On the other hand, the less mature concept for the ASRG leads to many questions which will impact the system level mass of using this approach. Many outstanding issues need addressing before the risk of adopting the ASRG can be understood. These issues are:

1) The design of the ASRG qualification and flight units are not fully defined, and may be significantly different from the current engineering unit design.

2) Lifetime of the Stirling convertors not demonstrated.
    a. Life test planned to start in near future.
3) Lifetime of controller electronics and algorithm not demonstrated.
    a. Controller algorithm is new and in process of being tested.
    b. Controller electronics are proof of concept and use many commercially available parts, with space rated equivalent identified.
    c. Lifetime analysis for Controller electronics is not completed.
4) Failure modes and reliability of ASRGs not fully identified, analyzed or demonstrated.
    a. FMECA and reliability analyses are still ongoing.
    b. Redundant units may be required to mitigate potential faults
5) Die level radiation tolerance of controller electronics unknown.
    a. Bremsstrahlung radiation and secondary particle generation effectively limit the radiation tolerance of parts to 100 krad at the die level without excessive shielding required. The currently-used ASRG controller electronics do not meet this requirement.
    b. Parts substitutions may be required to meet EE mission requirements, potentially requiring a re-qualification of the controller
6) Use of excess waste heat from ASRG needs to be understood.
    a. May need additional thermal hardware (e.g., heat loops), electrical heaters and/or RHUs to heat system due to the lower amount of waste heat available compared to the MMRTG and the unique thermal environment of the ASRG.
7) The cost of qualification is still uncertain.
8) ASRG operating performance in different operating environments is not fully understood.
9) The interactions of ASRG-generated environments (e.g., vibration and EMI) upon the flight system are not fully defined, particularly in off-nominal cases (e.g., one failed ASRG engine).

All of these issues can be resolved given adequate time and money. Choosing the ASRG as a baseline for this study would introduce a level of uncertainty which could not be adequately captured at his point in the study. More time and analysis is required to understand some of these implementation issues and how they impact the flight system as a whole. The implementation and system level impacts of MMRTGs are much better known (assuming Plutonium availability and DoE manufacturing capability as described), leaving the implementation risk much lower.

Given enough time and money, any of the three RPSs can be used for EE. The MMRTG provides a less risky but more massive, Plutonium-intensive solution over the less mature ASRG implementation. The ARTG solution is judged to be too risky and immature for either the 2015 or 2017 launch opportunities evaluated in this study.

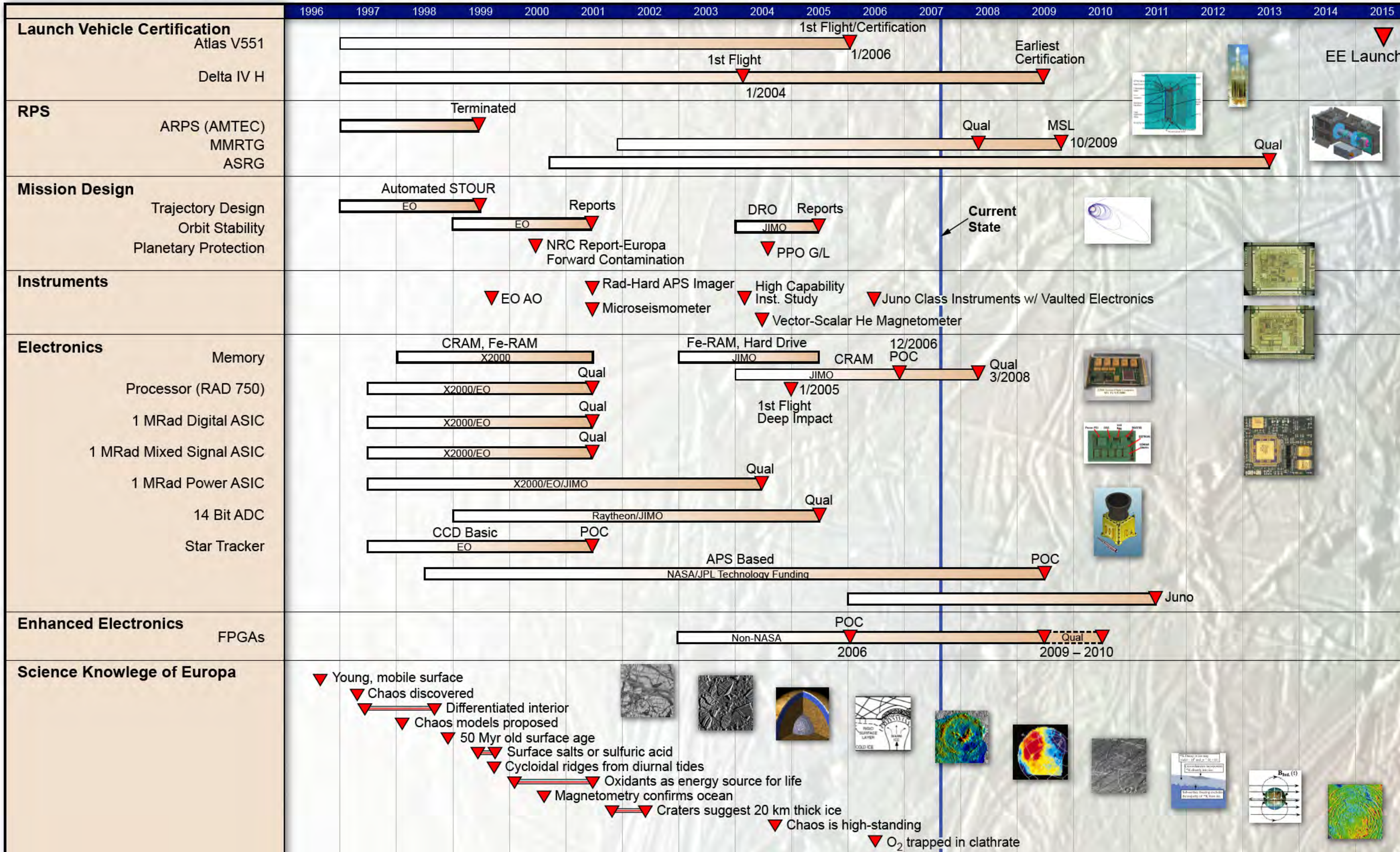
## 4.8 Technology Needs

### 4.8.1 New Technology Required

There are no new technologies required to implement the mission as currently envisioned. Major NASA investments have been made over the past decade in the areas of radiation hardened components, development of power source technology, launch vehicle qualification, and trajectory tour design tools. Additionally, the Departments of Defense and Energy as well as industry have invested in technologies and developments which directly benefits the current Europa concept. In 1996, the Galileo spacecraft was just beginning to return vast amounts of data about Europa. Years of additional data return as well as nearly a decade of data analysis has resulted in much better refined models and questions related to the fundamental objectives for the next mission to Europa. Many of these developments are depicted in **FO-6.** Engineering developments are required in most areas to adapt current designs to perform within the radiation environment and to meet the planetary protection requirements. A

# FOLDOUT 6
## RISK REDUCTION TIMELINE

## More than a decade of investment has resulted in dramatic risk reduction for Europa Explorer



summary of the technology readiness assumptions is provided in **Table 4.8-1**.

### 4.8.2 Enhancing New Technologies and Capabilities

Although current technologies are sufficient to perform a scientifically engaging mission to Europa and meet all the science objectives, new technologies and capabilities could enhance the mission if they become available in a timeframe compatible with the mission development schedule. Examples of such technologies and capabilities include: ASRGs, ARTGs, non-volatile memory, advanced sensors, on-board target data selection and targeting, and X-band antenna arrays for DSN.

#### 4.8.2.1 Radioisotope Power System (RPS)

The MMRTG was selected for the baseline EE mission. DOE and NASA are engaged in the development of two other RPS options: the Advanced Stirling Radioisotope Generator (ASRG) and the Advanced RTG (ARTG). These units all use GPHS modules and operate at a power level greater than 110 watts electric ($W_e$) at beginning of mission (BOM). A comparison of critical parameters for these devices is shown in **Table 4.8-2**. As with previous RPSs, the output power decreases over time due to the decay of the Pu-238 fuel and the gradual degradation of power conversion components. It should be noted that the power predictions shown in **Table 4.8-2** reflect both Pu-238 fuel decay and gradual degradation of the thermoelectric materials for the MMRTG and ARTG (both static power conversion systems), but only Pu-238 fuel decay for the ASRG (a dynamic power conversion system); other performance-degrading mechanisms have not been identified yet for the ASRG.

