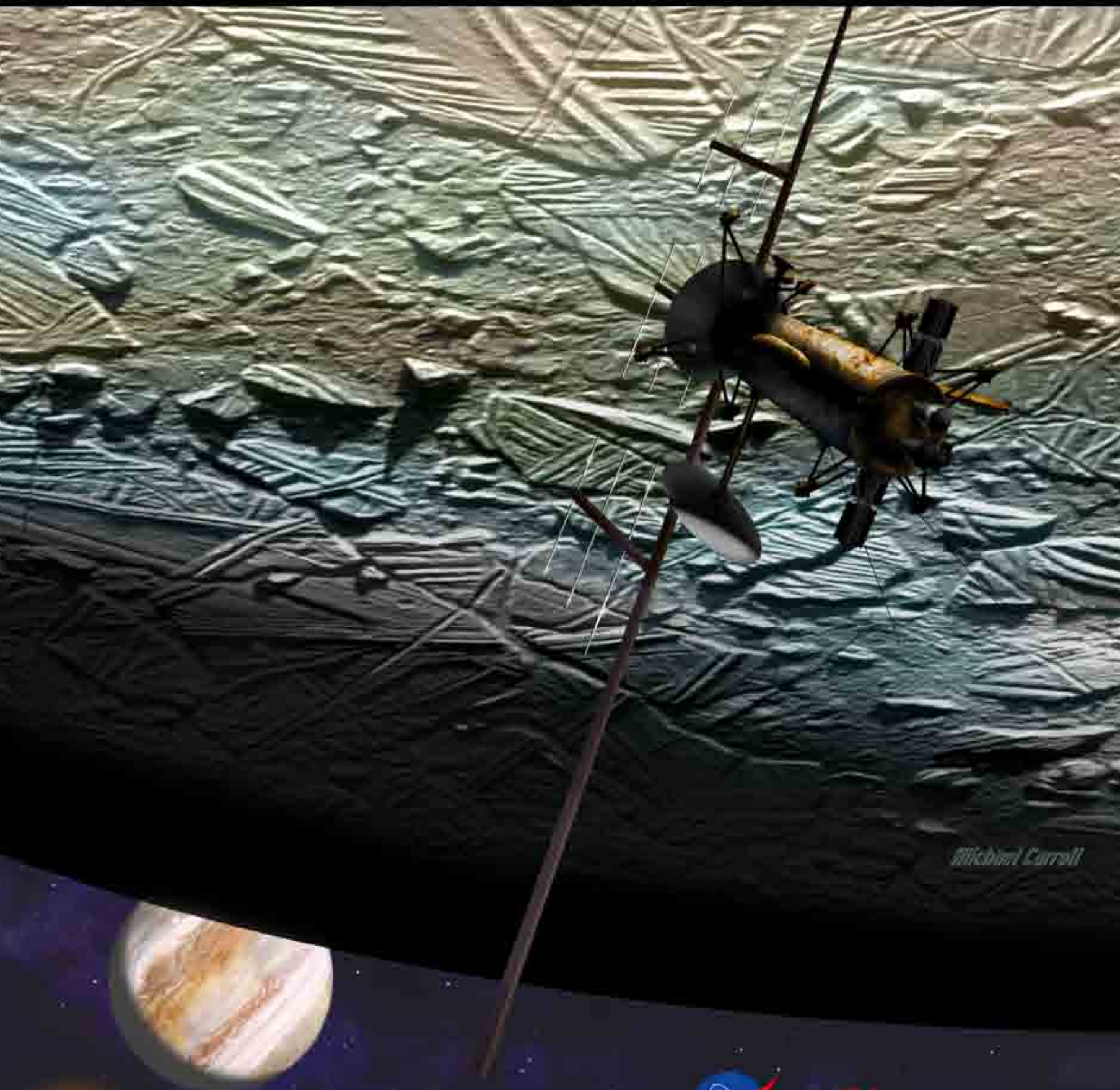


2007 Europa Explorer Mission Study: Final Report



Michael Carroll

Task Order #NMO710851 JPL D-41283 01 November 2007



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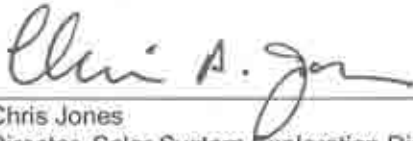
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The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Cover art provided courtesy of Michael Carroll.

Europa Explorer

Fact Sheet

Science Goal:
Explore Europa and
investigate its habitability

Science Objectives

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.

F. Europa's Neighborhood:

Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons.

Priority 1
Priority 2

Baseline Planning Payload

Investigations/Instruments

Wide-Angle Camera (WAC)

Medium-Angle Camera (MAC)

Narrow-Angle Camera (NAC)

IR Spectrometer (IRS)

UV Spectrometer (UVS)

Laser Altimeter (LA)

Ice Penetrating Radar (IPR)

Thermal Instrument (TI)

Magnetometer (MAG)

Ion & Neutral Mass

Spectrometer (INMS)

Particle & Plasma Instrument (PPI)

Radio Science – Gravity

Characteristics

3-color+panchromatic; IFOV of 1 mrad, framing mode

Stereo optics; panchromatic; IFOV of 0.1 mrad; pushbroom mode

IFOV of 10 μ rad;

Framing and pushbroom modes

0.4 to 5 μ m, 6 nm spectral resolution below 2.5 μ m, and 12 nm above 2.5 μ m; 558 spectral channels

EUV 55–110 nm, FUV 110–190 nm, NUV 190–350 nm

Both nadir and limb viewing

Multi-beam, 5-spot cross pattern; 1.064 μ m 5 MHz dipole & 50 MHz Yagi antennas with 1 and 10 MHz bandwidths

2 bands in the 8–16 μ m range, Visible channel for surface albedo

Dual sensors; 10 m boom; 0–1000 nT

1–300 Daltons & resolution > 500; 10^{-6} to 10^{-17} mbar for neutrals and < 100 eV ions

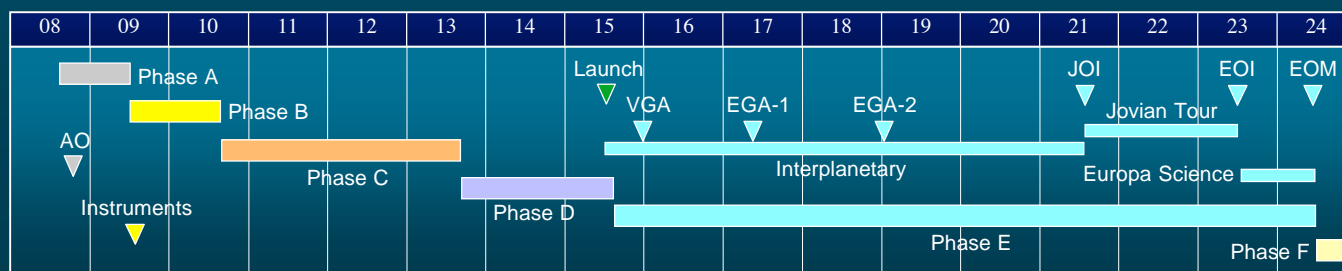
100's keV to 10 MeV electrons; Up to 100's MeV ions

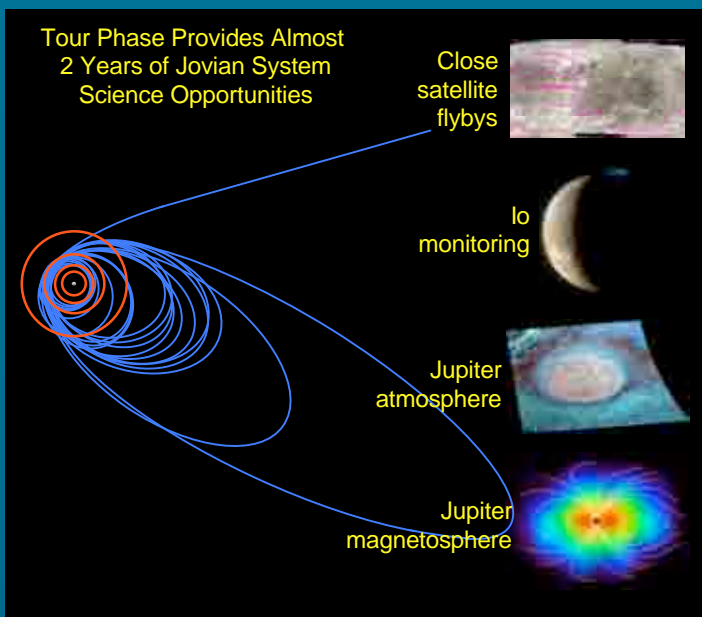
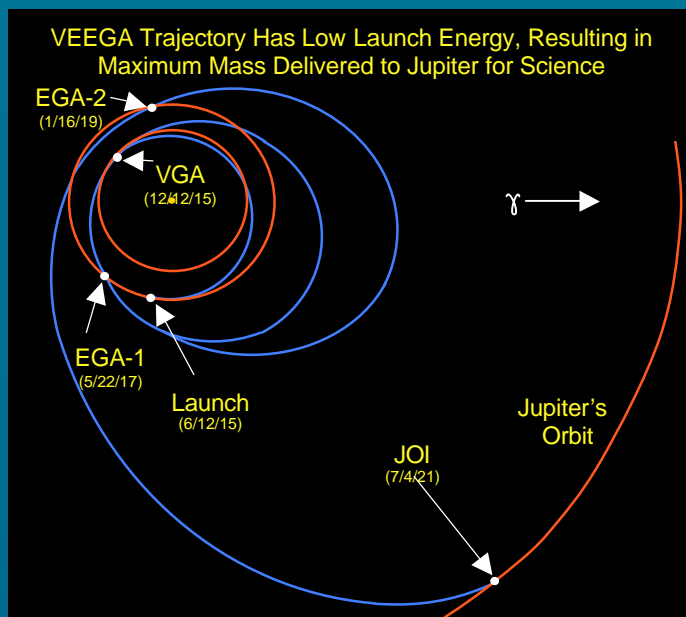
2-way Doppler, X- & Ka-band via telecom subsystem

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

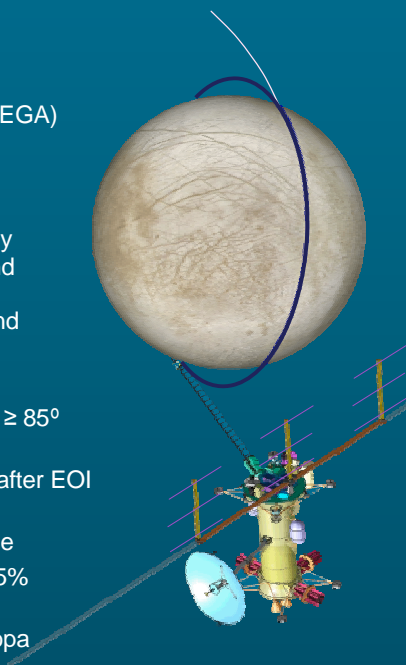
Schedule





Mission Overview

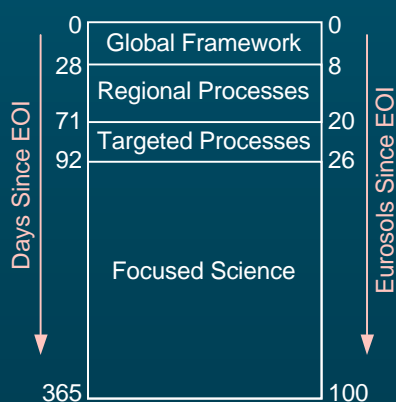
- Launch on Delta IV-H in June 2015
- Venus-Earth-Gravity Assist (VEEGA) trajectory
- Jupiter Orbit Insertion in July 2021
- 23 month tour of Jovian system, including additional science from many flybys each of Europa, Ganymede, and Callisto, continuous magnetospheric monitoring, regular monitoring of Io and Jupiter's atmosphere
- Europa orbit insertion in June 2023
- Initial, circular 200 km altitude orbit at $\geq 85^\circ$ 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



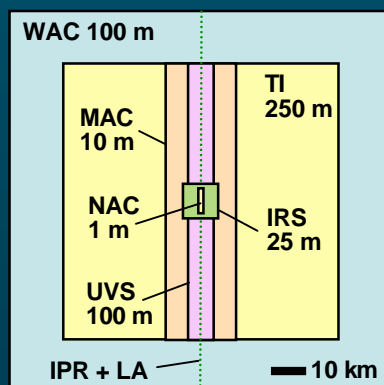
Flight System

- 7045 kg wet mass
- 158 kg planning payload
- Six MMRTGs provide power
- Two-axis gimballed 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

Ron Greeley, Co-Chair (Arizona State University)
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 Range: \$2.9 to 3.5	Best Estimate: \$2.4 Range: \$2.1 to 2.6

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

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 <i>in situ</i> 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.

the Priority 1 objectives, and which retains flexibility to achieve the Priority 2 objectives and extended science.

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 Mrad¹. 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 eurosols² (~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 European 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

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	
Remote sensing	8 instruments
Fields and particles	3 instruments
Radio science (gravity)	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

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.

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.

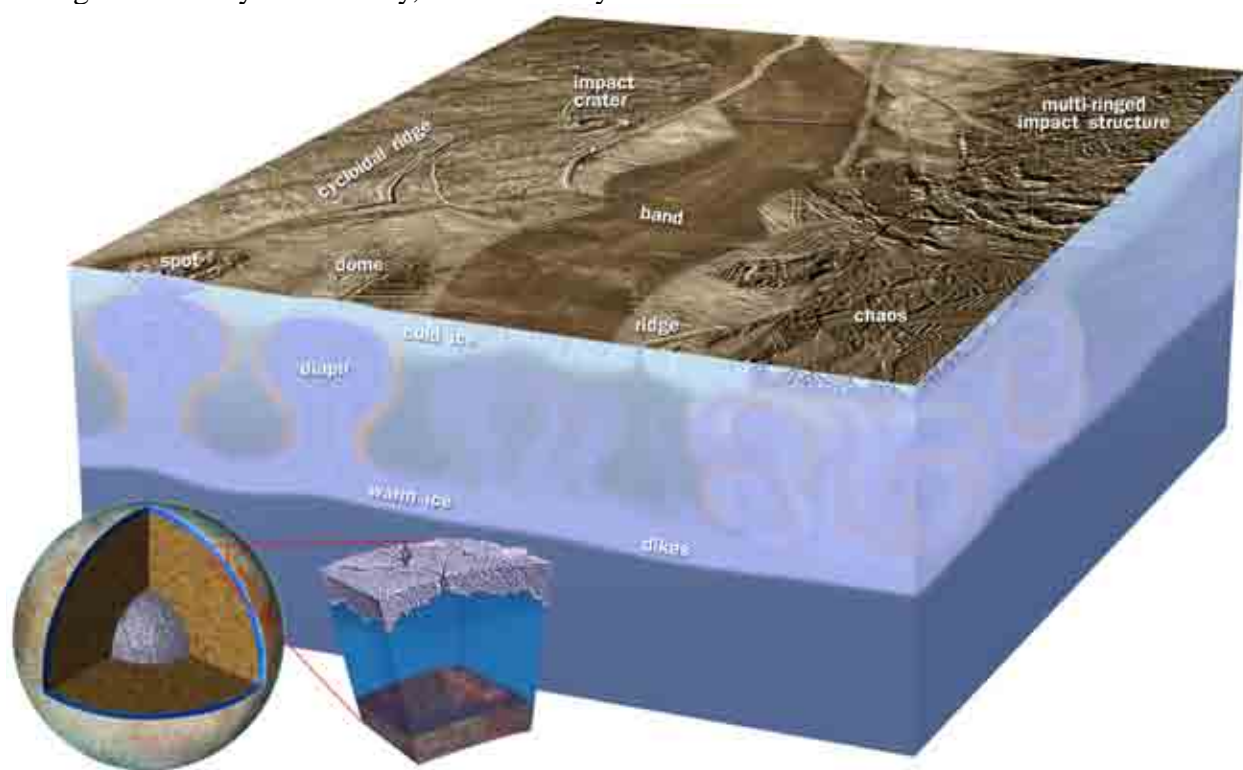


Figure 2.1-1. Schematic models of Europa's interior structure. Galileo gravity data suggests that Europa is differentiated into an iron core, rocky mantle, and H₂O-rich outer shell about 100 km thick, and Galileo magnetometer data implies that some of the H₂O is a liquid, forming a global ocean (foreground). 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

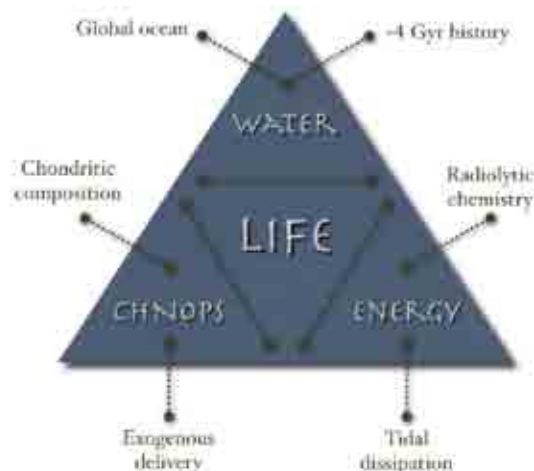


Figure 2.2-1. Pyramid of habitability. Our present understanding of the conditions for life can be distilled down to three broad requirements: 1) a sustained liquid water environment (Europa’s global ocean, which has likely existed for 4 Gyr), 2) elements (e.g. C,H,N,O,P,S) that are critical for building 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 O₂, H₂O₂, CO₂, SO₂, SO₄, 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 European 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

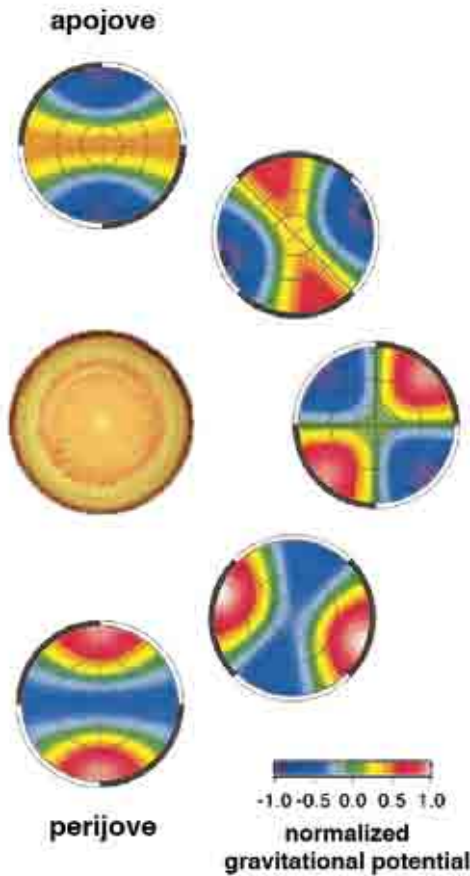


Figure 2.2-2. Europa experiences a time-varying gravitational potential field as it moves in its eccentric orbit about Jupiter (eccentricity = 0.0094), with a 3.551 day (1 eurosol) period. Europa's tidal amplitude varies proportionally to the gravitational potential, so the satellite flexes measurably 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 European 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

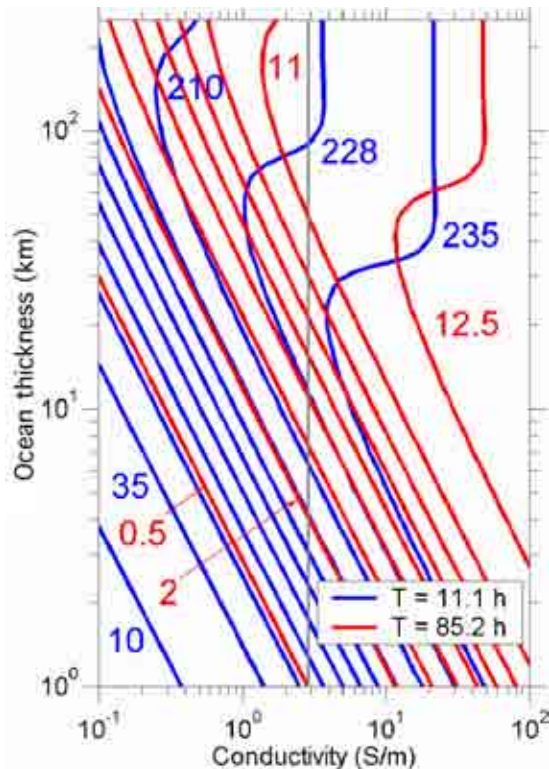


Figure 2.2-3. Contours of the induced magnetic field (in nT) generated at the surface of Europa, predicted at Jupiter's synodic rotation period of 11.1 hr (blue) and at Europa's orbital period of 85.2 hr (red), as a function of ocean thickness and ocean conductivity. For relatively large values of ocean 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 H₂O in Europa's 1–2.5 μ m 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 O₃ (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 complementary 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 SO₂, or from ocean-derived sulfates. As on Callisto and Ganymede, CO₂ 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, O₂, SO₂ 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

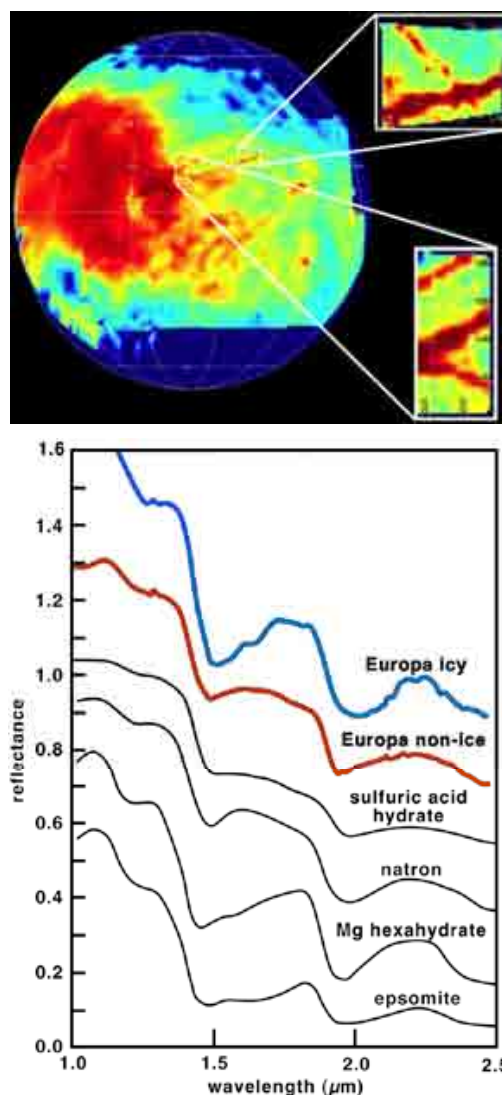


Figure 2.2-4. Reflectance spectra of hydrated materials on Europa. The distribution of hydrated materials on Europa (top, red) correlates with geologically disrupted terrains and triple bands (insets), and with the trailing hemisphere. Candidate materials for Europa's non-ice component (bottom) include sulfuric acid hydrate (H₂SO₄•nH₂O) 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

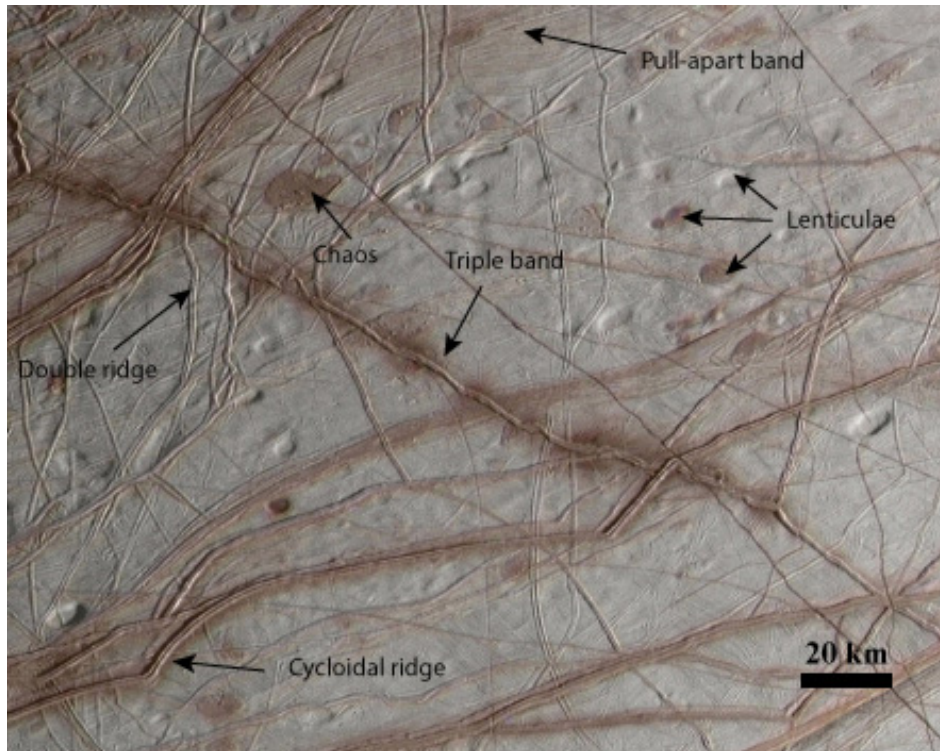


Figure 2.2-5. A selection of Europa's diverse surface features showing different types of surface deformation, which in turn provide information about geological processes and their possible connections to the tidal processes and the subsurface ocean.

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 European 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 [Figueroa 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 O₂, the surface pressure is just $\sim 2 \times 10^{-12}$ 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.

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 electro-magnetic 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

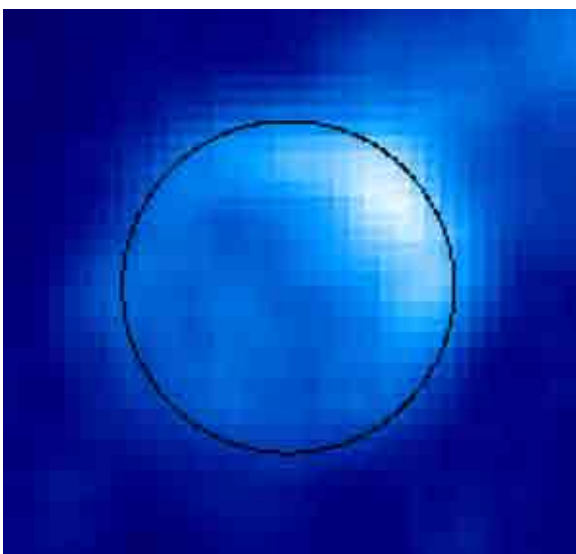


Figure 2.2-6. Oxygen emission from Europa's atmosphere, observed in ultraviolet wavelengths (1356 angstroms) with the Hubble Space Telescope [McGrath *et al.* 2004]. This image shows the atmosphere to be bright in the anti-jovian hemisphere, suggesting significant heterogeneity and complexity.

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 through 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

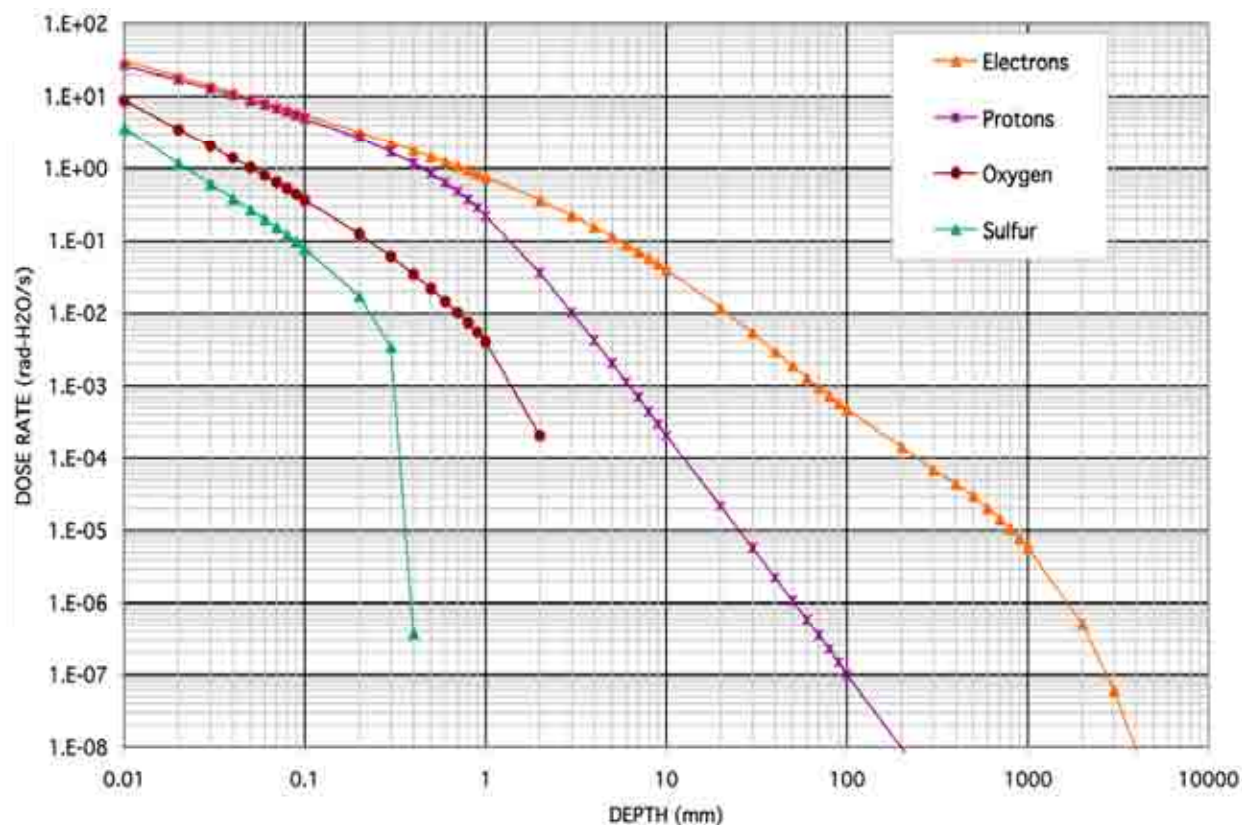


Figure 2.2-7. Estimated dose rate into Europa's trailing hemisphere as a function of depth in pure water ice. Molecular bonds will be broken and oxidants will be formed to these depths. Calculation uses energy spectra detected above Europa's surface by spacecraft and a model of the transport [Paranicas *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 H₂O molecule down to 1 cm is ionized in just 10⁴ 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

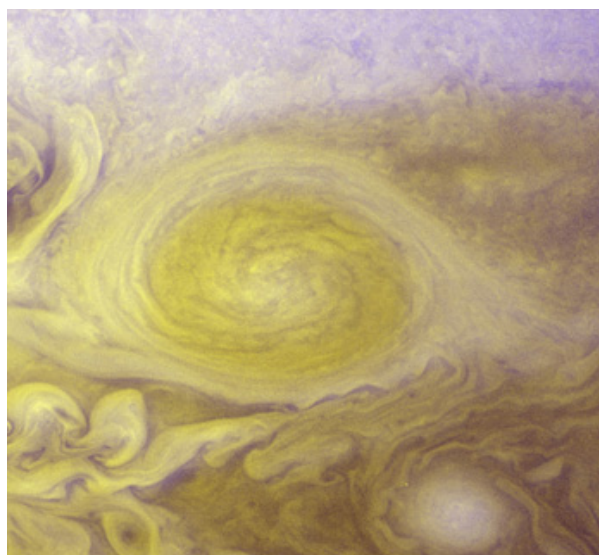


Figure 2.2-8. Image of Jupiter's "Little Red Spot" from the New Horizons spacecraft, colorized using Hubble Space Telescope images. Imaging resolution is about 15 km/pixel, which is about 10 times better than Hubble's. Images such as these permit an understanding of the development and dynamics of Jupiter's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

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.

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
• 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.	• How did the solar system evolve to its current diverse state?	Evolution
• 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

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

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

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. 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).	A1a. Telecom system. 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. 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.	A4a. Telecom system. A4b. Laser altimeter.		
	A5. Investigate the core and rocky mantle.	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 of 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. 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.	B1a. Radar sounder (nominally ~ 50 MHz, with ~ 10 MHz bandwidth). 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. 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.	B2a. Radar sounder (nominally ~ 5 or 50 MHz, with ~ 1 MHz bandwidth). 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 characterization 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. 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 targeted thermal observations at better than 250 m/pixel spatial resolution and temperature accuracy 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 desirable), and better than 12 nm through a spectral range of at least 2.5-5 μm . 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. 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. B3f. Determine surface color characteristics at ~ 100 m/pixel scale in at least 3 colors, over $>80\%$ of the surface. 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 characterization of selected sites. B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. 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.	B3a. Radar sounder (dual-frequency, nominally ~ 5 & ~ 50 MHz, with ~ 1 and ~ 10 MHz bandwidth). B3b. Thermal instrument. B3c. IR imaging spectrometer. B3d. Wide-angle camera (stereo) and laser altimeter. B3e. Narrow-angle camera and laser altimeter. B3f. Wide-angle camera, color. B3g. UV imaging spectrometer. B3h. Medium-angle camera. B3i. Telecom system.	
			Europa Explorer Themes: <div>OriginsEvolutionProcessesHabitabilityLife</div>			

continued

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 desirable), 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^{-8} 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 desirable), 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 characterization 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 desirable), 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^{-8} 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 $\Delta E/E = 0.1$ 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 $\Delta E/E = 0.1$.	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 $\Delta E/E = 0.15$, and ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥ 500 , and pressure range of 10^{-8} 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 desirable), 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.	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.

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 <i>in situ</i> 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 morphology 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 characterization 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. U/V 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.
	D3. Investigate global and local heat flow.		D2e. Identify and map any age-sensitive chemical and physical indicators (e.g. H ₂ O frost, ice crystallinity, SO ₂ , H ₂ O 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 desirable), 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 U/V spectrometer.
			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 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 resolution of better than or equal 1 m.	D4c. Medium-angle camera and/or Narrow-angle camera.
	D5. Characterize the physical properties of the regolith, and assess processes of erosion and deposition.		D4d. Identify and map any age-sensitive chemical and physical indicators (e.g. H ₂ O frost, ice crystallinity, SO ₂ , H ₂ O 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 desirable), 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 U/V spectrometer.
			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.

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^{-9} to 10^{-11} 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.
	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.	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.
			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.
		F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a gas giant planet.	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.
	F3. Study the interactions between Jupiter's magnetosphere and its satellites.		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.
			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 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 be 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) to 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

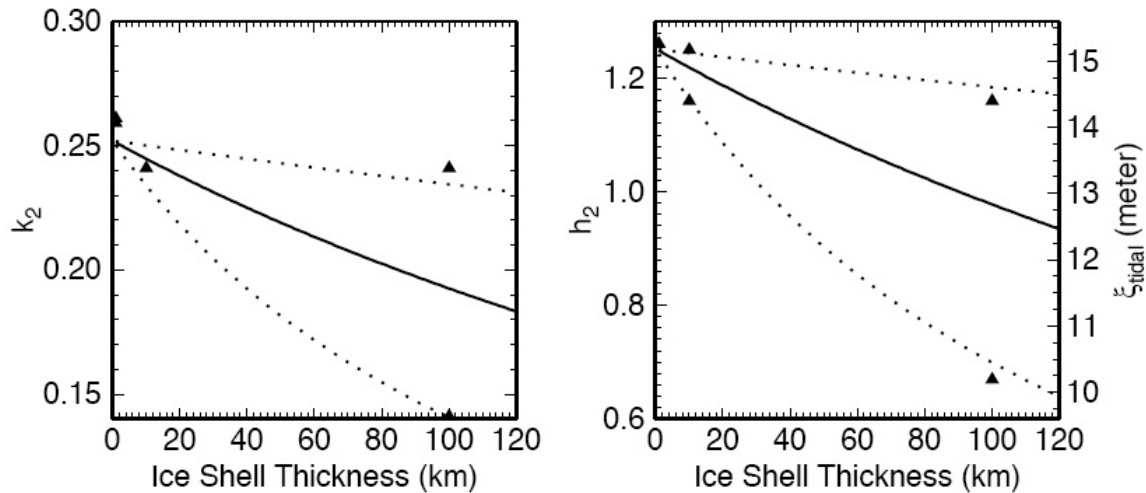


Figure 2.3-1. Sensitivity of Love numbers k_2 (left) and h_2 (right) to ice shell thickness and rigidity, with the assumption of a subsurface ocean. The right-hand plot also shows the amplitude ζ_{tidal} (half of the total measurable tide) as a function of ice shell thickness. Solid curves are for an ice shell rigidity of $\mu_{\text{ice}} = 3.5 \times 10^9 \text{ Pa}$, while the dotted lines are for $\mu = 10^9 \text{ Pa}$ (above) and $\mu = 10^{10} \text{ Pa}$ (below). A rocky core is assumed to have a radius of 1449 km and rigidity $\mu_{\text{rock}} = 10^{11} \text{ Pa}$, 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 ($T = 11.1 \text{ hr}$) and the orbital frequency of Europa ($T = 85.2 \text{ hr}$)

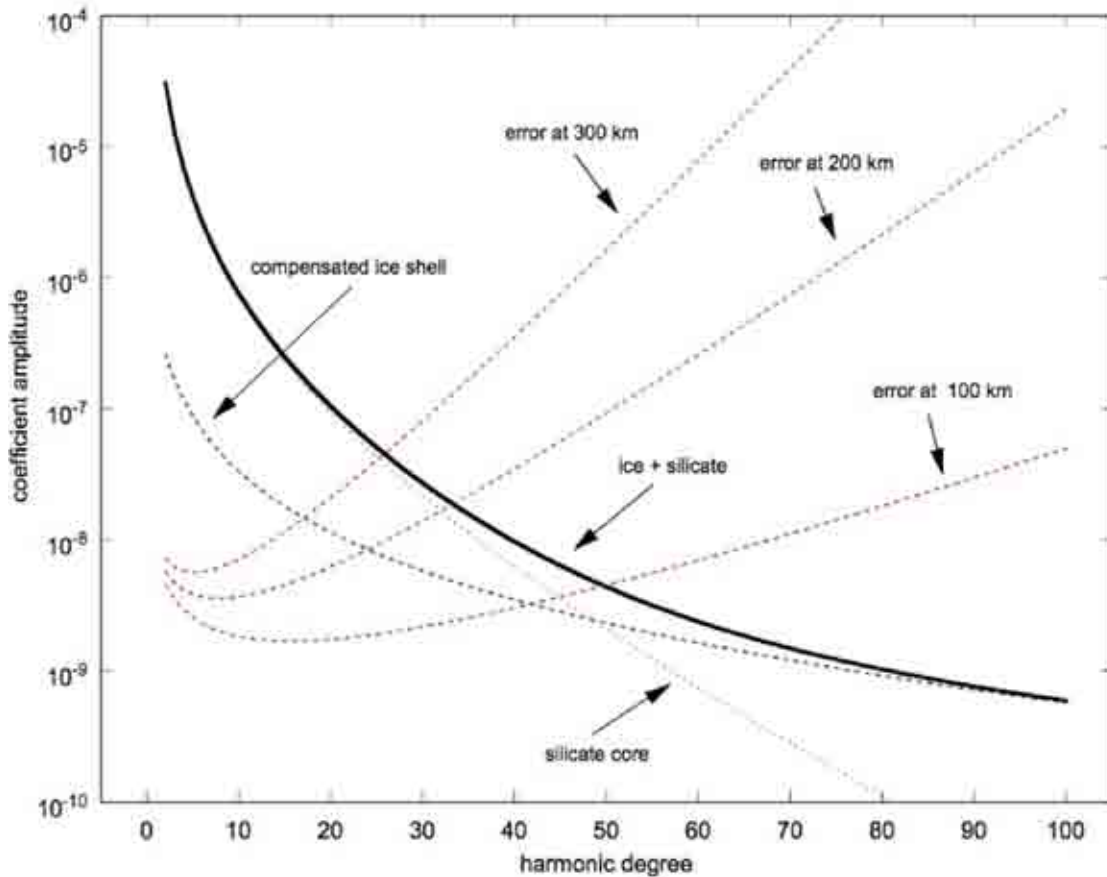


Figure 2.3-2. Models of Europa's gravity spectrum, assuming an ice shell 10 km thick with isostatically compensated topography above an ocean, and a silicate interior with mean surface 100 km below the ice surface. The variance spectra of the ice topography and silicate gravity are assumed similar to 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 magnetometry 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