As outlined in §4.7.9, there are still open issues related to using the ASRG on EE. If the ASRG questions are answered in sufficient time to insert this technology into the EE

***Table 4.8-1.*** *Technology Readiness*

| Area | Radiation Mitigation | Planetary Protection Mitigtation | Specific issues | |
|---|---|---|---|---|
| Embedded Materials | shield or replace | Heat Sterilization | Radiation | Pressure Transducer - investigate sensors used in Nuclear Reactors, new development or shield current sensors (mass for this already assumed) |
| | | | Planetary Protection | Li-ion battery will need qualification of alternate (irradiation) sterilization approach, or select alternate technology (mass/ performance trade) |
| External Materials | shield or replace | Chemical wipe and vacuum/radiation sterilization in flight | Radiation | None identified |
| | | | Planetary Protection | None identified |
| Circuit Design | Minimum allowable die level radiation hardness is 100krad, Each part within circuit will be assessed; timing and performance range will be incorporated into worst case analysis to ensure circuit functionality with rad-hard parts, testing of parts may be r | Heat Sterilization | Radiation | Parts: ADCs-14 bit best available to date; Memory - some types available, may limit design choices; FPGA - not qualified, dictates use of ASICs |
| | | | Planetary Protection | None identified |
| Sensors/Detectors | Sensor/detector performance requirements will be assessed: common mitigation approaches include; cooling detector, lowering accuracy requirements, deleting all non-essential performance or on-chip functionality, software "averaging" or "integration" algor | Heat sterilization or alternate sterilization during manufacturing process | Radiation | CCD, APS and other sensors will require specific attention and radiation mitigation design techniques such as cooling, software integration, deletion of extraneous features, relaxation of stringent requirements; in some cases dose rate will be larger issu |
| | | | Planetary Protection | Some sensors cannot be heat sterilized, in-flight radiation streilizatiuon may be possible form some sensors, sterilization during sensor manufacturing still unknown, alternate approaches may be required |
| Circuit Boards | See Embedded Materials | Heat Sterilization | Radiation | specific materials can be used |
| | | | Planetary Protection | None identified; baseline boards can be built using materials that are compatible with DHMR or radiation sterilization |
| Power Source | MMRTG inherently rad hard | Naturally heat sterilized | Radiation | ASRG Controller may not have minimum die level rad hardness parts |
| | | | Planetary Protection | None identified, exposed to radiation, vacuum and heat during flight |

***Table 4.8-2.** Comparison of RPS Concepts and Critical Parameters*

| Parameter | MMRTG | ARTG | ASRG – 650C | ASRG – 850 C |
|---|---|---|---|---|
| Mass | 44 kg | 40 kg | 20.2 kg | ~ 19 kg |
| Power (BOL) | 125 $W_e$ | 250 $W_e$ | 143 $W_e$ | ~ 160 $W_e$ |
| Additional Shielding | none | none | may be required | may be required |
| | | | | |
| Electric Power at BOL | 125 $W_e$ | 250 $W_e$ | 143 $W_e$ | ~ 160 $W_e$ |
| Electric Power at 14 years | 100 $W_e$ | 200 $W_e$ | 127.5 $W_e$ * | ~ 143 $W_e$ * |
| | | | | |
| Thermal Power at BOL | 2000 $W_t$ | 3000 $W_t$ | 500 $W_t$ | 500 $W_t$ |
| Thermal Power at 14 years | 1791 $W_t$ | 2686 $W_t$ | 448 $W_t$ | 448 $W_t$ |
| | | | | |
| # of GPHS modules | 8 | 12 | 2 | 2 |

MMRTG – Multi-Mission Radioisotope Thermoelectric Generator
ARTG – Advanced Radioisotope Thermoelectric Generator
ASRG-650C – Advanced Stirling Radioisotope Generator with 650°C hot side temperature
ASRG-850C – Advanced Stirling Radioisotope Generator concept with 850°C hot side temperature

* Note that efficiency is not constant over the Stirling convertor's life and is not optimized for BOL. The 0.8% radioisotopic decay, used in the calculations, was only an estimate, while the EOM (17 year past BOL) prediction was by analysis. Some of the decay is overcome by efficiency operating point changes over time.

mission, the unallocated mass would increase and the required number of GPHS modules would decrease (from 48 to 12) resulting in a positive benefit to the project.

The ARTG is still in its infancy in concept development. If it becomes available in time to insert into the EE mission, it is anticipated that a reduced mass and number of GPHS modules would result as well, though the actual amount is less certain.

#### 4.8.2.2 Non-volatile Memory

Availability of space qualified non-volatile memory continues to be an issue for future missions, even those without high radiation levels. The consumer media-centric market is clearly the driving force in memory technologies. Demand from the Consumer for the ability to store an ever-increasing number of songs, videos, and other media streams on handheld, low power entertainment/communication devices forces research into several topologies of flash-style memory. Two technologies that are used widely today and can be purchased readily: Flash and Silicon Oxide Nitride Oxide Semiconductor (SONOS). Two technologies are being developed which are nearing qualification: Chalcogenide and Ferro-electric.

The design for the EE data recorder is based upon the BAE 4 Mbit Chalcogenide memory device (CRAM). The EM grade parts are in production and available. A discussion with the management of BAE Systems revealed that a DoD customer has taken the devices one step further and commissioned the design of a package consisting of four 4 Mbit die, thereby quadrupling the density in (approximately) the same size footprint. These stacked devices were delivered to, and accepted by, the DoD customer and therefore are considered stable for use in this design. Until these stacked devices can be fully characterized and space qualified, a more conservative approach that assumes a small amount of on-board memory will be pursued. This activity is on-going and expected to conclude in mid-FY08.

Further developments in memory devices which can be used for on-board data storage could be inserted into the design to alleviate some of the current design constraints. This technology area will be closely followed so that advances which are qualified in time for insertion can be leveraged.

#### 4.8.2.3 Advanced Sensors

There are many types of sensors potentially available to work within this radiation and planetary protection environment. Special attention to the sensor selection and functionality will be required. Currently available sensors will need to have specific design implementations and features added for radiation tolerance. Dedicated fabrication runs will be necessary with testing for each fabrication lot. Screening procedures and lot acceptance will be required. As sensor technology advances, radiation tolerance of the underlying structures is expected to improve. Active doping, bulk material thinning, and low temperature operation techniques have been shown to improve radiation tolerance of silicon devices. Active pixel sensors are currently available for some applications and are shown to be much more rad-hard. This technology (and others such as 3D detectors) are being developed and may provide additional options in the near future.

Specific sensor requirements for the instruments are difficult to assess since the instruments have not yet been selected, and satisfaction of the planetary protection requirements may end up being the larger issue. As the technology continues to mature, advances in these areas will be vigorously pursued for performance and cost savings.

#### 4.8.2.4 X-band Antenna Arrays for DSN

Future upgrades to the DSN are in the planning stages including large arrays of smaller X-band antennas. Increased capabilities would enhance the data return rate, increasing the amount of data which could be gathered and returned every orbit. The current design assumes only the current capability of the DSN so any increased capability would only enhance the data return.

#### 4.8.2.5 Planetary Protection Risk Management

Taking into account the risk management approaches of: parts compatibility assessment, inclusion as a requirement for instrument AOs, additional Phase B review, and inclusion in the ATLO DTM trailblazer activity already described elsewhere in this document (§4.4.4, 4.6, 4.9.4), it is anticipated that no new planetary protection technologies are required.

However, alongside anticipated engineering developments to accommodate planetary protection requirements, current research activities into spacecraft and payload genomic diversity in the Mars Program may be beneficial to Europa exploration in the timeframe of the proposed mission. It is expected that this research will generate absolute knowledge of the number and types of organisms present on/in the space hardware. This may allow conservative margins applied in the NRC Space Studies Board report of 2000 for the estimation of bioburden to be eliminated. A lower actual starting bioburden will allow planetary protection compliance and schedule risk to be managed more cost-effectively, for example by increasing the proportion of the spacecraft sterilized by jovian irradiation without pre-launch sterilization processing, or by reducing the stringency of the ATLO environmental cleanliness requirement on account of incident irradiation sterilizing parts recontaminated during ATLO.

## 4.9 Risk Assessment

The study team has identified a number of risks to the success of EE mission. Programmatic risks were not assessed per the study guidelines. Each risk has been evaluated for likelihood and consequence on a scale from 1–5 for each rating, as is typically used for space flight missions, and shown on a 5 × 5 risk matrix as shown in **Figure 4.9-1**. Mitigation plans have been developed for each risk. Open risks are reviewed periodically, and those risks considered mitigated are closed. The subsequent sections give a brief discussion of each risk and the corresponding mitigation for each. The risk rating is given in the title of each subsection below as an ordered pair of consequence and likelihood. Section 4.10.10 discusses management strategies for these risks including specific actions taken to address cost.

### 4.9.1 Radiation *(RadE, RadPSM)*

Radiation is the largest risk factor for the Europa mission. The high radiation environment at Jupiter, and specifically the

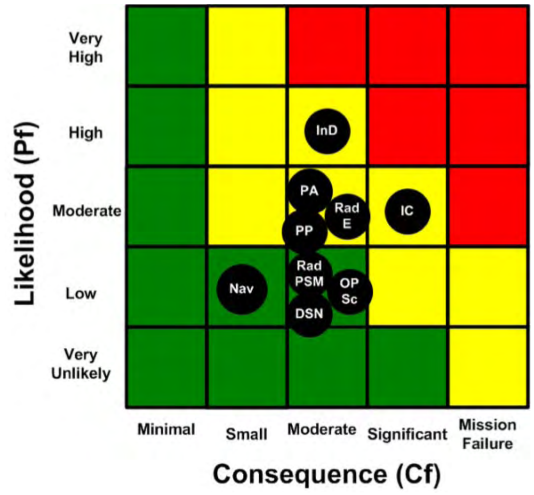



***Figure 4.9-1.*** *Europa Explorer risk evaluation.*

radiation exposure for the flight system while in Europa orbit, is a unique challenge for any flight system. This contributes to several areas of risk, each of which will be treated independently below. The study team has addressed this risk by convening several review teams to assess the particular risks in each area. A final review board was charged with the task to evaluate the results of each individual review and the radiation risk was determined to be well understood, challenging, and manageable by that board which included experts from various institutions and industries with domain knowledge in these areas.