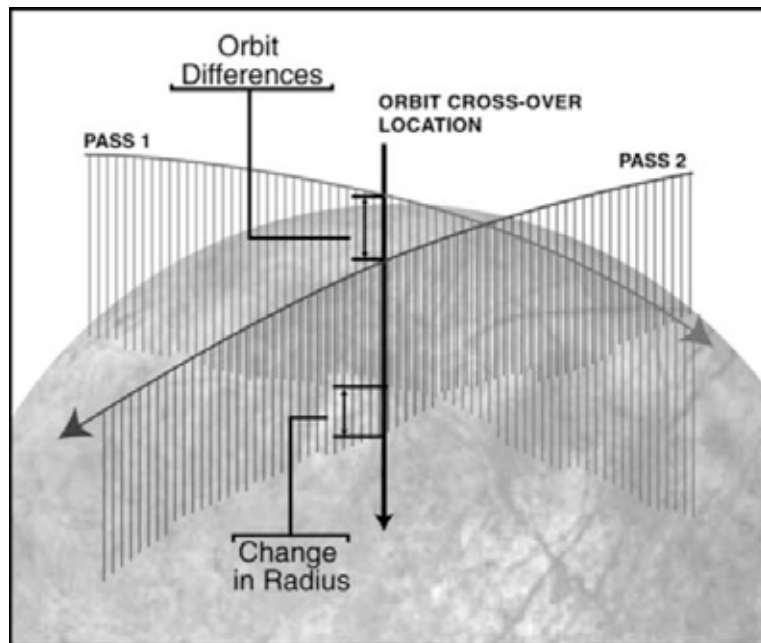


Figure 2.3-3. Illustration of the cross-over technique. Actual change in radius of Europa due to tidal and librational motions is determined by measuring altitude from the spacecraft to the surface, and by accounting for the distance of the spacecraft from the center of mass by means of Doppler tracking [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. Europa's Ice Shell: 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 subsurface 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

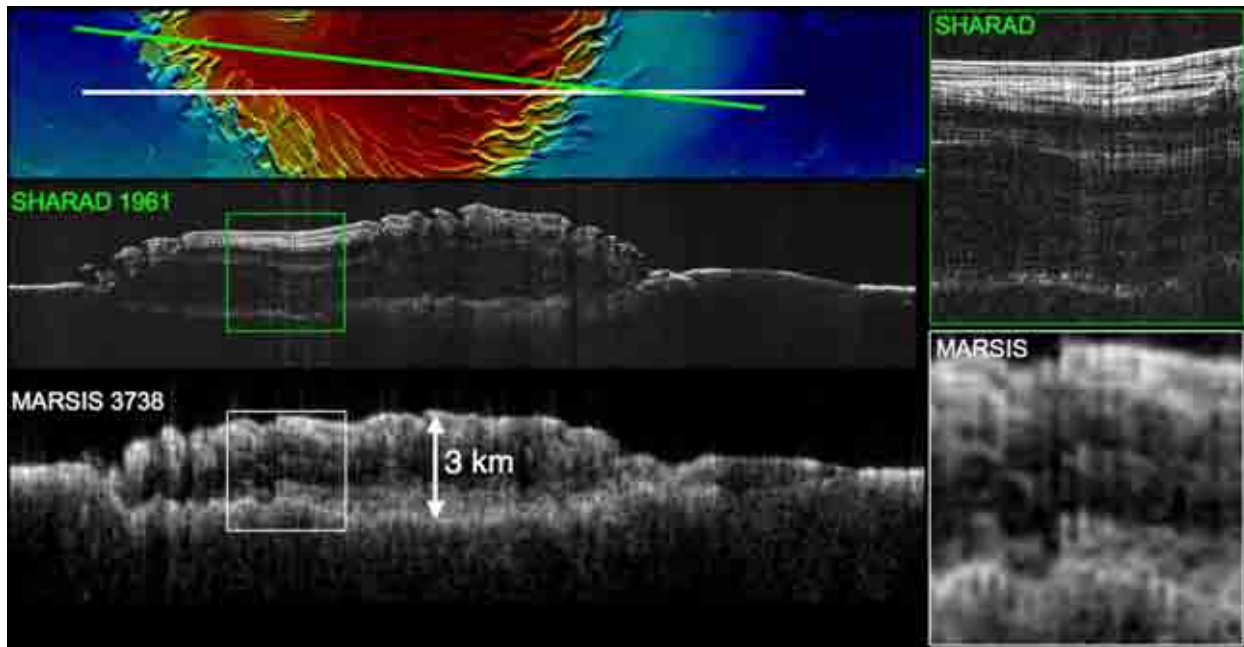


Figure 2.3-4. Orbital Subsurface Profiling of Mars North Polar Cap. These nearly co-linear profiles across the Mars North Polar Cap (MOLA data at top left) demonstrate the value of the complementary perspectives provided by the high-center frequency and high bandwidth profiling of the SHARAD instrument (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. Europa's Chemistry: 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

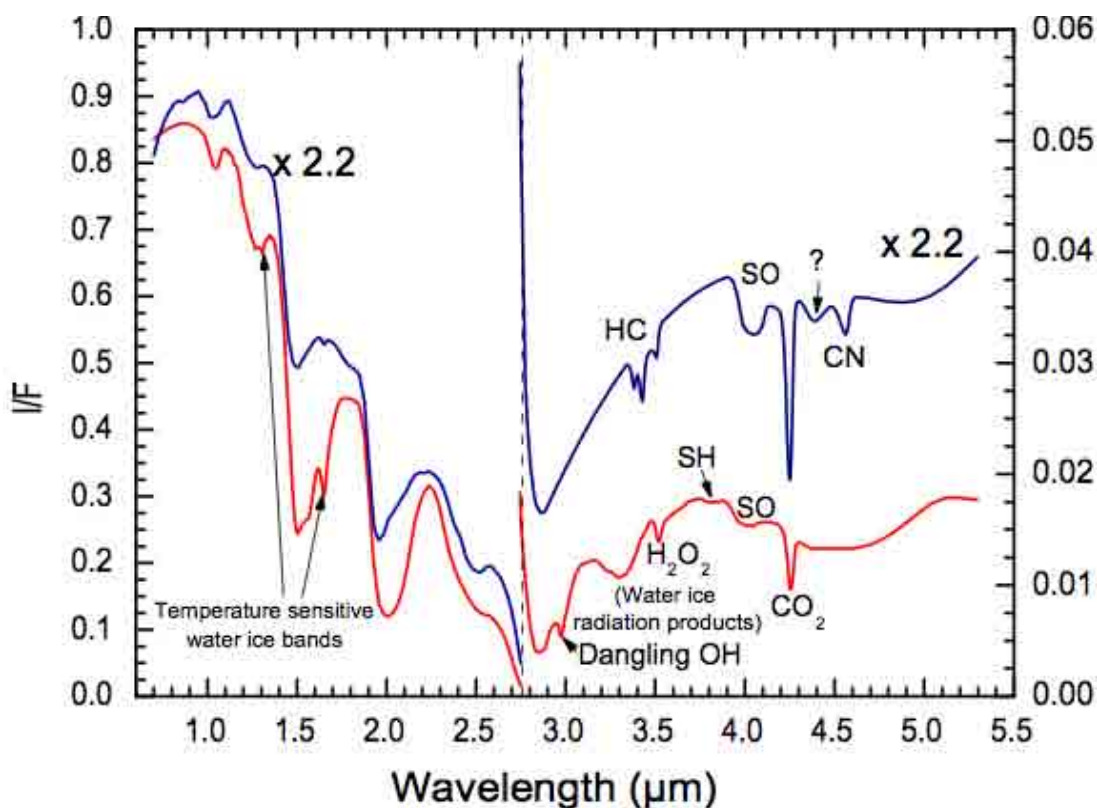


Figure 2.3-5. Notional reflectance spectra for icy (lower) and non-ice (upper) regions on Europa at 6 nm spectral resolution in the 1–5 μm spectral range. A variety of materials and molecules have been identified or inferred from the Galileo results. The spectra shown here are composites to show the 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 ≥ 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 $\Delta E/E \sim 0.1$ 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 ≥ 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

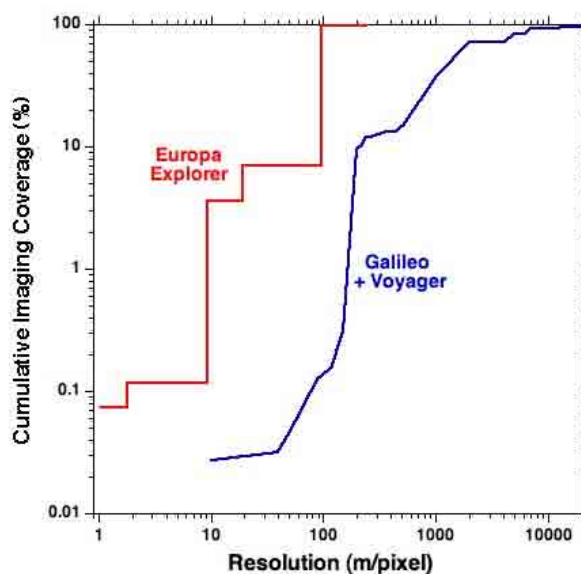


Figure 2.3-6. Cumulative imaging coverage of Europa's surface as a function of imaging resolution, illustrating the 1–2 orders of magnitude improvement of planned EE imaging coverage relative to that from Voyager and Galileo combined. Unlike the opportunistic coverage obtained from earlier fly-bys, EE's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

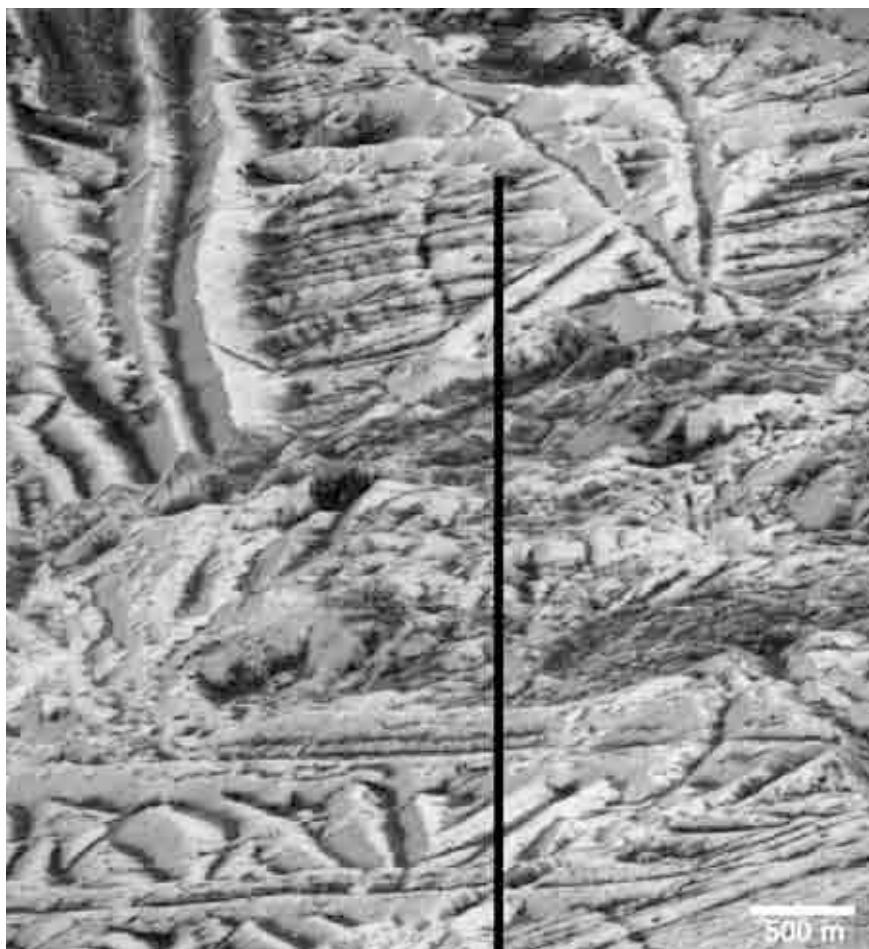


Figure 2.3-7. Highest resolution Galileo image of Europa, an oblique view at 6 m/pixel in the horizontal direction. Europa's surface is extremely rough at small scales, consistent with recent or current activity. It will be important to identify and characterize at very small scales promising sites for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



*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.*

100 m/pixel are recommended, with capability to observe the sunlit surface, stellar occultations over Europa's limb, and atmospheric emissions.

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 $\leq 45^\circ$, 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 electro-

magnetic 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 ≥ 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 ($\sim 15^\circ$) 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 \approx 92 days \approx 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.	<u>Gravity and altimetry</u> : 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. <u>Magnetometry</u> : Near-continuous measurements near Europa, globally distributed, at altitudes ≤500 km, for a duration of at least 1–3 months.	<u>Gravity and altimetry</u> : Knowledge of the spacecraft's orbital position to high accuracy and precision (~meters radially) via two-way Doppler. <u>Gravity</u> : Long undisturbed data arcs are required (> 12 hr periods without spacecraft thrusting; see §4.3), and momentum wheels to maintain spacecraft stability. <u>Magnetometry</u> : 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.	<u>Radar sounding</u> : 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°.	<u>Radar sounding and altimetry</u> : Data sets need to be co-aligned and time-referenced to 1 ms accuracy. <u>Radar sounding</u> : 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.	<u>Infra-red and ultraviolet spectroscopy</u> : 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. <u>INMS</u> : As low an orbit as feasible is desired, for direct detection of sputtered particles.	<u>Optical remote sensing</u> : 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 <i>in situ</i> exploration.	<u>Optical remote sensing</u> : 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. <u>Imaging</u> : 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. <u>Thermal mapping</u> : Day-night repeat coverage required; afternoon orbit is desirable.	<u>Optical remote sensing</u> : Boresight co-alignment of all nadir-pointed imaging and profiling instruments is highly desirable. <u>Radar sounding and altimetry</u> : Data sets need to be co-aligned and time-referenced to 1 ms accuracy. <u>Magnetometry</u> : 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. <u>Ultraviolet spectroscopy</u> : 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.	<u>Magnetometry and particles</u> : 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.	<u>Magnetometry</u> : 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. <u>Particles and plasma</u> : 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.

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

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

All Campaigns, Continuous Observations:	
<ul style="list-style-type: none"> • Radio Science - Gravity • Magnetometer • Laser altimeter • Thermal instrument (day and night) • Ultraviolet spectrometer (emissions and stellar occultations) • Particle and plasma instrument • Ion and neutral mass spectrometer 	
Campaign 1, Global Framework:	
8 eurosols ≈ 28 days, 200 km altitude, Checkout to EOI + 28 days	
1A:	<ul style="list-style-type: none"> • First-order gravity field and shape • Global color map (200 m/pixel) • IPR first-order shallow water search • Targeting of high-priority terrains and feature types
1B:	<ul style="list-style-type: none"> • Global stereo map (200 m/pixel) • IPR first-order deep ocean search • Targeting of high-priority terrains and feature types
Campaign 1 science data acquired ≈ 480 Gb	
Campaign 2, Regional Processes:	
12 eurosols ≈ 43 days, 100 km altitude, EOI + 28 days to EOI + 71 days	
2A:	<ul style="list-style-type: none"> • Regional gravity field and shape • Regional-scale color map (100 m/pixel) • IPR regional-scale shallow water search • Targeting emphasizes regional-scale processes
2B:	<ul style="list-style-type: none"> • Regional-scale stereo map (100 m/pixel) • IPR regional-scale deep ocean search • Targeting emphasizes regional processes
Campaign 2 science data acquired ≈ 800 Gb	
Campaign 3, Targeted Processes:	
6 eurosols ≈ 21 days, 100 km orbit, EOI + 71 days to EOI + 92 days	
<ul style="list-style-type: none"> • Coordinated, process-oriented, targeted observations 	
Campaign 3 science data acquired ≈ 490 Gb	
Campaign 4, Focused Science:	
74 eurosols ≈ 263 days, 100 km altitude, EOI + 92 days to EOI + 355 days	
<ul style="list-style-type: none"> • Coordinated, process-oriented, targeted observations 	
Campaign 4 science data acquired ≈ 1.8 Tb	

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

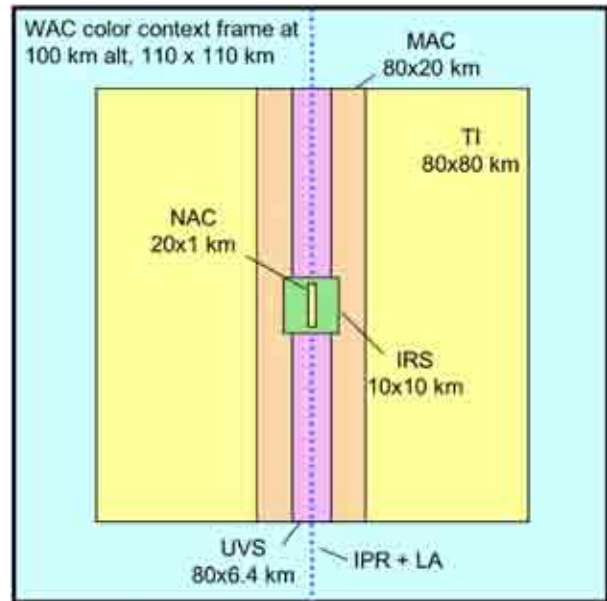


Figure 2.4-1. Coordinated Targeted Observations, with scales based on a 100 km altitude. Targeted observations are set within WAC color context (100 m/pixel, 3-colors plus broadband monochromatic). Coordinated targeted observations consist of: Thermal Instrument observations (large yellow, 250 m/pixel, 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).

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).

- 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 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					Baseline Campaigns					
				1A	1B	2A	2B	3	1A	1B	2A	2B	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.	3	2	2	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 <i>in situ</i> 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	4.5	
% scores:				34%	43%	60%	64%	78%	40%	59%	71%	83%	91%	

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 descope 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: $\leq 10^{-4}$ of contaminating the European 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
<i>Instruments:</i>		
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 European 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

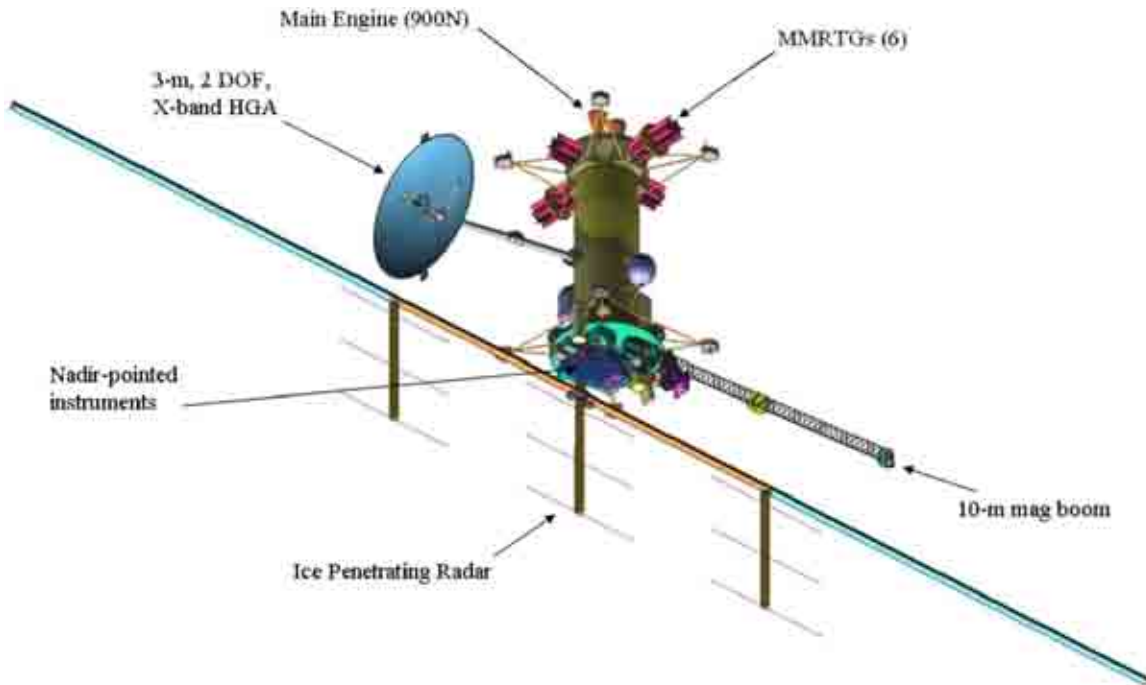


Figure 3.1-1. The 2006 reference mission concept builds upon almost a decade of concept development and utilizes both Cassini and Galileo experience for large outer planets orbital missions

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
<ol style="list-style-type: none"> Blue text represents differences from the EE baseline configuration. 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. 							

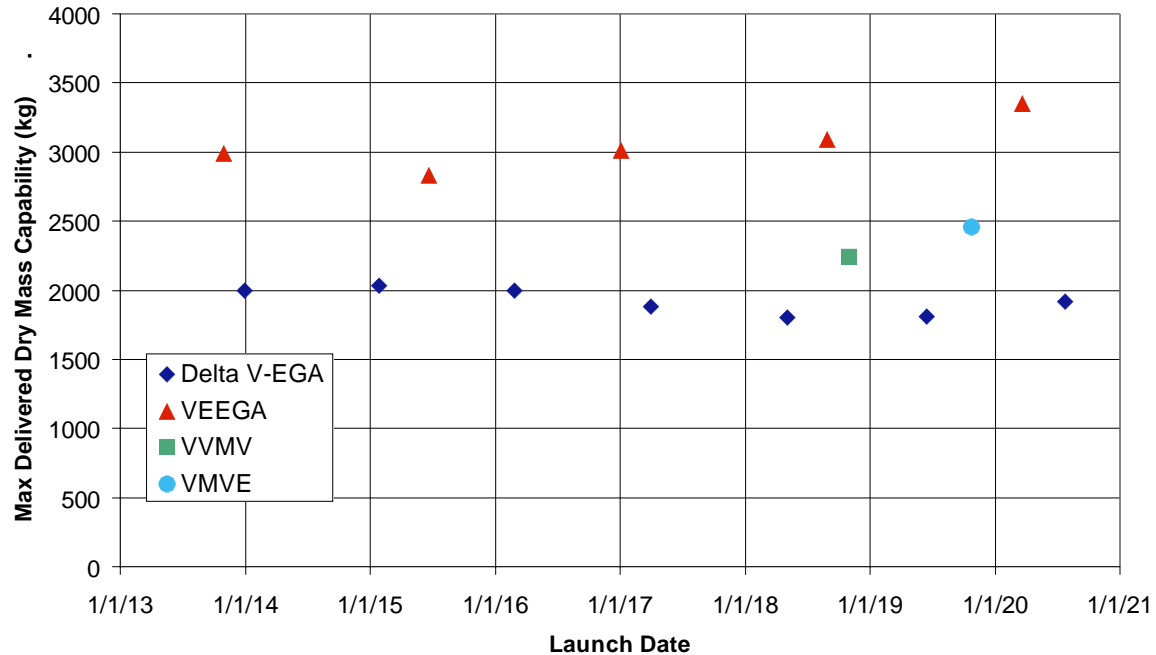


Figure 3.4-1. Maximum Flight System Dry Mass Capability vs. Launch Year for the Delta IV-H

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	<ol style="list-style-type: none"> 1. Delta IV 4050H-19 2. Support and procurement provided by Launch Planning Office at KSC 3. Launch mass capability of 7230 kg to C₃ of 14.1 km²/s² for the June 2015 VEEGA opportunity
Flight System	<ol style="list-style-type: none"> 4. Single Orbiter 5. Spacecraft <ul style="list-style-type: none"> • MMRTG Power Source supplied by the Department of Energy • Chemical Propulsion—dual mode Bi-propellant system • X-Band Telecommunications (Ka-Band up/down link for gravity science) 6. Launch Vehicle adapter 7. 11 individual instrument payload selected via NASA Announcement of Opportunity
Ground System	<ol style="list-style-type: none"> 8. Ground Data System 9. Flight Operations Team (engineering and science) 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 addressed 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 European 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 σ)	S/C body pointing control accuracy during nadir-oriented non-thrusting orbital period.
Pointing stability	10 μ rad/s (3 σ)	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 $\sim 1 \times 1 \times 1$ 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 μ rad/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		Approximate Dimensions (cm)	Field of View
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)		
Wide-angle Camera (WAC) - color	3	5	1	0	1	0	1	80	4.2	0	1	5 × 5 × 5 (optics) 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) 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) 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) 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) + 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) 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) 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) 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) 10 (stand-down)	50	32.5	0	20	0	10	0	10	20 × 30 × 20 (electronics) + 30-m dipole (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 + 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 $\frac{1}{4}$ of the array in the along-track direction. For the orbital ground speed of 1.3 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 broadband 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 $\sim 30^\circ$

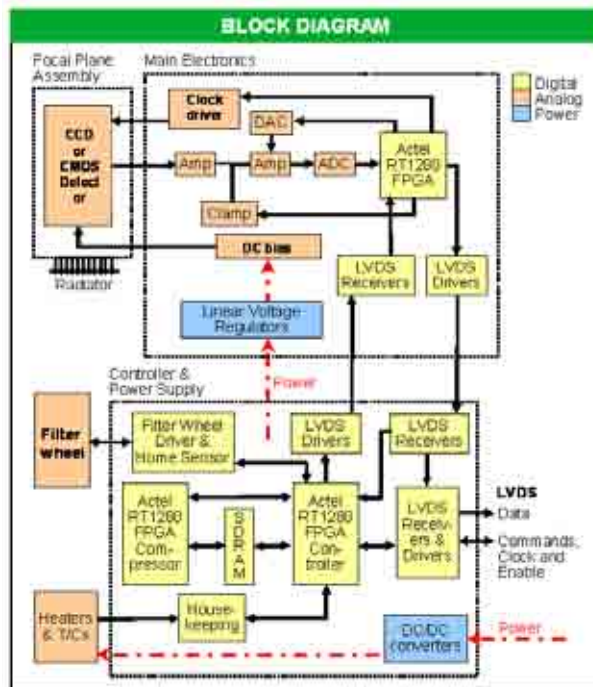


Figure 4.2-1. Camera system block diagram; the same block diagram applies to all three notional EE cameras (WAC, MAC, and NAC).

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 $10 \mu\text{rad}$ 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 requirements. 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 $5 \mu\text{m}$ with a spectral resolution of 6 nm below $2.5 \mu\text{m}$, and 12 nm above $2.5 \mu\text{m}$, 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 $\sim 80 \text{ K}$ 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 $\pm 60^\circ$ 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 \times , 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

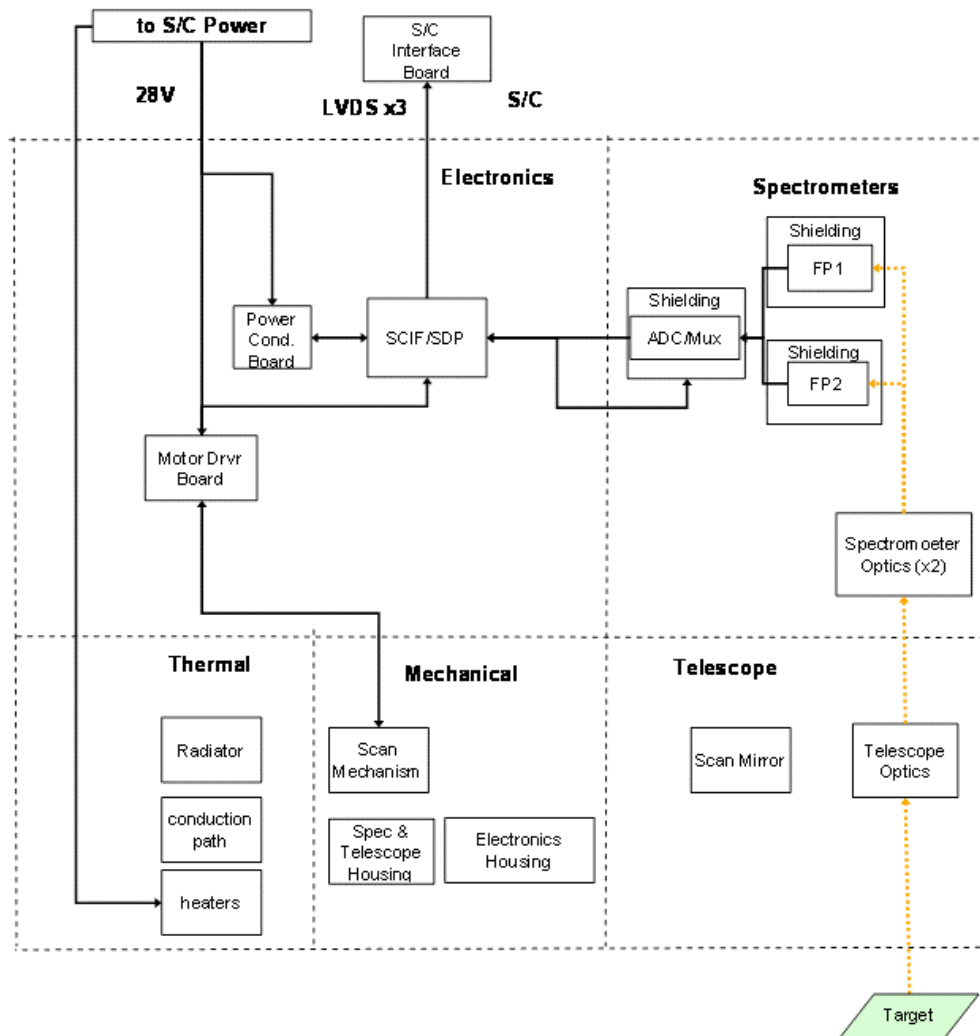


Figure 4.2-2. IRS Block Diagram

the Cassini VIMS instrument and the Chandrayaan Moon Mineralogy Mapper (M³).

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 2 mJ 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

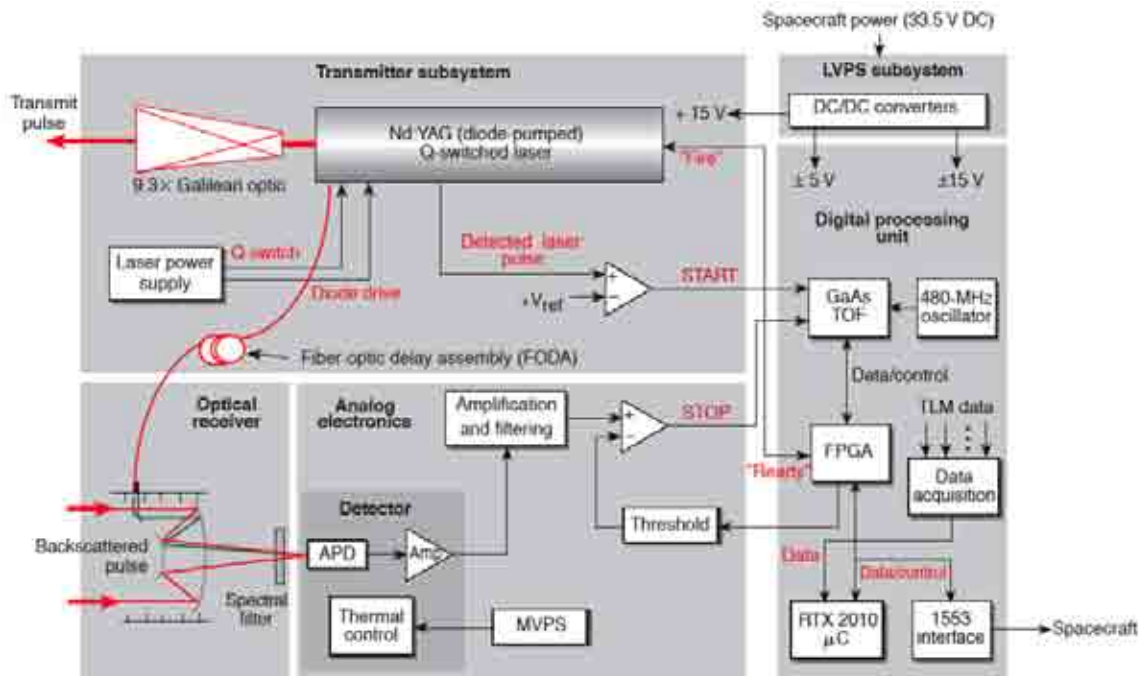


Figure 4.2-3. Block diagram of the NEAR Laser Rangefinder, a similar type of instrument to what would be flown on EE. The five subsystems of the NLR instrument consist of the transmitter subsystem, the low-voltage power supply (LVPS), the optical receiver, the analog electronics, the digital processing 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].

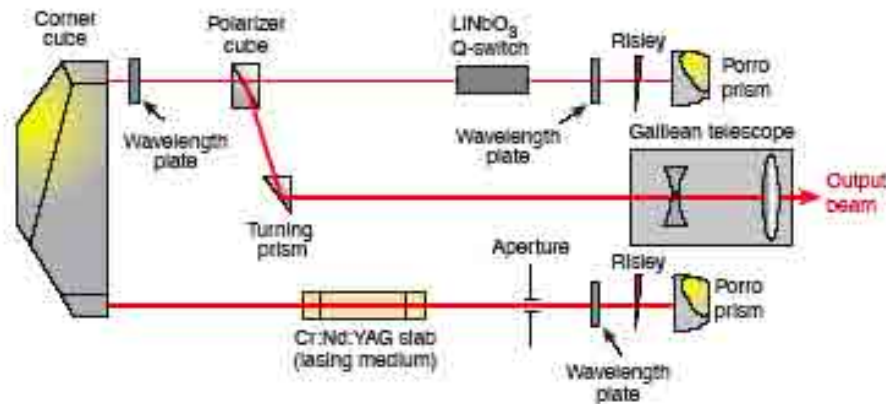


Figure 4.2-4. Optical Schematic from the NEAR Laser Rangefinder. NLR laser resonator cavity configuration is a polarization-coupled U-shaped cavity design. The Cr,Nd:YAG zigzag slab is side-pumped by a diode laser array to optimize conversion efficiency [Cole 1998].

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

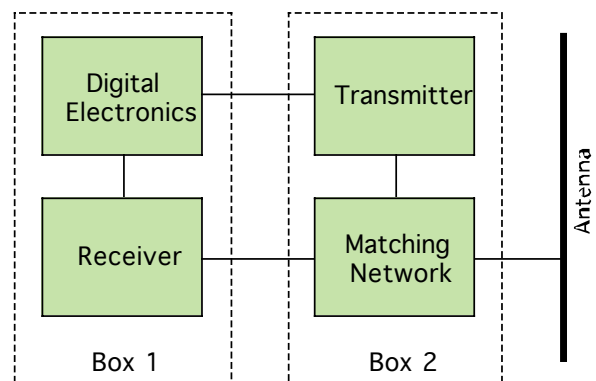


Figure 4.2-5. IPR functional block diagram.

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

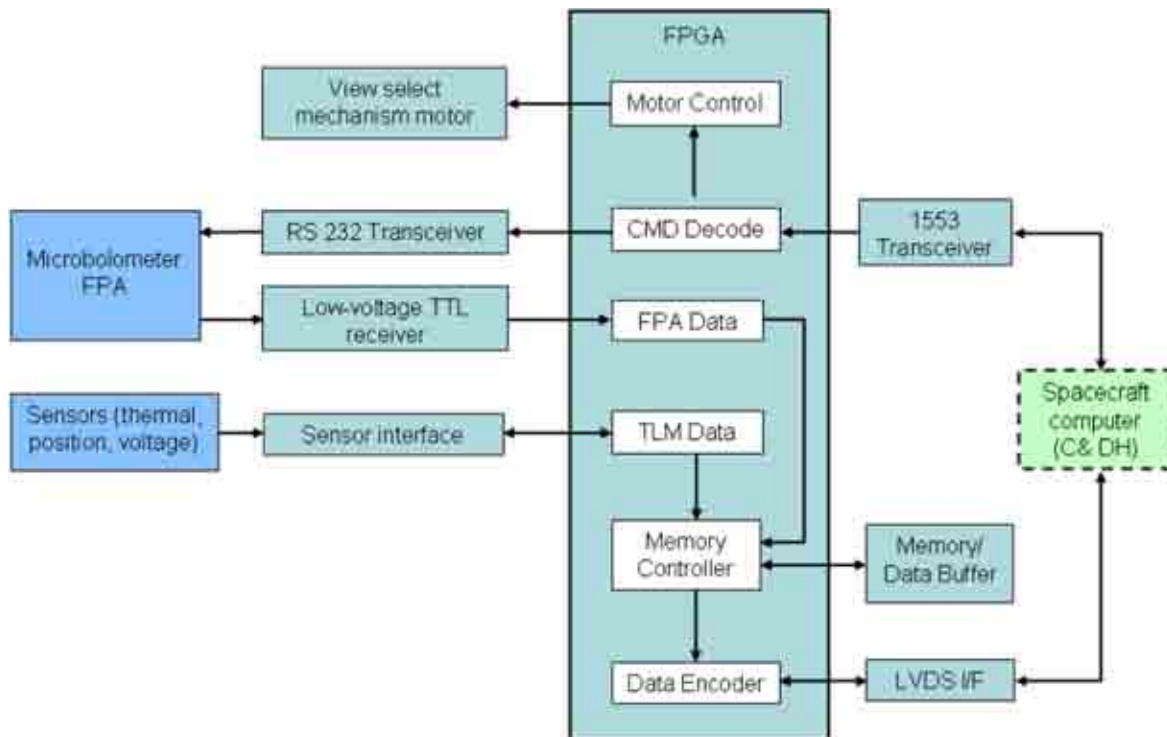


Figure 4.2-6. Thermal Instrument block diagram.

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

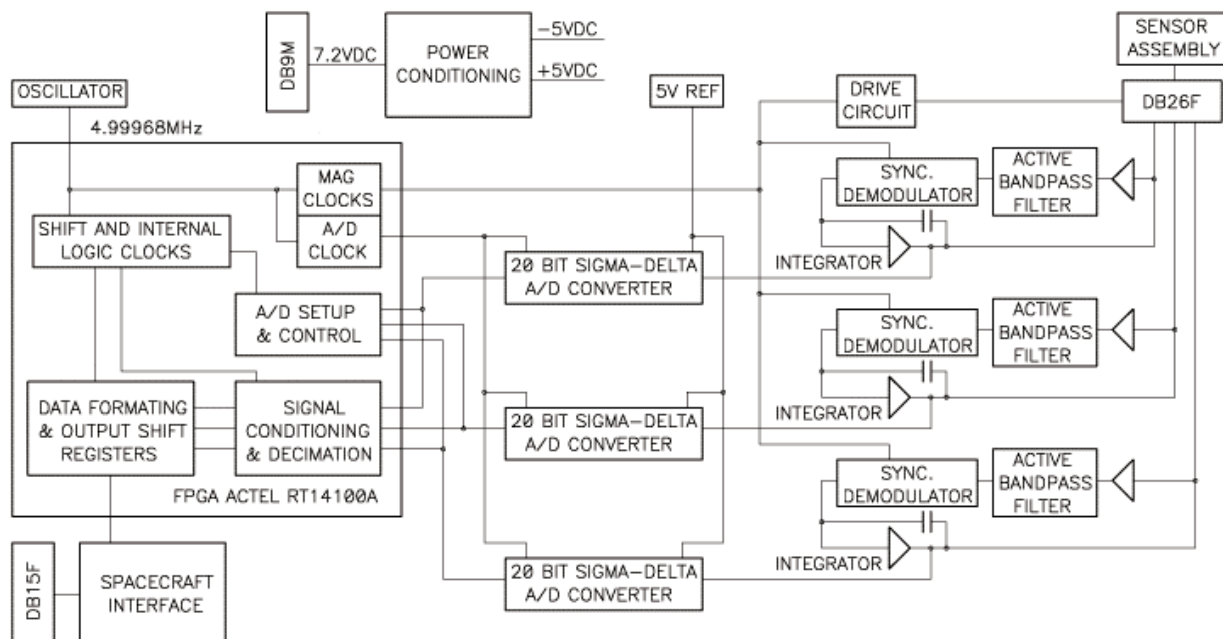


Figure 4.2-7. Magnetometer block diagram.

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,

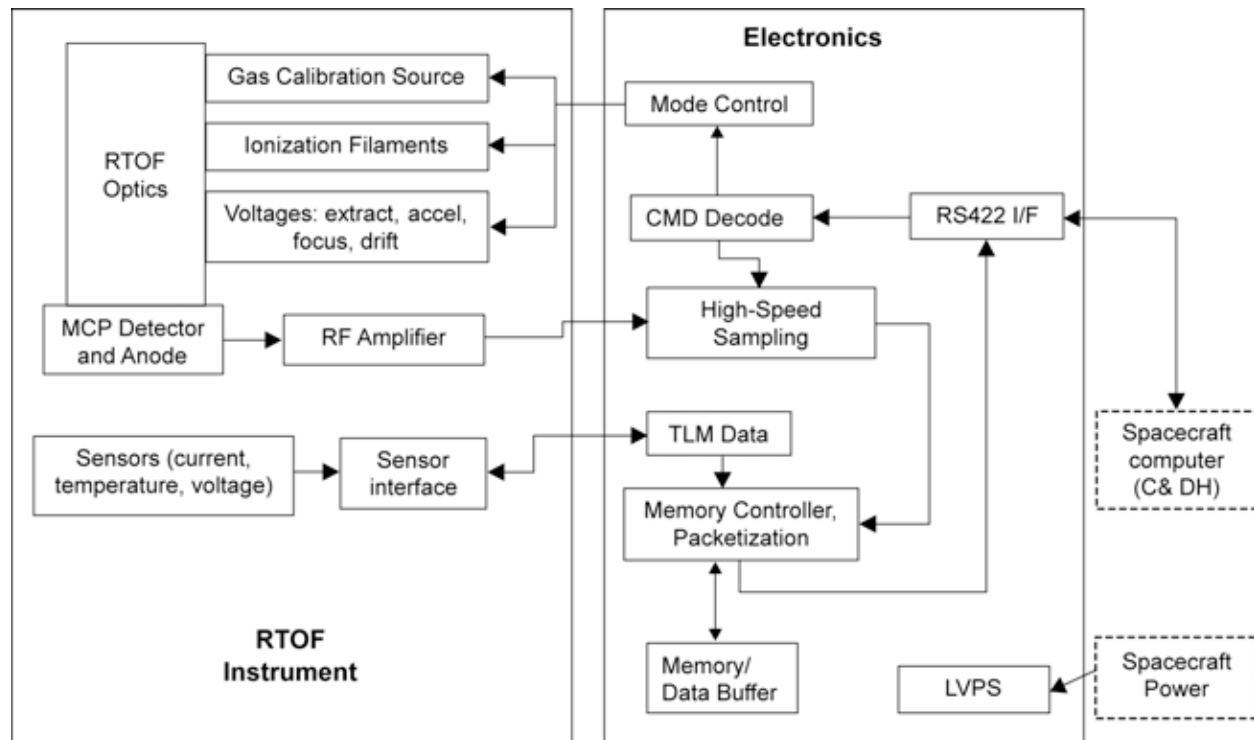


Figure 4.2-8. INMS Block Diagram.

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 $\sim 15^\circ$. 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 $160^\circ \times 15^\circ$. 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 $\sim 1.5\pi$ steradians ($75^\circ \times 360^\circ$). Angular resolution is $\sim 30^\circ$.

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

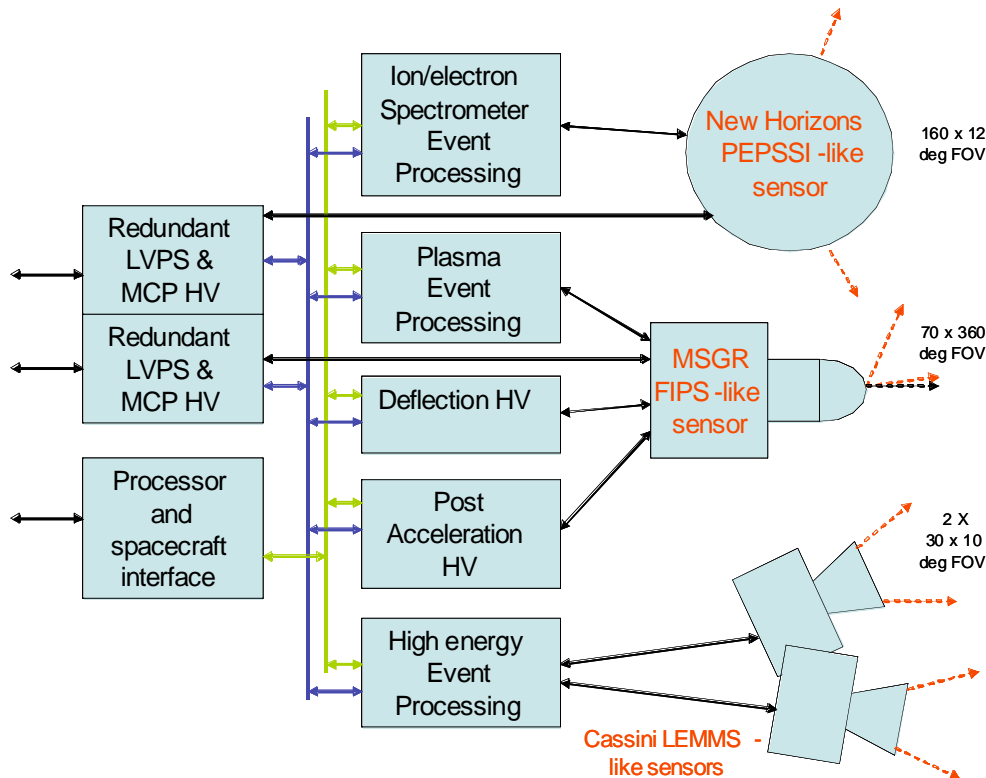


Figure 4.2-9. Particle and Plasma Instrument (PPI) block diagram.

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 \times 64 spatial pixels. Each of the 64 spatial pixels is 1 mrad ($\times \sim 0.75$ 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.

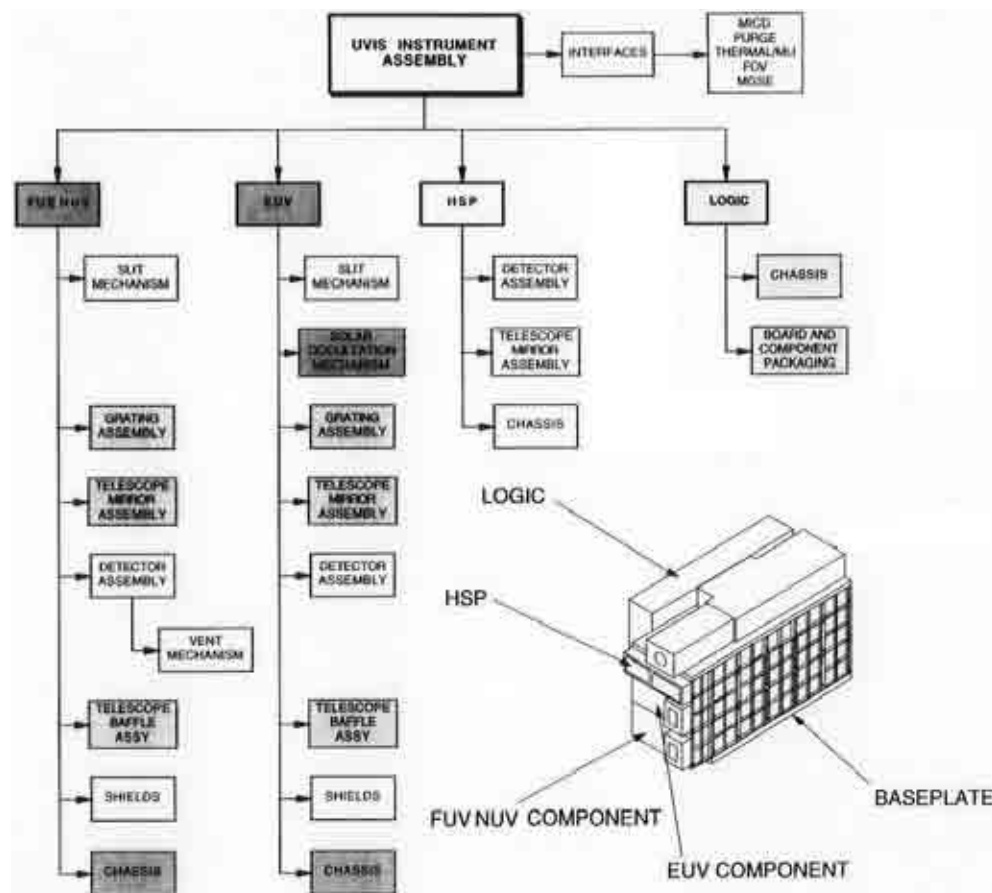


Figure 4.2-10. UVIS instrument from Cassini showing two spectrometers (a NUV channel will also be included) and the high speed photometer.

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 $14.1 \text{ km}^2/\text{s}^2$ 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 Δ DOR observations from the Deep Space Network (DSN).

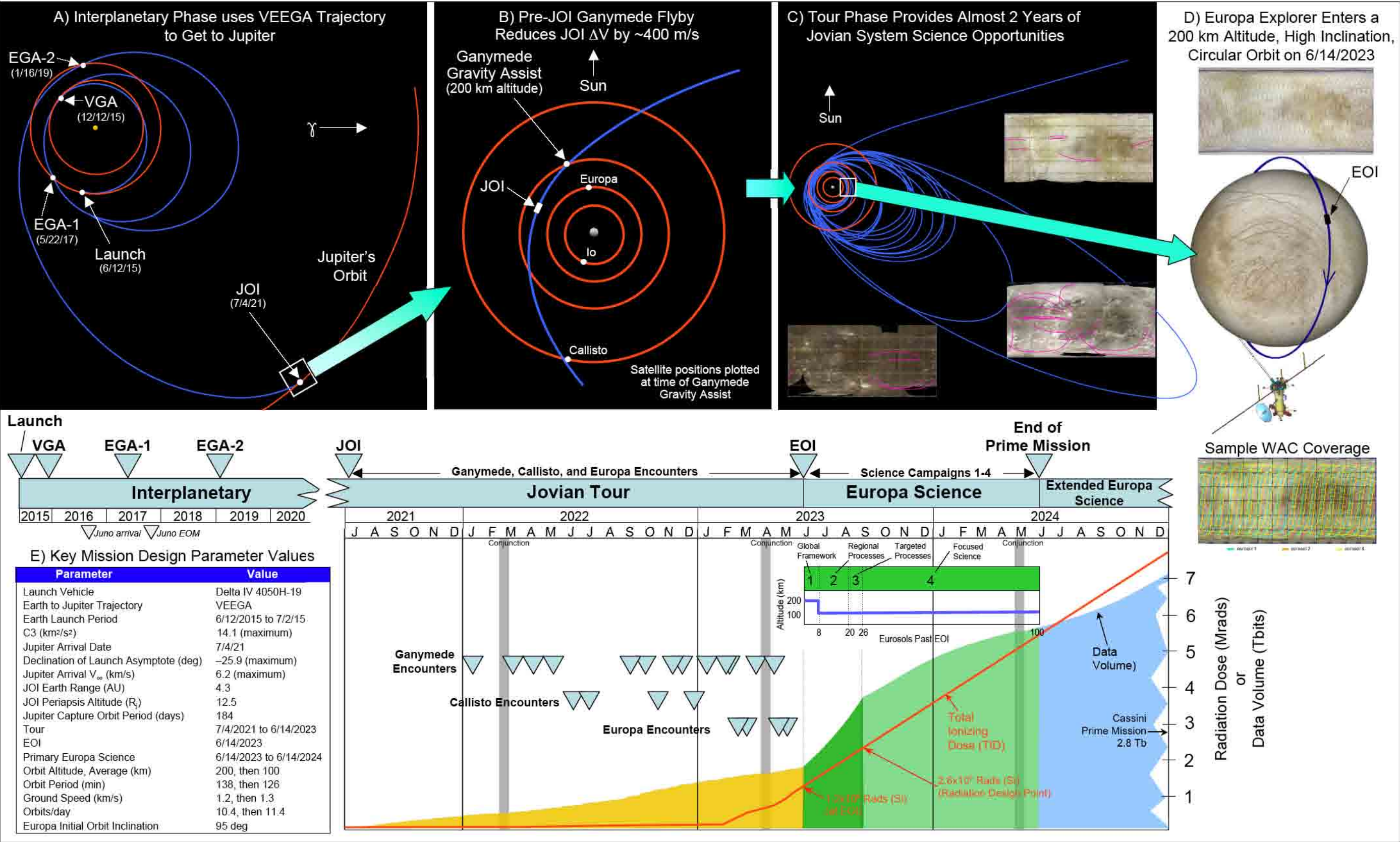
4.3.4 Trajectory at Jupiter

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 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 (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: Campaign 1: Global Framework Campaign 2: Regional Processes Campaign 3: Targeted Processes 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



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_{∞} [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 $13 \text{ km}^2/\text{s}^2$.
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	

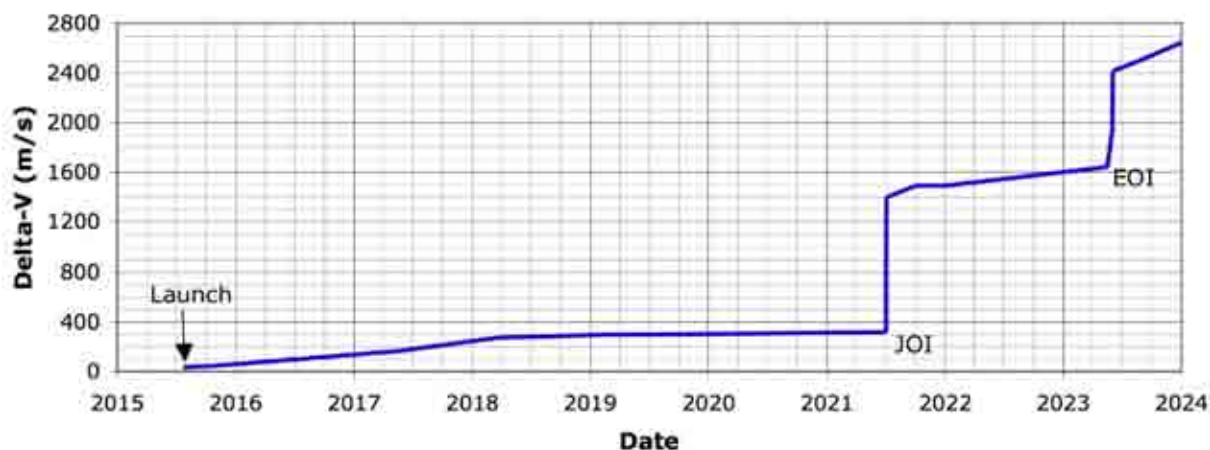


Figure 4.3-3. Distribution of ΔV as a function of mission timeline.

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.

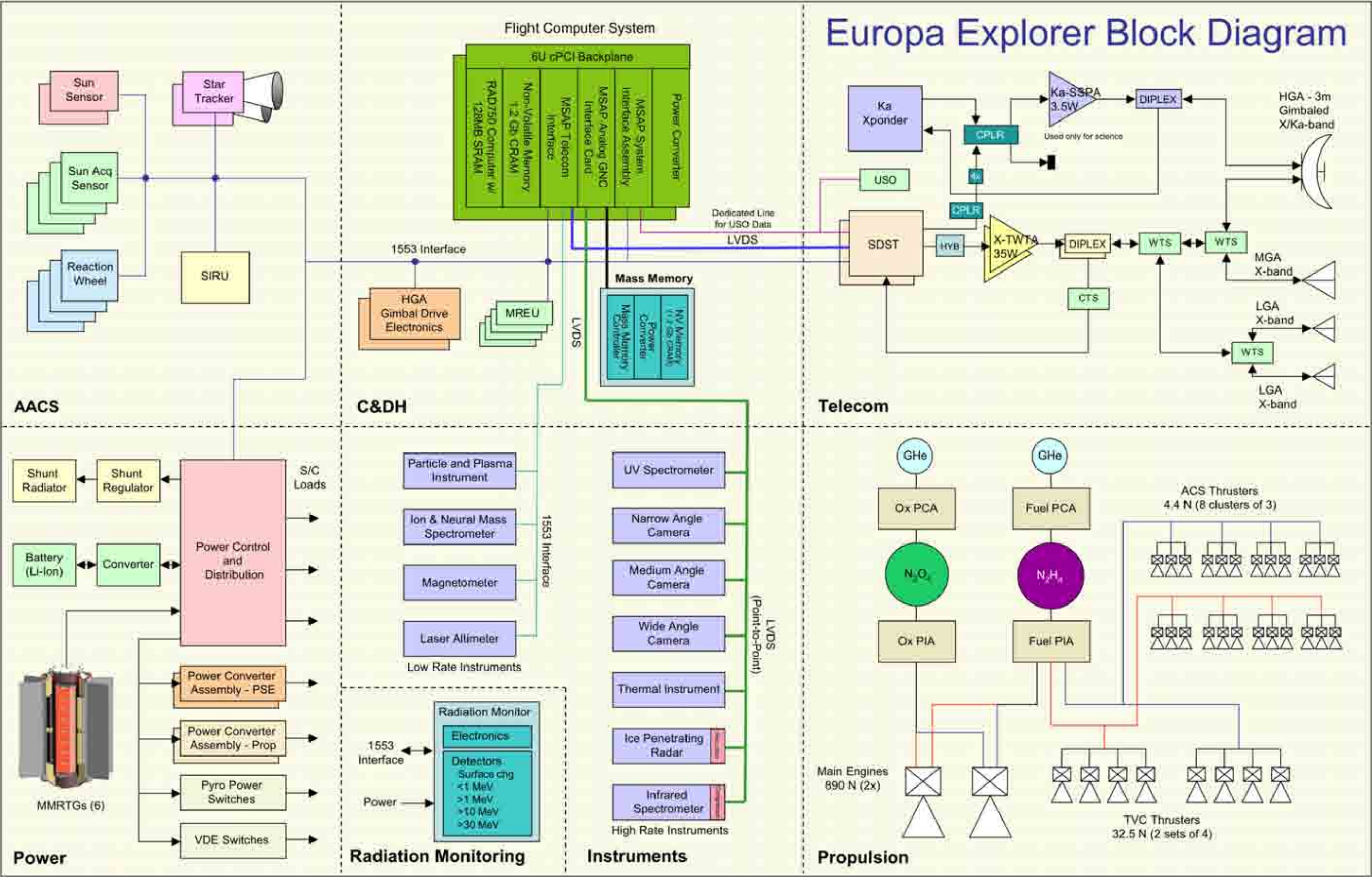
The EE flight system is a redundant, 3-axis stabilized flight system powered by Radioisotope Power Systems (RPSs). The conceptual block diagram is shown in **FO-3**. The flight system includes an articulated 3-m high-gain antenna (HGA), using X-band, for high rate science downlink. The baseline flight 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



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 \times 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,

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 4.4-1. Deployed Configuration of the EE Flight System

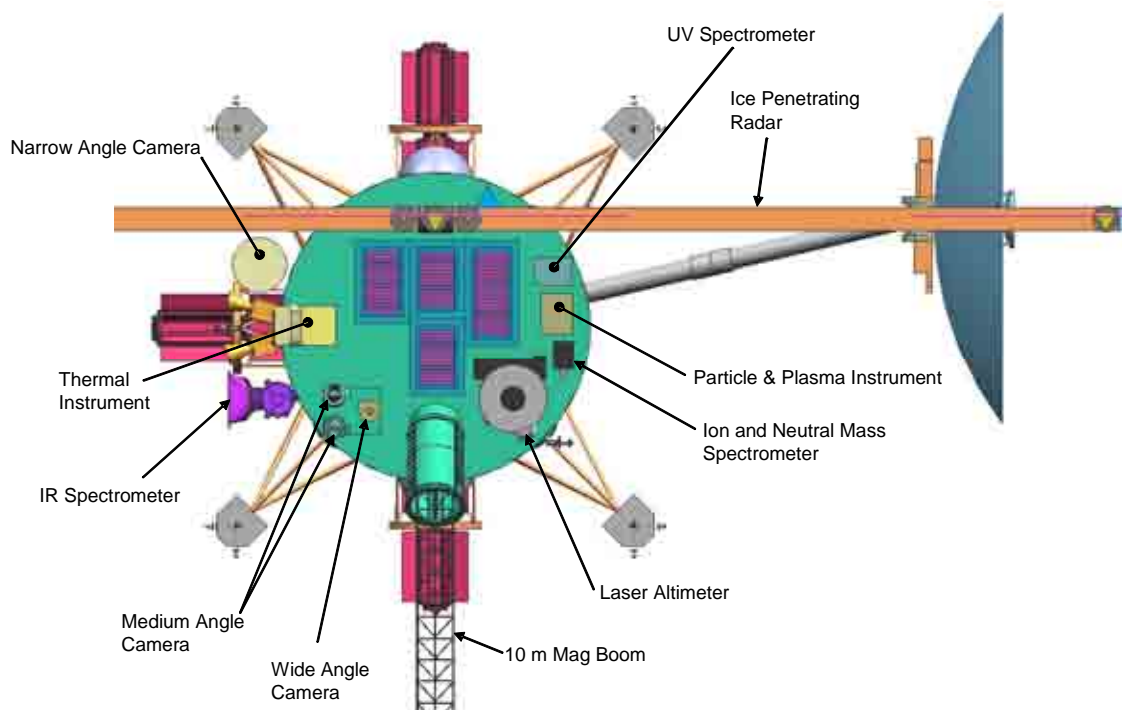


Figure 4.4-2. Science Instrument Configuration of the EE Flight System

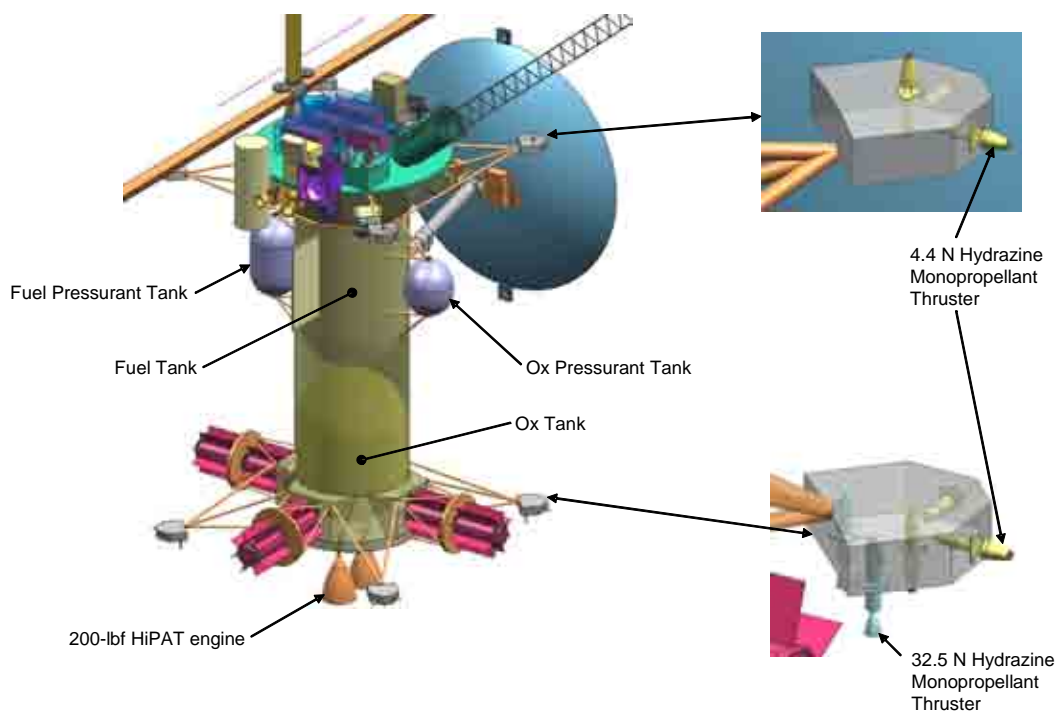


Figure 4.4-3. Propulsion System Configuration of the EE Flight System

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

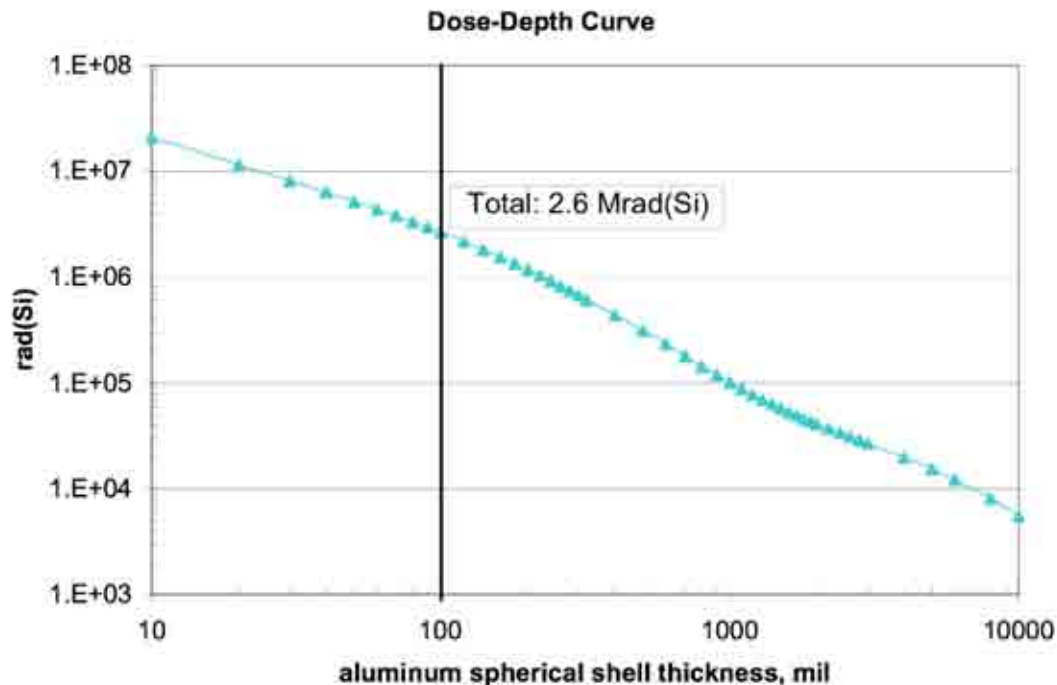


Figure 4.4-4. EE Radiation Dose Depth Curve

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 x 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 (DPSE) 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;

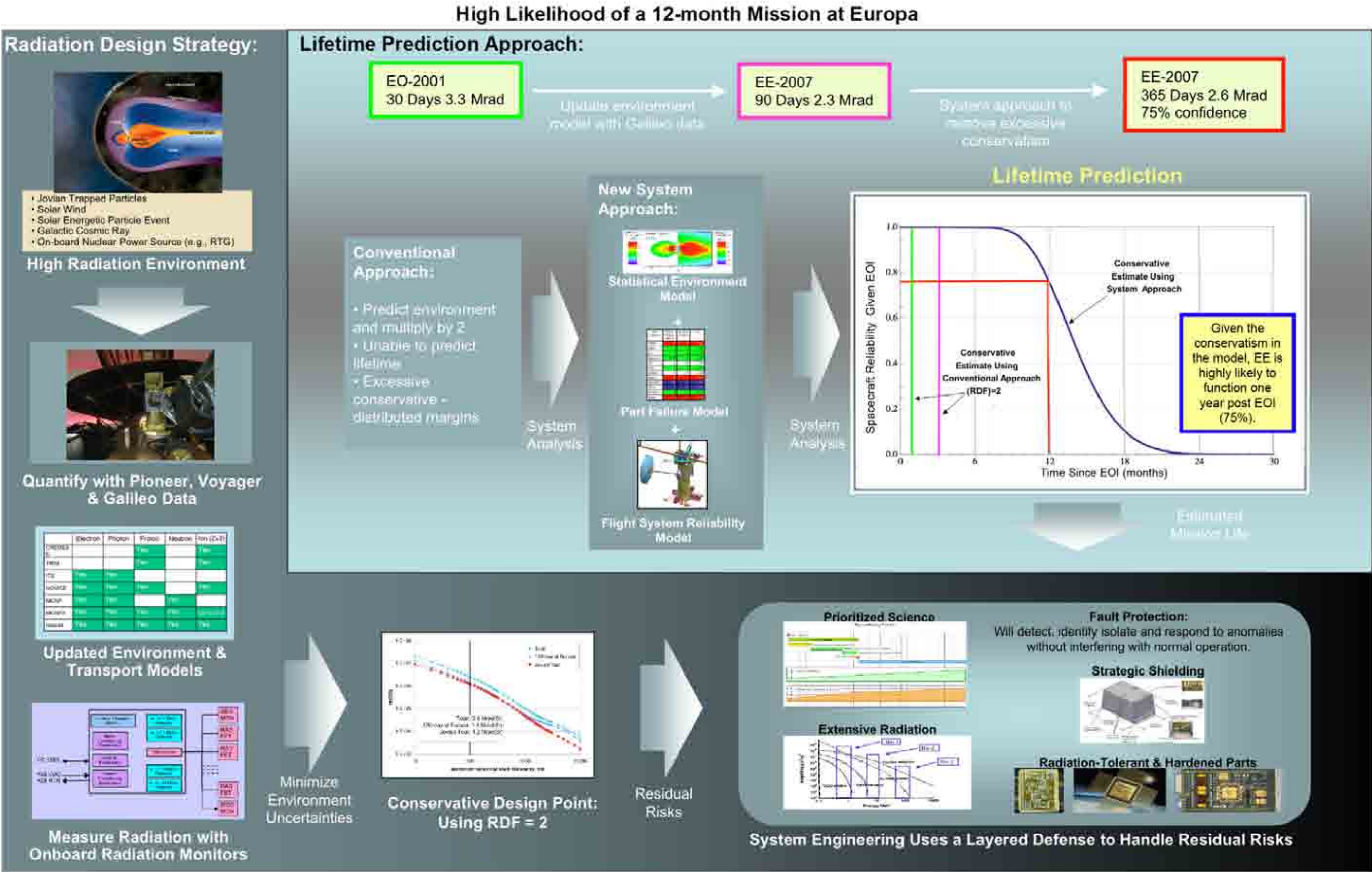
- develop a training program to indoctrinate and train engineers and scientists on the radiation issues. It will be available to all project staff, partners and suppliers. The program is based on the documents stated above. It will include classroom training, online tutorial and extensive documentation.

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

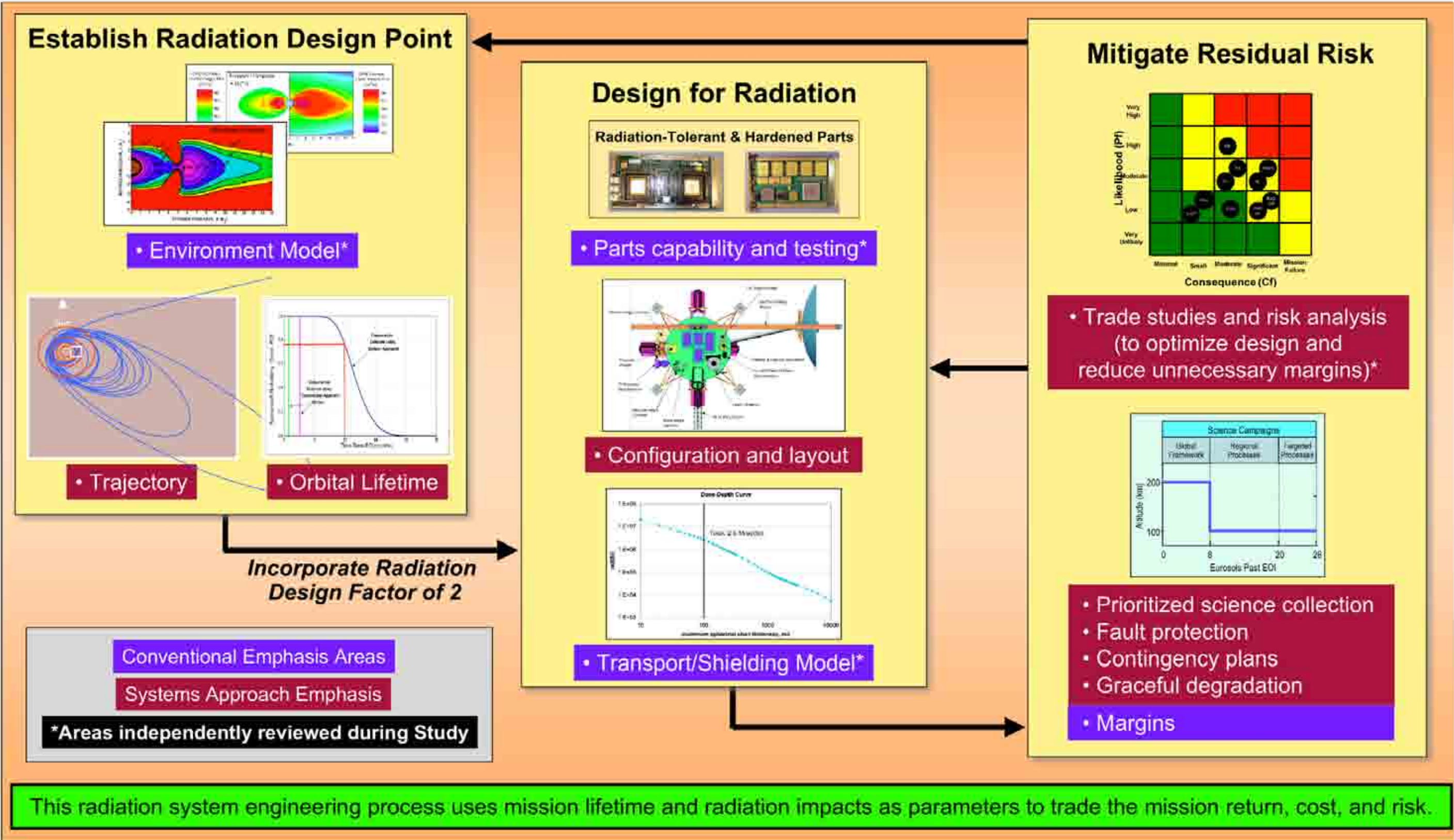
Project management has ultimate responsibility for all radiation aspects of the mission and delegates the day-to-day activities to the DPMR. The DPMR will work closely with the PSE, the DPSE, the MAM, Payload System Engineer, PS (as the representative of the science teams) and the PM in trading off between 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 §4.7.7.



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 μ rad 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

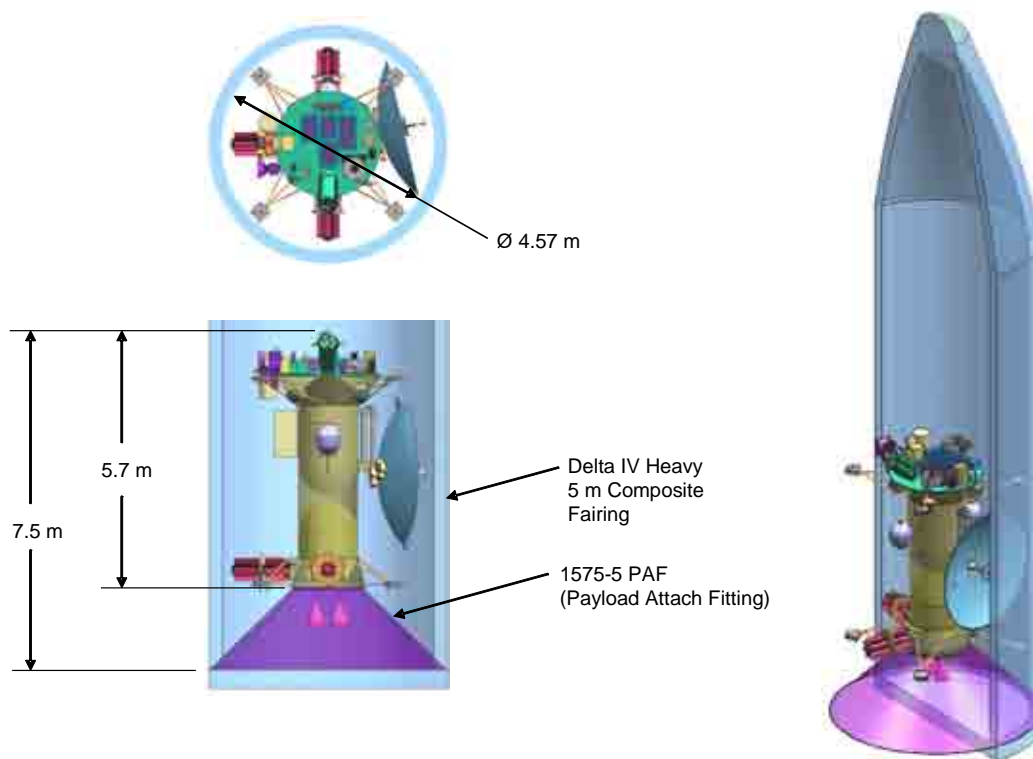


Figure 4.4-5. Stowed Configuration of EE Flight System in Delta IV-H LV Fairing

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**.

System-Level Mass Summary

The EE flight system has a total launched wet mass of 6215 kg (CBE), and is comprised

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

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

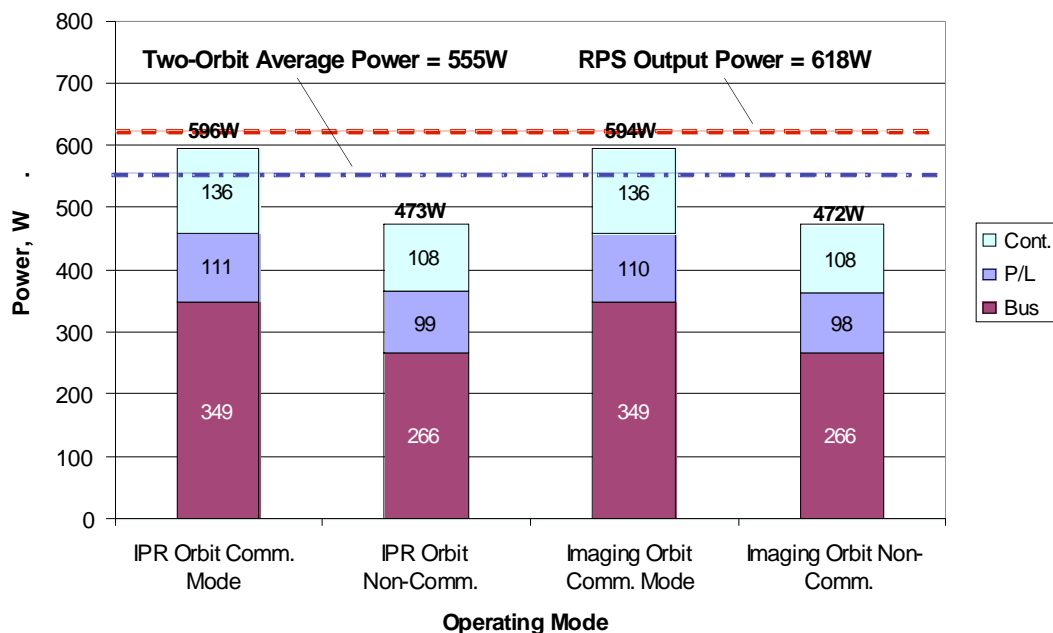


Figure 4.4-6. Europa Explorer Power Modes and Average Power Level (30% Subsystem Power Contingency Shown).