##### 4.9.1.1 Radiation Environment (RadE 3,3)

The radiation environment for the Europa mission comes from energetic charged particles trapped in the Jovian magnetosphere, energetic nuclei that form galactic cosmic rays, and energetic protons produced in solar proton events. By far, the most uncertain environment is the component due to the Jovian magnetosphere. The total ionizing dose (TID) at the end of the the first 120 days after EOI for EE is 2.6 Mrads (behind 100 mils of aluminum). Just under half of the total dose (1.2 Mrads) is received during the ~2 year Jovian Tour, with the balance (1.4 Mrads) received in Europan orbit. High energy electrons are the primary contributor to the TID.

If the radiation environment is higher than expected, the mission may fail earlier than intended and some science requirements may not be achieved. The environmental risk includes the following factors:

- Uncertainty in the models used to predict the environment.
- Underprediction of the variability of the environment due to lack of knowledge in long-term environment cycles.
- Unanticipated spikes in the environment such as that seen by Galileo.

Mitigations for the risk associated with radiation environment knowledge are radiation design margins for components and materials, use of designs that fail gracefully to prevent sudden mission loss, and an operations concept that is robust to data loss in the later phases of the mission through overlapping science measurements.

One type of mitigation used to control radiation effects in devices is to shield objects of concern with dense material, reducing the charged particle fluence at the sensitive object. Radiation shielding has been incorporated into the mechanical design of electronics enclosures to reduce the TID hardness requirement from several Mrads (Si) to 300 krads (Si). If the shielding is less effective than anticipated, the radiation environment of electronic components may exceed the TID hardness of the components, causing early system failure. Uncertainty in shielding effectiveness can be due to several factors, as follows:

- Uncertainties in particle transport models and computer codes.
- Simplifications in the spacecraft geometry model that affect the fidelity of the transport simulation.
- Secondary particle emission from the shielding material into components that may cause related problems, such as an increase in displacement damage or SEE rates.

Mitigations for this risk are design margins, extra review from knowledgeable peers of transport models and simulations, testing to verify models, and use of multi-layer shields to more efficiently absorb secondary particles such as neutrons that may increase displacement damage or SEE rates.

##### 4.9.1.2 Radiation Effects in Parts, Sensors and Materials (RadPSM 3,2)

Designs for this environment must be robust beyond the level normally accomplished for space flight design. We anticipate that many of the designers working on mission systems will be inexperienced in design for such a harsh radiation environment. This inexperience may lead to unanticipated vulnerabilities in the Europa mission electronics and sensors, leading to mission degradation or failure.

Radiation effects expected in the Europa mission are (i) total ionizing dose (TID) effects in electronic components, (ii) displacement damage (DD) effects in components and materials, (iii) single event effects (SEE) in electronic components, and (iv) surface and internal charging. Since mitigations for charging issues are different than for other radiation effects, internal charging is treated as a separate risk.

If radiation effects in parts and materials are more severe than expected, early failures may occur resulting in loss of science. Science instruments and instruments used for pointing and navigation are sensitive to radiation effects in electronic components and in sensors. This risk results from several important sources. First, even with the use of radiation hardened parts, the project may not be able to identify some key components that will withstand the shielded environment. Test techniques used to verify component suitability may overpredict component hardness due to inadequate accounting for radiation rate or source type effects that are negligible at lower doses. Finally, unanticipated failure mechanisms may be present or may become important at high doses or at high displacement damage levels that are not of concern for missions conducted at nominal total dose exposures.

If radiation effects in sensors are more severe than anticipated, mission science may be reduced through either effects in the science instruments themselves or in failure of the flight system to meet pointing or similar requirements. The sources of this risk are uncertainty in the ability to find sensors that meet the stringent radiation requirements of the mission and increased backgrounds in sensors from interactions with the radiation environment that result in unacceptably high signal to noise ratio, or other key parameters. As an example, charged particle interactions with CCDs used in optical instruments cause saturated pixels. If the number of saturated pixels is too high, image quality is affected, and may result in images that fail to meet science requirements. In this example, the failure is a gradual degradation, rather than a hard failure. This is typical of risks associated with sensor radiation hardness.

Mitigations for this risk are to utilize design experience from Galileo and Cassini, provide mission design guidelines early in the design cycle, conduct design workshops to train designers on the environment and survivability issues and techniques, and develop recommended lists of known acceptable parts with radiation screening requirements for parts not on the recommended list. The Europa project will make use of experts in radiation effects in devices to define qualification test programs with high fidelity for the technologies of concern, increase design margins for electrical parameters expected to change due to radiation effects, increase the use of design review by peers knowledgeable in radiation effects in devices and materials, and use design techniques that fail gradually with radiation effects to allow graceful degradation if unanticipated effects are seen in flight.

Mitigations for this risk also include the use of shielding where appropriate (including modeling and/or test to show secondary particle generation is acceptably low), sensor testing to verify technology meets requirements, and robust design with adequate margins. An increased level of knowledgeable peer review is also useful to reduce the likelihood of this risk.

#### *4.9.1.3 Internal Charging (IC 4,3)*

The high levels of charged particles near Europa are also a source of internal charging within flight system materials. The result of this charging is often a large electrostatic discharge within the flight system that causes material damage and an electromagnetic pulse damaging to electronics. The choice of materials, the use of charge dissipating designs, and the robustness of electronic designs to internal discharge effects will greatly affect the frequency and consequence of internal discharges. If not mitigated properly, discharges resulting from internal charging may result in mission degradation or failure.

Mitigations for this risk include the use of JPL rigorous design guidelines for ESD and grounding. For example:

1) specifications on the maximum length of ungrounded wire length
2) specifications on the use of necessary bleed resistors and bleed path analysis
3) specifications on the restriction on the use of floating (e.g. ungrounded) metal area.

In addition IC risk mitigation will include utilization of design experience from Galileo and Cassini, early testing of materials to define acceptable use for a Europa mission, providing mission design guidelines early in the design cycle (Phase A), and conducting design workshops to train designers on the environment and charging issues.

### 4.9.2 Instrument Development (InD 3,4)

Instrument development is considered a high risk for the Europa mission because the instrument designs will be unique, due to the high radiation environment and the Europa specific planetary protection requirements. The instrument selection is outside the purview of the Europa project, each with an individual scientist and with unique mass and power constraints. If instrument development and accommodation is not managed appropriately, schedule and cost reserves may be needed to resolve late-breaking problems, or mission science may be compromised.

The Europa project will assign instrument interface engineers to work with each instrument provider to ensure that the spacecraft accommodates the specific instrument needs. Design guidelines will be generated for the instrument teams to describe thermal and radiation constraints and to provide recommendations for design issues and parts and material selection. In addition, the NASA instrument confirmation reviews that are held prior to the system confirmation review will provide mitigation for this risk by identifying potential instrument issues early in the project lifecycle.

### 4.9.3 Operations

#### *4.9.3.1 Science Operations (OpSc 3,2)*

If science and spacecraft operations planning response to faults is not flexible and capable of rapid reconfiguration and recovery to nominal operations, some science goals might not be met within the baselined mission duration. The concept of operations for the Europa mission will require science operations and sequence planning on a weekly basis while accommodating science priorities for several instruments and science team members. Operations will necessitate planning tools and coordination that is more advanced than a typical orbiter or flyby mission. If operations are not coordinated appropriately or if planning tools are not correctly designed and implemented, cost and schedule reserves may be needed to address late-breaking problems, or science may be compromised.

The mitigations for this risk are to prepare science team plans and tools early, and provide sufficient opportunities for training and practice through the use of flight schools, mission simulations, operational readiness tests, and a thorough exercising of the science operations processes during Venus and Earth flybys and the Galilean satellite flybys prior to EOI. The SDT has developed a set of priorities and will continue to do advanced planning for various mission scenarios to allow for quick response. Detailed knowledgeable peer reviews of the planning and coordination process and tools will be conducted sufficiently early to allow effective implementation of the operations process.

Science operations will make use of extended fault isolation, response and recovery designs beyond current practice to prevent major loss of science in the presence of minor faults. Enhanced ground and flight system operability features will be implemented to enable rapid and largely automated reconfiguration and recovery from all faults. The science ops team will practice and train during Cruise/Tour encounters.

#### *4.9.3.2 Navigation (Nav 2,2)*

The Europa orbiter navigation includes multiple flybys in a short period of time to accomplish the mission design scenario. If the flybys are not executed correctly, or if stable orbits are not achieved as planned, science may be compromised or lost. If Europa mapping orbits with moderate stability (lifetime > 2 weeks) cannot be achieved, higher frequency of Orbit Trim Manuevers (OTM) (> 1 per week) will increase propellant consumption and reduce science data collection quality and quantity. This could also result in increased operations staffing and cost.