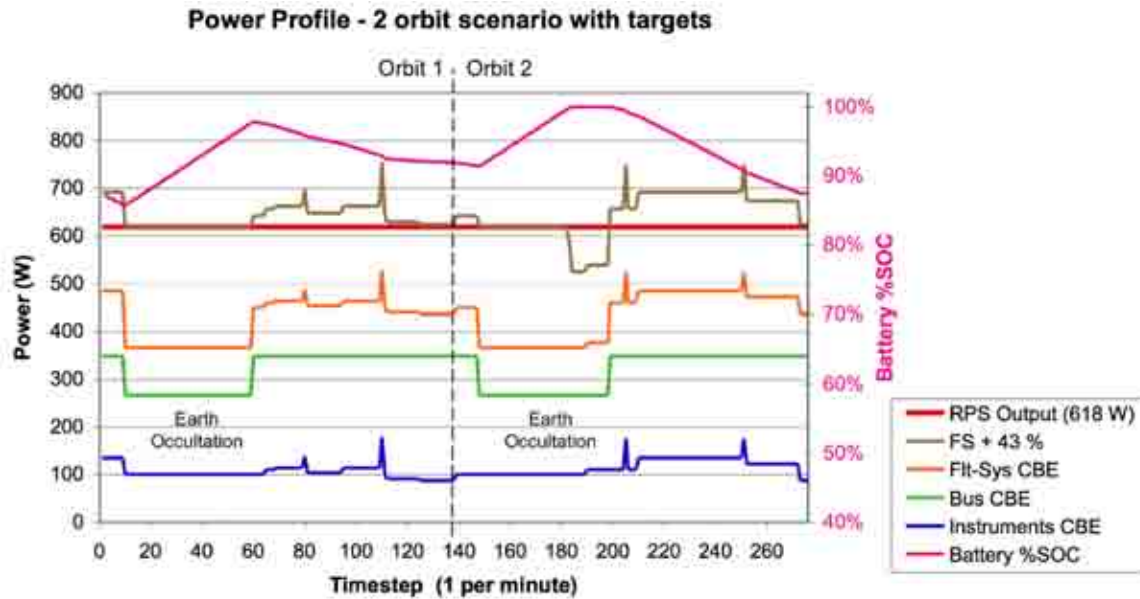


Figure 4.4-7. Power Profile for Two Orbit Scenario

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 gimballed 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 $C_3 = 14.1 \text{ km}^2/\text{s}^2$.
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

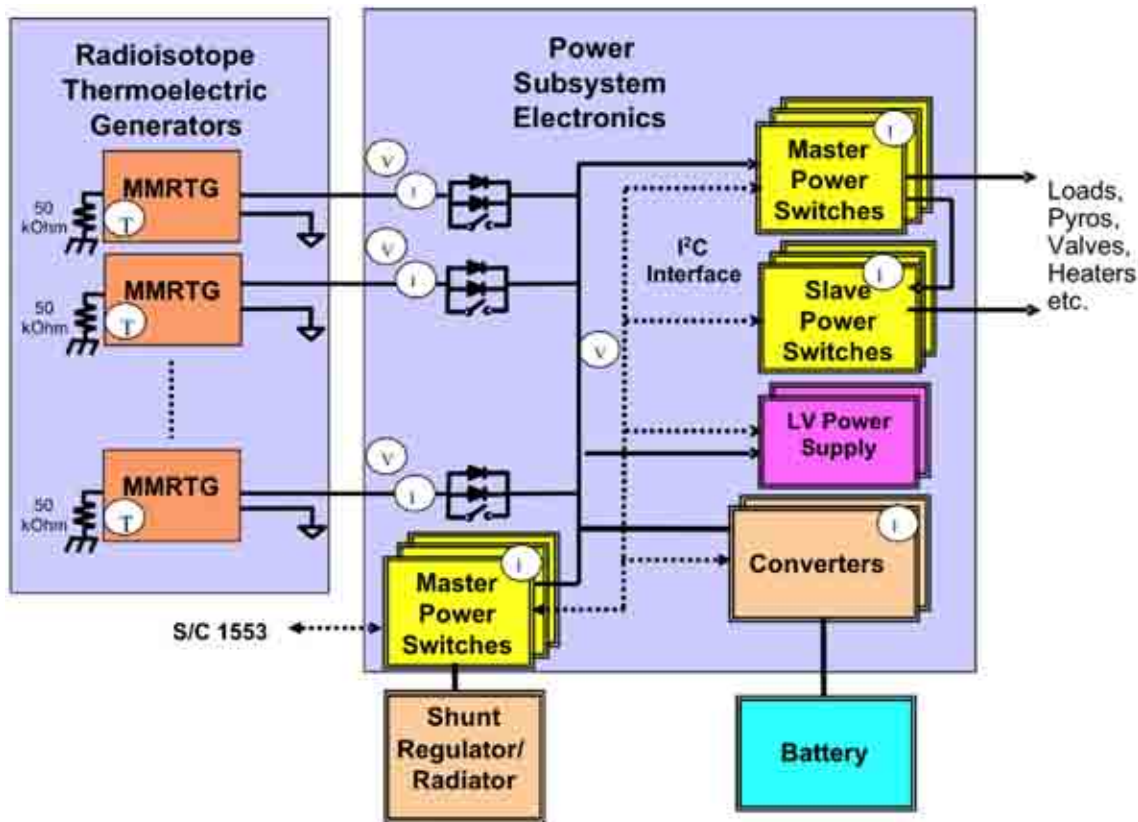


Figure 4.4-8. Power System Block Diagram

- 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

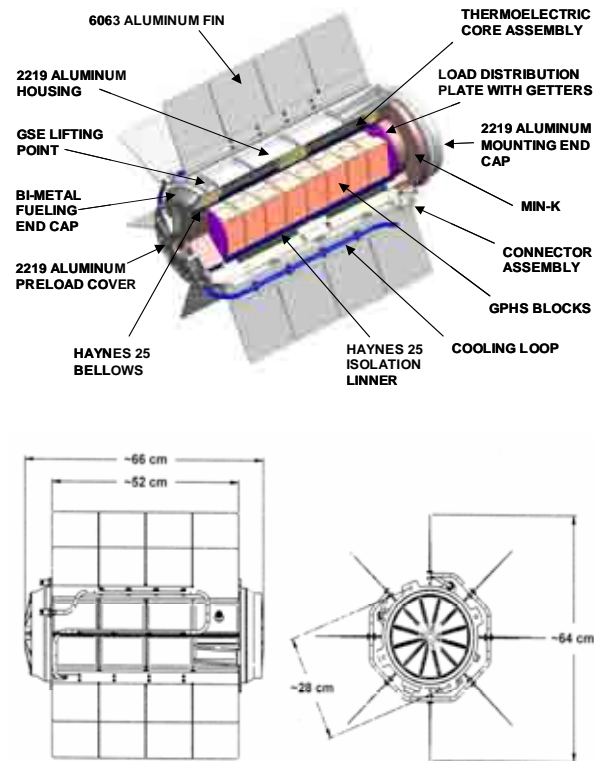
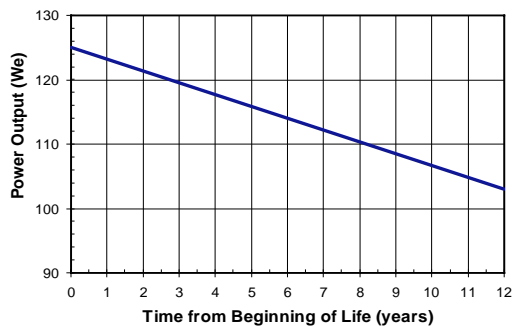


Figure 4.4-9. Performance and Configuration of the MMRTG

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,

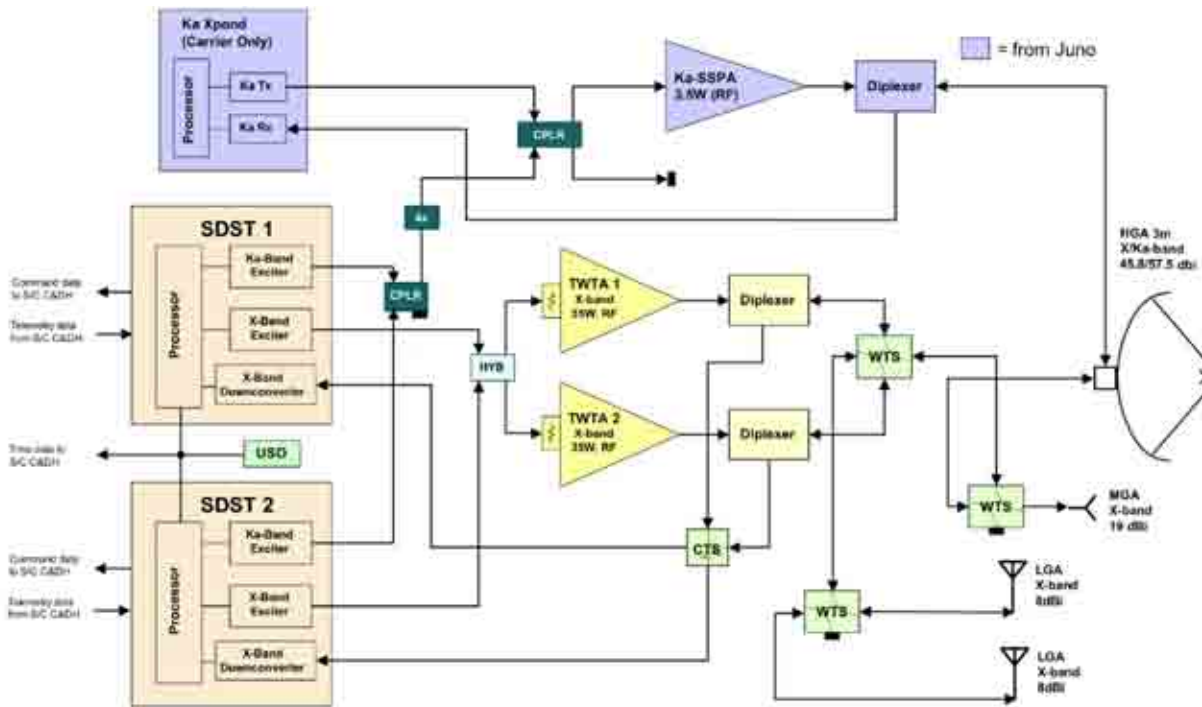


Figure 4.4-10. Telecom Subsystem Block Diagram

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 spacecraft 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 accom-

modate 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

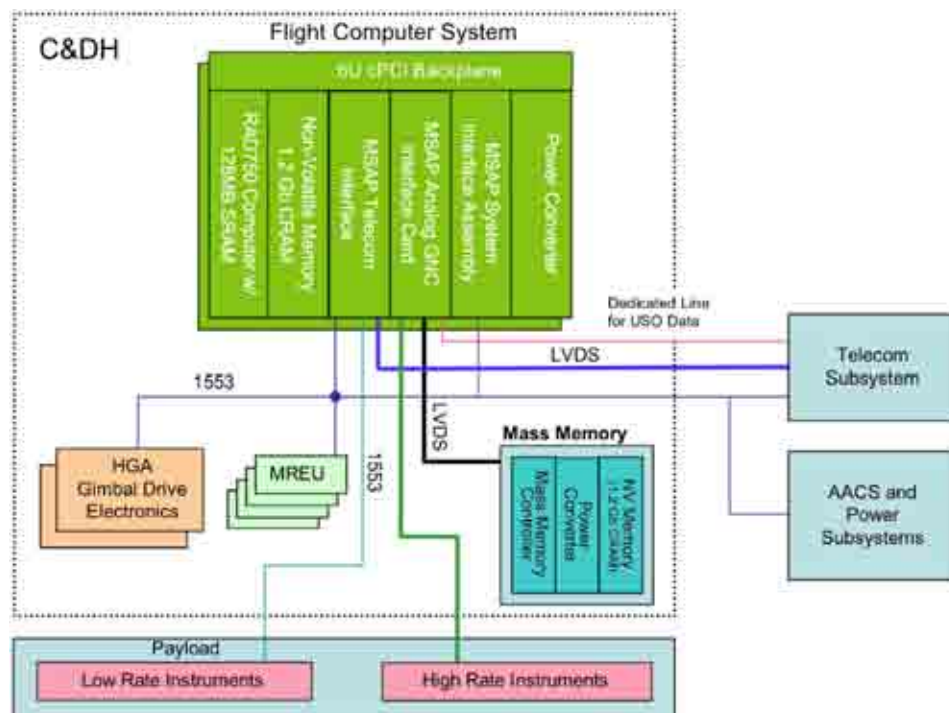


Figure 4.4-11. C&DH Block Diagram

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.

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 μ rad/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

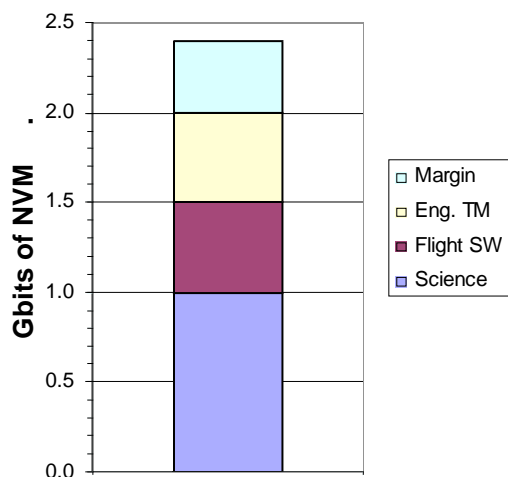


Figure 4.4-12. Non-Volatile Memory (NVM) Allocation to Science and Engineering

(no more than once a day) by firing the 4.4 N thrusters.

The articulation function is primarily for the two-axis gimballed 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

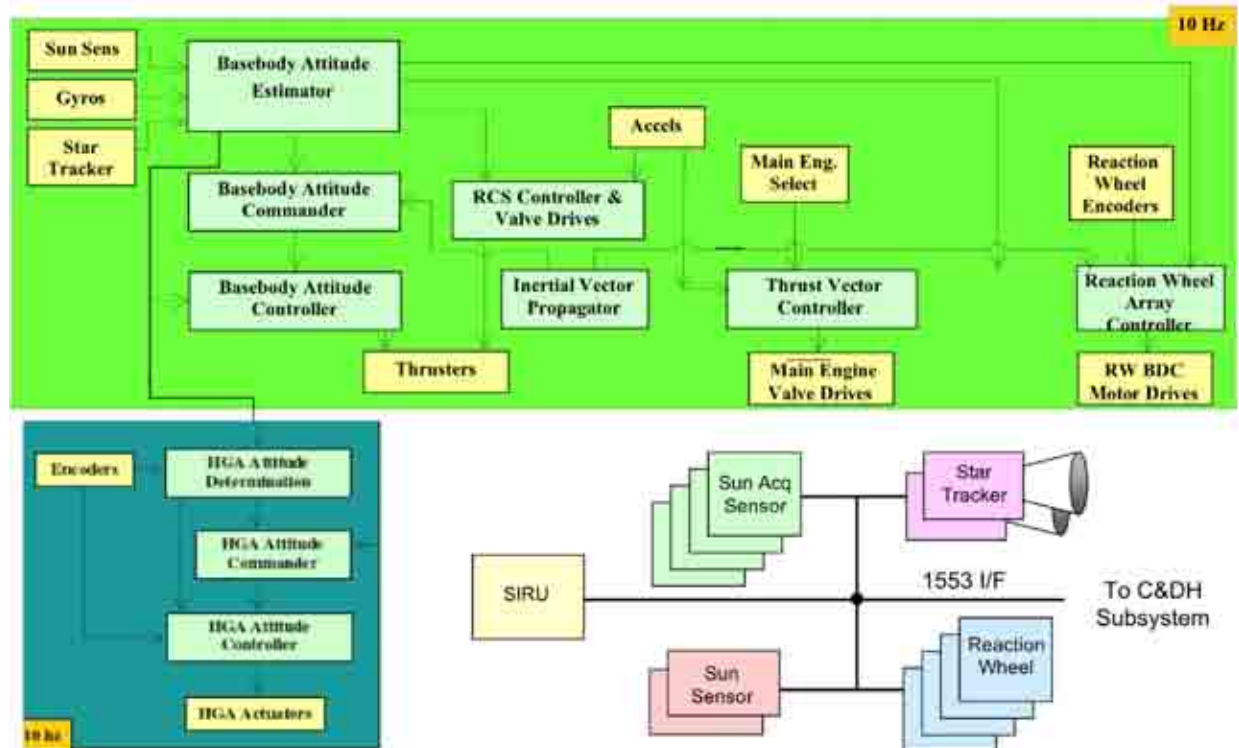


Figure 4.4-13. AACS Functional Block Diagram

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 commanded 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.

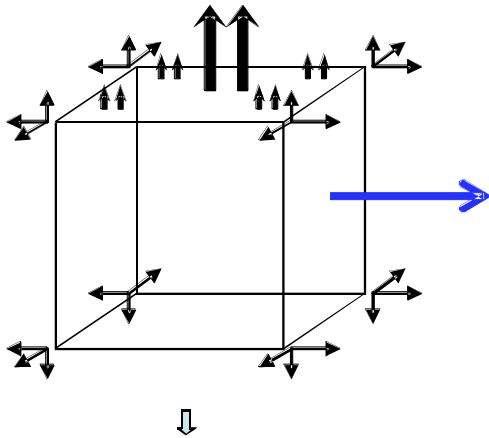


Figure 4.4-14. Engine and thruster Configuration (Main engines (2) and TVC thrusters (8) shown on +Z deck. Remaining thrusters (24) are configured in 8 clusters of 3 thrusters each.)

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 desaturations, 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.

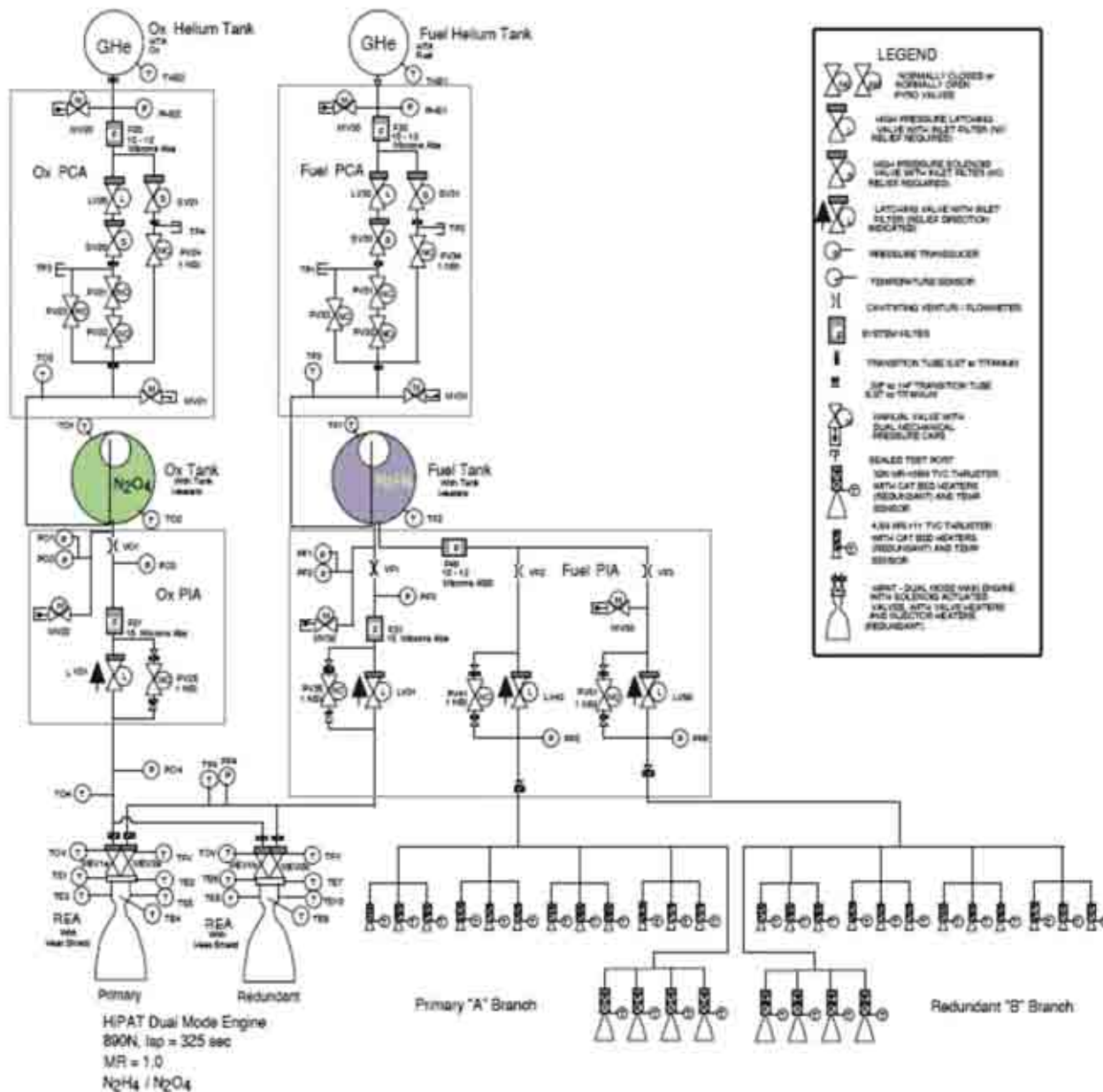


Figure 4.4-15. Propulsion System Schematic for EE

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

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

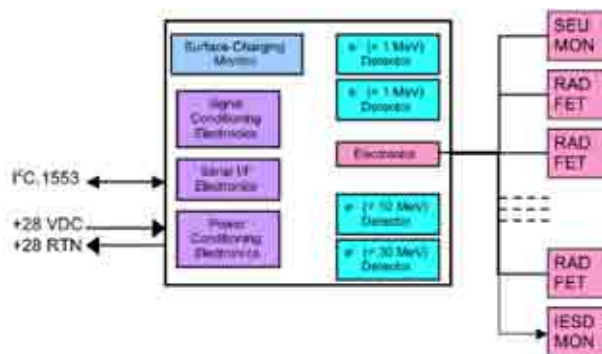


Figure 4.4-16. *Radiation Monitoring Subsystem measures actual radiation dose throughout the flight system*

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 performed 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

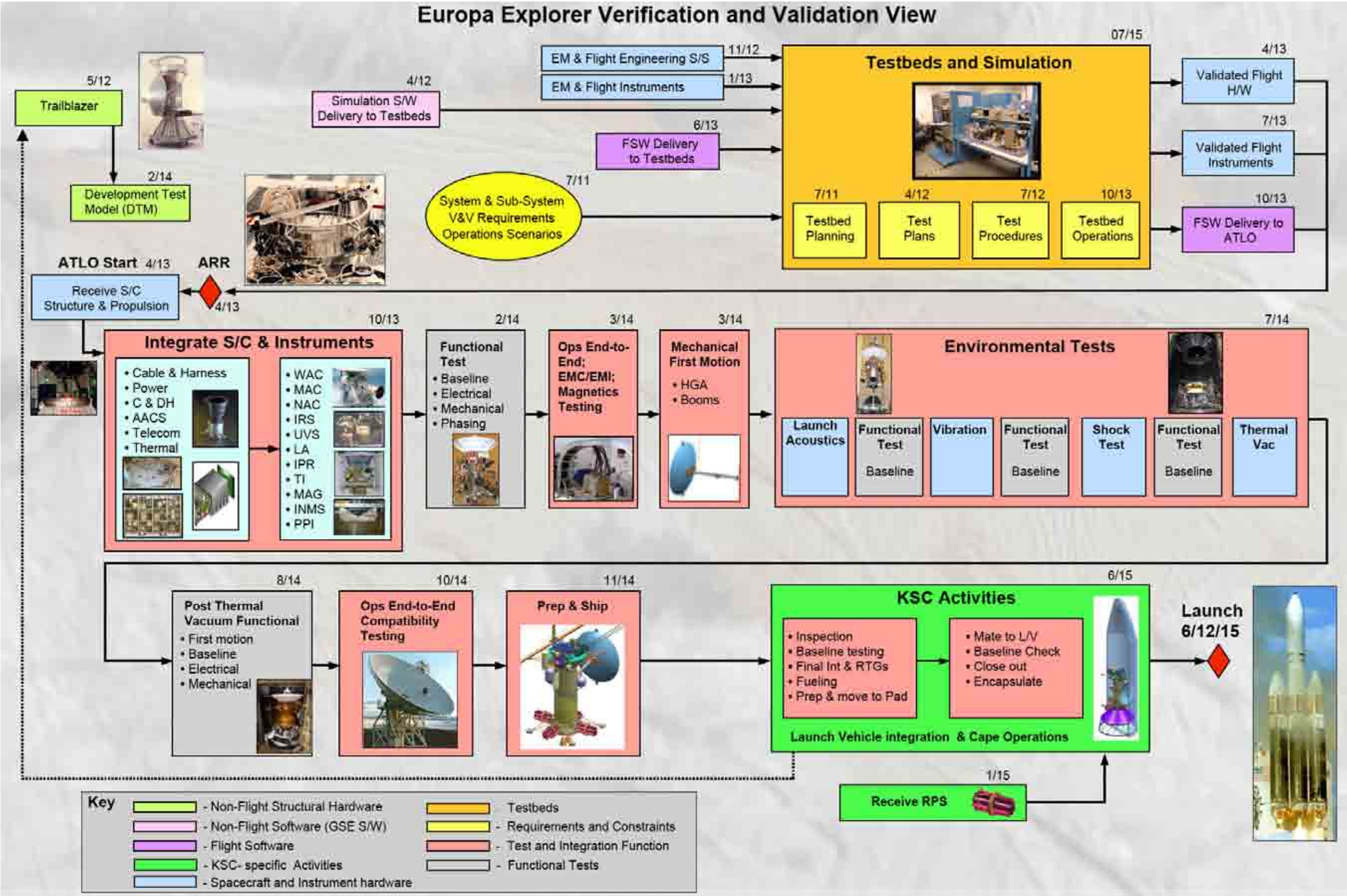
Europa and its vicinity is a challenging and hazardous environment for operating any science mission. Mapping Europa requires a large and complex payload that collects large volumes of science data. The largely unknown

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



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, Callisto, 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					
Interplanetary Cruise	72 months	84 months	7 months	14 months	7 months
Primary Science	12 months	48 months	26 months	9 months	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) 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

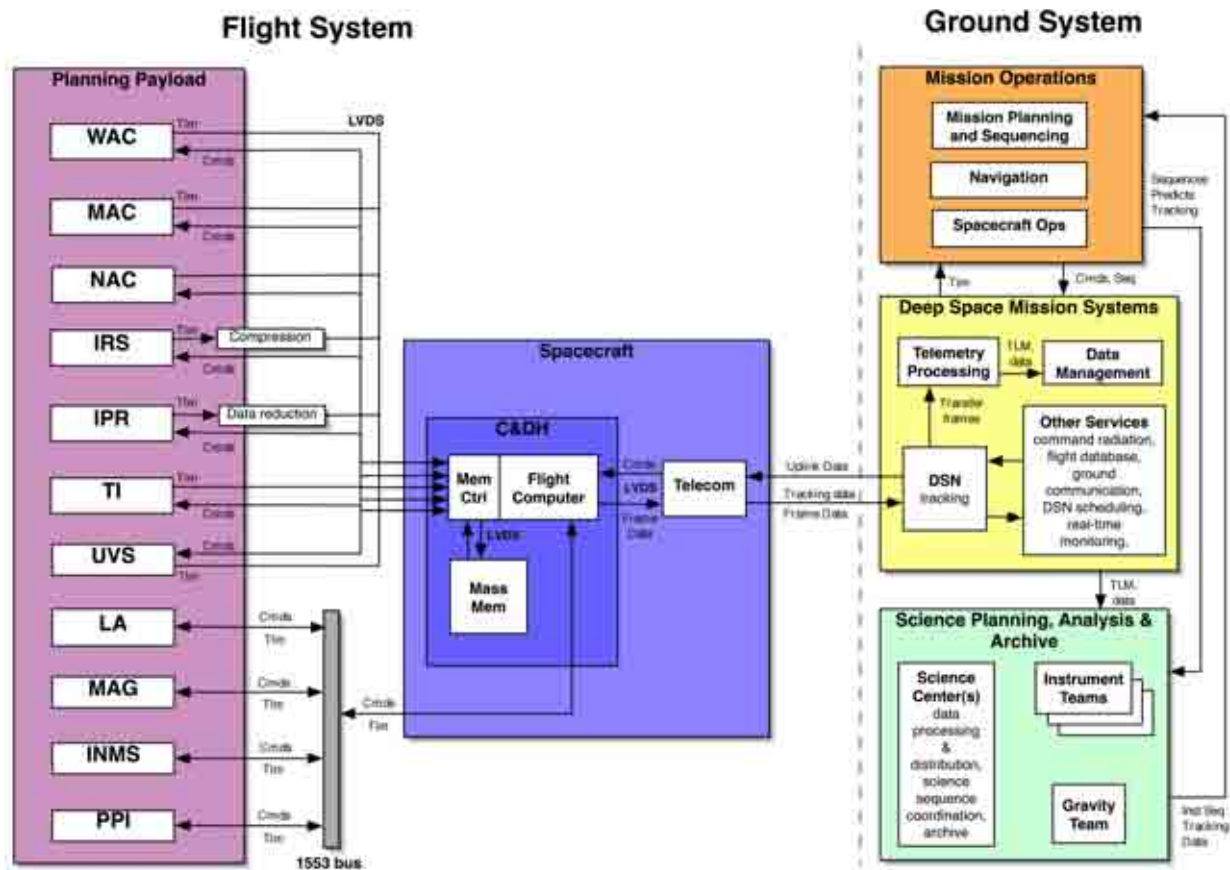


Figure 4.5-1. End-to-End Data Flow Diagram

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 specialized 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 360 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

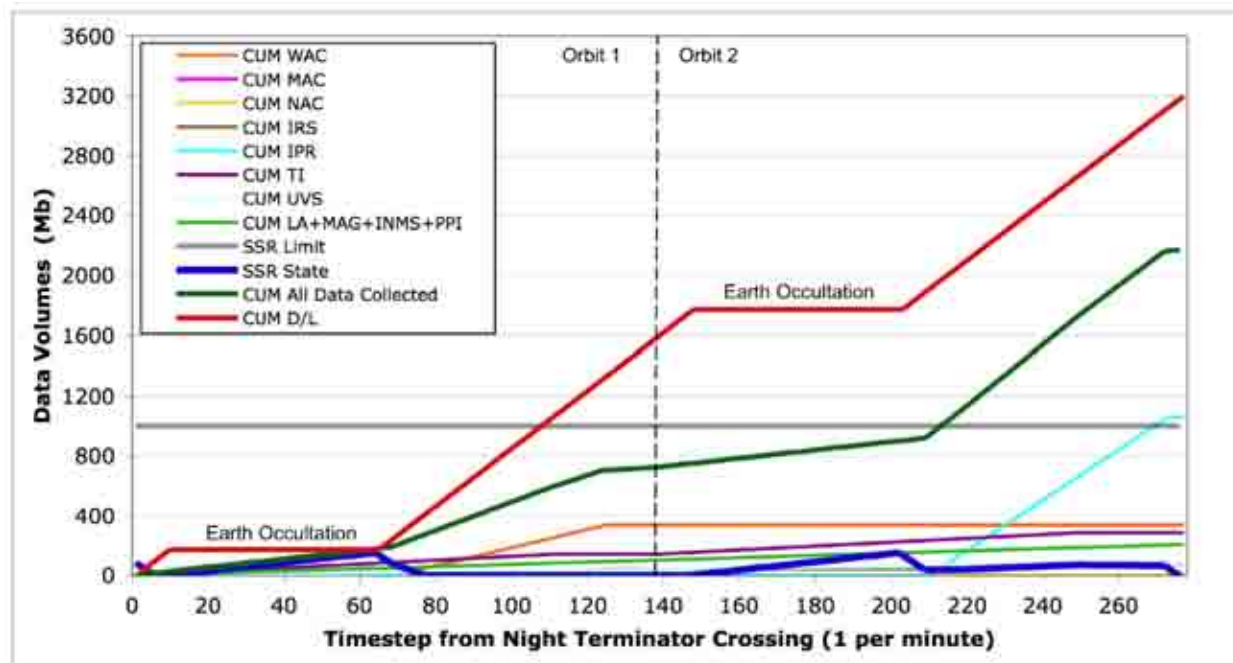


Figure 4.5-2. Cumulative data volume for a 2-orbit repeating cycle

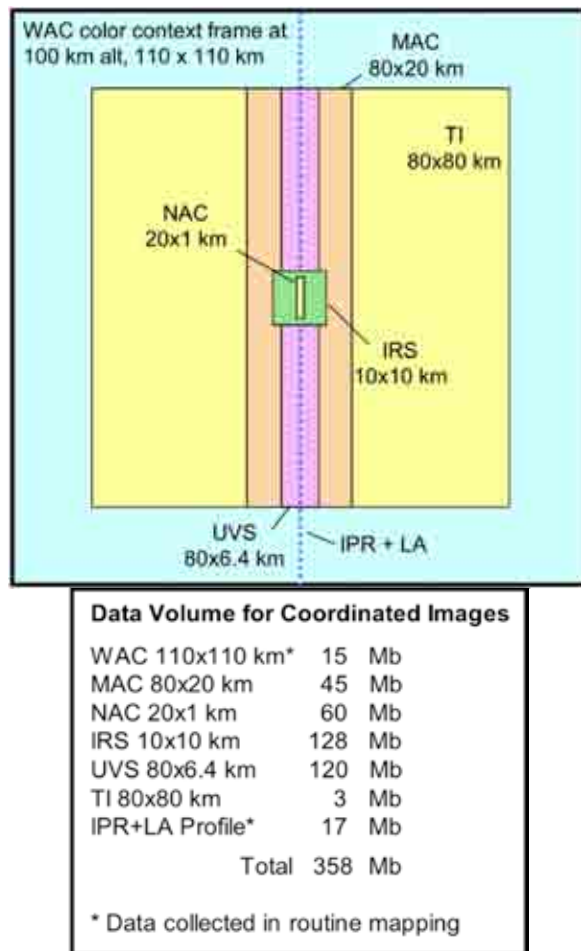


Figure 4.5-3. Coordinated Target Images

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			100 km		
		Rate (Mb/s)	Mapping Duty Cycle	Data Redux Factor	Rate (Mb/s)	Mapping Duty Cycle	Data Redux Factor
Telecom system	Ka-band, 8 hours/day 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	0.28	45%	107	0.28	45%	107
	Full resolution target mode Target Mode	30.0	-	1	30.0	-	1
TI	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.

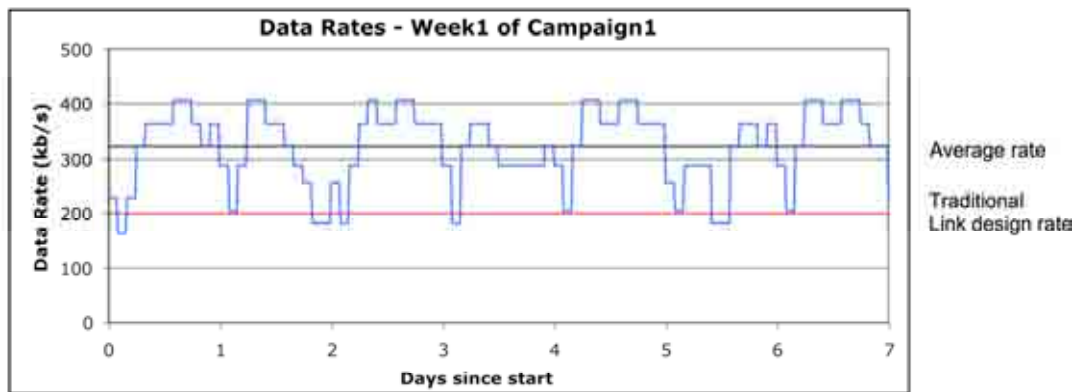


Figure 4.5-4. Data Rates Variations After Each Occultation

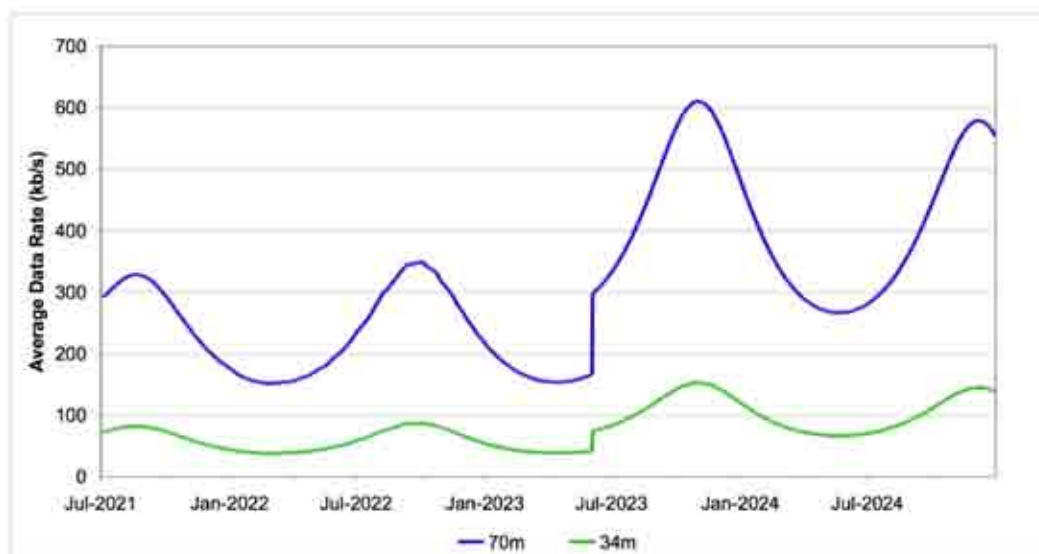


Figure 4.5-5. Average Data Rates for 34 m and 70 m Stations

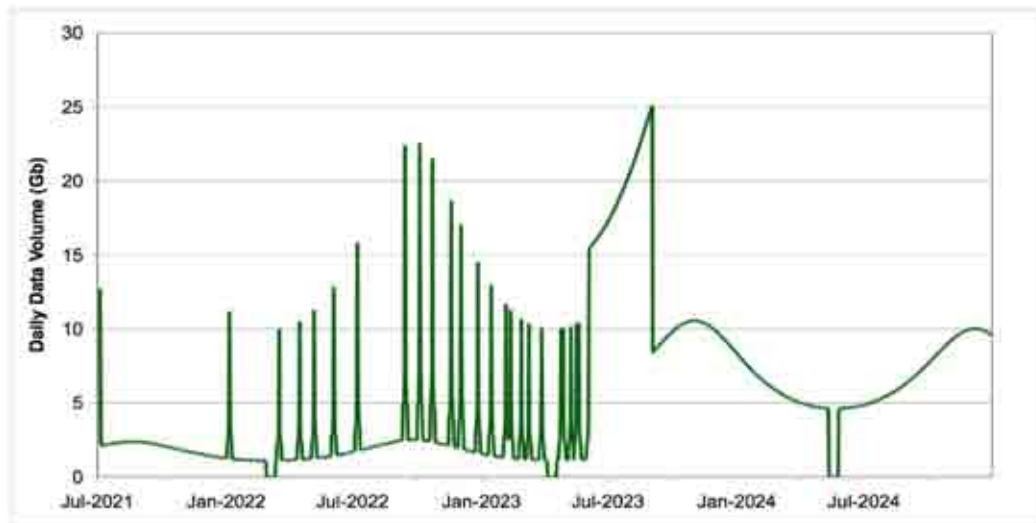


Figure 4.5-6. Daily Data Volumes

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

Reference S/C (Baseline)	Campaign 1: Global Framework						Campaign 2: Regional Processes						Campaign 3: Targeted Processes						Total Targets	% total vol	Total 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)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Avg Targ per day	Cam Tot Targ	Cam Tot 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
MAC¹	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
NAC²	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
IRS³	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
IPR⁴	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

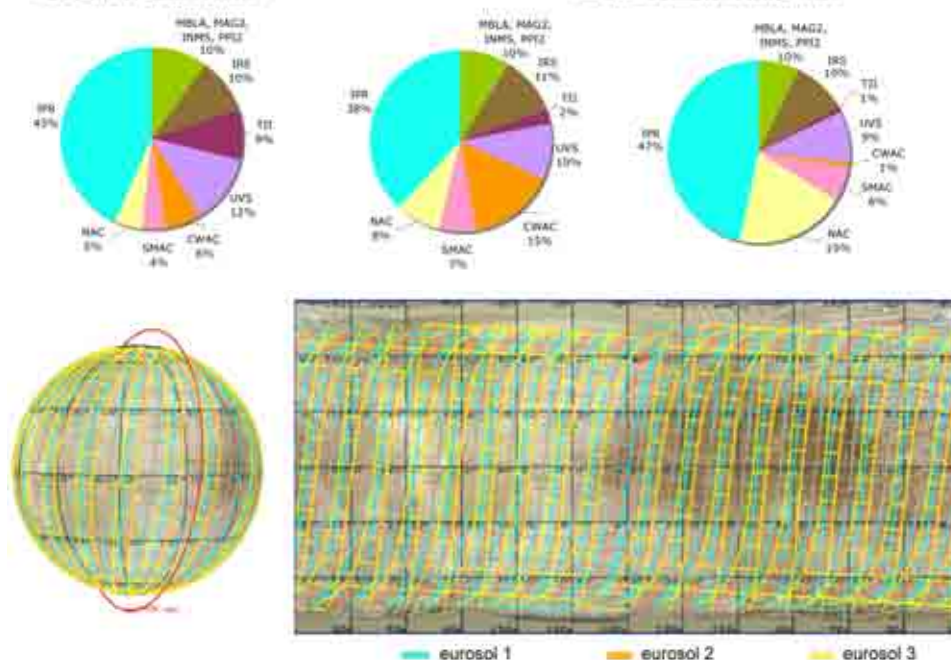


Figure 4.5-7. WAC coverage in Campaign 1

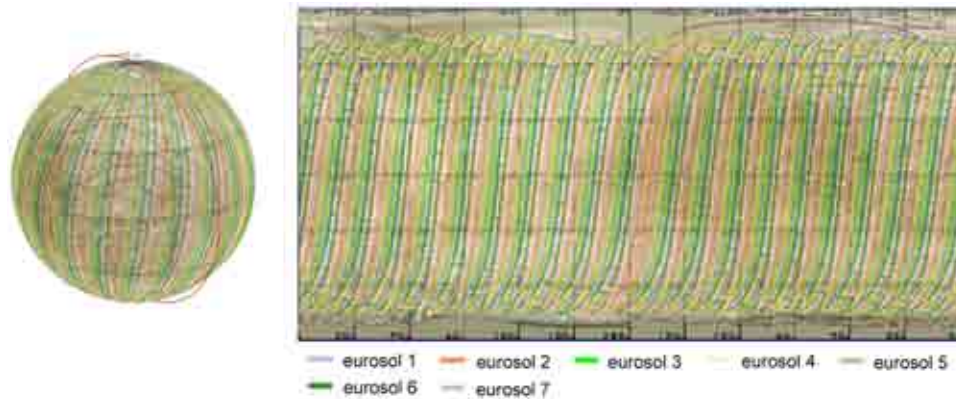


Figure 4.5-8. WAC coverage in Campaign 2

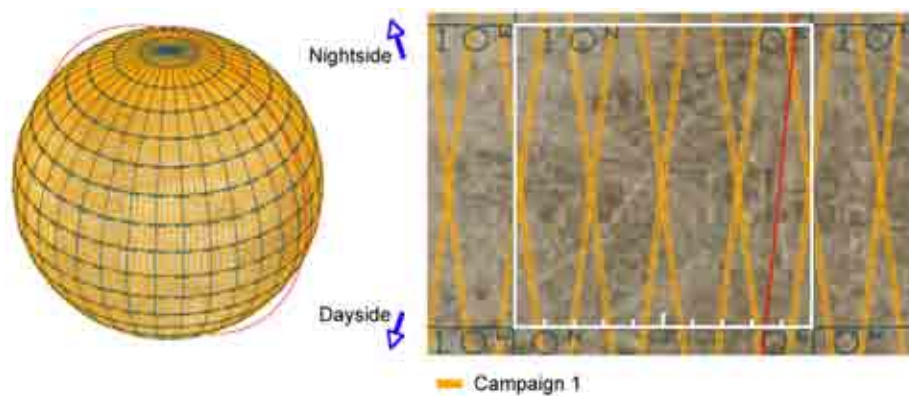


Figure 4.5-9. Ground Track coverage in Campaign 1

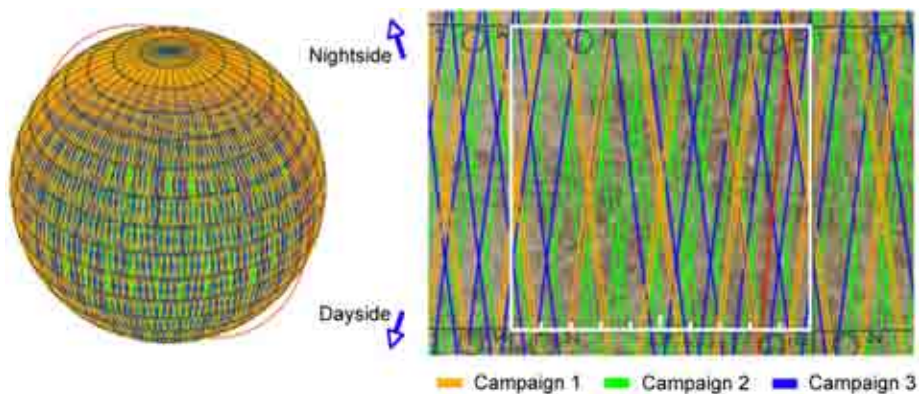


Figure 4.5-10. Ground Track coverage in Campaigns 1,2,3

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

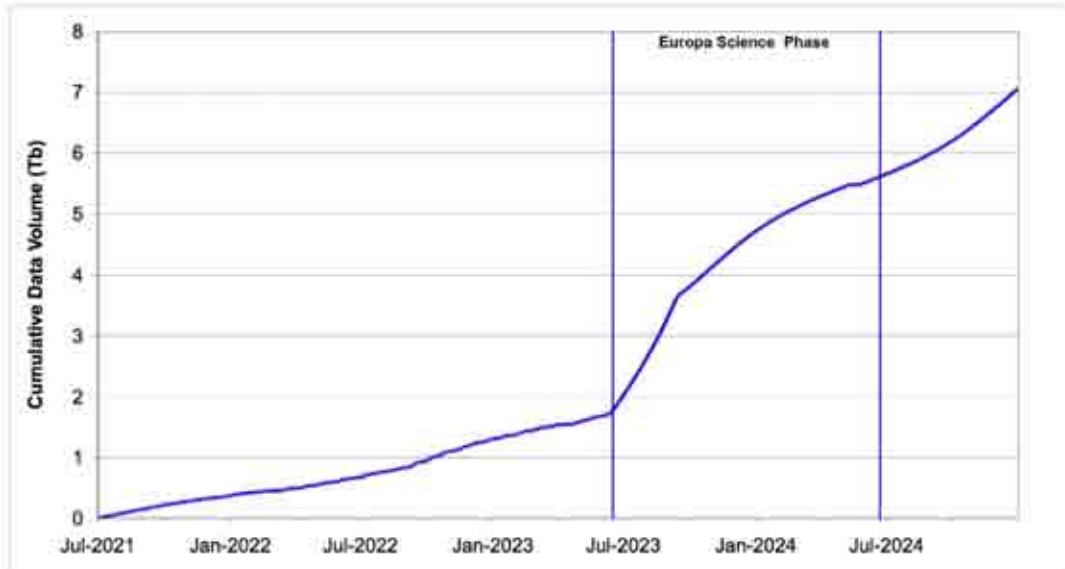


Figure 4.5-11. Cumulative Data Volume Returned

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 opportu-

nities, 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 European 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				
<i>Callisto</i>	4	370 – 3600	80 – 120	2.8 – 4.7
<i>Europa</i>	5	100 – 2800	60 – 100	0.4 – 1.9
<i>Ganymede</i>	14	450 – 8050	70 – 170	1.2 – 6.9
Non-Targeted Encounters				
<i>Callisto</i>	1	325,000	70	
<i>Europa</i>	13	107,000 – 460,000	5 – 135	
<i>Ganymede</i>	7	28,000 – 430,000	55 – 114	
<i>Io</i>	17	276,000 – 490,000	8 – 174	

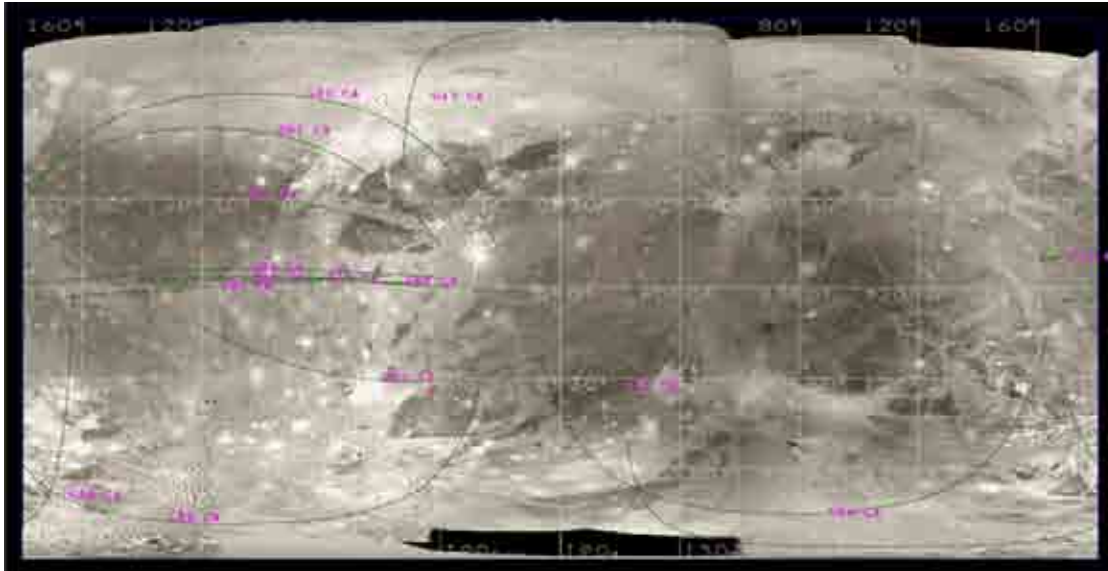


Figure 4.5-12. Ganymede Flyby encounters

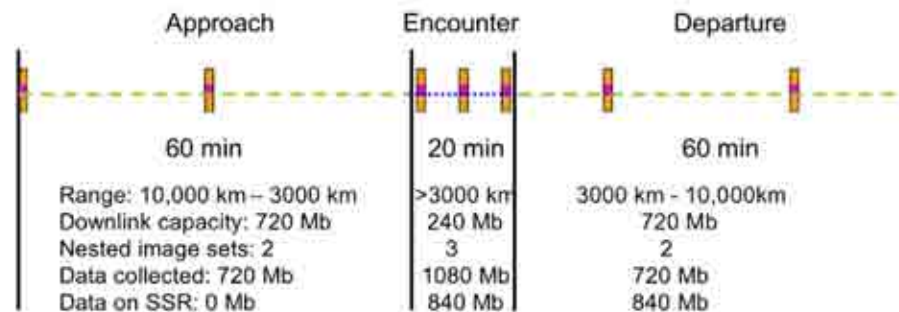


Figure 4.5-13. Example encounter timeline with coordinated target observation data sets

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 European 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:

- Microbial burden at launch.*
- Cruise survival for contaminating organisms.*
- Organism survival in the radiation environment adjacent to Europa.*
- Probability of landing on Europa.*
- The mechanisms of transport to the European subsurface.*
- 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 European 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 European 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 1×10^{-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 $\sim 1 \times 10^9$ (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 $P_{cEOI} < 1$ 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/m² 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 ΔV 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, gimbal 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 launch 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 DPSEER is essential to the early project. Early planning will include documentation 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 this 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.

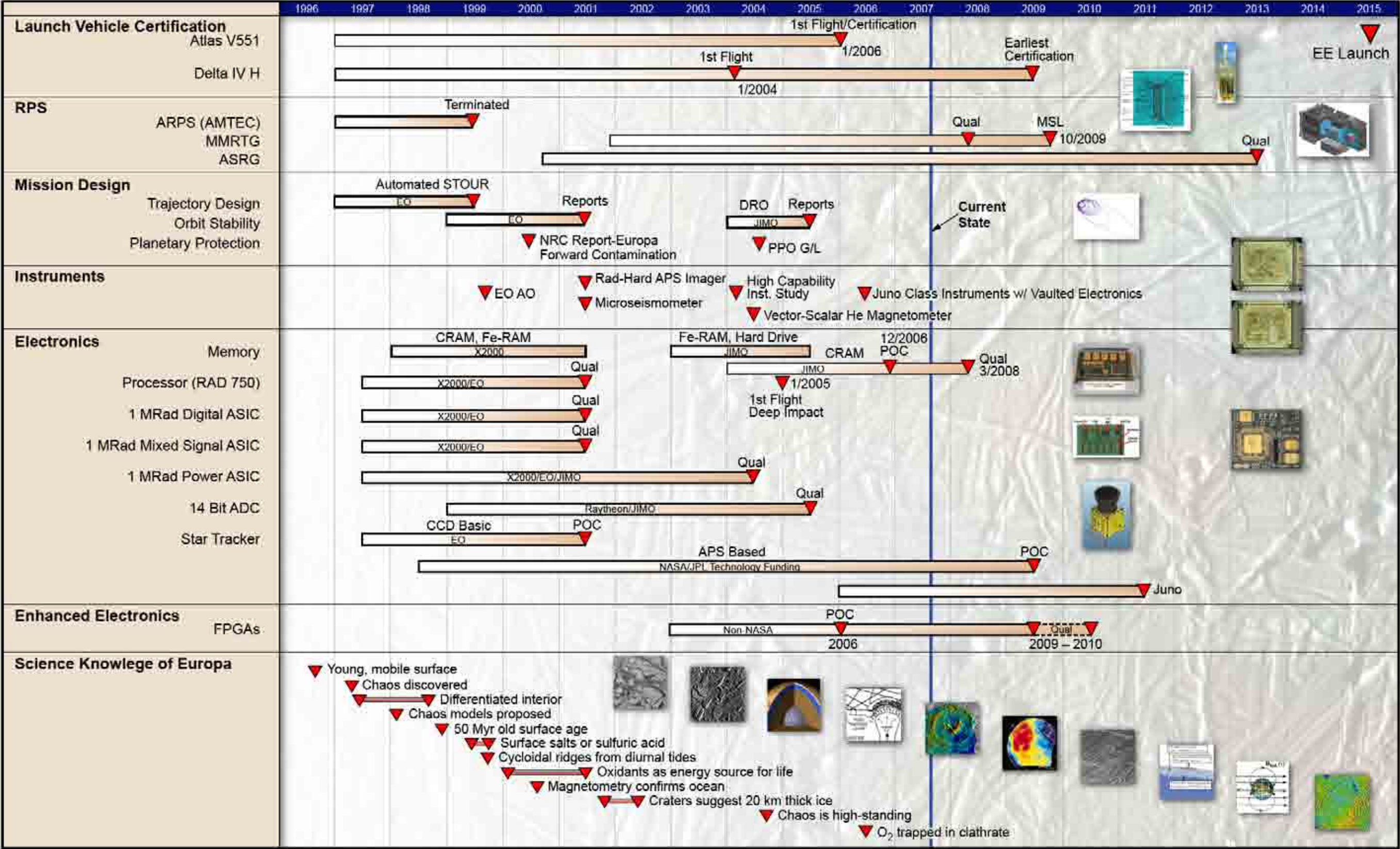
Given enough time and money, any of the three RPSs can be used for EE. The MMRTG provides a less risky but more massive, Plutonium-intensive solution over the less mature ASRG implementation. The ARTG solution is judged to be too risky and immature for either the 2015 or 2017 launch opportunities evaluated 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 tool design tools. Additionally, the Departments of Defense and Energy as well as industry have invested in technologies and developments which directly benefit 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

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 Mitigation	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 issue
			Planetary Protection	Some sensors cannot be heat sterilized, in-flight radiation sterilization 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

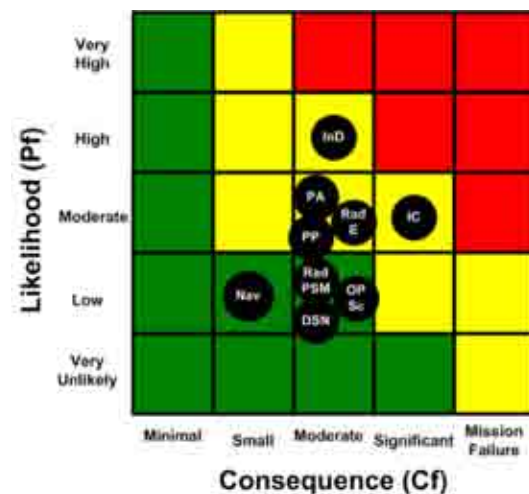


Figure 4.9-1. *Europa Explorer risk evaluation.*

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 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 European 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 krad (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 integrity 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 infrastructure for: planning, acquisition, compliance 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 (DPSE), 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

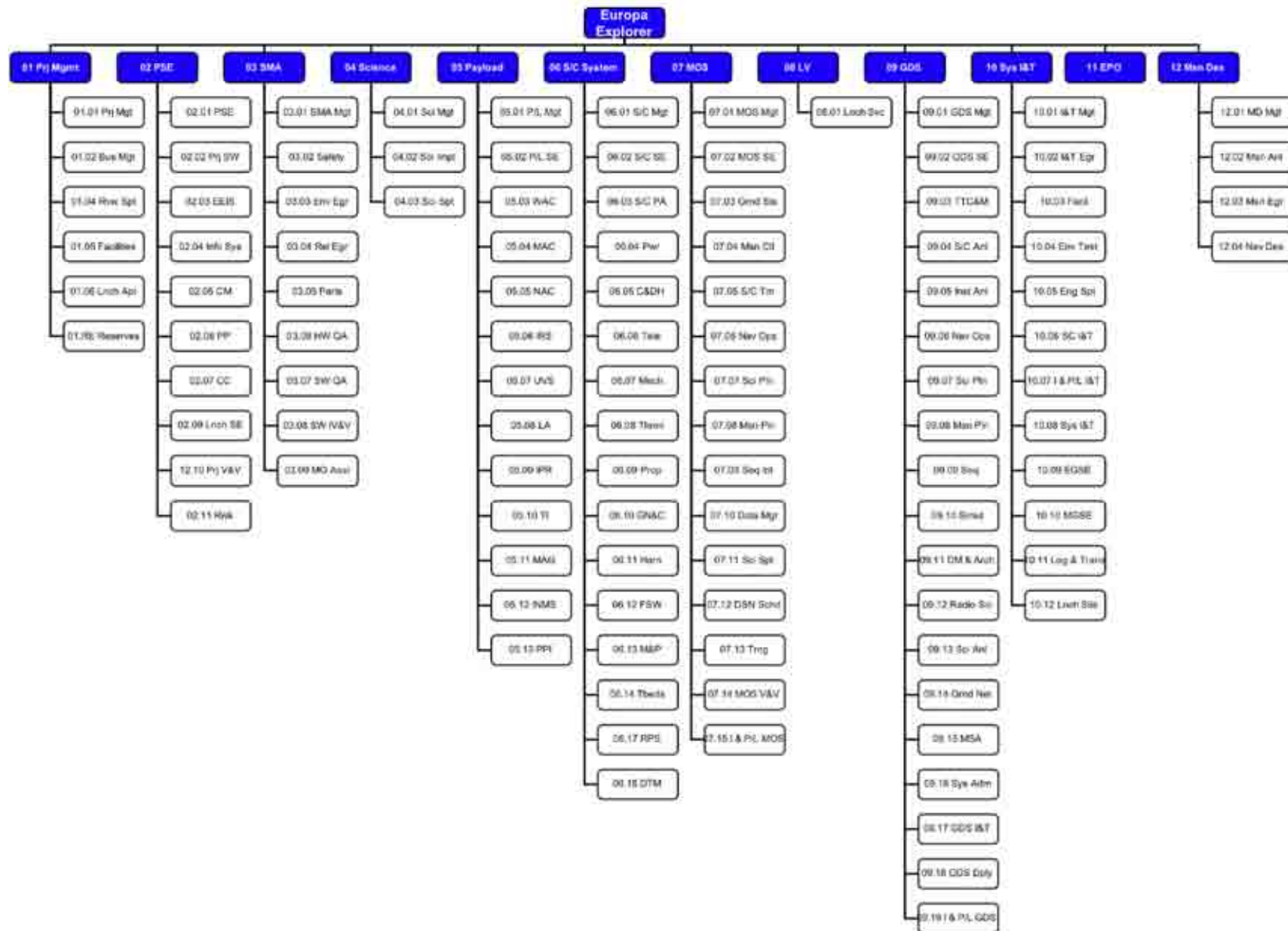


Figure 4.10-1. Europa Explorer Work Breakdown Structure.

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

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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. 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.

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

WBS Element	Phase A/B	Phase C/D	Phase E	Total (\$MFY07)
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%

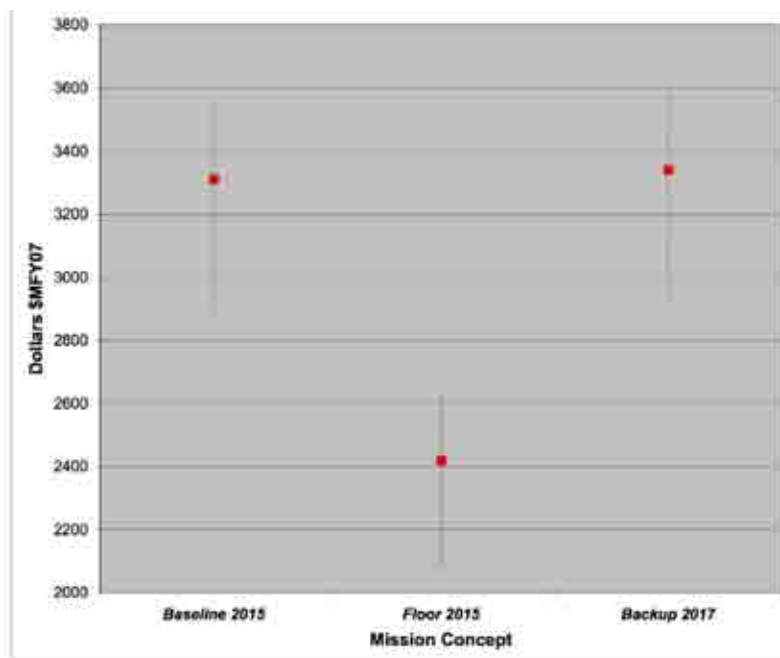


Figure 4.10-2. Europa Explorer cost summary with uncertainty

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**.

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.

4.10.9 Budget Reserve Strategy

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 takes into account project complexities such as multiple flight elements, new developments, environmental issues, etc and is used for Phases B through D. This

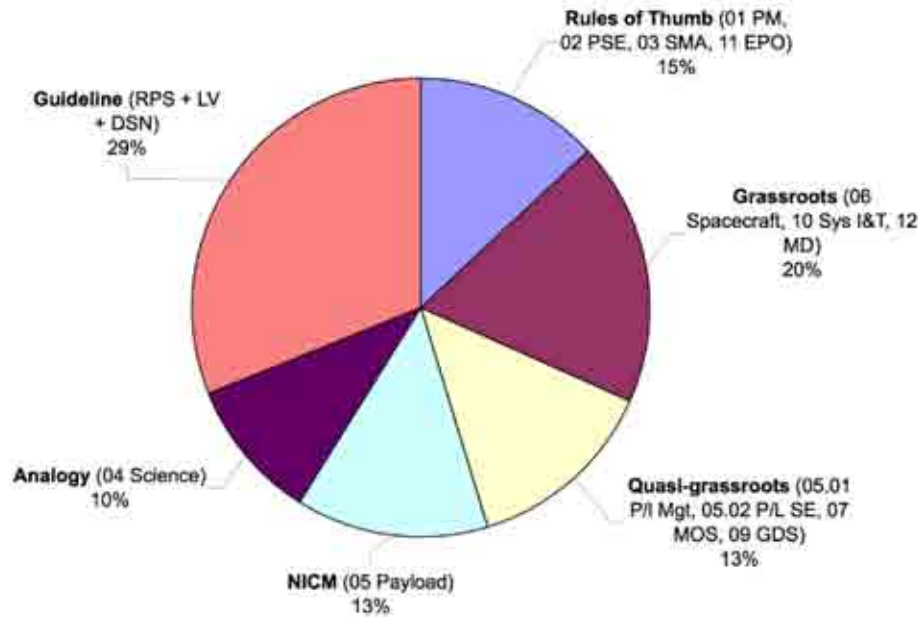


Figure 4.10-3. Cost Share by estimation method (excluding reserves).

methodology resulted in a suggested reserve posture of 37% for the baseline mission and 42% reserves for the floor mission (additional reserve to account for added risk associated with the ASRG implementation).

A 15% reserve is carried on Phase E.

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 DPSEER 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 descope 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.

6.0 BACK-UP LAUNCH OPPORTUNITIES

The baseline mission concept utilizes a launch opportunity in June 2015 and a VEEGA trajectory. As noted in Appendix E, there are many alternative launch opportunities and associated trajectory types for transfer from Earth to Jupiter. An alternate VEEGA opportunity in January of 2017 was selected as the backup to the 2015 opportunity due to its higher delivered mass performance and similar flight times and propulsive needs. The other alternatives were not pursued for analysis herein.

The January 2017 launch opportunity provides better mass performance, allows easier ramping of the funding profile, and allows more time to solicit and select the

payload than does the baseline. There is almost no impact on the spacecraft design except that the propellant tanks would be sized slightly (~2%) larger to provide the larger ΔV . Since the time-of-flight from Earth to Jupiter is roughly half a year shorter for the 2017 case, even though the launch is 18 months later, arrival at Jupiter is only 14 months later. **Table 6.0-1** compares these key parameters describing the June 2015 and January 2017 launch opportunities. Postponement of the launch until the March 2020 VEEGA launch opportunity would allow for the development of the ARTG and launch on an Atlas V 521 as shown in **Table 6.0-1**.

Additional data is presented in §3, **Table 3.4-2**.

Table 6.0-1. 2017 Backup Trajectory Provides Better Delivered Mass Performance and More Development Time than the 2015 Baseline. The 2020 Backup Offers the Potential for a Smaller Launch Vehicle at the Risk of ARTG Technology Development Delays.

	June 2015	January 2017	March 2020
Trajectory Type	VEEGA	VEEGA	VEEGA
Launch Period (days)	21	21	21
C_3 (km ² /s ²)	14.1	10	9.8
Launch Vehicle	Delta IV-H	Delta IV-H	Atlas V 531
Minimum Heliocentric Range (AU)	0.67	0.72	0.70
Flight Time to Jupiter (years)	6.1	5.7	5.9
Jupiter Arrival	July 2021	Sept 2022	February 2026
Jupiter Arrival V_∞	6.2	6.1	5.6
Mission ΔV required	2755 m/s	2798 m/s	2400 m/s
Power Source	6 MMRTGs	6 MMRTGs*	3 ARTGs
Injected Mass (kg)	7230	>7780	>3695
Dry Mass Delivered to Europa Orbit (kg)	2837	>3013	>1500
2008 Funding Required (\$MFY07)	8	5	n/a
2009 Funding Required (\$MFY07)	162	32	n/a

* Further refinement could make this mission feasible with ASRGs on an Atlas V 551

7.0 SUMMARY

The 2007 Europa Explorer mission study demonstrates that a mission to Europa is scientifically compelling, technologically ready, and consistent with the budgetary expectations of a flagship mission. The 2007 study refines and validates the cost, schedule and risk results of the Europa Explorer (EE) study performed by JPL in 2006, resulting in a mission concept which is ready to proceed into Phase A. There were three major focus areas of the 2007 study effort. First, cost estimates with supporting detail were generated. The second area of focus was the independent validation and documentation of the radiation design approach. Thirdly, the team focused on understanding and documenting the operational scenario trade space including several scenarios which emphasize different priorities. The costing and operational scenarios work was done for both the floor and baseline mission concepts. The floor mission was intended to provide the lowest cost option which still met the science objectives. Lowering the mass and power adequately to launch on an Atlas V 551 was crucial to this cost savings. **Table 7.0-1** describes the key parameters which define the floor and the baseline mission concepts.

7.1 Cost Estimate

The total cost estimate by fiscal year was assessed using a WBS line item specific approach to focus on areas with the largest uncertainty. The instrument cost estimates are understandably rough as the final payload is

anticipated to be selected by NASA HQ via AO; estimates for the payload were made by augmenting instrument cost models for the additional complexity required to operate in a high radiation environment. Workforce estimates were obtained for areas in which grass-roots estimating approaches were used. Schedules were generated to understand the basic lead times for the Project and for the estimated budget profile which would be required. A risk assessment was performed which resulted in a significant risk list which includes severity of potential impacts and potential mitigation approaches.

7.2 Radiation Design Assessment

The main purpose of this task was to characterize the residual radiation risk. A series of five independent reviews were performed focusing on the identified approach to the radiation design for the EE mission concept including assumed radiation dosage, shielding approach, part technologies and mission lifetime. This assessment culminated with the final review board stating that the current approach was sound and conservative. The board reports are included as part of Appendix C, Radiation Assessment Report. The recommendations from each independent review will be addressed as the planning for the subsequent project phases continues.

7.3 Operational Scenarios

The complex nature of this mission results in constraints on the allowable operational scenarios. The high radiation fluence in Europa orbit both limits the ultimate lifetime

Table 7.0-1. Key Characteristics for both Mission Architectures

	Baseline	Floor
Launch Vehicle	Delta IV-H	Atlas V 531
Launch Date	June 2015	June 2015
Trajectory	VEEGA	VEEGA
Flight Time to Jupiter	6.1 yr	6.1 yr
Tour Duration	2 yrs	2 yrs
Radiation Design Point	2.6 Mrad	2.3 Mrad
Europa Orbital Lifetime	1 year (75% confidence)	6 months at >75% confidence, 6 months costed
Europa Science Phase Daily Data Volume	20 Gbits/day	7 Gbits/day
Payload mass (CBE)	~158 kg	~77 kg
# of Instruments/investigation	11 + radio science - gravity	8 + radio science - gravity
Power source	6 MMRTG	5 ASRG
Payload orbital average power (CBE)	~106 W	~58 W
Unallocated Dry Mass	~185 kg	~127 kg
Estimated Mission Cost	\$3.3 BFY07	\$2.4 BFY07

of the flight system and also creates a complex interaction between flight system design, mission operations system design and operational approaches. This EE study team focused on the in-depth understanding of how the flight and mission operations systems interact to ensure that the science objectives are met. The engineering team worked hand-in-hand with the SDT to reach agreement on data gathering and return strategies for both the floor and baseline missions to ensure that the science goals and objectives could be met with flexible operational scenarios that are within small extensions of the experience base of current missions.

7.4 Mission Concept Readiness

This study has resulted in a mission concept which comprehensively addresses the over-arching science goal: Explore Europa and investigate its habitability. The mission offers two years of Jupiter system science, culminating with a year of low-altitude Europa science. The last decade (**FO-5**) has brought significant advancements in launch vehicle

capability, rad-hard electronics and memory, mission design and radiation modeling tools, and scientific knowledge of Europa, allowing the current concept to achieve a Phase A readiness level of maturity. The optimization of many parameters is still outstanding until the final project and science teams are assembled. Draft Level 1 science requirements are proposed herein (§4.1.1) but will need to be negotiated between NASA HQ, the SDT and Project Management. Specific project implementation decisions will modulate the exact cost, schedule, technical details and operational approach, but the results of this study should provide a fairly accurate basic framework within which decisions can be made and the general mission concept can be executed.

7.5 Science Value

The science value of the baseline and floor missions was discussed in §2.4.5 and summarized at the investigation level in **Table 2.4-4**. **FO-8** includes the full science value matrix evaluated at the measurement level.

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE						FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS				
Goal	Science Objective	Science Investigation	Measurement	Instrument		Global Framework		Regional Proc.		Temp. Proc.	Global Framework		Regional Proc.		Temp. Proc.
						1A	1B	2A	2B		1A	1B	2A	2B	
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. 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).	A1a. Telecom system. A1b. Laser altimeter.		3	3	4	4	5	3	4	4	3	5
		A2. Determine the induction response from the ocean over multiple frequencies.	A2a. Magnetic field measurements at 8 vectors and a sensitivity of 0.1 nT, near-continuously for at least one month.	A2a. Magnetometer.		3	4	4	4	4	3	4	4	4	4
		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). 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.	A3a. Laser altimeter. A3b. Telecom system.		4	4	5	5	5	4	5	5	5	5
		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. 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.	A4a. Telecom system. A4b. Laser altimeter.		3	3	4	4	5	3	4	4	3	5
		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 60 s accuracy. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient. A5b. Topographic profiles to resolve coherence with gravity, with better than or equal to 1 m vertical accuracy. A5c. Magnetic field measurements at 8 vectors and a sensitivity of 0.1 nT, near-continuously for several months.	A5a. Telecom system. A5b. Laser altimeter. A5c. Magnetometer.		2	2	3	3	4	2	2	3	3	4
	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 of 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. 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.	B1a. Radar sounder (nominally ~ 50 MHz, with ~ 10 MHz bandwidth). B1b. Wide-angle camera (stereo) and laser altimeter.		2	2	3	3	4	3	3	4	4	5
		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. 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.	B2a. Radar sounder (nominally ~ 5 or 50 MHz, with ~ 1 MHz bandwidth). B2b. Wide-angle camera (stereo) and laser altimeter.		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.	B3a. Global identification and local characterization 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. 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 targeted thermal observations at better than 250 m/pixel spatial resolution and temperature accuracy. 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 desirable), and better than 12 nm through a spectral range of at least 2.5-5 μm . 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. 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. B3f. Determine surface color characteristics at ~ 100 m/pixel scale in at least 3 colors, over $>80\%$ of the surface. B3g. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 1 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. B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. 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.	B3a. Radar sounder (broad-frequency, nominally ~ 5 & ~ 50 MHz, with ~ 1 and ~ 10 MHz bandwidth). B3b. Thermal instrument. B3c. IR imaging spectrometer. B3d. Wide-angle camera (stereo) and laser altimeter. B3e. Narrow-angle camera and laser altimeter. B3f. Wide-angle camera, color. B3g. UV imaging spectrometer. B3h. Medium-angle camera. B3i. Telecom system.		2	2	3	3	4	3	3	4	4	5
						2	2	3	3	4	2	3	3	4	5
						1	1	2	3	4	1	3	3	4	5
						1	2	3	4	4	1	2	3	4	4
						1	1	1	1	1	1	2	3	3	4
						4	4	5	5	5	4	4	5	5	5
						0	0	0	0	0	2	3	4	4	5
						2	2	3	3	4	2	3	3	4	5
						1	1	2	2	3	1	2	3	3	4

Europa Explorer Themes:

Origins

Evolution

Processes

Habitability

Life

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.

continued

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE						FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS				
Goal	Science Objective	Science Investigation	Measurement	Instrument		1 Global Framework		2 Regional Proc.		3. Targ. Proc.	1 Global Framework		2 Regional Proc.		3. Targ. Proc.
						1A	1B	2A	2B		1A	1B	2A	2B	
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 desirable), 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		2	2	3	4	5	2	2	3	4	5
			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^{-11} mbar, and energy resolution of 10%.	C1b: INMS		0	0	0	0	0	2	2	3	3	3
			C1c: Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal to 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		0	0	0	0	0	2	2	3	4	5
			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 desirable), and better than 12 nm through a spectral range of at least 2.5-5 μm .	C2a: IR imaging spectrometer		2	2	3	3	3	2	2	3	4	5
		C2: Relate compositions to geological processes, especially communication with the interior.	C2b: Global identification and local characterization of physical and dielectric subsurface properties, 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		2	2	3	3	4	2	2	3	4	5
			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 to 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm .	C2c: UV imaging spectrometer		0	0	0	0	0	2	2	3	4	5
			C2d: High-resolution visible stereo imaging of targeted features, at better than or equal to 10 m/pixel.	C2d: Medium-angle camera (stereo)		2	2	2	3	4	2	2	3	4	5
			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		2	2	3	3	4	2	2	3	4	5
			C2f: Detailed morphological characterization of targeted features through imaging at better than or equal to 1 m/pixel.	C2f: Narrow-angle camera		0	0	0	0	0	1	2	3	3	4
			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 to 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		2	2	2	3	3	2	2	3	4	5
		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 desirable), and better than 12 nm through a spectral range of at least 2.5-5 μm .	C3a: IR imaging spectrometer		1	1	2	3	4	1	2	3	4	5
			C3b: Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal to 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		0	0	0	0	0	2	2	3	4	5
			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^{-11} mbar, and energy resolution of 10%.	C3c: INMS		0	0	0	0	0	2	2	3	3	3
			C3d: Characterize the structure of the sputter-produced atmosphere using ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emission, 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		0	0	0	0	0	2	2	3	4	5
			C3e: Determine global distribution of bombarding energetic electron flux, and detect sputtered impacting energetic ions, by measuring magnetospheric electrons in the energy range 100 keV to 10 MeV, with pitch angle distribution and A/E/E ~ 0.1 over Europa's surface, and ion from 15 keV to 750 keV from the ram direction.	C3e: Particle and plasma instrument		1	2	3	4	5	1	3	4	5	5
			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		4	4	5	5	5	4	4	5	5	5
			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		5	5	5	5	5	5	5	5	5	5
			C3h: Detailed morphological characterization of targeted features through imaging at better than or equal to 1 m/pixel.	C3h: Narrow-angle camera		0	0	0	0	0	1	2	3	3	4
	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 A/E/E ~ 0.1 .		C4a: Particle and plasma instrument		1	2	3	4	5	1	3	4	5	5
			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 A/E/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^{-11} mbar, and energy resolution of 10%.	C4b: Particle and plasma instrument and INMS		1	1	2	2	2	1	3	3	3	4
			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 desirable), 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.	C4c: IR imaging spectrometer		1	1	2	3	4	1	2	3	4	5
			C4d: Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal to 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		0	0	0	0	0	2	2	3	4	5
		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		5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5
						5	5	5	5	5	5	5	5	5	5

Europa Explorer Themes:

Origins	Evolution	Processes	Habitability	Life
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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.

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE						FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS				
Goal	Science Objective	Science Investigation	Measurement	Instrument		Global Framework		Regional Proc.		Targ. Proc.	Global Framework		Regional Proc.		Targ. Proc.
						1A	1B	2A	2B		1A	1B	2A	2B	
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 <i>in situ</i> 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 morphology at ~10 m/pixel over targeted sites. 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. 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. D1d. Global identification and local characterization 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. D1e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D1a: Wide-angle camera (color) and Medium-angle camera. D1b: Wide-angle camera (stereo). D1c: Medium-angle camera (stereo) and laser altimeter. D1d: Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth). D1e: Narrow-angle camera.		3	3	4	4	4	3	3	4	4	4
					4	3	3	4	4	2	3	3	4	4	
					2	2	2	2	3	2	2	3	4	4	
					2	2	3	3	4	3	3	4	4	4	
					0	0	0	0	0	1	2	3	3	4	
		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. 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. D2c. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel. D2d. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. D2e. Identify and map any age-sensitive chemical and physical indicators (e.g. H ₂ O frost, ice crystallinity, SO ₂ , H ₂ O 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 desirable); 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.	D2a: Thermal instrument. D2b: UV spectrometer. D2c: Medium-angle camera (stereo). D2d: Narrow-angle camera. D2e: IR spectrometer and UV spectrometer.		2	2	3	3	4	2	2	4	4	4
					0	0	0	0	0	4	3	4	4	4	
					4	4	2	2	3	2	3	4	4	4	
					0	4	4	0	0	1	1	2	3	3	
					4	2	2	3	3	2	3	4	4	4	
		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.		2	2	3	3	4	2	2	3	4	4
					3	3	4	4	4	3	3	4	4	4	
					2	2	3	3	4	3	3	4	4	4	
					2	2	2	2	3	2	3	4	4	4	
					1	2	2	3	3	2	3	4	4	4	
		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. 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. D4c. Determine small-scale surface morphology, with stereo imaging at ~1 to 10 m/pixel over targeted high-priority sites, with vertical resolution of better than or equal 1 m. D4d. Identify and map any age-sensitive chemical and physical indicators (e.g. H ₂ O frost, ice crystallinity, SO ₂ , H ₂ O 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 desirable); 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.	D4a: Wide-angle camera (color). D4b: Thermal instrument. D4c: Medium-angle camera and/or Narrow-angle camera. D4d: IR spectrometer and UV spectrometer.		3	3	4	4	4	3	3	4	4	4
					2	2	3	3	4	3	3	4	4	4	
					2	2	2	2	3	2	3	4	4	4	
					4	4	4	4	4	4	4	4	4	4	
					2	2	3	3	4	2	2	3	4	4	
		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. D5b. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel. 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.	D5a: Thermal instrument. D5b: Narrow-angle camera. D5c: Magnetometer.		2	2	3	3	4	2	2	3	4	4
					4	4	4	4	4	1	2	3	3	4	
					2	3	4	4	4	2	3	4	4	4	

Europa Explorer Themes:

Origins

Evolution

Processes

Habitability

Life

3

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.

continued

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE					FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS									
Goal	Science Objective	Science Investigation	Measurement	Instrument	1 Global Framework	2 Regional Proc.	3 Targ. Proc.	1A	1B	2A	2B	3 Targ. Proc.	1A	1B	2A	2B	3 Targ. Proc.		
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.	2	4	4	2	4	4	4	4	2	4	4	4	4		
		E2. Characterize the atmosphere 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 ΔE/E=0.1, and measuring ions from 10 eV to 10 keV with 15 degree angular resolution to ΔE/E=0.15.	E2a. Particle and plasma instrument.	1	2	3	4	4	4	4	4	2	3	4	4	4		
			E2b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E2b. Magnetometer.	2	3	4	4	4	4	4	2	3	4	4	4			
			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 ⁻⁴ to 10 ⁻¹⁰ mbar, and energy resolution of 10%.	E2c. INMS.	4	4	4	4	4	4	2	3	3	4	4				
			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 5 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.	4	4	4	4	4	4	2	3	3	4	4				
		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.	2	3	4	4	4	4	2	3	4	4	4				
		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 ΔE/E=0.15.	E3b. Particle and plasma instrument.	1	3	4	4	4	4	1	3	4	4	4					
		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 ΔE/E=0.1.	E4a. Particle and plasma instrument.	1	3	4	4	4	4	1	3	4	4	4				
			E4b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E4b. Magnetometer.	2	3	4	4	4	4	2	3	4	4	4				
	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 ΔE/E=0.15.	E4c. Particle and plasma instrument.	1	3	4	4	4	4	1	3	4	4	4						
	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. Camera (including color & stereo), IR spectrometer, UV spectrometer, Radar Sounder, and Thermal instrument.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
			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. Camera (especially color), IR spectrometer, UV spectrometer, Radar Sounder, and INMS.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
			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.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
			F1d. Determine the interior structures and processes operating in the Galilean satellites in relation to the formation and history of the Jovian system and potential habitability of the moons, by means of: magnetic field measurements; Doppler gravity measurements.	F1d. Magnetometer and Telecom system.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
		F1e. Investigating the small bodies and rings in the Jovian system, by means of: visible imaging; IR spectroscopy; and UV spectroscopy.	F1e. Camera, IR spectrometer, and UV spectrometer.	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
		F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a 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, Camera, IR spectrometer, and Thermal instrument.	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
	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, Camera, IR spectrometer, and Thermal instrument.	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
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 auroral and satellite footprints; radio occultations.	F3a. Magnetometer, Particle and plasma instrument, UV spectrometer, and Camera.	4	4	4	4	4	4	4	4	4	4	4	4	4	4			
Total score (of 351)					108	138	184	208	242	146	207	270	304	351					
% s					30%	38%	50%	57%	66%	40%	57%	74%	83%	96%					
Eurosols into orbital mis					4	8	14	20	26	4	8	14	20	26					
Days into orbital mis					14	26	64	71	82	14	26	64	71	82					
Europa Explorer Themes:					Origins	Evolution	Processes	Habitability	Life										
					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.													

8.0 TEAM MEMBERS AND ROLES

8.1 Team Overview

The study was conducted by two closely interacting teams. The NASA-chartered SDT focused on the science aspects while the JPL/APL Engineering Team focused on the technical and programmatic aspects of the mission concept. There was extensive interaction between the two teams throughout the study ensuring that the science goal and objectives were feasible given the technical and programmatic constraints and approaches. A listing of the team members, their affiliations and their areas of expertise are given in **Tables 8.1-1** and **8.1-2**.

The SDT held four face-to-face meetings and weekly telecons. The SDT invited specific individuals to present at the SDT meetings to ensure a broad input on the science and potential investigational methods. Two sub-

groups, one for defining science value and the second to directly work operational scenarios and science observational strategies were formed which focused the efforts.

Additionally, the EE SDT worked very closely with the JSO SDT to understand and evaluate the ability of each mission concept to achieve the science objectives of the alternate concept. A joint White Paper is being prepared to document this evaluation and will be released later this year.