This operations navigation risk mitigation will be accomplished by early coordinated design of flight and ground software and test sequences to enable quick updates to the spacecraft operations. Risk mitigation will also include increased Delta V contingency budget which will mandate an increase in on-board propellant to allow flexibility to perform additional OTMs if necessary. During implementation phase the operations team will create rapid OTM development and validation process, science planning tools that cope with discontinuous trajectories, rapid re-planning and on-board ephemeris updates.

### 4.9.4 Planetary Protection (PP 3,3)

The planetary protection requirements will require that the Europa flight system receive sterilization processing prior to launch to achieve specified cleanliness levels in order to avoid contamination of the Europa environment**.** If cleanliness levels are not met, cost and schedule reserves may be required to address contamination problems late in the process, or Europa may be contaminated. If implementation of planetary protection requirements is more difficult than anticipated and design requirements change, there could be cost and schedule impacts.

The risk will be mitigated by defining design guidelines and assessing parts and materials in time for Instrument AO as well as by scheduling a PP Implementation Review in Phase B to confirm approach, and by providing guidance to all subsystem and instrument contributors to ensure that the cleanliness levels can be met well ahead of the clean and test program which will occur just before launch. The Europa radiation environment will be used for additional spacecraft sterilization. Schedule and cost reserve will be applied to additional sterilization if needed. In the event that all of these prove insufficient, instrument level de-scoping (as was employed on Viking) will be considered while protecting the overall science integritry of the mission.

#### 4.9.5 Plutonium Availability (PA 3,3)

Plutonium availability for use in radioisotope power sources is limited. If the supply of plutonium remains limited, then the number and type of MMRTGs available will be reduced, and enough units to meet the needs of the Europa mission may not be available. This risk is common to all flagship missions to the outer planets. The Europa project is baselined to make use of plutonium supplies that are currently in storage with the DOE.

The mitigations for this risk include a design that minimizes power requirements, descope operational capabilities to operate in a reduced power mode and plans to demonstrate compatibility with the ASRG if it becomes necessary to switch to an alternate RPS power source.

#### 4.9.6 DSN Availability (DSN 3,2)

The Europa spacecraft has baselined the use of the DSN 70-m equivalent capability throughout the mission. The current 70 m subnet is aging, and the expectation is that system outages may be increasing, leading to the need for replacement capability and potential lost or compromised science.

This risk is mitigated in part by the Europa concept of operations, which has in the baseline design multiple opportunities to observe the same target. Science data lost during short tracking outages can be reacquired in future orbits two to three weeks later. For longer outages of days or weeks, data collection would continue at lower rates with the 34 m stations until a given 70 m station can be restored to service. During mission operations, chronic or persistent loss of 70 m tracking would cause the mission to be re-planned. High priority science goals would be accomplished at the cost of increased mission duration, reduced observation margins, increased data compression, and reduced observation frequency for lower priority goals. Other options such as using antenna resources outside the DSN, or arraying 34 m antennas could also be pursued to mitigate this risk if the 70 m subnet is not available.

### 4.10 Programmatics

The project management will draw from the experience in the successful design and implementation of long-life, deep-space missions such as Voyager, Galileo, Cassini, and New Horizons. Galileo and Cassini are especially relevant to the outer planets flagship mission development as they both involved major inter-center and international collaboration in probe development and instrumentation.

#### 4.10.1 Management Approach

The complex, multi-element, architecture that is likely to be chosen for the flagship mission calls for a cohesive partnership between the entities making up the project. The management approach follows NPR 7120.5D and incorporates NASA lessons learned. The project approach includes: a Work Breakdown Structure (WBS), technical management processes conducted by veteran systems engineers, and integrated schedule/ cost/risk planning and management. The project will take advantage of existing infra-structure for: planning, acquisition, compli-ance with the National Environmental Policy Act (NEPA), compliance with export control regulations (including International Traffic in Arms Regulations), independent technical authority (as called for in NPR 7120.5D), mission assurance, ISO 9001 compliance, and earned value management (EVM).

#### 4.10.2 Organization and Decision Making

The project will be led by a Project Manager (PM), who is responsible for all aspects of project development and operations. Deputy Project Managers will be chosen from any external organizations that are delivering significant elements of the mission. Additionally, a Deputy Project Manager for Radiation will be chosen to coordinate and manage all aspects of radiation approaches and mitigations. A Project Scientist will be appointed who will represent science interests to the Project.

Decisions will be made at the lowest level possible while ensuring that a decision made in one system does not adversely affect another or the science data return. Pursuant to NPR 7120.5D, the project will include a project-level "Communications Plan" to its list of planning documents, which will include the dissenting opinion process. This detailed plan for communication and decision-making is due in Phase B, though a draft will be completed in Phase A due to the anticipated Project complexity. The PM will be the final project authority for all decisions that cannot be resolved at lower levels. Should NASA select individual principal investigator-led science investigations, the Project Scientist may also have a prominent role in arbitrating between science priorities in support of science planning for the mission. For decisions involving the quality and quantity of science data deliverables, the Project Scientist will provide concurrence.

Replacement of key personnel, including the PM, Project Scientist, and Deputy PMs, will be made only with concurrence by NASA. Any change in mission objective or in a mission Level 1 requirement will be made only with concurrence from the Program Director at NASA.

#### 4.10.3 Teaming

No specific strategic partners or major subcontractors have been identified during this study, though some thought has been given to how a major partnership could be executed. The procurement burden associated with a major (or several major) subcontracts totaling $260M has been included in the Project management WBS, however. Appropriate MOUs, MOAs and subcontracts would be developed and executed between major partners for EE, and would comply with all export laws and regulations. Technical Assistance Agreements (TAA) governing technical interchange between the Project and any international partners would be applied for early in the Project development stages to facilitate further discussions.

Discussions with European colleagues have been on-going in regards to US participation in the LAPLACE: *A mission to Europa and the Jupiter System* Mission Concept Study proposal submitted by Principal Investigator Michel Blanc of CESR, France, to the ESA Cosmic Vision Programme. NASA HQ has been apprised of the interactions between members of this study team and the CESR proposal team. It is anticipated that ESA and perhaps other space agencies will provide enthusiastic support and partnering in a NASA-led Europa mission.

#### 4.10.4 Roles and Responsibilities

The PM is accountable to NASA for the formulation and implementation of the project as well as its technical, cost, and schedule performance. The PM will be responsible to the NASA Program Office. The PM will prepare and approve monthly reports to the Program Office and the NASA Management Office (NMO). All element-level management and financial reporting is through the PM. The PM is also responsible for the risk management activities of the project. The PM will be supported by a Deputy Project Manager(s), Project Scientist (PS) and Deputy PS, Project Systems Engineer (PSE), Deputy Project System Engineer for Radiation (DPSER), Mission Manager, Mission Assurance Manager (MAM), Payload Manager, Spacecraft Manager and Business Manager. Individuals will be appointed to these positions who have relevant experience and unique strengths with the goal of building a strong team.

#### 4.10.5 Work Breakdown Structure

The EE Work Breakdown Structure (WBS) is derived from JPL's Standard WBS Version 4 and is shown **Figure 4.10-1**. The WBS is compliant with Appendix G of NPR 7120.5D. The detailed WBS and dictionary are included in Appendix D.

#### 4.10.6 Schedule

The PM controls the project schedule, with support from a Project Schedule Analyst. An