The invited talks were from: Chris Chyba and Kevin Hand (Princeton and Stanford—Astrobiology), Karl Hibbitts (APL—Impactor), Tom Gardner (Raytheon—Lander), Jim Shirley and Eric Slimko (JPL—Landers), Mike Watkins (JPL—Gravity Measurements from Sub-satellites), Karl Strauss (JPL—Mass Memory Technology), Mark Allen (JPL—Radar Spectrometry), Amanda Hendricks (JPL—UV Spectroscopy), Wendy Edelstein

Table 8.1-1. Science Definition Team

Member	Affiliation	Expertise
Ron Greeley—Co-Chair	Arizona State University	Europa
Bob Pappalardo—Co-Chair	Jet Propulsion Laboratory	Europa and Jupiter System
Krishan Khurana	University of California – Los Angeles	Magnetic Fields
Bill Moore	University of California – Los Angeles	Interiors
Don Blankenship	University of Texas	Subsurface and Radar
Louise Prockter	Applied Physics Laboratory	Geology and JSO SDT Co-Chair
Diana Blaney	Jet Propulsion Laboratory	Multi-wavelength imaging
Tom McCord	Bear Fight Institute	Surface Composition
Bruce Bills	Goddard Space Flight Center	Geophysics/Interior
Chris Paranicas	Applied Physics Laboratory	Particles and plasma
Mitch Sogin	Marine Biological Laboratory	Astrobiology

Table 8.1-2. Engineering Team

Member	Affiliation	Expertise
Karla Clark—Lead	Jet Propulsion Laboratory	Project Management and Systems Engineering
Rob Abelson	Jet Propulsion Laboratory	Systems Engineering
Ed Jorgenson	Jet Propulsion Laboratory	Cost
Peter Kahn	Jet Propulsion Laboratory	Systems Engineering
Karen Kirby	Applied Physics Laboratory	Systems Engineering
Rob Lock	Jet Propulsion Laboratory	Mission Planning and Operational Scenarios
Guy Man	Jet Propulsion Laboratory	Systems Engineering
Bob Rasmussen	Jet Propulsion Laboratory	Systems Engineering
Bill Russell	Jet Propulsion Laboratory	Schedules
Rusty Woodall	Jet Propulsion Laboratory	Mission Assurance
James Kinnison	Applied Physics Laboratory	Systems Engineering - Risk Assessment
Andy Spry	Jet Propulsion Laboratory	Planetary Protection
Ken Klaasen	Jet Propulsion Laboratory	Instruments
Nick Pinkine	Applied Physics Laboratory	Operations
Greg Welz	Jet Propulsion Laboratory	Operations

(JPL—Radar Interferometry), Bob Johnson (UVA—Particle Sputtering), Lonnie Lane (JPL—UV Spectroscopy), Soren Madsen (JPL—Radar Interferometry), Paul Rosen (JPL—Radar Instrumentation), Ali Stefanini (JPL—Radar Sounding), Peter Seigel (Caltech—Radar Spectroscopy), John Spencer (SWRI—Thermal Imaging), Jeff van Cleve (Ball Aerospace—Thermal Imaging), Hunter Waite (SWRI—INMS), Mau Wang (JPL—INMS), and Maria Zuber (MIT—Laser Altimetry).

Because of the challenge and complexity of the radiation issue, a task was undertaken to provide an independent assessment of the EE approach to radiation design and mitigation and to characterize the residual radiation risk. A series of peer reviews and workshops was organized to allow discipline experts to evaluate specific focus areas. Six such peer evaluations were conducted. The final integrated system review summarized the findings from the discipline reviews and integrated the approaches into a broad system approach. Members of these peer reviews and their affiliation are listed in [Table 8.1-3](#).

8.2 APL Role

Louise Prockter and Chris Paranicas from APL are members of the SDT. APL also supplied people for the independent radiation assessment as identified above. APL took the lead role in the Project Risk Assessment and a supporting role in the Instrument activity.

8.3 GSFC Role

In addition to Bruce Bills' support to the SDT, GSFC also supplied people for the independent radiation assessment as identified above.

8.4 GRC Role

GRC supported the evaluation of the materials radiation assessment as identified above. GRC Advanced Radioisotope Power System personnel (Jeff Schrieber and Dick Shaltens) also supported one SDT meeting to discuss the potential impacts of using ASRGs for this mission.

8.5 APL-JPL Outer Planets Steering Group

The Study Team interacted with and was advised by a steering group consisting of the following people:

- Walt Faulconer—APL: Civilian Space Business Area Executive
- Rob Strain—APL: Space Department Head
- Rob Gold—APL: Space Department Chief Technologist
- Chris Jones—JPL: Director for Solar System Exploration
- Doug Stetson—JPL: Manager of the Solar System Mission Formulation Office
- Jim Cutts—JPL: Chief Technologist for Solar System Exploration and Manager of the Strategic Mission and Advanced Concepts Office

8.6 Study Results Review

Different parts of this concept study report have been reviewed by independent sets of discipline specialists and by APL/JPL management as follows:

1. The team has already sought and gained the support of the NASA PPO for the PP approach concept. [email from Cassie Conley to James A. Spry, Wed, 22 Nov 2006 13:53:22]
2. The Science Goal and Objectives were subjected to a review by an independent panel of planetary scientists.
3. The Science Goal and Objectives and the mission concept were presented at the Outer Planets Assessment Group (OPAG) meeting in June 2007 and at the Committee on Planetary Exploration (COMPLEX) meeting in July 2007.
4. The implementation has been reviewed by a technical, management, and cost review board internal to JPL and APL.
5. Finally, the overall concept study report was reviewed by both JPL and APL management prior to submission.

Table 8.1-3. Radiation Assessment Team

Team Member	Affiliation
Environments Review	
Chris Paranicus—Chair	Applied Physics Laboratory
Barry Mauk	Applied Physics Laboratory
Richard Thorne	University of California – Los Angeles
Tom Armstrong	Fundamental Technology
Steve Levine	Jet Propulsion Laboratory—Juno Deputy Principal Investigator
John Cooper	Goddard Space Flight Center
Shielding and Transport Analysis	
Jeff Johnson—Chair	Oak Ridge National Laboratory
Laurie Waters	Sandia National Laboratory
Ken Adams	Science Applications International Corporation
Richard Kemski	Jet Propulsion Laboratory
Mark Looper	The Aerospace Corporation
Parts	
Ron Lacoe—Chair	The Aerospace Corporation
Ken LaBel	Goddard Space Flight Center
Ethan Blansett	Sandia National Laboratory
Steve McClure	Jet Propulsion Laboratory—Juno Parts Engineer
Materials	
Jim Sutter	Glenn Research Center
Chuck Barnes	Jet Propulsion Laboratory
Bill McAlpine	Jet Propulsion Laboratory—Juno Radiation Engineer
Systems	
Richard Kingsland—Chair	Implementation Technology Inc
Steve Leete	Goddard Space Flight Center
John Bolt	Applied Physics Laboratory
Greg Levanas	Jet Propulsion Laboratory
Glenn Reeves	Jet Propulsion Laboratory
Integrated Systems	
Joe Srour—Chair	The Aerospace Corporation
John Henley	Science Applications International Corporation
Ralph McNutt	Applied Physics Laboratory
Dave Kusnierkiewicz	Applied Physics Laboratory—Chief Engineer
Sammy Kayali	Jet Propulsion Laboratory—Juno Mission Assurance Manager
Duncan MacPherson	Jet Propulsion Laboratory—Engineer Fellow
Gentry Lee	Jet Propulsion Laboratory—Engineer Fellow

A. ACRONYMS AND ABBREVIATIONS

AACS	Attitude and Articulation Control Subsystem
ACS	Attitude Control System
A/D	Analog to Digital
ADC	Analog to Digital Converter
AMTEC	Alkali Metal Thermoelectric Converter
amu	atomic mass unit
AO	Announcement of Opportunity
APD	Avalanche Photodiode
APL	Applied Physics Laboratory
APL	Approved Parts List
APS	Active Pixel Sensor
ARPS	Advanced Radioisotope Thermoelectric Generator
ARR	ATLO Readiness Review
ARTG	Advanced Radioisotope Thermoelectric Generator
ASD	Acquisition Sun Detector
ASIC	Application Specific Integrated Circuit
ASRG	Advanced Sterling Radioisotope Generator
ASU	Arizona State University
ATLO	Assembly, Test and Launch Operations
AU	Astronomical Unit
B	Magnetic Field Strength
BOE	Basis of Estimate
BOL	Beginning of Life
BOM	Beginning of Mission
C	Centigrade
C_3	Launch energy per unit mass; also the square of the hyperbolic excess velocity
C22	Callisto encounter number 22 (Galileo)
C&DH	Command and Data Handling subsystem
CADRe	Cost Analysis Data Requirements
CBE	Current Best Estimate
CCAFS	Cape Canaveral Air Force Station
CCD	Charge-Coupled Device
CDR	Critical Design Review
CEASE	Compact Environmental Anomaly Sensor
cg	Center of Gravity
CID	Charge Injection Device
CMMI	Capability Maturity Model Integration
CMOS	Complementary Metal–Oxide–Semiconductor
COMPLEX	Committee on Planetary and Lunar Exploration
CODACON	Coded Anode Array Converter
COSPAR	Committee on Space Research
C_{ov}	Coefficient of Variation

CPU	Computer Processing Unit
CRAM	Chalcogenide Random Access Memory
DAC	Digital to Analog Converter
Db	deadband
DC	Direct Current
DD	Displacement Damage
Deg	degree
DG	Divine-Garrett
DHMR	Dry Heat Microbial Reduction
DoD	Department of Defense
DoE	Department of Energy
DOR	Differential One-way Range
DPA	Destructive Physical Analysis
DPM	Deputy Project Manager
DPMR	Deputy Project Manager for Radiation
DPP	Design Practices and Principles
DPSER	Deputy Project System Engineer for Radiation
DRAM	Dynamic Random Access Memory
DRO	Distant Retrograde Orbit
DSM	Deep Space Maneuver
DSN	Deep Space Network
DTM	Development Test Model
Δ DOR	Delta-Differential One-way Range
Δ V-EGA	Delta Velocity – Earth Gravity Assist
EAC	Estimate at Completion
EDAC	Error Detection and Correlation
EDL	Entry, Descent and Landing
EE	Europa Explorer
EEE	Electrical, Electronic and Electromechanical
EGA	Earth Gravity Assist
EGE	Europa Geophysical Explorer
EHF	Extremely High Frequency
EIS	Environmental Impact Statement
ELDRS	Extreme Low Dose Rate Sensitivity
EM	Engineering Model
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
EO	Europa Orbiter
EOI	Europa Orbit Insertion
EOM	End of Mission
EPA	Environmental Protection Agency
EPD	Energetic Particle Detector
EPF	Europa Pathfinder
ESA	European Space Agency

ESD	Electrostatic Discharge
ESG	Europa Sub-group
ESSP	Europa Surface Science Package
EUV	Extreme Ultraviolet
eV	electron Volt
EVM	Earned Value Management
Fe-RAM	Ferroelectric-random access memory
FER	Frame Error Rate
FET	Field-Effect Transistor
FIPS	Fast Imaging Plasma Spectrometer
FMECA	Failure Modes Effect and Criticality Analysis
FO	Foldout
FOV	Field of View
FPGA	Field Programmable Gate Array
FPP	Flight Project Practices
FSS	Fine Sun Sensor
FSW	Flight Software
FUV	Far Ultraviolet
G	Giga
Gb	Gigabit
G/L	Guidelines
G&C	Guidance and Control
GDS	Ground Data System
G-G	Gravity Gradient
GIRE	Galileo Interim Radiation Electron
GNC	Guidance, Navigation and Control
GPHS	General Purpose Heat Source
GRACE	Gravity Recovery And Climate Experiment
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
Gyr	Billion years
h ₂	tidal Love number
HEPA	High Efficiency Particulate Air
HGA	High Gain Antenna
HQ	Headquarters
hr	hour
HRSC	High Resolution Stereo Camera
Hz	Hertz
IC	Internal Charging
IESD	Internal Electrostatic Discharge
IFOV	Instantaneous Field of View
IML	Icy Moons Lander
IMS	Infrared Mapping Spectrometer

IMU	Inertial Measurement Unit
InD	Instrument Development
INMS	Ion and Neutral Mass Spectrometer
INSRP	Interagency Nuclear Safety Review Panel
IPR	Ice-Penetrating Radar
IR	Infrared
IRS	Infrared Spectrometer
I&T	Integration and Test
ITAR	International Tariff And Trade Regulation
ITI	Implementation Technology, Inc.
ITL	Integrated Test Laboratory
J	Joule
JEDI	Juno Energetic-particle Detector Instrument
JIMO	Jupiter Icy Moons Orbiter
JMI	Jovian Moon Impactor
JOI	Jupiter Orbit Insertion
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
k	kilo
K	Kelvin
k ₂	potential Love number
keV	kilo- Electron Volt
km	kilometer
KSC	Kennedy Space Center
L	Magnetic Shell Parameter
LA	Laser Altimeter
LA	Launch Approval
LAE	Launch Approval Engineering
LANL	Los Alamos National Laboratory
LED	Light Emitting Diode
LEMMS	Low Energy Magnetospheric Measurement System
LGA	Low Gain Antenna
LILT	Low Intensity Low Temperature
LOLA	Lunar Orbiter Laser Altimeter
LOS	Line of Sight
LROC	Lunar Reconnaissance Orbiter Camera
LV	Launch Vehicle
LVA	Launch Vehicle Adapter
LVDO	Low Voltage Dropout (Regulator)
LVDS	Low-Voltage Differential Signaling
LVPS	Low voltage power supply
m	meter
m	milli

μ	micro
M	Million (Mega)
M ³	Moon Mineralogy Mapper
Ma	Million years
MAC	Medium-Angle Camera (Descoped payload)
MAC	Medium-Angle Stereo Camera (Baseline payload)
MAG	Magnetometer
MAGIC	MSAP Analog GNC Interface Card
MAM	Mission Assurance Manager
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding
MDAS	Mission Data Analysis System
MEL	Mass (Master) Equipment List
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
Mb	Megabit
mbar	millibar
MCR	Mission Concept Review
MDR	Mission Definition Review
MER	Mars Exploration Rover
MeV	Mega- Electron Volt
MEV	Maximum Expected Value
MGA	Medium Gain Antenna
MHD	Magnetohydrodynamics
MHz	Megahertz
MLI	Multi-layer Insulation
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MREU	MSAP Remote Engineering Unit
MRI	Medium Resolution Instrument
MRO	Mars Reconnaissance Orbiter
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MON	Monitor
MOS	Mission Operation System
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
M&P	Materials and Processes
MPV	Maximum Possible Value
MRO	Mars Reconnaissance Orbiter
MSAP	Multi-Mission Spacecraft Architectural Platform
MSIA	MSAP System Interface Assembly
MSL	Mars Science Laboratory
MSO	Mars Science Orbiter
MSTB	Mission System Testbed
MTIF	MSAP Telecom Interface

MVPS	Medium voltage power supply
n	nano
N	Newton
N	number
NAC	Narrow-Angle Camera
NASA	National Aeronautics and Space Administration
Nav	Navigation
NAVCAM	NAVigational Camera
NEAR	Near Earth Asteroid Rendezvous
NEPA	National Environmental Protection Agency
NICM	NASA Instrument Cost Model
NLR	NEAR Laser Rangefinder
NMO	NASA Management Office
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPR	NASA Program Requirement
NRC	National Research Council
nT	nanoTesla
NTO	Nitrogen Tetroxide
NUV	Near Ultraviolet
NVM	Non-volatile Memory
OPAG	Outer Planets Assessment Group
OpSc	Science Operations
ORNL	Oak Ridge National Laboratory
ORT	Operational Readiness Test
OSTP	Office of Science and Technology Policy
OTM	Orbital Trim Maneuver
Pa	Pascal
PA	Plutonium Availability
PAF	Payload Attach Fitting
PCA	Power Converter Assembly
PDR	Preliminary Design Review
PEL	Power Equipment List
PEPSSI	Pluto Particle Spectrometer Science Investigation
PET	Proton/Electron Telescope
PI	Principal Investigator
PIA	Power Interface Assembly
PIA	Propulsion Interface Assembly
PIDDP	Planetary Instrument Definition and Development Program
PIND	Particle Impact Noise Detection
PL	Payload
PM	Project Manager
PMCM	Parametric Mission Cost Model
POC	Proof of Concept

PP	Planetary Protection
PPI	Particle and Plasma Instrument
PPO	Planetary Protection Office(r)
PRA	Probabilistic Risk Assessment
PS	Project Scientist
PSE	Project System Engineer
PSG	Project Science Group
QPSK	Quadrature-Phase-Shift Keying
Qual	Qualification
RadE	Radiation Environment
RADFET	Radiation Sensing Field Effect Transistor
RadPSM	Radiation Effects in Parts, Sensors, and Materials
RAM	Random Access Memory
RDF	Radiation Design Factor
RFA	Request for Action
RFP	Request for Proposal
RGA	Residual Gas Analysis
RHU	Radioisotope Heater Unit
RLAT	Radiation Lot Acceptance Test(ing)
RMS	Radiation Monitoring Subsystem
ROD	Record of Decision
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPS	Radioisotope Power Source
RSE	Radiation System Engineer
RTG	Radioisotope Thermoelectric Generator
RTI	Real Time Interrupt
RTOF	Reflection Time of Flight
RW	Reaction Wheels
s	second
S	Siemens
SAIC	Science Applications International Corporation
SAR	Safety Analysis Report
S&M	Structures and Mechanisms
SAMPEX	Solar, Anomalous, Magnetospheric Particle Explorer
S/C	Spacecraft
SDST	Small Deep Space Transponder
SDT	Science Definition Team
sec	second
SEE	Single Event Effects
SEL	Single Event Latch-up
SER	Safety Evaluation Report
SEU	Single Event Upset
SHARAD	Shallow (Subsurface) Radar

SMD	Science Mission Directorate
SNL	Sandia National Laboratory
SNR	Signal to Noise Ratio
SONOS	Silicon Oxide Nitride Oxide Semiconductor
SPF	Single Point Failure
SRAM	Static Random Access Memory
SRR	System Requirements Review
SS	Sub-system
SSES	Solar System Exploration Subcommittee
SSPA	Solid State Power Amplifier
SSR	Solid State Recorder
ST	Star Tracker
ST5	Space Technology 5
STOUR	Satellite Tour (trajectory software)
T	Tera-
T	Tesla
TAA	Technical Assistance Agreements
Tb	Terabit
TBD	To Be Determined
TCM	Trajectory Correction Maneuver
TCS	Thermal Control Subsystem
TDI	Time-Delay Integration
THEMIS	Thermal Emission Imaging System
TI	Thermal Instrument
TID	Total Ionizing Dose
TLM	Telemetry
TMC	Technical, Management, and Cost
TOF	Time of Flight
TTC&M	Tracking, Telemetry, Command and Monitoring
TVC	Thrust Vector Control
TWG	Technical Working Group
TWTA	Traveling Wave Tube Amplifier
UCLA	University of California Los Angeles
U of A	University of Arizona
U of Col	University of Colorado
U of H	University of Houston
UTJ	Ultra Triple Junction
UTMC	United Technologies Microelectronics Center, Inc
UVS	Ultraviolet Spectrometer
UVIS	(Cassini) Ultraviolet Imaging Spectrometer
VDE	Valve Drive Electronics
VEEGA	Venus-Earth-Earth Gravity Assist
VGA	Venus Gravity Assist

VRHU	Variable Radioisotope Heater Unit
V&V	Verification and Validation
WAC	Wide-Angle Camera
WBS	Work Breakdown Structure
WY	Work Year
YAG	Yttrium Aluminum Garnet
yr	year
§	Section

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C. RADIATION ASSESSMENT REPORT

C1. Introduction

Missions that spend a significant time in Jupiter's radiation belts face unique design challenges. Radiation damage to electronic parts is expected to be the main life-limiting factor for such missions. Significant investment has been made in the last ten years in studying and preparing for a mission that could return to Jupiter to further investigate recent discoveries, most notably, from Galileo. Programs such as X2000, Europa Orbiter, JIMO, and other radiation programs (NPOESS, DoD missions) provided much needed knowledge to go forward. Juno has discovered a very unique mission design which allows it to accumulate only a small amount of radiation dosage through the first 2/3 of the mission. The combination of a central vault, rad-soft parts (25–50 krad) and the unique mission design allows Juno to meet its science objectives while reaching only about 500 krad behind 100 mils of Al. These previous efforts and the Juno experience are in the basis of a Europa orbiter radiation design [Boland 2006] and then further refined in 2007. This Appendix augments the main Europa Explorer Mission Study: Final Report by documenting two key activities performed in 2007; external technical peer review of the radiation design for EE and the newly developed mission lifetime model.

C2. External Peer Review Process and Findings

EE has a comprehensive approach to handle radiation. An independent peer review process, involving external experts, favorably validated the project approach. A series of five external, independent peer reviews were commissioned from 4/18/07–5/10/07 to provide independent validation of the approach. Four reviews/workshops covered disciplines of: radiation environment and modeling; transport analysis and shielding design; parts and materials; and systems engineering and operations. The results of these reviews were reported to a larger panel of systems experts consisting of chief engineers and managers with radiation design and mission experience. The results of the reviews are included in §C8. Detailed radiation design material was presented to the board and is not repeated here.

The chair of the reviews and the organizations involved are shown in [Figure C2-1](#). The charge to the board, board membership, affiliations, finding, recommendations and RFAs are provided in §C8. In addition to the review objectives listed, the board was also asked to identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

The project found the boards' findings and recommendations both comprehensive and useful. The Integrated Systems Peer review board finding was:

“In general, the JPL team is performing high-quality work in preparing for the Europa Explorer mission. At the present review, the Europa team did a very good job of presenting an overview of their progress, recommendations, and plans in radiation-related areas. The visibility of radiation issues and the integration of radiation expertise on the Europa program are commendable and essential for success. Very good teamwork and healthy communications are evident. The inclusion of an excellent peer review process on the program is notable.”

Summaries of the findings for each of the review are listed on [Foldout 9 \(FO-9\)](#).

The “Materials” technical peer review was handled differently due to the existence of an extensive design document “Materials Survivability and Selection for Nuclear Powered Mission,” JPL D-34098 June 2006, developed by the Prometheus Project [Willis 2006]. This document has been restricted for NASA distribution only. It provides a brief description of Radioisotope Power Systems (RPS) powered missions (all in high radiation environments), and a brief discussion of radioisotope power sources. Separate sections give an overview of major radiation effects on materials. Next, the document describes the effects of radiation on materials that have been “binned” into major classes. The document ends with an engineer's “roadmap” as to how to qualify and test additional materials for

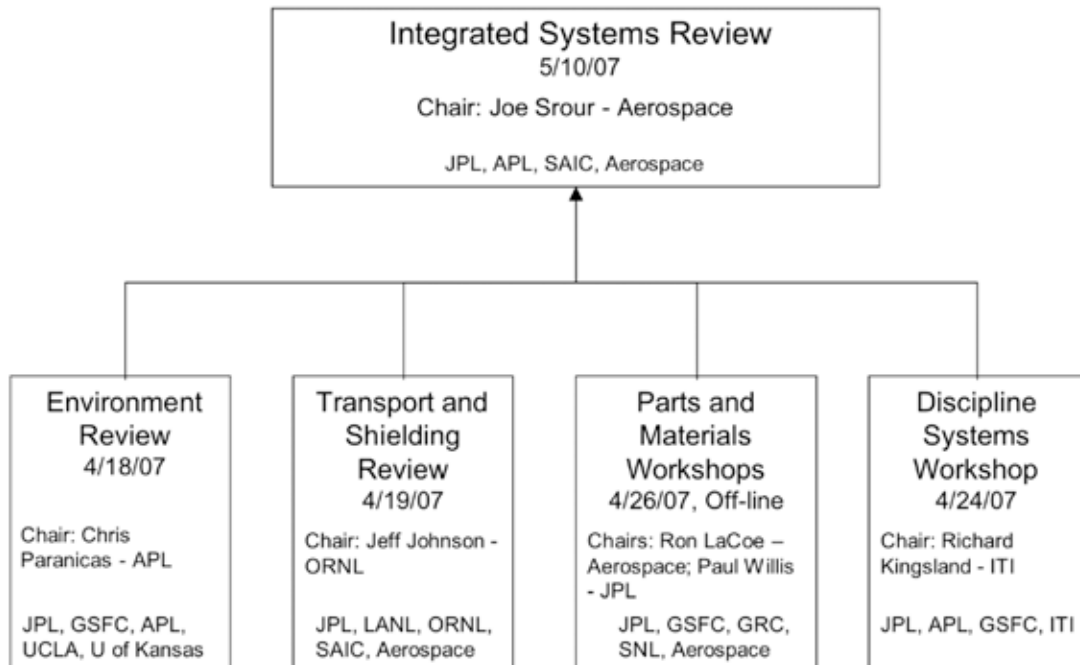


Figure C2-1. Five External Technical Peer Reviews for Radiation Assessment

acceptability in high radiation environments. This document should serve as a “mini-handbook” and perhaps first source of radiation physics for the flight system engineer.

Prior to publication, the document was thoroughly reviewed by Chuck Barnes and Bill McAlpine, both having strong backgrounds in nuclear physics and materials effects at JPL. Jim Sutter of NASA GRC also reviewed this document in May 2007 and submitted the following comment:

“This document provides a significant basis for many of our future science missions. Particular attention to the capabilities of Advanced Stirling were helpful and will be shared with the GRC team. Aside from the interests of GRC, groups working several Constellation programs throughout NASA and DOE should have this document at their ready.

“Specific projects underway between ORNL and GRC on the Materials survivability will utilize this document. The use of several organic-related materials in Stirling devices for larger RPS devices are actively pursued. This points to the timeliness of your document. I’ve marked several comments throughout the document . . .”

The RFAs from each review were assessed and dispositioned; see §C8.7. The Integrated Systems Board Chair has reviewed and concurred with the responses to the recommendations from the Integrated Systems Review; see §C8.7. Whether RFAs are closed in Phase A or Phase B is identified in that section.

C3. Mission Duration And Margin

To predict and design for mission lifetime in a high radiation environment requires system engineering previously unavailable. Past missions used conservative design practices and subsequently lasted well past their design points. There was no method available to understand the probability of achieving a given mission lifetime. A tool is now available to systematically understand how the flight system design approach impacts its lifetime. The tool takes as input the desired mission duration and a confidence level. Given those two inputs, the new mission life prediction model will provide a radiation design point for the mission. This model incorporates statistical information and uncertainties including those due to the radiation environment, electronic parts hardness and flight system reliability.

Summary of Radiation Peer Reviews			
	Review Objectives	Key Board Findings	Key Board Recommendations
Environment Model	<p>Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?</p> <ol style="list-style-type: none">Is the GIRE model an appropriate representation of the environment?Have we incorporated past experience appropriately?Is the way we use the statistical data appropriate?<ol style="list-style-type: none">Usage of mean vs. 1 σ vs. 2 σ values.Usage of average level in a 90-day window from multiple year data.Is the treatment of the C22-type events or “storms” appropriate?Is our conclusion on the probability of actual radiation level below design level appropriate?Have we captured assumptions and considered design margins appropriately?Is the plan for Phase A appropriate?	<ol style="list-style-type: none">The radiation dose approach results in an estimate for TID that is reasonable and conservative.The current version of the original Divine and Garrett model is the GIRE model. This model and its predecessors are the standard model for calculating radiation dose for Jupiter mission planning. These models are based primarily on <i>in situ</i> data from the Pioneers, Voyagers, and Galileo. GIRE matches the mean data well but it is not yet designed to include variability with parameters such as time and Jovian longitude.Limitations of the model include the following. The greater than 10 MeV electron estimate is too conservative. This estimate was based on very limited data coverage above 10 MeV in the original calculation. No publications revisiting these data have appeared since the original modeling. One panel member suggested that while GIRE has been updated to include new data it has never been fully rebuilt, with a proper weighting of all previous data and in light of new calibrations and analyses.	<ol style="list-style-type: none">Model the near-environment of Europa including the induced magnetic field of the satellite. Further analyze the Galileo energetic charged particle data near Europa. Also, run test particles (high energy electrons for dose and heavy ions for SEUs) through a hybrid or MHD model of the Europa environment to study the altitude at which primarily MeV charged particles are excluded from the environment.The high-energy electron data and GIRE modeling of it is potentially critical to the TID. We have two recommendations for improving our understanding of these electrons. First, re-examine the 21 and 35 MeV electron data from 2 experiment sources on Pioneer 10 and 11; also look at angular response to improve pitch angle distributions in model. Second, run a radial transport model that includes losses (e.g. Salamambo) to follow 10-100 MeV electrons from the radial distance of Europa to the inner magnetosphere and compare these fluxes with synchrotron observations.
Transport Analysis and Shielding	<p>Is the approach to transport analysis and to shielding mass calculation appropriate?</p> <ol style="list-style-type: none">Is the modeling assumption and approach appropriate?<ol style="list-style-type: none">Ray-trace-in vs. ray-trace-out methods.Treatment of secondary and bremsstrahlung effectsGiven the phase of the project, is the model fidelity acceptable?Is our spot shielding approach appropriate?What are the alternative shielding approaches and which additional ones should we consider in Phase A/B?Is our radiation design point selected appropriately?Have we captured assumptions and considered design margins appropriately?Is the plan for Phase A appropriate?	<ol style="list-style-type: none">Given the information presented in the review material and presentations, the committee feels the shielding mass estimates are conservative at this phase of the design process. If the follow-on analyses address the issues raised by the committee, the uncertainty on the mass estimate can be reduced.The committee did not find any major flaws in the approach or assumptions used in the analyses presented to them. From the information presented, it appears the Jovian/Europa environment will be the main design driver in regards to the shielding design strategy. Consequently, focusing the preliminary shield design on TID for this environment was determined to be acceptable. The committee did, however, note that an investigation into the other environments and addressing DD and SEE should be performed as early as possible to validate the assumptions for this analysis The major areas for improvement and additional focus come naturally in the design process. For this mission, these would be in improvement in the radiation transport model fidelity and reducing and/or quantifying the uncertainties in the radiation environment sources. These two areas will yield the highest payoff in yielding an optimized design with adequate design margin for mission success and reducing mission risk.	<p>In addition to the recommendations on the Request for Action Forms (RFAs), the committee makes the following recommendations:</p> <ol style="list-style-type: none">The results of the calculations and experimental measurements should include error bars to distinguish statistical fluctuations from physical trends. This will aid in quantifying the uncertainty associated with the analysis or experiment.Initiate Rad Hard APL early. Identify all known rad hard parts. Identify all rad soft parts (memories, ADC's, DC/DC converters, etc.) and perform industry survey radiation testing to find the hardest, most SEL-immune part(s) in these families. Include this information in the RFPs as guidance for contracted items.Parts should be tested to higher doses to determine out of spec performance. This could yield potential mass savings in the shield design.The pressure transducers had the lowest TID capability and accounted for a significant fraction of the Pre Phase A shield mass. Pressure transducers are routinely used in the civilian reactor industry in high radiation fields. We recommend investigating these devices to see if they are applicable for this mission.

continued

	Review Objectives	Key Board Findings	Key Board Recommendations
Systems and Operations	<p>Do we have a technical approach that handles radiation for the Europa environment for systems, autonomy and operations? Do we have a technical approach that handles uncertainties?</p> <ol style="list-style-type: none">1. Do we understand the implication of radiation during operation? (e.g. instantaneous faults, faults over time, SEU)2. Do we have a sound system and mission approach to radiation?3. c. Do we have a failed-operational approach for the operation of the mission? (How do we deal with unanticipated faults? How about testing?)4. Have we captured assumptions and considered design margins appropriately?5. Is our plan for phase A appropriate?	<ol style="list-style-type: none">1. Radiation is the biggest hurdle to this mission and thus far seems to be understood well enough to validate the credibility of the mission.2. The failed operations approach and autonomous recovery seems reasonable given the limited lifetime of Europa system in the radiation environment. But this approach must be coupled to a program to gain the best possible understanding of the system and its possible response modes and the best possible design practices to minimize complex feedback mechanisms and unwanted coupling between system elements.3. The mass memory limitation is a significant design driver affecting the telecommunications system design and operation with follow through consequences to the use and demands on the DSN.4. The AOs prepared for the Instrument Systems must be comprehensive and deal with the spacecraft interface in the areas of shielding and the radiation support that will be provided to the instrument builders. Other non radiation areas, e.g., thermal are also identified as areas requiring careful definition.	<p>The Board as a group generated a total of 25 RFAs, these include the Board's recommendations. Many of the RFAs are aligned with ongoing activities or activities planned by the Europa team and the document will demonstrate the importance the Board places on the activity and identify areas for emphasis and focus. Some RFAs are similar in nature but generated by different authors. Each is included in the compilation below to assure the authors concerns and focus is communicated to the Europa team. The RFAs are organized by author. They fall into 5 broad categories:</p> <ol style="list-style-type: none">1. Uncertainties in the radiation environment2. Coordination, quality and ITAR restrictions on radiation protection3. Internal spacecraft charging4. Optimized fault recovery definition and operations5. Interface coordination between spacecraft developer and instrument developers
Parts	<p>Are the parts and design assumptions for implementation sound?</p> <ol style="list-style-type: none">1. In the current stage of study, pre-phase A, we choose to address parts and materials by examining classes of parts. Do we have the appropriate assumptions and approaches for parts and material?2. Are there any classes of parts that we do not have solution?3. What Phase A/B tasks are critical to start early?4. Have we captured assumptions and considered design margins appropriately?5. Is the plan for Phase A appropriate?	<ol style="list-style-type: none">1. In the current stage of study, pre-phase A, the project chose to address parts by examining class of parts. This approach is appropriate but the presentations did not cover instruments/sensors and supporting electronics that reside near the exterior to the spacecraft and may prove the most problematic from a total-dose perspective.2. All classes of parts have a path toward a solution. However, there are certain classes of parts that have significant risks: ASICs, volatile memory, non-volatile memory, processors, ADC/DAC, linear voltage regulators, op amps and comparators.3. Optoelectronics need to be evaluated early for TID and displacement damage as well as transient effects.4. As to assumptions and design margins, the flow down of total dose requirements due to the environment and the application of shielding to levels as low as 100 Krad appears to be reasonable.	<ol style="list-style-type: none">1. Reexamine the potential application of FPGAs for this program. The program should become familiar with the RH products and roadmaps for Xilinx, Actel and Aeroflex FPGAs.2. Develop a strategy for ASIC procurement. Examine commercial foundry and structured-ASIC approaches.3. Building LVDOs using discretes should be considered.4. Examine approaches where key electronics is left unpowered during the cruise phase of the mission to increase TID margins.5. Study issues related to the proper evaluation of the reliability of parts from low volume foundries.6. To get a better handle on "realistic" TID requirements for specific parts, a 3D ray trace of the Cassini spacecraft using the Europa Explorer orbit should be performed.

continued

	Review Objectives	Key Board Findings	Key Board Recommendations
Integrated Systems	<p>Do we have a sound systems and mission approach to radiation?</p> <ol style="list-style-type: none">1. Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?2. Is the approach to transport analysis and to shielding mass calculation appropriate?3. Are the parts, material and design assumptions for implementation sound?4. Do we have a technical approach that handles radiation for the mission/systems?5. Do we have a technical approach that handles uncertainties?6. Is our plan for Phase A appropriate?	<ol style="list-style-type: none">1. More analyses and trades are needed regarding the currently baselined mission design, which involves a Jovian tour prior to injection into Europa orbit. The present design minimizes post-launch ΔV by including that tour, and thereby delays Europa orbit insertion. That delay increases mission risk. Further analyses and trades should examine the impact of an earlier exit from the planned Jovian tour on the total radiation dose. Inclusion of radiation dose timelines for different mission scenarios would be beneficial. The cost of the additional ΔV needed for alternative mission profiles should also be considered.2. Dosimetric adaptability is important for Europa. If the onboard dosimeters reveal that the radiation environment is significantly more severe than expected, then plans must be in place to handle that situation.3. NASA AOs for Europa Explorer instruments must contain a sufficient amount of detail regarding radiation requirements for the mission. Key areas for inclusion are the radiation environment, shielding guidelines, parts information (e.g., what classes of parts are allowed or excluded, such as FPGAs), and the types of radiation support that will be provided by JPL to instrument suppliers.4. The Europa Explorer team has made good initial progress toward identifying those technical achievements that will constitute mission success. Additional work is needed in that area to quantify, and obtain concurrence on, the minimum science achievements for a successful Europa mission.5. Detailed planning is needed for the materials and parts radiation testing program. That planning should include identification of appropriate radiation facilities and their cost, estimation of the number and types of materials and parts to be tested, consideration of irradiation and measurement conditions and approaches, deciding on the types of radiation effects to be examined in parts (i.e., the numerous singleevent effects (upset, latchup, burn-out, gate rupture, transients), total ionizing dose effects (including ELDRS), displacement damage effects), and manpower estimates for testing.6. The panel concurs with the statement made at the review that the radiation environment and parts capabilities in that environment must be known well to avoid significant issues for the Europa Explorer mission.7. The area of radiation effects on materials and selection of appropriate materials for the Europa mission needs more work. The presentation made to the review panel provided general information of value, but seemed generic and less focused on the mission at this point than the other areas presented.	<ol style="list-style-type: none">1. Perform additional analyses and trades to examine alternative mission profiles.2. Develop plans to handle radiation environments that are more severe than expected.3. Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments.4. Quantify and obtain concurrence on minimum science criteria for a successful mission.5. Perform detailed planning for the parts and materials radiation testing program.6. Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring.7. Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.

The specified mission lifetime of 1-year at Europa at 75% confidence led to a design point of 2.6 Mrad Si behind 100 mil of Al. Holding the design point constant, it is expected that as early conservative assumptions are replaced with more realistic estimates later in the design process, radiation dose margin will grow. This margin can be subsequently re-allocated to longer lifetime, or to mission design changes that could enhance science return. This model has been favorably peer reviewed by some of the most experienced engineers in JPL and APL.

Understanding the interactions between design and mission lifetime involves four steps:

- model the radiation environment including the transport mechanism
- model the reliability of individual parts exposed (with certain levels of intervening shielding) to the Jovian radiation environment
- combine the environment model and part models into a flight system model representative of the Europa design, and
- quantify the flight system model, using data for the individual parts.

C3.1 Radiation Environment and Transport Model

The TID environment for a representative Europa mission was obtained using the GIRE average model with the Divine-Garrett Model pitch angle variations. NOVICE, a 3-dimensional adjoint transport code, was used for the modeling the transport of the radiation through the flight system.

C3.2 Parts Reliability Model

The probability that a part will fail due to radiation exposure during the Europa science mission was calculated using the *stress-strength* formulation described in Section 14 of NASA's PRA Procedures Guide [Stamatatos *et al.* 2002]. The *stress* is equated to the Total Ionizing Dose (TID) received by the part. Since this dose increases monotonically with time, a time-dependent model for part failure (or its complement, reliability) can be determined. Part *strength*, in this approach, is identified as the part hardness with respect to radiation.

The probability density function for part TID is predicated upon statistical models for the Jovian radiation environment developed by

[Jun *et al.* 2005], and [Boland *et al.* 2006]. A lognormal probability density function was used to model uncertainty in the TID, predicated upon Jun *et al.* [2005].

A lognormal probability density function was also used to model uncertainty in part hardness. Parameters for these models, which are dependent upon part type, are summarized in [Table C3-1](#). For a given part category, the mean rating is the rating assigned to the part by the manufacturer. Failure is defined as hard or catastrophic, meaning that the part either is unable to function, or its function is so severely degraded that it cannot support the other hardware in the circuit.

The values in [Table C3-1](#) are critical in determining mission life. General observations are as follows:

- The mean failure level is the part rating multiplied by the scaling factor, which is define as $D_F(i)$, where i represents the i^{th} part type.
- If the shielding is comparable for all components, then the weakest component is determined by D_F for that component along with the coefficient of variation (C_{OV}) for that component.

Table C3-1. Radiation Hardness for Various Categories of Electronic Parts

Part Category	Mean Rating Mrad	Scaling Factor	C_{OV}
Digital CMOS	1	3	0.15
CMOS Memory	1	2	0.15
Hardened Linear	1	2	0.15
High Performance Linear	0.15	2	0.15
I/O	1	3.5	0.15
ADC	1	2	0.15
Hybrid	1	1.5	0.20
Transistors	1	3	0.15
Power MOSFET	0.6	1.5	0.15
Other	1	1.5	0.15
Sensors	1	2	0.15
GaAs	8	3	0.15

- In most cases the mission life will be determined by the weakest component unless additional shielding is added to raise the effective value of D_F to a level that is comparable to that of other components used in the flight system.
- Although there is a general knowledge of the types of parts that will be used, along with their rated radiation levels, there is less certainty about either the scaling factor or C_{OV} .

The coefficient of variation was determined from earlier work on radiation data for Cassini, along with evaluations of data for newer radiation hardened and radiation tolerant parts. In most cases the distribution of radiation responses was relatively tight, which is reflected by the 0.15 value (15%) that was used for all devices except the hybrid. There are exceptions, where data showed that larger values of C_{OV} should be used. Nevertheless, the 15% C_{OV} value appears to be reasonable for most electronic parts.

Even though rather simple statistical methods are being applied to this problem, there are physical reasons that can be used to argue that the actual distribution should be truncated at both the low and high ends. The basic argument is that device properties are constrained within a relatively narrow range by the electrical specifications. Parts with extreme variations in physical properties will be screened out by the electrical parameters, along with the requirement to subject flight parts to burn in.

C3.3 Combined Environment, Transport and Parts Model

The flight system model assumes that there are “vulnerable” parts, which either work (possibly at a degraded but acceptable level) or

fail (either totally or past some unacceptable level of degradation). This is consistent with the model for parts. The flight system model also assumes that only hazards associated with escalating radiation dose are important. Other hazards that would increase the background hazard rate are ignored. Comparison of this model with a flight system model which ignores the radiation hazard demonstrates the validity of this simplifying assumption (i.e., radiation is the dominant failure mechanism at Europa).

All parts will not have the same “vulnerability” to the Jovian radiation. For example, GaAs parts are so radiation resistant that their contribution to flight system failure can be neglected. Parts that are fairly radiation intolerant (e.g., Spec Linears and Power MOSFETs) will receive additional shielding which will also diminish their contribution to flight system failure (e.g., spot shielded to a RDF of 3 instead of the usual factor of 2). Consequently, the duration of the science mission at Europa will be dominated by the lifetimes of those parts with intermediate levels of vulnerability to radiation.

Parts in redundant circuits will be exposed to comparable radiation levels. Although two redundant parts will have somewhat different part-specific dose levels at which they will fail (as expressed by the C_{OV} in the [Table C3-1](#)), both parts will, nevertheless, tend to fail at similar times (i.e., the redundant parts cannot be modeled as totally independent). Therefore, the radiation environment lessens the typical advantages associated with redundancy.

[Table C3-2](#) is a summary of the design issues considered in this stochastic model. Effects were quantified if possible. Otherwise conservative assumptions are imposed.

Table C3-2. List of System Issues Modeled in the Stochastic Flight System Model

Decreases Lifetime	Increases Lifetime
Incomplete part testing to identify weak parts	Radiation Design Factor of 2
Weakest part can bring down the whole system	Parts are not tested to failure
Uncertainties in parts and materials reliability model	Qualification failure does not lead to loss of functionality
Uncertainties in radiation environment model	Unlikely extreme value sometimes for radiation dose
Uncertainties in transport model	Neglect annealing
Hazards that would increase the background rate is not considered (e.g. transient, displacement damage)	Neglect redundancy and cross-strapping
Electron charging from high energy electrons not considered	Conservative circuit design
	Only statistic of hard failure is considered—robust operation in the presentation of degradation is not considered

Salient uncertainties in the estimate include the:

- actual number of parts whose *intermediate levels of vulnerability to radiation* will dominate the duration of the Europa science mission;¹
- radiation impacts on powered-off parts;
- extent of the loss of reliability in redundant circuits;
- part properties (especially the scaling factors);² and
- probability distributions appropriate for the various part categories.³

C3.4 Quantified Model Results

The model produces a probability of failure assessment versus time. As shown in **Figure C3-1**, EE is highly likely to function one year post EOI (75% confidence).

A second analysis was performed by first developing a PRA model for the flight system

using SAPHIRE [<http://saphire.inel.gov>], [Smith et al. 2005], quantifying the flight system reliability in the absence of radiation, and finally modifying the initial reliability estimate by considering the impact of radiation on the flight system based on the statistics shown in **Table C3-1**. This analysis is based on past Prometheus/JIMO and Mars Science Orbiter work but tailored to the EE flight system level model and using mean time to failure for like elements from MER database. The results from this second analysis are similar to **Figure C3-1** in that there is high confidence that the duration of the science mission at Europa will be between one and two years. This independent analysis correlates very well with the first estimate.

An appropriate perspective on the results is that they demonstrate confidence in a design process rather than representing a rigorous technical analysis of a specific flight system design. The deliberative process associated with development of **Figure C3-1** involved discussing various flight system configurations, understanding failure mechanisms and modeling approaches and integrating into a comprehensive tool which can be used by system engineers to understand trade offs in mission concepts and implementation. This model was favorably peer reviewed by some of the most experienced engineers in JPL and APL on July 10, 2007. Review involving a broader community is planned in the near future.

C4. Reduction of Uncertainty for Environmental Model

The environmental model requires refining and updating to quantify and reduce uncertainties by incorporating known data and new understandings. This work will be ongoing throughout development but high priority tasks include improving the high-energy particles model used to predict the environment and better understand transient phenomenon in the environment such as seen by Galileo. For EE, the mission fluences of trapped high-energy electrons and protons are expected to be very high compared to those encountered in past interplanetary and planetary missions that NASA has flown. The high-energy electrons and protons are mostly responsible for total ionizing dose (TID)

¹ The flight system model, as stated previously, assumes that there are “vulnerable” parts, which either work or fail. All parts will not have the same “vulnerability” to the Jovian radiation. Radiation resistant parts are unlikely to fail, while radiation intolerant parts will receive additional shielding. Consequently, the duration of the science mission at Europa will be dominated by the lifetimes of those parts with *intermediate levels of vulnerability to radiation*. The number of such parts that will actually be flown is unknown.

² Scaling factors in **Table C3-1** relate the part rating to the best estimate of where the part will actually fail. Failure, of course, is defined as hard or catastrophic. For a given part, hard failure depends on the robustness of the circuit as well as the actual radiation tolerance of the specific part. Different circuits will have inherently different degrees of robustness, and for any particular part category in **Table C3-1**, some parts within that category will be less vulnerable to radiation than others. This introduces uncertainty into the **Table C3-1** scaling factors.

³ Lognormal probability density functions were used for part hardness. These are considered the most appropriate, given the current state of knowledge. However, Weibull distributions may afford reasonable representations for certain types of parts. There is also concern that the actual distribution should be truncated at both the low and high ends for physical reasons. Both of these issues can impact the predicted mission life.

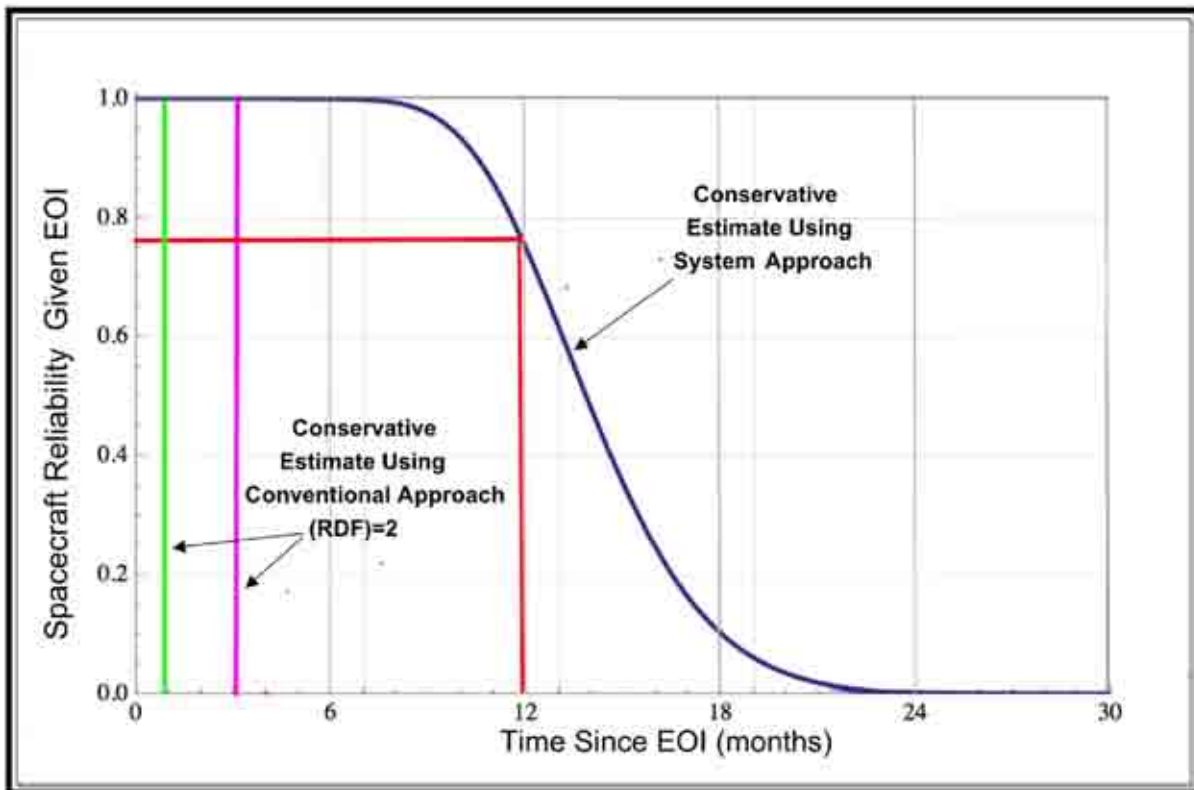


Figure C3-1. Probability of a given duration of the science mission at Europa. The blue curve is the conservative lifetime estimate of 1 year based on this new system approach. The new equivalent design point is 2.6 Mrad Si occurs at 120 days after EOI using the mean value of the GIRE radiation model. The green and the magenta lines are estimates based on using the conventional approach; the green line is for the Europa Orbiter estimate in 2001 of 30 day lifetime after EOI and the magenta line is the subsequently improved EE estimate in 2007 of 90 days after EOI based on an updated Europa environment model from Galileo data. Given the conservatism in the model, EE is highly likely to function one year post-EOI (75% confidence).

effects on flight systems and science instruments.

The TID environment for a representative Europa mission was obtained using the GIRE average model with the Divine-Garrett Model pitch angle variations. For the Jovian tour portion of the mission, the trajectory is assumed to be in the same family as the “99-35” low radiation moon tour trajectory developed for the Europa Orbiter project. **Figure C4-1** shows the electron and proton fluence accumulated during the tour prior to going into Europa orbit.

For the purposes of radiation design, the flight system was assumed to orbit Europa at an altitude of 200 km. The trapped electron and proton fluences for the first 120 days in

orbit were calculated using the GIRE model and are shown in **Figure C4-2**. Note that the radiation environments in **Figure C4-2** do not include possible local shielding effects by Europa. When considering a particle’s (especially for electrons) bounce and drift motion in a magnetic field together with any particle interactions with Europa itself, a large reduction of the charged particle environment near Europa is expected. These energy-dependent reduction factors have been calculated [Paranicas *et al.* 2007] and are presented in **Figure C4-3**. Finally, **Figure C4-4** shows the dose-depth curve using the environments described above, which is the selected design TID environment for the EE mission study.

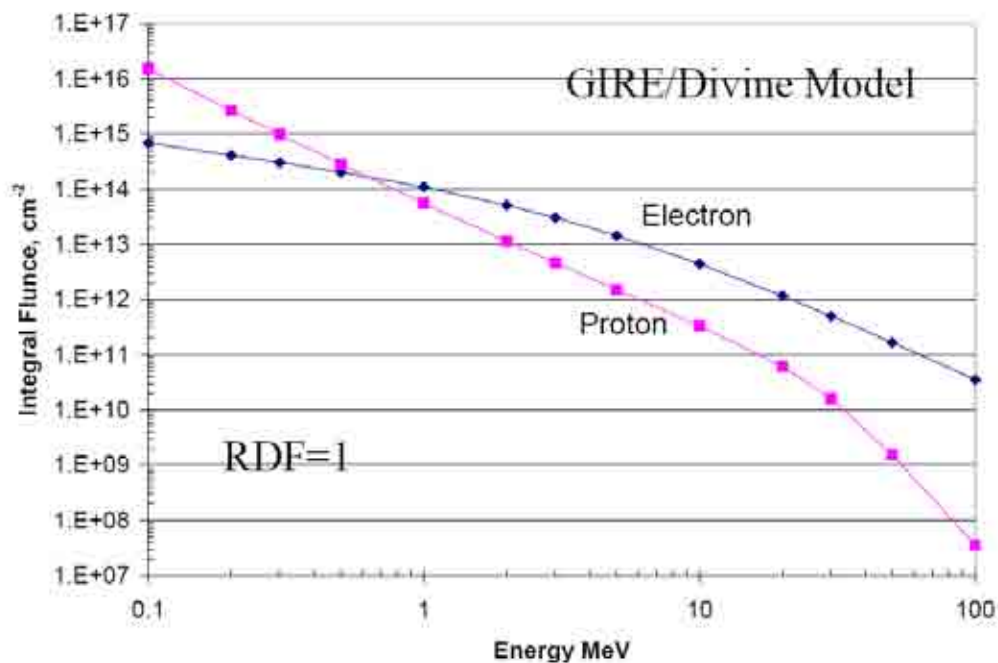


Figure C4-1. Jovian Tour ("99-35" trajectory) electron and proton fluences.

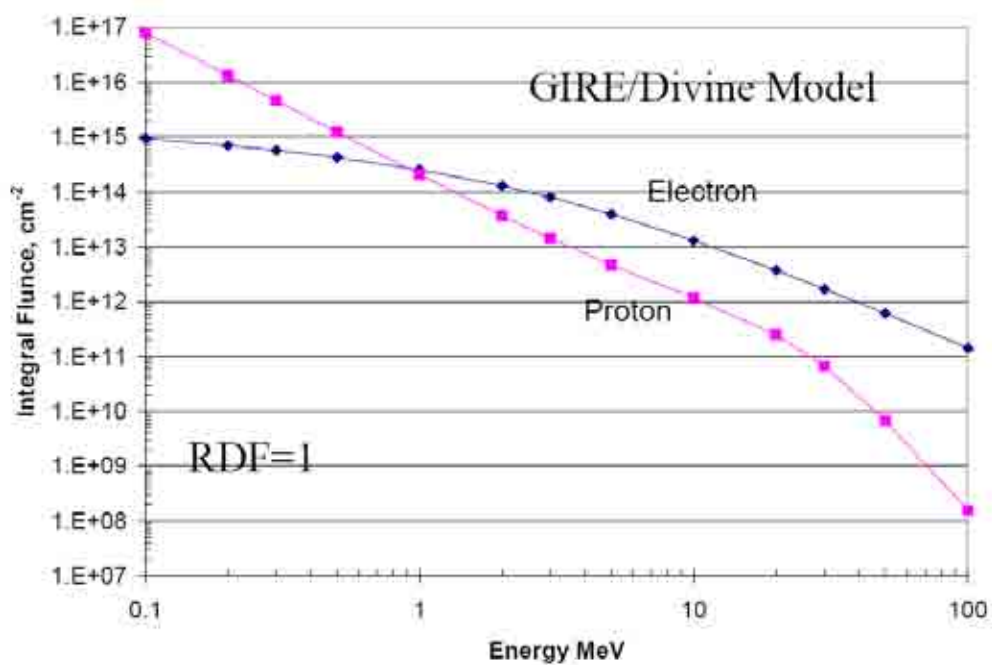


Figure C4-2. Europa 120-day science orbit electron and proton fluences (not including local shielding effect)

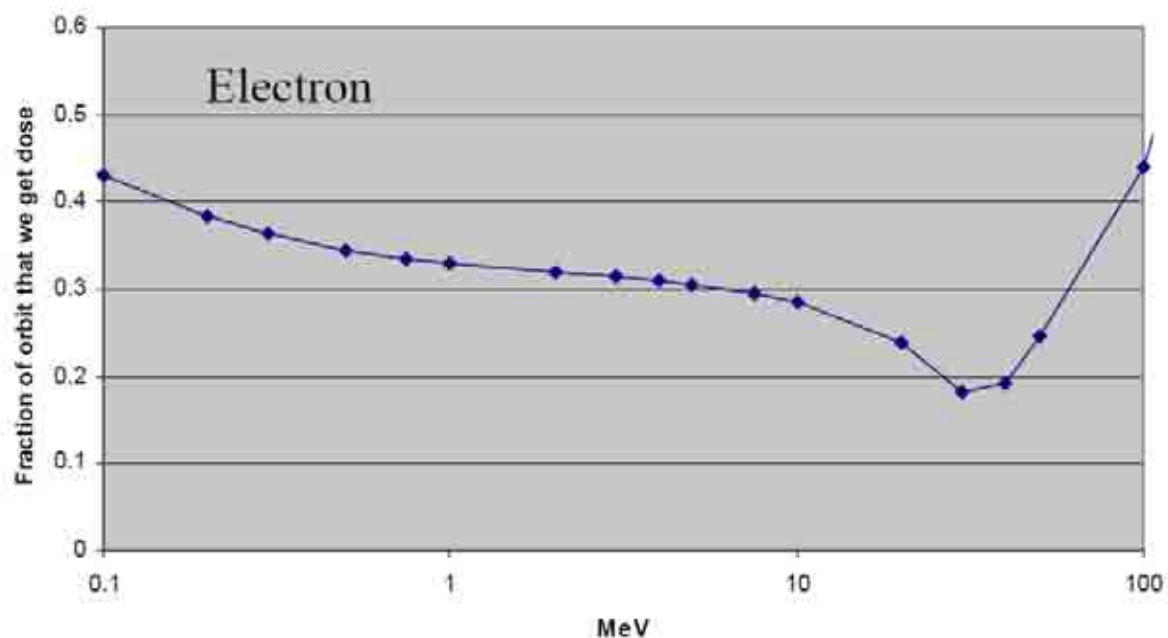


Figure C4-3. Energy dependent reduction factor of the electron environment at Europa (200 km altitude).

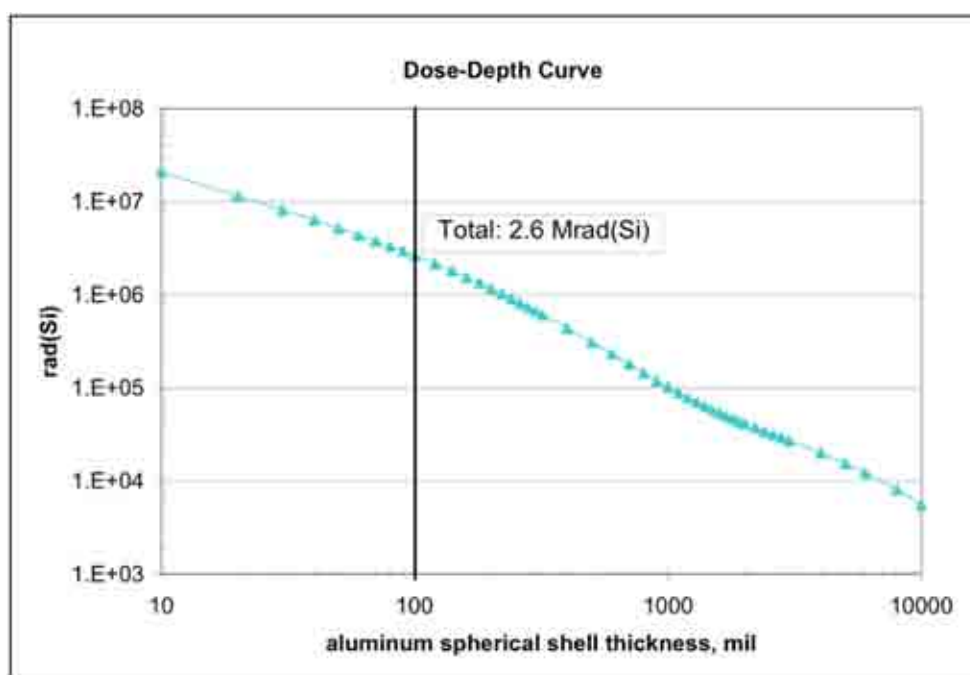


Figure C4-4. Dose-depth curve, includes the local shielding effect, at Europa as a function of aluminum spherical shell thickness.

Following a careful review by a team of experts, several concerns were raised about the conservatism of the GIRE/Divine family of radiation models. Some of the main ones are listed below:

- 1) Europa can block and scatter the charged particles interacting with it thereby reducing the radiation fluxes in its vicinity. Paranicas et al. [2007] attempts to estimate these effects. These variations need to be included in future models of the Europa radiation environment (current assessments were done by hand).
 - 2) The GIRE (and Divine) model is based on Pioneer electron data at 30 MeV as the Galileo data only went up to 11 MeV. The uncertainty in the distribution of electrons above 11 MeV primarily impacts the dose calculations for highly shielded radiation sensitive components. It is planned to revisit the original Pioneer data and determine if the calibrations are still valid and to estimate the results of possible uncertainties in the Pioneer data. Other measurements from Galileo may also be useful in evaluating the energy range above 30 MeV and will be investigated.
 - 3) GIRE currently is based on the VIP4 magnetic field model. Newer models [e.g., *Khurana and Schwarz 2005*] may provide a better representation in longitude/local time and should also be considered in modeling the Jovian radiation belts. Steps will be taken to secure an up to date version of the Khurana model for comparison with the VIP4 model predictions.
 - 4) Instead of (B,L) coordinates for ordering the radiation environment around Jupiter, it has been suggested that the first adiabatic invariant and R_j be used. This ordering method will also be investigated.
- C5. Reduction of Uncertainty for Transport and Shielding
- The transport and shielding analysis model interfaces to use the best available flight system mechanical design Computer Aided Design (CAD) model need to be simplified and the uncertainty in the resulting shielding

design needs to be quantified. In the EE radiation environment, optimized shielding design is very important to minimize shielding mass. Any added shielding mass is considered to be “dead” mass that does not have any active function for flight systems or science instruments and is deemed unnecessary.

A variety of radiation transport codes exist in the community. JPL mainly uses NOVICE, a 3-dimensional adjoint transport code, for the TID calculations. It is widely used in the space radiation shielding community, and compares well with other codes for TID calculations and shielding designs. (**Figure C5-1**).

One of the major uncertainties associated with the transport calculation originates from mass modeling. The mass modeling refers to a geometric representation of flight system structure in a radiation transport calculation. Ideally, as much of the flight system mass as possible should be captured in the calculations to maximize the shielding effect of existing mass. This will allow unnecessary shielding mass to be reduced. The geometry of the flight system is manually input into NOVICE and therefore it is very time-consuming to model all the small details of the flight system. Compromises between the modeling detail and the resources (budget and schedule) available for the transport calculation are often required. This results in a conservative estimate of the radiation effects and shielding mass. A CAD interface program that automatically generates a NOVICE geometric input file will be very beneficial for capturing as much existing mass as possible in the radiation transport calculations for faster mass modeling and for minimizing shielding mass. There is a plan to investigate a possibility of using an advanced CAD interface program in the early stages of the project. This effort will result in new ways the shielding design engineer, mechanical design engineer and the radiation system engineer can work together.

Another major uncertainty associated with NOVICE is the accuracy of its predictive capability. Although NOVICE has been used in past JPL flight projects, there has not been comprehensive study for validating and verifying the NOVICE results against experiments or against other well-validated codes. This is true not only for TID, but also for other radiation effects such as displacement

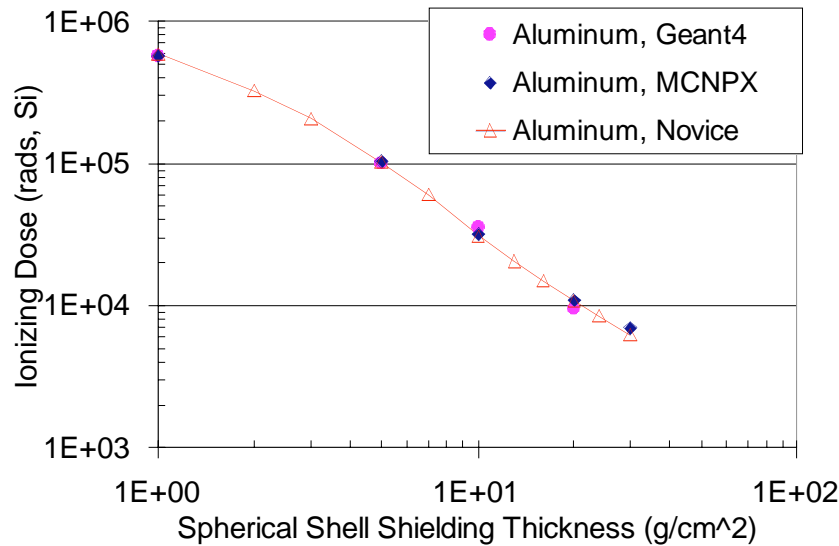


Figure C5-1. A sample dose-depth curve comparison using representative radiation transport codes, NOVICE, MCNPX, and Geant4, shows that the use of NOVICE for transport modeling is consistent with other modeling techniques.

damage dose and single event effects. A benchmark program will be established in the early stage of the project to better understand the predictive capability of NOVICE (and other codes) and thus to reduce the uncertainty associated the radiation transport calculations.

C6. Modeling Electronic Parts and Materials

The model associated with the behavior of electronic parts and materials requires updating to accurately reflect the parts included in the system design. The approach is to select and test parts and materials and quantify their radiation hardness for flight system design.

C6.1 Electronic Parts

The high radiation environment of the EE will have a large impact on the selection of electronic parts and the implementation of design practices that will ensure a successful mission. Although the effects of galactic cosmic rays on electronic parts are common to most space missions, few flight systems have had to deal with the high total dose and displacement damage requirement of the trapped radiation belts near Jupiter. The success of the Galileo and Cassini missions shows that JPL's approach in designing flight system for this environment is highly effective. That same approach will be used for the EE, adapting it to new part technologies

that have been developed since the Cassini mission.

Three basic ideas are essential to succeed in this challenging environment.

- Parts must be selected and evaluated early in the program, considering both radiation vulnerability and reliability.
- Sufficient conservatism must be used in the design, providing extra margin and eliminating single-point failures.
- Robust testing of hardware and software must be done during and after the design phase. The distinction between hardware and software is blurred by the extreme complexity of modern integrated circuits and the use of fault tolerant techniques to mitigate soft errors from galactic cosmic rays.

Despite the success of previous missions with high radiation environments there are several challenges that have to be dealt with for the EE. The most important is dealing with new part types and technologies. Parts used on the Cassini program are obsolete and (for the most part) unavailable, requiring new parts and some changes to qualification methods. Although hardened parts considered for the mission have been qualified for DoD missions, those qualification methods are based on tests with gamma rays that will underestimate

damage in the specific radiation environment near Jupiter.

Specific challenges for radiation qualification include:

- Displacement damage from electrons and protons, which will require additional testing as well as the development of methods to combine displacement and ionization damage in devices.
- Enhanced low dose rate damage (ELDRS), which causes more damage to occur at the low dose rates in space for bipolar transistors and some types of linear integrated circuits. This can be accommodated by testing devices at low dose rate. The dose rate will be about two orders of magnitude higher than the actual mission dose rate in order to complete the testing in reasonable time intervals.
- New degradation modes, such as the decrease in breakdown voltage of power MOSFETs when they are exposed to high radiation levels.
- Synergistic effects between the different environments, such as increases in the single-event upset rate that are caused by total dose and displacement damage which reduce internal circuit margins.

JPL has developed an approach to deal with these issues for the previous JIMO mission and for the current Juno mission. The EE approach will be based on past experience from these projects.

Reliability is another challenge because of the long mission duration. It may be necessary to update reliability models for advanced part. However, the approach used in the past—which requires derating of maximum current and voltage specification, as well as restrictions on temperature—has been very successful. Recent experience on the MER, which continue to work far beyond their expected life, shows that the existing approach for reliability is effective for newer technologies.

Conservative design practices are imposed by the design principles at JPL, and are part of the reason for the success of earlier missions. An essential part of the design practice is using a radiation design factor (RDF) to ensure that there is extra margin between the anticipated radiation environment and the “design point”

used for circuit design and part degradation. The starting point for design is establishing an internal data base that derates electrical parameters to account for the effects of radiation damage, temperature, and aging (reliability). Designers then use the derated parameters to implement their circuit and system designs. In order to be effective, radiation characterization data must apply to the specific device lots that are used in the actual mission.

The worst-case data base addresses permanent damage, but not single-event upset effects. SEU phenomena are more difficult because their effects are usually circuit specific. In order to deal with them a companion data base will be developed that includes upset rates for SEU and functional interrupts. Voltage derating will also be included for catastrophic effects, such as latchup (CMOS) and gate rupture (power MOSFETs).

After the circuits are designed, they are subjected to a separate analysis that verifies whether they meet the worst-case requirements, and to determine the effects of failures on the overall performance of the specific circuit or subsystem (failure mode effects analysis). A circuit that results in “single string failure” is not allowed.

Some decisions regarding key part technologies can have a large impact on the mission. One of the most important is whether to use FPGA technologies, and if they are used, which specific technologies and design verification methods to require. FPGAs have many advantages, including reduced cost and greater flexibility during design, but newer FPGAs are extremely complex. This makes it difficult to verify that the specific design will actually work in all of the modes required in the total flight system application. Reliability and radiation damage can potentially alter FPGAs, producing faults that are difficult to categorize and guard against in a mission that must have extremely high reliability. Until further qualification work can be successfully completed, FPGAs are not acceptable for this mission. Custom design options (e.g., ASICS and full custom circuits) provide an alternative to FPGAs. It is more straightforward to test and verify circuit functionality for custom

designs, but the cost and development time is far longer than for FPGAs.

Unhardened commercial devices are used to a limited extent, testing and qualifying them to verify that they will meet radiation and reliability requirements. Examples include discrete transistors, and optoelectronic devices such as LEDs, laser diodes, and optocouplers. The main risk in using such devices is that once the commitment is made, there is no viable hardened option if the qualification approach shows that the commercial circuit will not work satisfactorily. The key to success is understanding the part technology and failure mechanisms, and performing qualification testing early in the program.

Knowledge of the physics of radiation failure and existing data for electronic parts was used to estimate radiation hardness levels and risk for various part categories, as shown in [Table C6.1-1](#).

Hardened digital CMOS and memory devices are available that are expected to meet mission requirements, reducing risk for those important device categories. The most difficult categories are high-performance linear devices, hybrids (particularly power converters and power switch assemblies), power MOSFETs, and sensors. Despite the higher risk, it should still be possible to identify devices that will meet EE requirements. The key is to work on the high-risk areas first, and ensure that the components being considered are tested and evaluated in a way that ensures

they will meet the radiation and long-term reliability goals of the program.

There are a number of ways to deal with high-risk parts. Some of the most important are discussed below.

- **Electrical Screening:** It is often possible to develop electrical screens that can be used to reduce the variability of the radiation response of electronic parts. This has done this for linear integrated circuits and for optoelectronic devices and can be a very effective way to extend the operating range of devices by eliminating the weaker devices through electrical screens.
- **Annealing and Related Mitigation Methods:** Various approaches can be used to anneal the effects of radiation damage. Some effects can be annealed by subjecting devices to a temperature of about 120°C for several hours, providing a potential mitigation approach for devices that are placed in modules where special heaters could be used to implement a controlled annealing cycle. In other cases increasing the forward current applied to a device can enhance annealing. That method was used to restore operation of the tape recorder on Galileo after it failed on the last orbit.
- **Cold spares** are another option, although not all radiation effects are reduced when devices are unbiased.
- **Shielding:** The last element in adapting parts with lower radiation tolerance is to

Table C6.1-1. Basic Part Categories, Status and Risk.

Part Category	Mean Rating (Mrad)	Status	Risk and Variability
Digital CMOS	1	Rad-hard lines available (2 vendors)	Low
CMOS Memory	1	Rad-hard available, but limited density	Medium for higher density devices
Hardened Linear	1	Limited selection of rad-hard devices	Medium for hardened linear; high for rad-tolerant
High Performance Linear	0.15	Few high-performance devices are available.	High
I/O	1	Rad-hard devices available	Low
ADC	1	Rad-hard devices are available (12-bit); 14-bit in development	Low for 12-bit, medium for 14-bit; very high for > 14 bit
Hybrid	1	Uncertain	High
Transistors	1	Hardened devices are available	Medium because of plethora of applications
Power MOSFET	0.6	Hardened devices available, but require more evaluation before they can be used.	High unless extra shielding is used
Sensors	1	Highly variable	High; sensors will require extensive effort
GaAs	8	GaAs devices are available	Low; reliability probably more important than radiation damage

add shielding. This is more difficult for Europa, because of the volume and mass required, but it is still a viable option in most cases.

These methods are all potentially effective. In most cases there is sufficient information available to determine how to proceed, but specific work will be needed.

The approach used for testing and qualification is an essential part of risk reduction. The first step is to make sure that parts are qualified and applied in a way that is consistent with mission requirements, and also recognizes all of the failure modes and mechanisms that can cause parts to fail from radiation and reliability.

Catastrophic part failure is the main overall concern because most circuits will work even with parts that have degraded significantly. Conservative design practices add additional margin for parametric degradation, but do not necessarily affect catastrophic degradation. Radiation testing needs to consider the actual environment—electrons and protons—and it will probably be necessary to do radiation tests with those particles instead of cobalt-60 gamma rays for linear circuits, optoelectronics, and other technologies where displacement damage is important.

Low dose rate effects are an important area for risk. ELDRS testing is essential for many bipolar technologies. However, the best approach is to select devices that are insensitive to ELDRS in order to avoid the extreme complication of combining displacement and ELDRS effects in bipolar devices for this mission.

Older missions have assumed that part derating for aging is independent from radiation damage, which can penalize design parameters because the two factors are combined independently. Less allowance can be used for aging when we apply extreme derating for radiation damage (except in special cases where aging and radiation damage are directly linked), allowing parts to work effectively for much longer time periods and at higher radiation levels.

The success of previous JPL missions with severe radiation requirements provides the foundation for part qualification and design practices that are necessary for these classes of missions. The most important challenge for the

EE is to extend the older approaches to the newer part technologies that will be used on the mission. Key issues include reliability mechanisms and modeling, which will have to be updated for newer technologies; displacement damage effects that add to total dose damage, reducing the effective radiation hardness level of parts when the actual environment is considered; dealing with the low dose rate damage problem; and establishing an approach for single-event testing and design that is effective in a wide range of circuit applications.

The most important factor is to select parts and perform testing and qualification early in the program, allowing sufficient time to substitute alternative parts or to modify designs. Equally important is recognition of the underlying mechanisms that affect radiation response and reliability of the various part technologies, as well as synergisms between them that could reduce the effective radiation survival level.

Risk can be further mitigated by using redundancy and cold spares, or by providing an overall architecture that allows some of the radiation damage to recover through thermal or current-enhanced annealing.

C6.2 Materials

Many materials may have to be qualified by testing because much of the data is forty years old, inaccurate, and uses gamma ray in air instead of electrons in vacuum. The most damaging radiation effects on materials are from ionizing dose and displacement damage. The deposition of ionizing doses may cause: darkening of optics; bond breakage/crosslinking in polymers; discoloration of polymers; degradation of adhesives, films, wire insulation and coatings; deposition of internal charge; and secondary effects due to x-ray production. Displacement damage occurs mainly in crystalline materials or where atoms are held in fixed positions. It can occur from exposure to neutrons, electrons, protons or heavy ions. Materials commonly affected include metals, glasses, ceramics and especially semiconductor devices. Metals may show signs of displacement only at high doses. Glasses (amorphous) will usually show signs of compaction (4–5 %) change in density. Ceramics and crystalline components usually

show signs of expansion (3–6 %) decrease in density.

The test program must include all 15 classes of materials defined in JPL D-34098 [Willis 2006] and they are: polymers, elastomers, cables & wiring, polymer adhesives, composites, multi-layer insulation, “teflon” fluoropolymers, lubricants, metals, permanent magnets, ceramics, optical glasses, optical coatings, optical fibers, and thermal control coatings. A test plan is proposed. To simulate the Europa spectrum, a “group fluence” concept (bins), is proposed as shown in **Figure C6.2-1**.

The standard approach to materials testing subjects the specimens to a broad spectrum of radiation energies and flux intensities. Such an approach is both costly and time consuming. With the “group fluence” scheme, material specimens would only be tested to the environment they are expected to encounter during the mission. By restricting these tests to a more limited range of energies and flux intensities, needed data can be obtained with an abbreviated schedule and lower budget.

An additional benefit is this scheme permit degraded materials to be identified early in the project with only survivors passing into the latter tests. Facilities have already been identified that can implement this approach. In general the JPL’s flood gun facility will be

used for the surface damage testing, JPL’s Dynamitron linear accelerator will be used for intermediate range testing, and the Gaertner Radiation Laboratory at Rensselaer Polytechnic Institute will be used for the high end (i.e. > 25 MeV) energy levels. Special test requirements can be accommodated by other test facilities listed in Appendix 11, pp. 56–57 of the [Willis 2006] document. A set of draft flight system charging requirements have been developed to address surface charge build up and internal charging and they are provided in §8.

EE mission components are most likely to include: power cables, communications cables, connectors and materials such as Teflon, Tefzel, Phenolic, MLI, thermal control paints, optical coatings, composites, and others. Apart from mechanical degradation, the build up of internal static charges and consequent arcing is also of concern, and requires assessment.

In summary, materials degradation and possible charge accumulation is definitely an issue for Europa missions. The benefits of the proposed approach include simplified and cost-efficient testing, with results directly applicable to mission environments. These experiments should provide proof of the survivability of materials used in this mission. They will also provide a manageable model for the mission life estimation critical for

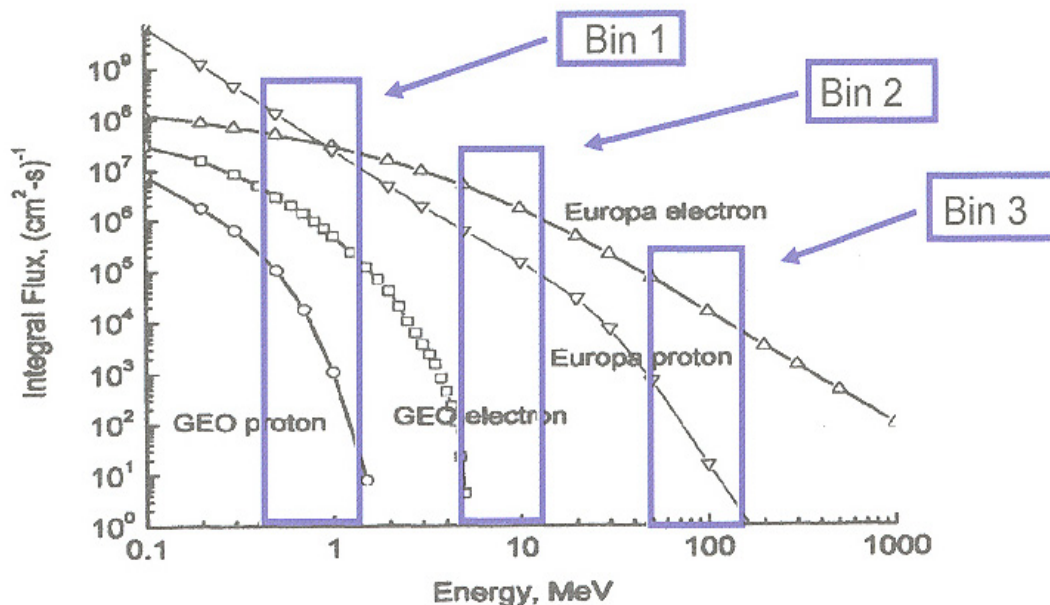


Figure C6.2-1. Test Approach By “Group Fluence”

system engineering trades. Based on our understanding of radiation damage, the experience gained with previous missions, the learning experience gained from Prometheus, Juno, and a defensible plan for testing and qualification, the EE is in a good position to assess materials usage for a successful Europa mission.

C7. Radiation Dosimeter

The TID radiation environment is intrinsically variable at Europa. Aside from uncertainties in our knowledge of the average environment as determined by available models, the variations in Europa's longitude/latitude, magnetic field, and its plasma environment all contribute additional unknowns. Moreover, the uncertainties associated with radiation transport analysis and mass modeling mean that there will be concerns associated with the actual device performance in the Europa environment even

if it was known exactly. Thus, as the mission environment evolves, the operations of the EE could be affected if the departures of the environment and systems performance from that predicted are larger and more systematic than expected. It may be possible, however, to manage if not control this type of risk by continually monitoring the actual environment at critical locations in the flight system. In particular, the measurement of the radiation characteristics (e.g., dose, electrostatic charging, SEU) at key locations around the flight system would allow an ongoing assessment of the actual status of the mission and its likelihood of success. This would permit real time risk assessment for the Europa mission at a relatively low cost in mass, power, data rate, and money. A Radiation Monitoring Subsystem has been added to the flight design. For more information, see §4.4.3.9.

C8. Supporting Material

1. Environment Modeling Peer Review Board Report, April 18, 2007
2. Transport Analysis and Shielding Peer Review Board Report, April 24, 2007
3. Discipline Systems and Operations Workshop Board Report, April 26, 2007
4. Parts Workshop Board Report, April 26, 2007
5. Integrated Systems Peer Review Board Report, May 21, 2007
6. RFA Disposition Status, June 4, 2007
7. Disposition of Recommendation for the Integrated Systems Peer Review, July 5, 2007
8. Draft Flight System Charging Requirements

1. *Environment Modeling Peer Review Board Report, April 18, 2007*

4/18/07

Technical Peer Review Board Report

Subject: Radiation Environment for Europa Explorer

To: Guy Man

From: Chris Paranicas

Review Objectives:

Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?