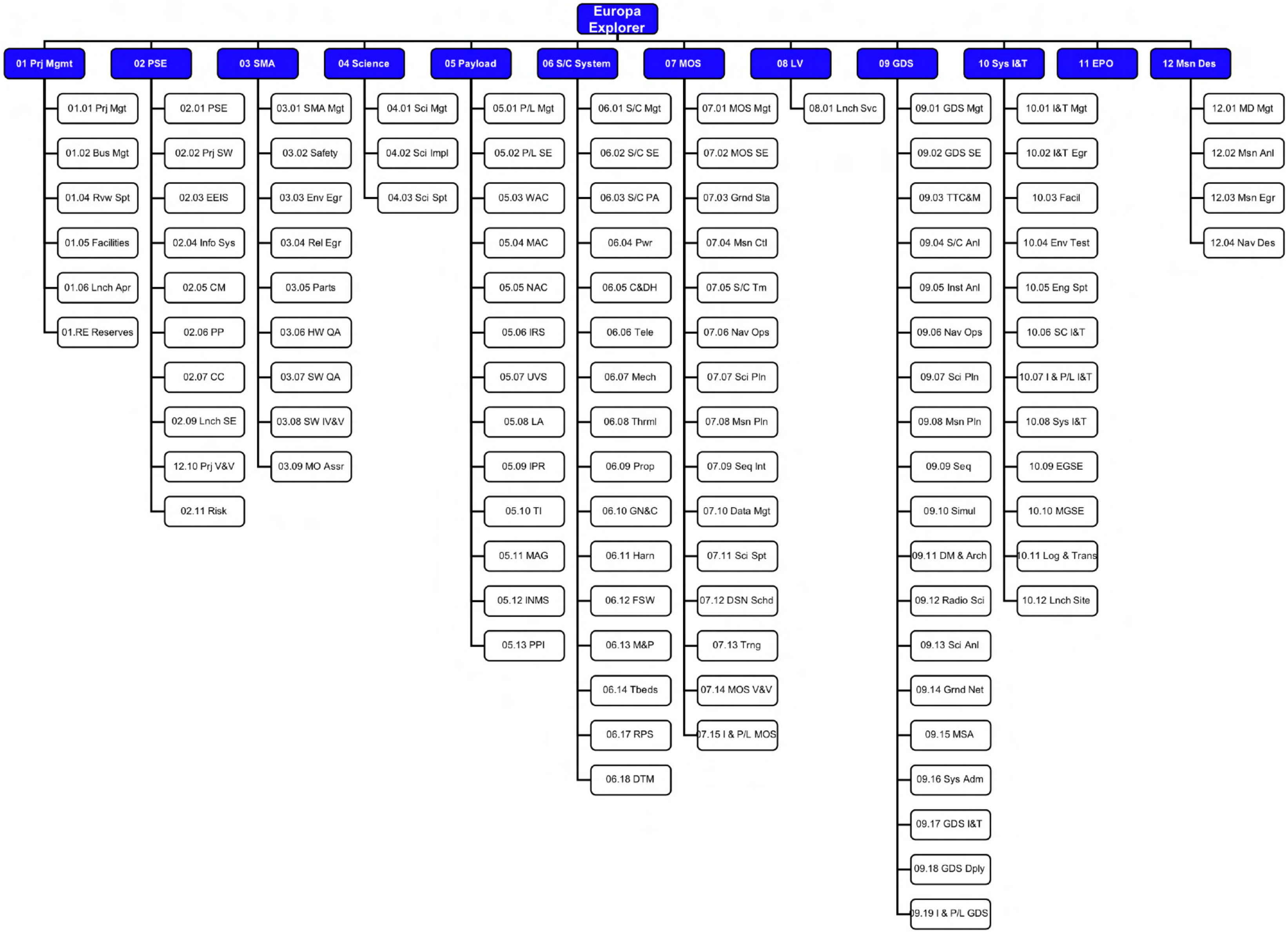



***Figure 4.10-1.*** *Europa Explorer Work Breakdown Structure.*

Integrated Master Schedule identifies key milestones, major reviews, and receivables/deliverables (Rec/Dels). Funded schedule reserves shown in the project master schedule for the June 2015 launch opportunity, **FO-7**, are funded at the peak burn rate, and meet JPL DPP requirements. The project utilizes an integrated cost/schedule system in Phase B, in order to fully implement an EVM baseline in Phases C/D/E. Inputs will be supplied to NASA's CADRe support contractor for reporting at major reviews. Schedule and cost estimates at completion (EACs) will be prepared at regular intervals as part of the EVM process. Major project review milestones (not all shown) are consistent with NPD 7120.5D.

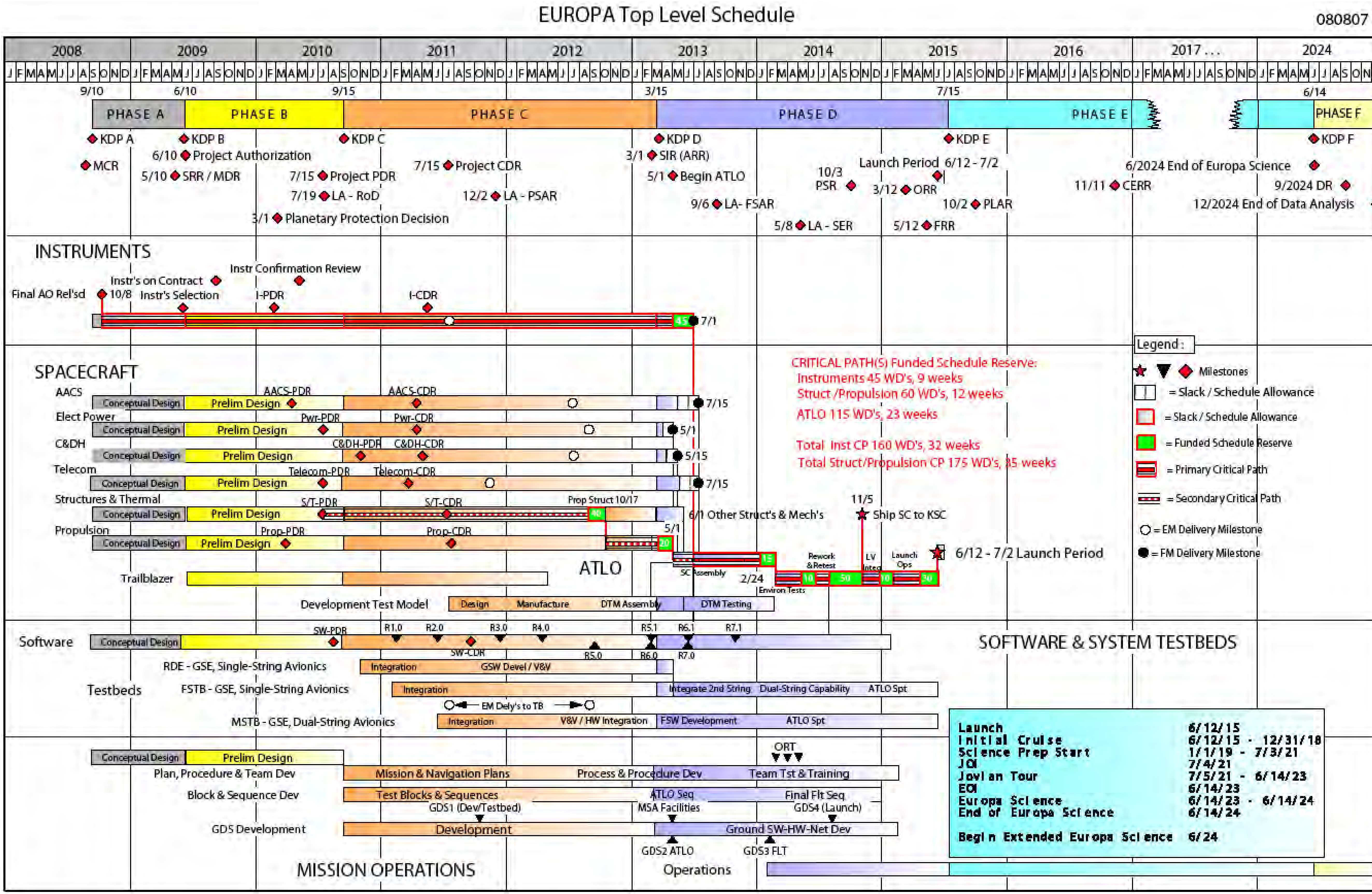
The Phase A portion of the project schedule is very short compared to past flagship class missions. Significant work on this basic mission concept has already been performed over the past years including the Europa Orbiter Project (in Phase B when cancelled in 2001), Prometheus/JIMO (Completed Phase A when indefinitely delayed in 2005), Europa Geophysical Explorer Concept Study in 2005 and Europa Explorer in 2006. Since the science objectives have been vetted by the science community several times over the past few years and are highly stable, it is unlikely that significant changes would occur, nor would the response implementation be likely to change significantly as the project moves into Phase A. This is very different from previous mission concepts as they moved from Pre-Phase A into Phase A. The focus of the EE Phase A would be to complete the Gate Products required and to facilitate the selection of the science instruments. The length of Phases A/B is primarily driven by the schedule to produce the instrument Announcement of Opportunity (AO) and advance the selected instruments to PDR level of maturity. Any early work to facilitate the maturation of the instrument implementations would benefit the schedule and reduce project risk.

The critical path, is the instrument solicitation, development and delivery, and is shown in red in **FO-7**. Schedule reserves of 9 weeks for instrument delivery and 23 weeks in ATLO, totaling 160 work-days or 32 weeks are available along this critical path. Later delivery of the instruments to ATLO may be possible as that schedule is firmed up in Phase A. Note that the time to Instrument PDR and subsequent Project PDR is the most pressing. This critical path is contingent on the release of the instrument AO. Basic schedule milestones on this path are aggressive, have been estimated by the study team based on previous flagship-class instrument AO schedules and would need to be assessed and modified by NASA Headquarters' personnel. Any effort to reduce the time between instrument selection and Project PDR would greatly mitigate the risk associated with instrument (identified Project Risk InD). Thus, early identification of parts, materials, design guidelines etc for mitigating the radiation and planetary protection challenges would be highly effective. Instrument Confirmation Reviews were inserted in the schedule prior to Project PDR to enable NASA HQ to assess the design maturity of the instrument concepts especially as related to radiation and planetary protection implementation. If deemed necessary by NASA HQ, early changes to the instrument complement could be made to lower overall project risk.

There is a secondary critical path through the design of the primary structure leading into the delivery and integration of the propulsion system which is also highlighted by a red dotted line in **FO-7**. Schedule reserves of 175 work-days or 35 weeks are available along this critical path. This critical path may be mitigated somewhat during preliminary design by further de-coupling the structure from the propulsion subsystem. This will need to be worked as a part of Phase B.

A milestone for a Planetary Protection Decision has been inserted in Phase B. A basic approach to meeting the planetary protection requirements has been outlined and agreed to by the PPO at NASA Headquarters. This milestone is anticipated to be a review of the more detailed implementation approach including any major outstanding issues related to mission design, flight system design or operations concepts. This review may ultimately be combined with the Project PDR if it is more effective to do so.

A trailblazer activity is scheduled to occur at the launch facility early in the project lifecycle to ensure that the spacecraft design is compatible with the launch vehicle and facility


EUROPA Top Level Schedule
080807
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017 . . .
2024
PHASE A
PHASE B
PHASE C
PHASE D
PHASE E
PHASE F
9/10
6/10
9/15
3/15
7/15
6/14
KDP A
KDP B
KDP C
KDP D
KDP E
KDP F
MCR
6/10 Project Authorization
5/10 SRR / MDR
7/15 Project PDR
7/19 LA - RoD
3/1 Planetary Protection Decision
7/15 Project CDR
12/2 LA - PSAR
3/1 SIR (ARR)
5/1 Begin ATLO
9/6 LA- FSAR
5/8 LA - SER
10/3 PSR
3/12 ORR
5/12 FRR
Launch Period 6/12 - 7/2
10/2 PLAR
11/11 CERR
6/2024 End of Europa Science
9/2024 DR
12/2024 End of Data Analysis
INSTRUMENTS
Final AO Rel'sd
Instr's on Contract
10/8 Instr's Selection
Instr Confirmation Review
I-PDR
I-CDR
7/1
SPACECRAFT
AACS
Elect Power
C&DH
Telecom
Structures & Thermal
Propulsion
Conceptual Design
Prelim Design
AACS-PDR
AACS-CDR
Pwr-PDR
Pwr-CDR
C&DH-PDR
C&DH-CDR
Telecom-PDR
Telecom-CDR
S/T-PDR
S/T-CDR
Prop Struct 10/17
Prop-PDR
Prop-CDR
7/15
5/1
5/15
7/15
6/1 Other Struct's & Mech's
11/5
Ship SC to KSC
Trailblazer
ATLO
SC Assembly
2/24
Environ Tests
Rework & Retest
LV Integ
Launch Ops
6/12 - 7/2 Launch Period
Development Test Model
Design
Manufacture
DTM Assembly
DTM Testing
CRITICAL PATH(S) Funded Schedule Reserve:
Instruments 45 WD's, 9 weeks
Struct /Propulsion 60 WD's, 12 weeks
ATLO 115 WD's, 23 weeks
Total Inst CP 160 WD's, 32 weeks
Total Struct/Propulsion CP 175 WD's, 35 weeks
Legend:
Milestones
= Slack / Schedule Allowance
= Slack / Schedule Allowance
= Funded Schedule Reserve
= Primary Critical Path
= Secondary Critical Path
= EM Delivery Milestone
= FM Delivery Milestone
Software
SW-PDR
SW-CDR
R1.0
R2.0
R3.0
R4.0
R5.0
R5.1
R6.0
R6.1
R7.0
R7.1
SOFTWARE & SYSTEM TESTBEDS
Testbeds
RDE - GSE, Single-String Avionics
FSTB - GSE, Single-String Avionics
MSTB - GSE, Dual-String Avionics
Integration
GSW Devel / V&V
Integrate 2nd String
Dual-String Capability
ATLO Spt
EM Dely's to TB
V&V / HW Integration
FSW Development
ATLO Spt
Plan, Procedure & Team Dev
Mission & Navigation Plans
Process & Procedure Dev
Team Tst & Training
ORT
Block & Sequence Dev
Test Blocks & Sequences
ATLO Seq
Final Flt Seq
GDS1 (Dev/Testbed)
MSA Facilities
GDS4 (Launch)
GDS Development
Development
Ground SW-HW-Net Dev
GDS2 ATLO
GDS3 FLT
MISSION OPERATIONS
Operations
Launch 6/12/15
Initial Cruise 6/12/15 - 12/31/18
Science Prep Start 1/1/19 - 7/3/21
JOI 7/4/21
Jovian Tour 7/5/21 - 6/14/23
EOI 6/14/23
Europa Science 6/14/23 - 6/14/24
End of Europa Science 6/14/24
Begin Extended Europa Science 6/24

limitations at the launch site for transporting and loading of the RPSs. This activity starts at a very low level in Phase A and continues with increasing activity until the approach to RPS installation is validated in Phase C.

The current schedule is based on a June 2015 VEEGA launch opportunity as it is the earliest launch opportunity possible and has the lowest performance capability. Numerous other launch opportunities exist (See §3.4.2 and Appendix E) with a similar VEEGA opportunity in January 2017. If this latter launch opportunity is preferred, the schedule can be adjusted easily for the 18-month delay and could possibly remove the Instrument AO from the critical path.

#### 4.10.7 Estimated Mission Cost

The current EE Phase A through E life-cycle cost estimate for the baseline mission concept is $3.3 BFY07 while the floor mission cost estimate is $2.4 BFY07. The WBS level 2 summary is reported in **Table 4.10-1** and **4.10-2**, respectively, and in **Figure 4.10-2**. The drivers for the cost differences between the baseline and floor mission concepts are given in **Table 4.10-3**. These estimates represent the full life cycle and conservatively assume individual instruments instead of instrument suites, and additional subcontracting. See Appendix D for more discussion of basis of estimates. No offsets have been taken for potential domestic or foreign contributions. Early funding for additional support to the Instrument Announcement of Opportunity (AO) has been included.

A cost target of $3 BFY07 was given as a guideline in the study kickoff meeting. The baseline and floor mission cost estimates bracket this $3 BFY07 target. Variations of these two concepts would produce cost estimates between these two data points.

The cost estimate for the baseline mission if launched in the backup January 2017 launch opportunity is $3.3 BFY07 and is shown in **Figure 4.10-2**. The uncertainties are larger on the lower end due to the conservative set of assumptions used for costing. If a less conservative approach is taken, then the uncertainty bars grow larger on the upper end and shorter on the lower end.

Cost uncertainty was developed by evaluating each WBS element against an assessment of the uncertainty inherent in the methodology used to determine them. For example, the Project Management cost was derived using a very conservative wrap factor applied to the reserves base. Thus, the uncertainty would be low for this element and the absolute value could appear very high as indicated by comparison to both Cassini and Juno. Also, Science team estimates are based on the number of instruments. Once selected, it would be very likely that several of the currently identified individual instruments

***Table 4.10-1.** Europa Explorer Baseline Cost Estimate by WBS Level 2*

| WBS Element | Phase A/B | Phase C/D | Phase E | Total ($MFY07) |
|---|---|---|---|---|
| 01 Project Management | 24 | 77 | 34 | 135 |
| 02 Project System Engineering | 13 | 67 | 20 | 100 |
| 03 Safety & Mission Assurance | 13 | 67 | 20 | 100 |
| 04 Science | 21 | 54 | 203 | 278 |
| 05 Payload System | 45 | 350 | 0 | 395 |
| 06 Spacecraft System | 88 | 367 | 0 | 456 |
| 07 Mission Operations System | 2 | 39 | 234 | 275 |
| 09 Ground Data System | 3 | 41 | 25 | 68 |
| DSN Aperture | 0 | 2 | 120 | 123 |
| 10 Project System Integration & Test | 4 | 38 | 0 | 42 |
| 11 Education and Public Outreach | 1 | 6 | 13 | 20 |
| 12 Mission Design | 5 | 10 | 0 | 16 |
| Reserves | 64 | 414 | 100 | 578 |
| Launch System Total | 0 | 502 | 0 | 502 |
| Radioisotope Power Source Total | 22 | 201 | 0 | 223 |
| **Total** | **306** | **2,234** | **770** | **3,310** |

***Table 4.10-2.*** *Europa Explorer Floor Mission Cost Estimate by WBS Level 2*

| WBS Element | Phase A/B | Phase C/D | Phase E | Total ($MFY07) |
|---|---|---|---|---|
| 01 Project Management | 23 | 65 | 26 | 114 |
| 02 Project System Engineering | 11 | 55 | 15 | 81 |
| 03 Safety & Mission Assurance | 11 | 55 | 15 | 81 |
| 04 Science | 13 | 33 | 123 | 168 |
| 05 Payload System | 28 | 211 | 0 | 239 |
| 06 Spacecraft System | 88 | 364 | 0 | 452 |
| 07 Mission Operations System | 2 | 34 | 191 | 227 |
| 09 Ground Data System | 3 | 39 | 23 | 64 |
| DSN Aperture | 0 | 2 | 100 | 103 |
| 10 Project System Integration & Test | 4 | 38 | 0 | 42 |
| 11 Education and Public Outreach | 1 | 5 | 10 | 16 |
| 12 Mission Design | 5 | 10 | 0 | 16 |
| Reserves | 61 | 382 | 76 | 519 |
| Launch System Total | 0 | 176 | 0 | 176 |
| Radioisotope Power Source Total | 12 | 109 | 0 | 121 |
| **Total** | **262** | **1,577** | **580** | **2,419** |

***Table 4.10-3*** *Major technical differences that drive the majority of cost deltas between the baseline and floor mission concepts*

| | Baseline Mission | Floor Mission |
|---|---|---|
| Launch Vehicle | Delta IVH | Atlas 531 |
| RPS | 6 MMRTGs | 5 ASRGs |
| Payload Complement | 5 Simple, 6 Complex | 5 Simple, 3 Complex |
| Europa Mission Duration | 12 months | 6 months |
| Reserve on Phases B-D | 37% | 42% |

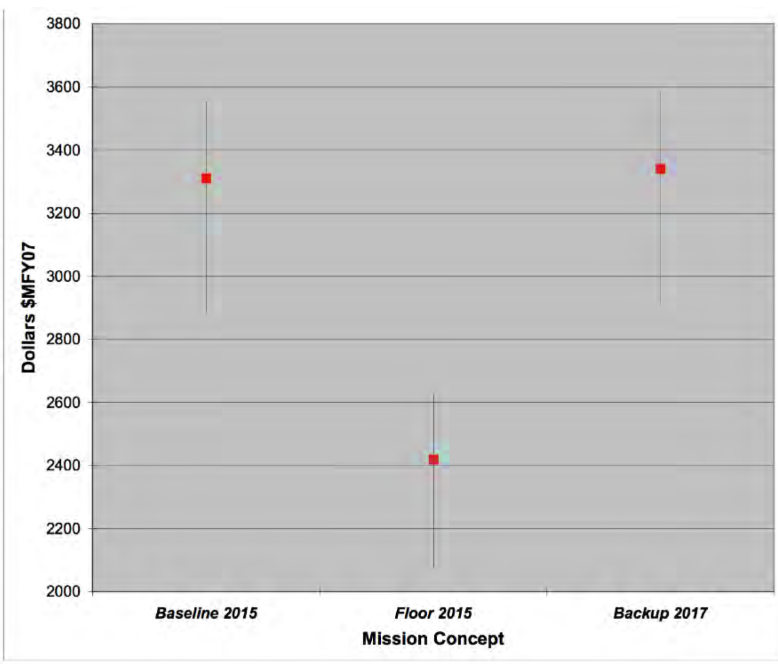



***Figure 4.10-2.*** *Europa Explorer cost summary with uncertainty*

would be combined into an instrument suite. Thus, the infrastructure costs would be less and the actual costs would likely be lower. The uncertainties are shown in **Table 4.10-4**.

Though the approach to cost uncertainty takes into account some potential ways to reduce mission cost, there are other potential methods which could not be addressed during this study. Such methods include:

- Decreasing length of mission
- Re-evaluating cost of science teams in Phase E
- Using 1 pass per day 70m after first month in Europa orbit
- Adding international collaborator(s)
- Removing one main engine and/or several thrusters
- Baselining the ASRG
- Evaluating shorter cruise trajectories
- Baseline larger SSR to enable Ka band on 34 m antennas and 1 pass per day downlink

***Table 4.10-4.*** *Cost Uncertainty by WBS Element*

| | Low | High |
|---|---|---|
| 01 Project Management | -20% | 5% |
| 02 Project System Engineering | -10% | 5% |
| 03 Safety & Mission Assurance | -5% | 10% |
| 04 Science | -20% | 5% |
| 05 Payload System | -20% | 10% |
| 06 Spacecraft System | -15% | 15% |
| 07 Mission Operations System | -20% | 10% |
| 09 Ground Data System | -20% | 10% |
| DSN Aperture | -10% | 5% |
| 10 Project System Integration & Test | -10% | 10% |
| 11 Education and Public Outreach | 0% | 0% |
| 12 Mission Design | -10% | 5% |
| Reserves | | |
| Launch System Total | | |
| Radioisotope Power Source Total | | |

### 4.10.8 Cost Estimating Methodologies

The cost estimating methodologies used to develop the Europa Explorer cost estimate are described in **Table 4.10-5.** This hybrid methodology uses cost rules of thumb and analogies, the system NASA Instrument Cost Model (NICM), grassroots and quasi-grassroots techniques. Launch services and radioisotope power source costs were provided by NASA Headquarters. **Figure 4.10-3** summarizes the cost share percentage by estimation method. Appendix D includes the cost estimating process description and the

***Table 4.10-5.*** *Cost Estimating Methodology*

| WBS Element | Description |
|---|---|
| 01 Project Management | Phase A-D = 5%, Phase E = 3% of CBE cost excluding RPS and LV. |
| 01. RE Reserves | • Cost Risk Subfactors - Reserves base excludes LV and RPS<br>• 10% * Phase A + Risk Subfactors * Phase B - D<br>• 15% Phase E |
| 02 Project System Engineering | Phase A-D = 6%, Phase E = 3% of CBE cost excluding RPS and LV. |
| 03 Safety & Mission Assurance | Phase A-D = 6%, Phase E = 3% of CBE cost excluding RPS and LV. Includes Project level SMA and Spacecraft System SMA. |
| 04 Science | • Phase A-D scaled as a scaling of Phase E Science using Juno analogy<br>• Phase E costs scaled on Simple/Complex Instrument designation, w/ Data Analysis |
| 05 Payload System | • P/L Mgmt and P/L SE used Team X cost model<br>• Nominal NICM model estimate with 70% cost scaled for PP and radiation. Individual instrument cost estimates include Instru. Mgmt, Instru SE, Instru. PA and Instru. I&T. |
| 06 Spacecraft System | • Grassroots w/ line organization review. WBS 06.01 Spacecraft Management scaled as 2% of total spacecraft cost excluding RPS |
| 07 Mission Operations System | • Ground Segment Team (Team G) estimate |
| 09 Ground Data System | • Ground Segment Team (Team G) estimate |
| DSN Aperture | • Ground Segment Team (Team G) estimate using *DSN Aperture Fee* tool. |
| 10 Project System Integration & Test | • Grassroots w/ line organization review |
| 11 Education and Public Outreach | • Phase A-D - 0.5%, Phase E = 2% of CBE cost excluding RPS and LV. |
| 12 Mission Design | • Grassroots w/ line organization review |
| 08 Launch System w/ Nuclear Support | Source: *Requirements and Ground rules for Flagship Mission Studies*, Table 1 ROM Launch Services costs for Atlas 5 and Delta IV Heavy launch vehicles. Table values reported in $FY06 and escalated to $FY07 dollars. Includes nuclear payload costs. |
| 06.17 Radioisotope Power Source | Source: *RPS Cost Est for Flagship_v4*, 4/10/2007. RPS prices include qualification costs. |

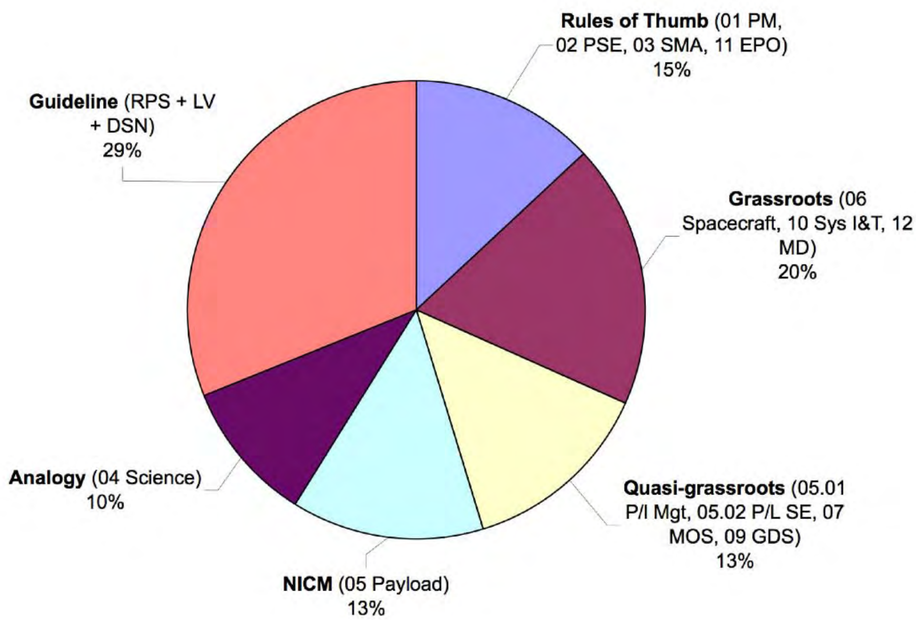



***Figure 4.10-3.*** *Cost Share by estimation method (excluding reserves).*

bases of estimate for each individual method including:

- Cost rule of thumb range as derived from cost actuals for 14 missions used for rules of thumb scaling. This technique is applied to the predominantly level of effort activities.
- Cost analogy used for Science Team sizing
- The NICM system model inputs, nominal instrument cost estimates, and planetary protection and radiation effects scaling factors.
- Summary bases of the grassroots estimates for spacecraft, system, integration and test, and mission design. Formal cost guidelines and detailed development schedule support the grassroots estimates. Each cost estimate has gone through multiple line organization reviews.
- Quasi-grassroots underlying assumptions for the Ground Segment Team (Team G) estimates for MOS, GDS and DSN aperture costs.
- HQ provided Launch system and Radioisotope Power Sources (RPS) costs.

#### 4.10.9 Budget Reserve Strategy

The reserves base is the current best estimate (CBE) cost excluding RPS and launch system. A 10% reserve level is carried on Phase A activities. JPL has established a consistent methodology for estimating required reserves based on previous history and specific attributes of the Project implementation. This methodology is called Cost Risk Subfactor Analysis and takes into account project complexities such as multiple flight elements, new software teams, extreme environmental issues, etc. Reserves for Phases B through D are established by the JPL Cost Risk Subfactor analysis approach The risks associated with this mission are:

- Known architecture (orbiter) in new environment (radiation, planetary protection)
- High radiation and PP requirements including development for instruments
- New software approach
- Multiple science objectives (assuming Jupiter system science)

These cost risk subfactors result in a suggested reserve posture of 37% for the baseline mission. An additional subfactor for the floor mission is associated with the choice of the less mature ASRG leading to 42% reserves for the floor mission.

A 15% reserve is carried on Phase E. The Cost Risk Subfactor analysis is included in Appendix D. For this study, the Study Leader was instructed to adopt a “conservative costing philosophy” in order to avoid cost growth as the mission became better defined. Recent Science Mission Directorate experience with the overly optimistic initial costing of large flagship missions such as James Webb Space Telescope was cited as a model to avoid. Accordingly, this study used the cost risk subfactor analysis to identify risk areas and establish reserves at fairly high level commensurate with the maturity of the mission concept and the modest investment in mission studies to date (< 1% of mission cost). During Phase A, these risk areas will be examined in more detail and its expected that some of them will be retired. As a result, following the Phase A studies the level of reserves will decrease and will continue to do so at subsequent project key decision points. Commensurately, the confidence in implementing the mission within the overall estimate provided here is expected to grow.

#### 4.10.10 Risk Assessment and Management Strategy

Mitigations to the primary cost risk factors have been identified and related to the Project Risk list (§4.9) by acronym. They fall into three primary areas:

- The instrument AO and delivery is on the critical path (InD) and relates specifically to the late selection of the instrument cost risk subfactor. An approved parts and materials list including planetary protection (PP) and radiation characteristics (RadPSM) is planned in support of the AO. In addition, design guidelines (RadPSM, PP and IC) and provider workshops are planned. An additional $9M has been added in Pre-Phase A and Phase A to directly support efforts to mitigate this risk by providing as much information for potential instrument providers as early as possible. This will allow maturation of the instrument concepts prior to final selection and thus reduce the mis-matches found after selection and prior to Project PDR.
- Radiation design (RadE and RadPSM) is cross cutting and relates specifically to the new environment, harsh environment and new software cost risk subfactors. The cost estimate includes a Radiation System Engineer in WBS 02 Project System Engineering and additional staffing at all system engineering levels including WBS 05 Payload. The DPSER is responsible to manage all aspects of the radiation design and reports to the DPMR. It also assumes early development of parts and materials lists, and design guidelines for Radiation (RadPSM), Planetary Protection (PP) and Internal Charging (IC).
- Planetary Protection (PP) is cross cutting and relates specifically to the new environment and harsh environment cost risk subfactors for sterilization processing and is mitigated by early attention with a review added in Phase B to confirm approach and assess implementation. This risk is also mitigated by the previous activities discussed above. The basic approach to PP is to sterilize the assemblies at the box level and allow the radiation environment to sterilize the external surfaces. This approach has been vetted by the HQ PPO and deemed reasonable as an approach. This early review allows time for the engineering team, including instrument engineers, to determine the true feasibility of this approach. If it is deemed unworkable, then a revised approach developed by analysis may be necessary. This backup approach would be within the cost estimate for the sterilization. If, in the highly unlikely event, that full system sterilization is deemed the only approach, then the reserves proposed herein may not be enough to cover that cost and/or the proposed schedule will be unachievable.
- The PSE and Payload Manager are delegated the day-to-day responsibility for the mitigation of the instrument development and delivery schedule risk. The DPSER is delegated the day-to-day responsibility for mitigation of the Radiation risks. The project Planetary Protection Engineer is delegated day-to-day responsibility for the mitigation of the planetary protection risk. The Project Manager has the ultimate responsibility for project risk. As such, a risk management process will be put in place in Pre-phase A and will monitor progress at least weekly as mitigation of these risks is most effective early in the project. The roles of DPMR, PSE, DPSER and Payload manager will be staffed in Pre-Phase A. The Safety and Mission Assurance organization will be utilized for independent assessment of the process.

#### 4.10.11 Planetary Protection Costing Approach

In estimating the additional time and cost for Dry Heat Microbial Reduction (DHMR) processing or irradiation in situ, a preliminary analysis based on the MEL was performed using recent information obtained during the planetary protection study performed for Mars Science Laboratory. Spacecraft design thru ATLO costs were incremented based on: 10% for newly developed hardware items, and 20% for C&DH hardware. This is a conservative assessment based on perceived difficulty of implementation given the maturity of the design. For instrument costing, a 10 % scaling factor is used based upon discussions with instrument developers and the heritage PP implementation based on Mars missions.

#### 4.10.12 NEPA Compliance and Launch Approval

Environmental review requirements will be satisfied by the completion of a mission-specific Environmental Impact Statement (EIS) for the EE mission. In accordance with the requirements described by NPR 7120.5D, the Record of Decision (ROD) for this EIS would be finalized prior to or concurrent with Project PDR.

The EE launch approval engineering (LAE) Plan will be completed no later than the Mission Definition Review (MDR). This plan will describe the approach for satisfying NASA's NEPA requirements for the EE mission, and the approach for complying with the nuclear safety launch approval process described by Presidential Directive/National Security Council Memorandum #25 (PD/NSC-25) and satisfying the nuclear safety requirements of NPR 8715.3. The LAE Plan will provide a description of responsibilities, data sources, schedule, and an overall summary plan for preparing:

- a mission-specific environmental review document and supporting nuclear safety risk assessment efforts;
- launch vehicle and flight system/mission design data requirements to support nuclear risk assessment and safety analyses in compliance with the requirements of NPR 8715.3 and the PD/NSC-25 nuclear safety launch approval process;
- support of launch site radiological contingency planning efforts; and
- risk communication activities and products pertaining to the NEPA process, nuclear safety and planetary protection aspects of the project.

It is anticipated that NASA HQ will initiate the EE environmental review document development as soon as a clear definition of the baseline plan and option space has been formulated. DOE would provide a nuclear risk assessment to support the environmental review document, based upon a representative set of environments and accident scenarios compiled by the KSC/Launch Services Program working with JPL. This deliverable may be modeled after the approach used on the Mars Science Laboratory (MSL) EIS.

DOE will provide a nuclear safety analysis report (SAR) based upon NASA-provided mission-specific launch system and flight system data to support the PD/NSC-25 compliance effort. The SAR would be delivered to an ad hoc interagency nuclear safety review panel (INSRP) organized for the EE mission. This INSRP would review the SAR's methodology and conclusions and prepare a Safety Evaluation Report (SER). Both the SER and the SAR would then be provided by NASA to EPA, DoD, and DOE for agency review. Following agency review of the documents and resolution of any outstanding issues, NASA, as the sponsoring agency, would submit a request for launch approval to the Director of the Office of Science and Technology Policy (OSTP). The Director of the OSTP would review the request for nuclear safety launch approval and either approve the launch or defer the decision to the President. Key dates and deliverables for the NEPA and nuclear safety launch approval processes are shown in **FO-7**.

As part of broader nuclear safety considerations, EE would adopt ATLO, spacecraft, trajectory, and operations requirements which satisfy the nuclear safety requirements described by NPR 8715.3.

Development of coordinated launch site radiological contingency response plans for NASA launches is the responsibility of the launch site radiation safety organization. Comprehensive radiological contingency response plans, compliant with the National Response Plan and appropriate annexes, would be developed and put in place prior to launch as required by NPR 8715.2 and NPR 8715.3. The EE project would support the development of plans for on-orbit contingency actions to complement these ground-based response plans.

A project-specific Risk Communication Plan will be completed no later than the Mission MDR. The Risk Communication Plan will detail the rationale, proactive strategy, process and products of communicating risk aspects of the Project, including nuclear safety and planetary protection. The communication strategy and process will comply with the approach and requirements outlined in the NASA Office of Space Science Risk Communication Plan for Deep Space Missions (1999) JPL D-16993 and the JPL Risk Communication Plan, 2002, JPL D-24012.

#### 4.10.13 Descope Strategy

As described in §2.4.2, the SDT has determined the planning payload for both the baseline and floor mission concepts. The approach to descoping from the baseline concept to the floor concept would be different depending on the reason the descope is required. Decisions based on risk may be different from those based on cost or mass. Thus, an approach must be developed which quantifies the science quality. This can only be done in conjunction with SDT and HQ. Once defined, science quality can be traded against science quantity, risk, schedule and cost. This approach allows the Project System Engineering Team to quantitatively define and explore the trade space. Informed decisions can then be made based in sound engineering trades and communicated to the sponsor, stakeholders and team. Only the PM can authorize descopes with the concurrence of the PS and HQ. If a level 1 requirement is effected, then HQ approval is required.

#### 4.10.14 Supporting Information

**See Appendix D for additional detail on the cost estimation process and results for the baseline, floor and backup mission concepts, including the TMC-required cost tables.**

## 5.0 MISSION CONCEPT ALTERNATIVE IMPLEMENTATION

Not Applicable.