- a. Is the GIRE model an appropriate representation of the environment?
- b. Have we incorporated past experience appropriately?
- c. Is the way we use the statistical data appropriate?
 - i. Usage of mean vs. 1σ vs. 2σ values.
 - ii. Usage of average level in a 90-day window from multiple year data.
- d. Is the treatment of the C22-type events or “storms” appropriate?
- e. Is our conclusion on the probability of actual radiation level below design level appropriate?
- f. Have we captured assumptions and considered design margins appropriately?
- g. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Dr. Chris Paranicas (Johns Hopkins University-Applied Physics Laboratory) - Chair
Dr. Richard Thorne (University of California at Los Angeles)
Dr. Steve Levin (Caltech – Jet Propulsion Laboratory)
Dr. Tom Armstrong (Fundamental Technology)
Dr. Barry Mauk (Johns Hopkins University - Applied Physics Laboratory)
Dr. John Cooper (Goddard Space Flight Center)

4/18/07

Scope of the Peer Review Material

(a summary of the information presented in bullets)

- Jupiter radiation model components, sources of data, and limitations
- Extrapolation of electron spectrum to high energy
- Comparison of model predictions with data, including with synchrotron radiation close to planet
- Assumptions and limitations of Jovian magnetic field model used
- Heavy ion detection and relevance to spacecraft
- Galileo orbit C22 flux enhancement event and how this is incorporated into radiation modeling
- Energetic electron direct and implicit (Galileo star-scanner data) detection
- How statistics are calculated in global radiation model
- Galileo radiation lessons learned including required capability of parts, hardware performance and unexpected events
- Radiation environment close to Europa
- Mission dose calculations and updates
- Summary of assumptions and design margins
- Outstanding issues for Phase A

4/18/07

Key Findings

The radiation dose approach results in an estimate for TID that is reasonable and conservative.

The current version of the original Divine and Garrett model is the GIRE model. This model and its predecessors are the standard model for calculating radiation dose for Jupiter mission planning. These models are based primarily on *in situ* data from the Pioneers, Voyagers, and Galileo. GIRE matches the mean data well but it is not yet designed to include variability with parameters such as time and Jovian longitude.

Limitations of the model include the following. The greater than 10 MeV electron estimate is too conservative. This estimate was based on very limited data coverage above 10 MeV in the original calculation. No publications revisiting these data have appeared since the original modeling. One panel member suggested that while GIRE has been updated to include new data it has never been fully rebuilt, with a proper weighting of all previous data and in light of new calibrations and analyses.

There is a great deal of scatter in the data among the many Galileo orbits and the panel discussed whether this scatter was truly time-, longitude-, etc. dependence or whether it could be reduced with a more up-to-date magnetic field model and/or re-plotting the data in invariant coordinates.

The Galileo orbit C22-like flux enhancements are low probability events and are not included in modeling the average fluxes. The panel finds that ideally the physics of such events be understood to properly incorporate these increases with weighting into the statistical averages.

The panel found that for a planned low altitude Europa orbit (100-200 km), the dose from 1-50 MeV electrons will be at least 50% lower than the dose at a radial distance of 9.4 R_J but at longitudes far from the satellite's longitude. This shielding effect by the moon could be enhanced further because of the induced magnetic field of the satellite and this requires further modeling.

Another radiation issue regards the radiation hardness of spacecraft parts and annealing. While Galileo's orbit took it deep into the radiation environment, the apoapsis of that spacecraft's orbit was in very low radiation so that some annealing took place during each orbit. A Europa orbiter might be continuously operating in an environment with a much higher dose floor.

4/18/07

Recommendations

Model the near-environment of Europa including the induced magnetic field of the satellite. Further analyze the Galileo energetic charged particle data near Europa. Also, run test particles (high energy electrons for dose and heavy ions for SEUs) through a hybrid or MHD model of the Europa environment to study the altitude at which primarily MeV charged particles are excluded from the environment.

The high-energy electron data and GIRE modeling of it is potentially critical to the TID. We have two recommendations for improving our understanding of these electrons. First, re-examine the 21 and 35 MeV electron data from 2 experiment sources on Pioneer 10 and 11; also look at angular response to improve pitch angle distributions in model. Second, run a radial transport model that includes losses (e.g. Salammbô) to follow 10-100 MeV electrons from the radial distance of Europa to the inner magnetosphere and compare these fluxes with synchrotron observations.

Evaluate the minimum dosimeter compliment that would be of value for diagnosing spacecraft, instrument, and science issues.

Gain a better understanding of the source and physics of the Galileo orbit C22 flux enhancement event so that the probability of such events can be folded into radiation modeling. Mechanisms to consider include: solar wind disturbances, Io volcanic activity, and Galileo wave activity during the event for local acceleration process.

In addition to accumulated dose, lessons from Galileo include that devices are “peak-flux” dependent. This means that radiation can disrupt functioning either because of large accumulated dose or because total flux of particles spikes suddenly. The effects of peak flux on parts should be studied: the modeling assumption should be examined in the light of peak-flux calculations.

To better manage the statistics the panel had 2 main suggestions. Organize the Galileo EPD data in μ -B space (i.e. re-plot the data by their first adiabatic invariant and observed scalar B, the magnetic field strength). Use K. Khurana’s global magnetic field model instead of the VIP4 model to re-plot the data. These improvements could potentially reduce statistical scatter of the charged particle data at each L shell.

Prepare a mission timeline with dose as a function of distance to Jupiter to help make trades about dose and distance.

2. *Transport Analysis and Shielding Peer Review Board Report, April 24, 2007*

FINAL - 4/24/07

Technical Peer Review Board Report

Subject: Transport Analysis and Shielding for Europa Explorer

To: Guy Man

From: Jeffrey O. Johnson

Review Objectives:

The radiation environments associated with the Europa Explorer mission arguably present one of the most demanding technical challenges for ensuring mission success. The radiation transport analyses to design an effective shielding package/strategy with appropriate design margin and not overly conservative assumptions will be critical. Consequently, a technical peer review board was convened with the objective of evaluating the radiation transport and shielding design process and assessing the approach. In particular, the committee was asked to answer the following questions.

Is the approach to transport analysis and to shielding mass calculation appropriate?

- a. Is the modeling assumption and approach appropriate?
 - i. Ray-trace-in vs. ray-trace-out methods.
 - ii. Treatment of secondary and bremsstrahlung effects
- b. Given the phase of the project, is the model fidelity acceptable?
- c. Is our spot shielding approach appropriate?
- d. What are the alternative shielding approaches and which additional ones should we consider in Phase A/B?
- e. Is our radiation design point selected appropriately?
- f. Have we captured assumptions and considered design margins appropriately?
- g. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Dr. Jeffrey Johnson (Oak Ridge National Laboratory) - Chair
Dr. Laurie Waters (Los Alamos National Laboratory)
Dr. Ken Adams (Science Applications International Corporation)
Mr. Richard Kemski (Caltech – Jet Propulsion Laboratory)
Dr. Mark Looper (The Aerospace Corporation)

FINAL - 4/24/07

Scope of the Peer Review Material

The committee was given a comprehensive presentation covering all the relevant aspects of the radiation transport analyses performed to date and the preliminary plans for support of Phase A of the project. In particular, the presentation included:

- An introduction to the various radiation environments (space and power source) of concern for the mission. The majority of this information was focused on the Jovian/Europa environments since they are considered the sources driving the shield design.
- An overview of radiation effects on electronics and materials indicating which radiation sources/environments are important to the TID, DD, and SEE damage mechanisms.
- A detailed description of the selected baseline radiation environment to be used in the preliminary shielding mass analyses for the Europa Explorer.
- A discussion of the various radiation transport tools used at JPL, along with their strengths, weaknesses, capabilities, and applicability. Some preliminary code comparison results were also presented in this section of the presentation.
- A detailed discussion of the shielding approaches used to arrive at the shielding mass estimates for the Europa Explorer
- A summary of the assumptions and design margins utilized in the preliminary analyses to date to aid in understanding the amount of conservatism that has been included.
- The radiation transport and shielding team's Phase A plan

FINAL - 4/24/07

Key Findings

- Given the information presented in the review material and presentations, the committee feels the shielding mass estimates are conservative at this phase of the design process. If the follow-on analyses address the issues raised by the committee, the uncertainty on the mass estimate can be reduced.
- The committee finds that the modeling assumptions and approach are appropriate for this phase of the design. The team has used several different tools in an effective manner and attempted to optimize their tools for the various aspects of the problem.
- For the TID analysis, the treatment of secondary and bremsstrahlung effects have been properly accounted for. However, beyond TID, secondary particle effects were not discussed and should be appropriately considered when assessing the SEE and DD damage effects.
- For Pre-Phase A, the model fidelity is appropriate and acceptable for obtaining preliminary shield mass estimates that are conservative.
- The approach for spot shielding is also appropriate. Employing a RDF of 3 at 150krad is considered to be a valid conservative assumption at this stage.
- The alternative shielding approaches investigated (primarily relative to shield material selection) are appropriate for TID. However, SEE and DD effects should be evaluated early in Phase A before final selection of shield materials is made. Further improvements and/or adjustments in the shielding approach may also be obtained in the integrated shield optimization design.
- The radiation design point selected was appropriate given the early stage of the project and the incomplete analysis of alternatives. The 9935 trajectory chosen as the baseline for the analyses presented should be evaluated against an actual design point trajectory. If it is representative of the actual trajectory, then the 9935 will have been appropriate for this analysis.
- The assumptions and design margins employed by the radiation transport team were determined to be appropriate for this stage of shielding analysis.
- The preliminary plan for Phase A presented to the committee was appropriate. However, the committee added additional suggestions outlined in the recommendations and RFAs that need to be carefully considered.

In summary, the committee did not find any major flaws in the approach or assumptions used in the analyses presented to them. From the information presented, it appears the Jovian/Europa environment will be the main design driver in regards to the shielding design strategy. Consequently, focusing the preliminary shield design on TID for this

FINAL - 4/24/07

environment was determined to be acceptable. The committee did, however, note that an investigation into the other environments and addressing DD and SEE should be performed as early as possible to validate the assumptions for this analysis. This was not deemed an omission, but rather an assumption that requires further validation and quantification in order to reduce the uncertainty. The major areas for improvement and additional focus come naturally in the design process. For this mission, these would be in improvement in the radiation transport model fidelity and reducing and/or quantifying the uncertainties in the radiation environment sources. These two areas will yield the highest payoff in yielding an optimized design with adequate design margin for mission success and reducing mission risk.

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Recommendations

In addition to the recommendations on the Request for Action Forms (RFAs), the committee makes the following recommendations:

1. The results of the calculations and experimental measurements should include error bars to distinguish statistical fluctuations from physical trends. This will aid in quantifying the uncertainty associated with the analysis or experiment.
2. Initiate Rad Hard APL early. Identify all known rad hard parts. Identify all rad soft parts (memories, ADC's, DC/DC converters, etc.) and perform industry survey radiation testing to find the hardest, most SEL-immune part(s) in these families. Include this information in the RFPs as guidance for contracted items.
3. Parts should be tested to higher doses to determine out of spec performance. This could yield potential mass savings in the shield design.
4. The pressure transducers had the lowest TID capability and accounted for a significant fraction of the Pre Phase A shield mass. Pressure transducers are routinely used in the civilian reactor industry in high radiation fields. We recommend investigating these devices to see if they are applicable for this mission.
5. It is not readily apparent to the committee what the design margin is relative to the parts testing program using mono-energetic Co-60 sources to represent the real environment. In other words, the committee was not certain as to whether the RDF is intended to encompass whatever uncertainty is introduced by testing parts with high-dose-rate gammas instead of in the real environment. The committee recommends developing a strategy to quantify this uncertainty so that it can be effectively accounted for in the integrated design margin associated with the shield mass calculations.

3. *Discipline Systems and Operations Workshop Board Report, April 26, 2007*

Systems & Operations

4/26/2007

Subject: Europa Explorer Systems Engineering Workshop on Radiation

To: Dr. Guy Man

From: Richard Kingsland

A workshop was held 4/24/2007 to conduct a peer review of the work performed regarding the Systems Engineering and Operations of the Europa Explorer system with focus on the radiation implications for a successful mission. The board received presentations (Outline Below) from G. Man who discussed the Europa mission, the design of the spacecraft, programmatics, and plans for Phase A; R. Lock who discussed mission operations and margins; and R. Rasmussen who discussed system strategy. The presentations were professional, detailed, well structured, and organized. The first half of the review was generally formal with some interaction with the board and the second half highly interactive with questions and answers. It is not a technical measure but it certainly bodes well for a program when the people working the project are not only doing a good job but are enthusiastic about the effort. Such was certainly the case.

Charge to the Board - Review Objectives:

Do we have a technical approach that handles radiation for the Europa environment? Do we have a technical approach that handles uncertainties?

Systems, Autonomy and Operations

- a. Do we understand the implication of radiation during operation?
(e.g. instantaneous faults, faults over time, SEU)
- b. Do we have a sound system and mission approach to radiation?
- c. Do we have a failed-operational approach for the operation of the mission?
(How do we deal with unanticipated faults? How about testing?)
- d. Have we captured assumptions and considered design margins appropriately?
- e. Is our plan for phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Richard Kingsland – Chair, Implementation Technology Inc.
Steve Leete, GSFC
John Bolt, JHU-APL
Greg Levanas, JPL
Glenn Reeves, JPL

Systems & Operations

Outline:

- 8:30 Introduction R. Kingsland
- 8:35 Mission Concept G. Man
- 8:50 Mission Drivers from Radiation G. Man
- 9:00 Layered Design Approach
 - Design of Spacecraft G. Man
 - Parts
 - Shielding
 - Fault Protection
 - Mission Operations R. Lock
 - Data Acquisition
- Inherent Robustness - Margins R. Lock
- 10:00 Programmatic G. Man/K. Clark
- 10:10 Plan for Phase A G. Man
- 10:15 Discussions - Systems Strategy R. Rasmussen
- 11:00 Board Discussion R. Kingsland
- 1:00 Adjourn

Systems & Operations

Response to Review Objectives:

- a. Do we understand the implications of radiation?
 - Yes, the implications are understood
 - Question how it gets communicated to the team
 - Question what level of uncertainty is used
 - Question on how dose rate effects the degradation of parts
- b. Do we have a sound system approach?
 - Yes the board agrees the system approach is sound at its current level of development and expects that this will be a continuing effort.
- c. Do we have a failed operational approach for operation?
 - Yes the concept of continuing science under fault conditions was accepted with priority of making sure the faulty source can be decoupled from the rest of the spacecraft. This board expects that this will be a continuing effort.
- d. Have we captured the assumptions and considered design margins
 - Several assumptions have been captured and they look fairly comprehensive.
 - Continuing work needed on identifying and quantifying assumptions.
 - Design Margins are identified and are largely qualitative at this point
 - Continuing work needed to quantifying margins.
- e. Is our plan for PHASE A appropriate?
 - Yes, but add to Phase A "plan to develop a road map for successful design". This roadmap should include a list of project priorities and a plan on how and when they will be addressed. Issues include parts obsolescence, ITAR implications on issues such as RADHARD parts availability, overseas, parts test program, early part family identification ...etc.
1. Any major flawed approaches or assumptions
 - The Europa team has prepared a comprehensive set of assumptions that seem complete. Ongoing work must continue to validate these assumptions and reduce the large uncertainties that currently exist.
2. Any Major omissions
 - None identified with the possible exception of internal charging
3. Areas for improvement or additional focus in the next design phase
 - Areas for additional study and focus are identified in the RFAs
4. Statement of perceived residual risk
 - Internal Charging
 - Radiation dose and dose rate uncertainties
 - Unknown spacecraft response to radiation and radiation induced faults
 - Inability to retain a skilled, spacecraft knowledgeable team on the program during the life of the mission

Systems & Operations

Key Findings:

1. Radiation is the biggest hurdle to this mission and thus far seems to be understood well enough to validate the credibility of the mission.
2. There is a general concern regarding the meaning of the radiation dose predictions, the uncertainties. Are we using mean, 1, 2, 3 sigma numbers?
3. The failed operations approach and autonomous recovery seems reasonable given the limited lifetime of Europa system in the radiation environment. But this approach must be coupled to a program to gain the best possible understanding of the system and its possible response modes and the best possible design practices to minimize complex feedback mechanisms and unwanted coupling between system elements.
4. There is concern regarding the elimination of FPGAs as a design option and the effect this restriction will have, especially on the instrument packages.
5. The radiation parts philosophy of preferring to prioritize getting radiation pedigree parts and then parts via radiation tolerant processes is a good approach. However the radiation system engineers must completely understand the basis of the parts vendors' pedigree and process.
6. The mass memory limitation is a significant design driver affecting the telecommunications system design and operation with follow through consequences to the use and demands on the DSN.
7. The Europa team has done an outstanding job of dealing with the comprehensive considerations generated by the radiation environment and developing innovative operational modes to address the foreshortened lifetime of the Europa spacecraft when operating in the radiation environment.
8. The spacecraft, during the Jovian tour phase of the mission prior to Europa, will operate in both higher and lower radiation environments. This bounding experience will enable a better understanding of the spacecraft responses to the radiation environment and allow fine tuning of the automated recovery modes prepared and selected for the fault-operations approach.
9. The spacecraft sensors and radar will not operate through any significant atmosphere and there is no concern regarding door, attenuation or other radiation driven atmospheric effects.
10. The AOs prepared for the Instrument Systems must be comprehensive and deal with the spacecraft interface in the areas of shielding and the radiation support that will be provided to the instrument builders. Other non radiation areas, e.g., thermal are also identified as areas requiring careful definition.

4. *Parts Workshop Board Report, April 26, 2007*

4/26/07

Technical Workshop Board Report

Subject: Radiation Effects on Parts for the Europa Explorer

To: Guy Man

From: Ronald Lacoe

Review Objectives:

Radiation Effects on Parts

Are the parts, material and design assumptions for implementation sound?

1. In the current stage of study, pre-phase A, we choose to address parts and materials by examining classes of parts. Do we have the appropriate assumptions and approaches for parts and material?
2. Are there any classes of parts that we do not have solution?
3. What Phase A/B tasks are critical to start early?
4. Have we captured assumptions and considered design margins appropriately?
5. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Members:

Ronald Lacoe, Aerospace Corporation (Chair)
Ken Label, NASA - GSFC
Ethan Blansett, Sandia NL
Steve McClure, JPL

Participants:

Randy Blue, JPL
Karla Clark, JPL
Allan Johnston, JPL
Guy Man, JPL

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Scope of the Peer Review Material

The following material was presented for discussion:

- An overview of the **proposed mission** including the concept overview and the mission duration, spacecraft features a description of the RTG power plant, and a comparison between Europa Explorer and Cassini.
- A description of the **radiation environment** including total ionizing dose, and displacement effects from intense Jovian radiation belts that is dominated by electrons and protons, galactic cosmic rays, radiation from the RTG and shielding assumptions.
- A description of **parts used on the Cassini baseline** for initial planning (needs updating) and short discussion on **issues that arose during Cassini** related to parts reliability, radiation effects and qualification.
- A discussion on **anticipated problem areas** for Europa Explorer and potential **new technology insertion opportunities** for Europa.
- A discussion on **potential radiation characterization issues** for the Europa Explorer, including total dose effects (including ELDRs, displacement damage effects, single event effects (including single event upset, latchup, single event gate rupture) and potential synergistic effects.
- A discussion on **potential reliability issues** for the Europa Explorer, including issues arising from multiple or non-constant activated processes, parts derating issues and particularly challenging qualification issues (hybrid devices, advanced memory devices, highly scaled digital devices, power semiconductors and optoelectronic devices).
- A discussion on potential **hardened digital technologies** including flight computers (RAD750), mass memory (SRAM, CDRAM), EEPROMs and flash memory, FPGA's (ruled out), multiplexers and ASICs.
- A discussion on **linear and mixed-signal hardened-parts** options such as ADCs, low dropout regulators, op-amps and comparators, voltage references
- A description on the part development effort for the X2000 program.
- Plan for Phase A.

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Key Findings

- In the current stage of study, pre-phase A, the project chose to address parts by examining class of parts. This approach is appropriate but the presentations did not cover instruments/sensors and supporting electronics that reside near the exterior to the spacecraft and may prove the most problematic from a total-dose perspective.
- All classes of parts have a path toward a solution. However, there are certain classes of parts that have significant risks:
 - ASICs: The rad hard foundries remain a viable alternative for the design and fabrication of Mrad hard ASICs. This approach, however, results in a lack of performance and increased power levels. The board discussed the potential for fabricating Mrad hard components in a commercial foundry using hardness by design approaches. This approach can be used for the fabrication of digital, analog and mixed-signal components. Total dose hardness has been demonstrated to 30 Mrad using this approach. This approach should be considered for this program from both a technical and cost point of view.
 - Volatile memory: SRAM + EDAC is viable for solid-state recorder memory and high-speed processor memory. 4 Mbit 1 Mrad SRAM has been demonstrated at BAE Systems. CRAM is a potential alternate for the solid-state recorder memory (see non-volatile memory). Risk-low to medium. SDRAM considered, but radiation effect risks for more advanced technologies likely to be problematic (TID, SEFI, latch-up).
 - Non-volatile memory: SONOS available at 256 Kbit at 300 Krad and demonstrated at 1 Mb at 300 Krad. Low risk solution for start-up memory. 4 Mb/1 Mrad CRAM has been demonstrated but is not yet in production. 16 Mbit CRAM is planned. If CRAM technology matures, it will be a viable option for solid-state recorder and start-up memory. CRAM is medium risk pending development. Flash memory and the Hitachi EEPROM are not likely options because of poor TID performance, although some newer flash components have shown TID hardness levels above 100 Krad.
 - Processors: The RAD 750 is a commercial CMOS processor/computer board available today. It is TID hard to above 100 Krad. The upgraded RAD 750 fabricated in a rad hard foundry has been demonstrated and it is likely to be available by 9/08. SEU performance on upgraded processor not yet known. Risk is low to moderate. Other rad hard processors (e.g. PPC 603 and MIPS processors) may be viable for certain processing tasks. The status of these processor options should be look at in the future.
 - ADC/DAC: There are viable 12 bit 300 Krad ADCs (20-50 MSPS). Higher resolution ADC such as 14 bit device is higher risk. For DACs, some of the

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newer components from TI, BICOM and BICOM3X series should be considered.

- Linear voltage regulators are problematic for total dose. There are a limited number of devices capable of performing to 100 Krad – 300 Krad. Need to consider both TID and displacement damage effects. Many will require significant qualifications. Risk is medium to high. Mitigation could be mixed signal ASICs.
- Op amps and comparators are problematic for total dose. There are a limited number of devices capable of performing to 100 Krad. Many will require significant qualifications. Risk is medium to high. Mitigation could be mixed signal ASICs.
- There are solutions for 5 volt rad hard logic. Lower voltage devices have limited availability. Mitigation would be mixed signal ASICs.
- Optoelectronics need to be evaluated early for TID and displacement damage as well as transient effects.

Critical tasks for Phase A/B:

- ASIC development
- Memory characterization
- ELDR testing on potential components
- The Phase A plan is appropriate if the above critical tasks are included.

Assumptions and Design Margins:

- The flow down of total dose requirements due to the environment and the application of shielding to levels as low as 100 Krad appears to be reasonable.

Recommendations

- Reexamine the potential application of FPGAs for this program. The program should become familiar with the RH products and roadmaps for Xilinx, Actel and Aeroflex FPGAs.
- Develop a strategy for ASIC procurement. Examine commercial foundry and structured-ASIC approaches.
- Building LVDOs using discretes should be considered.
- Examine approaches where key electronics is left unpowered during the cruise phase of the mission to increase TID margins.

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- Study issues related to the proper evaluation of the reliability of parts from low volume foundries.
- To get a better handle on “realistic” TID requirements for specific parts, a 3D ray trace of the Cassini spacecraft using the Europa Explorer orbit should be performed.

5. *Integrated Systems Peer Review Board Report, May 21, 2007*

5/21/07

Board Report

Subject: Technical Peer Review for Europa Explorer Radiation Integrated Systems

To: Guy Man

From: Joe Srour

Introduction

A meeting was held at JPL on May 10, 2007 to review the progress and plans in the general areas of radiation effects and radiation hardening for the Europa Explorer mission. Emphasis was placed on reviewing the envisioned strategies for system design and mission operations in the presence of a relatively severe radiation environment. This report includes the following items: objectives of the review; the review panel; the topics presented to the panel, including an agenda and list of presenters; key findings of the panel; recommendations by the panel; and RFAs.

Review Objectives

Do we have a sound systems and mission approach to radiation?

1. Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?
2. Is the approach to transport analysis and to shielding mass calculation appropriate?
3. Are the parts, material and design assumptions for implementation sound?
4. Do we have a technical approach that handles radiation for the mission/systems?
5. Do we have a technical approach that handles uncertainties?
6. Is our plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Participants

- Joe Srour - Chair, Aerospace Corporation
- John Henley, SAIC
- Sammy Kayali, JPL
- Dave Kusnierkiewicz, JHU-APL
- Gentry Lee, JPL
- Duncan Macpherson, JPL
- Ralph McNutt, JHU-APL

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Scope of the Peer Review Material

The following material was presented for review and discussion:

- Executive Summary of the work done to-date
- Radiation Environment Peer Review Board Report
- Transport Analysis and Shielding Peer Review Board Report
- Parts Workshop Board Report
- Materials Peer Review Report
- Discipline Systems and Operations Workshop Board Report
- Future Plans

Here is the agenda followed and the presenters:

Executive Summary/Mission Concept Overview	Guy Man, JPL
Radiation Environment Board Report	Chris Paranicas, JHU-APL
Transport Analysis and Shielding Board Report	Jeff Johnson, ORNL
Parts Workshop Board Report	Ron Lacoe, Aerospace
Materials Peer Review Report	Paul Willis, JPL
Discipline Systems and Operations Board Report	Richard Kingsland
Summary and Future Plans	Guy Man/Karla Clark, JPL

Key Findings

In general, the JPL team is performing high-quality work in preparing for the Europa Explorer mission. At the present review, the Europa team did a very good job of presenting an overview of their progress, recommendations, and plans in radiation-related areas. The visibility of radiation issues and the integration of radiation expertise on the Europa program are commendable and essential for success. Very good teamwork and healthy communications are evident. The inclusion of an excellent peer review process on the program is notable.

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The review panel offers observations and suggestions here for consideration by the Europa team. These comments are intended to augment the outstanding efforts conducted thus far, and may serve to stimulate additional design- and mission-related ideas of value. The present comments reflect, or originate from, the following sources: a) new observations made by the panel; b) observations made by presenters and other attendees that the panel wants to highlight and emphasize because of their potential value to mission success.

1. More analyses and trades are needed regarding the currently baselined mission design, which involves a Jovian tour prior to injection into Europa orbit. The present design minimizes post-launch ΔV by including that tour, and thereby delays Europa orbit insertion. That delay increases mission risk. Further analyses and trades should examine the impact of an earlier exit from the planned Jovian tour on the total radiation dose. Inclusion of radiation dose timelines for different mission scenarios would be beneficial. The cost of the additional ΔV needed for alternative mission profiles should also be considered.
2. Dosimetric adaptability is important for Europa. If the onboard dosimeters reveal that the radiation environment is significantly more severe than expected, then plans must be in place to handle that situation.
3. NASA AOs for Europa Explorer instruments must contain a sufficient amount of detail regarding radiation requirements for the mission. Key areas for inclusion are the radiation environment, shielding guidelines, parts information (e.g., what classes of parts are allowed or excluded, such as FPGAs), and the types of radiation support that will be provided by JPL to instrument suppliers.
4. The Europa Explorer team has made good initial progress toward identifying those technical achievements that will constitute mission success. Additional work is needed in that area to quantify, and obtain concurrence on, the minimum science achievements for a successful Europa mission.
5. Detailed planning is needed for the materials and parts radiation testing program. That planning should include identification of appropriate radiation facilities and their cost, estimation of the number and types of materials and parts to be tested, consideration of irradiation and measurement conditions and approaches, deciding on the 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 manpower estimates for testing.
6. The panel concurs with the statement made at the review that the radiation environment and parts capabilities in that environment must be known well to avoid significant issues for the Europa Explorer mission.

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7. The area of radiation effects on materials and selection of appropriate materials for the Europa mission needs more work. The presentation made to the review panel provided general information of value, but seemed generic and less focused on the mission at this point than the other areas presented.
8. Displacement damage (DD) effects on parts have not yet been addressed in detail in contrast to total ionizing dose effects. The Europa team is aware of that and plans to address the DD area. This area needs attention early on. A realistic nonionizing dose versus shielding depth curve needs to be developed that includes the following sources of displacement damage: a) the external particle environment; b) secondary neutrons produced in shielding materials by incident protons; c) neutrons produced by onboard RTGs. That curve will help in identifying parts that should be avoided because of their DD sensitivity in specific applications (e.g., instruments).
9. The total ionizing dose deposited at material surfaces by low-energy plasma environments is orders-of-magnitude larger than that typically considered for electronic parts. It is important to address the effects of that very severe environment on surface materials, coatings, windows, etc., through analysis and testing where needed. At the review, the Europa team indicated that they plan to address such effects.
10. Transient radiation effects (i.e., noise) in visible and infrared imaging sensors need more attention. That issue is likely to arise for some of the instruments. Work being performed in that area on other programs, such as the James Webb Space Telescope, may be helpful for the Europa mission.
11. Parts risk reduction activities need to be planned and conducted early (requirements, development, testing, etc.).
12. The feasibility and potential advantages of common buys of parts for instruments should be examined.
13. Additional trades of mass memory size, memory technology, radiation tolerance, and resulting telecommunications requirements are needed. Such trades may lead to a mission concept that provides more capability than that presently envisioned.
14. The Europa team should continue to assess whether FPGAs are appropriate for use on this mission. A stance on that issue will be needed for the instrument AOs (see Item 3) so that candidate suppliers will know if FPGAs are a design option.
15. The Europa team should consider using a CAD/radiation transport analysis tool interface, currently under development, as a means of enhancing the design evolution process.

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16. Radiation analysis code verification and validation was recommended in the Transport Analysis and Shielding presentation. Such work is important technically but may consume considerable time and funds. The cost and schedule impact and the technical return on investment should be considered before undertaking such an activity.
17. The degree of conservatism being exercised (e.g., in selecting radiation design margins, performing radiation environment definitions, etc.) appears to need further consideration. That is, in some cases the team may be overly conservative but in other cases may not be conservative enough. A balanced approach should be sought.
18. The approach to failed operations and recovery appears to need more attention. As suggestions, the Europa team should investigate approaches used by the DoD and prior considerations for the NASA Prometheus Project.
19. The Discipline Systems and Operations presentation raised the topic of ITAR concerns for non-US equipment for the Europa mission. The panel concurs that that area needs attention and planning early on.
20. There are large uncertainties associated with the Europa Explorer mission, some of which are radiation-related. Those uncertainties need to be quantified and the mission then tailored to deal with them.
21. As the Europa project moves forward, team leaders should strive to present a bigger-picture view of the mission. That approach will help all key players better understand and appreciate the scientific benefits, the mission trade-offs, risks, and contingency plans.

Recommendations

The following recommendations are offered by the review panel. These suggestions follow directly from the Key Findings given above and are numbered identically for reference purposes.

1. Perform additional analyses and trades to examine alternative mission profiles.
2. Develop plans to handle radiation environments that are more severe than expected.
3. Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments.
4. Quantify and obtain concurrence on minimum science criteria for a successful mission.

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5. Perform detailed planning for the parts and materials radiation testing program.
6. Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring.
7. Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.
8. Address displacement damage effects on parts early on.
9. Address the extremely high total ionizing doses that occur at material surfaces.
10. Give detailed consideration to transient radiation effects in sensors.
11. Plan and conduct parts risk reduction activities early on.
12. Consider common buys of parts for instruments.
13. Conduct mass memory trades in an attempt to improve mission capability.
14. Assess and decide whether FPGAs are appropriate for use on this mission.
15. Consider the use of a CAD/radiation transport analysis tool interface to enhance the design evolution process.
16. Consider the cost and schedule impact and the technical return on investment of code verification and validation before undertaking that activity.
17. Try to achieve a balanced approach to conservatism in the radiation-inclusive design.
18. Give additional attention to the failed operations and recovery approach.
19. Develop plans for handling ITAR concerns.
20. Quantify large uncertainties and tailor the mission to deal with them.
21. Present a bigger-picture view of the mission so that key players better understand and appreciate the scientific benefits, trade-offs, risks, and contingency plans.

6. *RFA Disposition Status, June 4, 2007*

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RFA Status for the EE Radiation Reviews

Review & RFA #	Submitted by	Concerns	Recommendations	Disposition	Date for Closure	Comments
1. Environment						
1.1	R. Thorne	Flux suppression near Europa has not been modeled	Update analysis by using a more realistic model	Advisory	Phase B	
1.2	R. Thorne	> 10 MeV electron need looks too conservative	Re-analyze high energy data from Pioneer	Accept	Phase A	
1.3	S. Levine	Divine model is out of date	Consider a fresh start with today's understanding	Advisory		
1.4	R. Thorne	C22-like injection not understood	Try to understand the physics leading to the event	Advisory	Phase B	
1.5	R. Thorne	Need best magnetic field mode for inclusion of current sheet	Incorporate Kristian Khurana's current sheet model	Advisory	Phase B	
1.6	T. Armstrong	Modeling scatter	Try using B observed to organize the fluxes	Advisory	Phase B	
2. Transport & Shielding						
2.1	L. Waters	Uncertainty of the transport methodology cannot be quantified	Establish a code v & v program	Accept	Phase A	Plan needs to be written in Phase A
2.2	J. Johnson	Tracability of tools, models and results have not been established	Establish a configuration management system	Accept	Phase A	Plan needs to be written in Phase A
2.3	J. Johnson	Radiation sources (e.g., GCR, SEP CME, and MMRTG) and the displacement damage and SEEs could be of equal importance to the shield design optimization and mass calculations	Extend the analyses to investigate these other sources very early on to quantify their effects relative to the Jovian/Europa environments	Accept	Phase B	Can be started in Phase A but realistically probably takes longer

RFA Status for the EE Radiation Reviews

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2.4	R. Kemski & K. Adams	Integration of the radiation group with the system engineering design team is paramount to mission success	Radiation transport analysts need to be integrated on all system engineering design teams impacted by the shielding analyses	Accept	Phase A	In plan from the start of Design work in Phase A
3. Parts & Material						
3.1	R. Lacoe	Need a strategy for ASICs development	In addition to considering ASIC development at rad-hard foundries, approaches that target fabrication at commercial foundries using hardiness-by-design techniques should be considered	Advisory	Phase A	All approaches to rad-hard will be pursued. Qualification implications of rad-hard by design approaches will be investigated during Phase A
3.2	R. Lacoe	Reliability of rad hard foundries	Develop a process to control the reliability of low wafer volume foundry even they suppose to be rad hard	Advisory	Phase A	Will follow JPL guidelines for this, will consider any additional requirements in Phase A/B
4. Systems & Ops						
4.1.1	J. Boldt	Availability of FPGA	Justify and reconsider	Advisory		Current guidelines do not allow FPGAs. This approach is based on limited testing on RTAX FPGAs and the combination of radiation, life and temperature not meeting EE requirements. It is more conservative to assume ASICs which require more cost and schedule. In Phase A and B, we will attempt to qualify FPGAs such that they can be used, but the plan needs to cover dollars and schedule in case that effort is not fruitful.
4.1.2	G. Reeves	"		Advisory		see 4.1.1
4.2	J. Boldt	ASIC development for instruments	Revisit decision	Advisory		see 4.1.1

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4.3	J. Boldt	Shield mass specification for instruments	Develop a reasonable method	Accept	Phase A	Detailed instructions will be developed to support AO
4.4.1	J. Boldt	Ops interface req for instruments	Develop and communicate an approach in AO	Accept	Phase A	Add spacecraft and instrument communication plan to do in Phase A
4.4.2	G. Reeves	"		Accept	Phase A	see 4.4.1
4.5	J. Boldt	No avionics architecture to support autonomous sys	Need avionics and FP req for instrument	Accept	Phase A	
4.6	S. Leete	DSN limitation	Consider relay satellites	Reject		Too costly
4.7.1	S. Leete	Internal electron charging from high energy electrons	Need a ESD approach	Accept	Phase B	In plan, will attempt to get in Phase A but may go into early Phase B
4.7.2	G. Levanas	"		Accept	Phase B	see 4.7.1
4.7.3	R. Kingsland	"		Accept	Phase B	see 4.7.1
4.8	S. Leete	ITAR is a big concern for foreign participation	Address ITAR early especially due to radiation concerns	Accept	Phase A	
4.9	S. Leete	Resource management is complex	Develop a plan	Advisory		Resource management plan will put special attention on radiation issues
4.10.1	S. Leete	Hardware providers will need a lot of help on radiation issues	Develop an implementation plan	Accept	Phase A	Concern is noted and plan will be developed in Phase A
4.10.2	G. Reeves	"		Accept	Phase A	see 4.10.1
4.11	S. Leete	Not clear what will project provide and what can hardware provide assume available from project	Develop a plan and flow information down	Accept	Phase A	Will address in Phase A
4.12	S. Leete	Team communication	Develop an implementation plan	Accept	Phase B	Will attempt to get in Phase A but may go into early Phase B, radiation control plan will be done in Phase A to support AO along with anything else relating to AO. There is Radiation Advisory Board to facilitate communication.
4.13	G. Reeves	Autonomous recovery requirements	Develop autonomous strategy starting from science	Accept	Phase A	
4.14	G. Reeves	Need a successful implementation plan in phase A	Develop a comprehensive implementation plan	Accept	Phase A	In plan, but are there details he is specifically concerned about over and above "normal" JPL requirements?

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4.15	G. Levanas	Unclear statistical uncertainty of TID	Clarify statistical uncertainty of TID and communicate with h/w builders	Reject		See Environment peer review
4.16	R. Kingsland	Using today's technology only is too limiting	Remove this restriction in Phase A	Advisory		Any new technologies and developments will be scuritized during early project for risk, cost, schedule and performance enhancement. A conscious decision will be made on individual developments given risk posture of project.
4.17	R. Kingsland	Higher assembly level tests for internal charging	Investigate the use of tests such as cable shield current injection and quadriaxial drive tests	Accept	Phase B	Will look at as a part of 4.7.1
4.18	R. Kingsland	High charge environment	Consider using Faraday shielded modules	Accept	Phase B	In design, commonly done for JPL missions such as these.
4.19	R. Kingsland	Need to develop a knowledgeable team to handle FP during ops	Plan for a worm to tumb team for this mission	Accept	Phase B	Plan will be developed for not a womb-to-tomb team to handle the worst case.
4.20.	R. Kingsland	How to create a radiation sensitive culture on EE	Train a core team early including dealing with ITAR	Accept	Phase A	In plan
4.21	R. Kingsland	It is not clear how design engr and parts engr work together	Sensitize them to work much closer for this mission and develop needed new processes	Accept	Phase A	In plan

7. Disposition of Recommendation for the Integrated Systems Peer Review, July 5, 2007

Peer review for EE Radiation Integrated Systems
Review Date: 5/10/07

6/21/07

#	Recommendation	Disposition	Project Response	Date for Closure
1	Perform additional analyses and trades to examine alternative mission profiles.	Accept	Will optimize mission plan to meet science priority and minimize risk.	Phase A
2	Develop plans to handle radiation environments that are more severe than expected.	Advisory	Will develop plan to handle actual radiation that is lower and higher than plan.	Phase A
3	Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments.	Accept	In plan	Phase A
4	Quantify and obtain concurrence on minimum science criteria for a successful mission.	Accept	In plan, will address in the EE Study Report	8/30/07
5	Perform detailed planning for the parts and materials radiation testing program.	Accept	In plan	Phase B
6	Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring.	Advisory	This is on-going. The project intends to work with the Radiation Advisory Board regularly on this and progress will be reviewed in technical peer reviews and all major reviews.	On going
7	Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.	Advisory	Much of this work is already done. It was not presented in detail. Results are published and will be used as a part of the Phase A support to the release of the AO.	Phase A
8	Address displacement damage effects on parts early on.	Accept	In plan. We typically deal with displacement damage in parallel with total ionizing dose.	Phase A
9	Address the extremely high total ionizing doses that occur at material surfaces.	Accept	In plan. We plan to follow JPL rigorous design guidelines for ESD and grounding, early testing of materials to define acceptable use for EE, providing mission design guidelines early in the design cycle, and conducting design workshops to train designers on the environment and charging issues.	Phase A
10	Give detailed consideration to transient radiation effects in sensors.	Advisory	Early work will be done to identify sensors for the approved part list in support of the AO. Transient work will be limited until actual sensors are selected for mission.	Phase A
11	Plan and conduct parts risk reduction activities early on.	Accept	In plan.	Phase A

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12	Consider common buys of parts for instruments.	Accept	We will study the trade for such action and develop plan in support of AO.	Phase A
13	Conduct mass memory trades in an attempt to improve mission capability.	Accept	We plan to revisit status of mass memory technology in Phase A. Any new technologies and developments will be scrutinized during early project for risk, cost, schedule and performance enhancement. A conscious decision will be made on individual developments given risk posture of project.	Phase A
14	Assess and decide whether FPGAs are appropriate for use on this mission.	Advisory	Current guidelines do not allow FPGAs. This approach is based on limited testing on RTAX FPGAs and the combination of radiation, life and temperature not meeting EE requirements. It is more conservative to assume ASICs which require more cost and schedule. In Phase A and B, we will attempt to qualify FPGAs such that they can be used, but the plan needs to cover dollars and schedule in case that effort is not fruitful.	Phase A/B
15	Consider the use of a CAD/radiation transport analysis tool interface to enhance the design evolution process.	Accept	Will further assess benefits and cost associated with pursuing this approach.	Phase A/B
16	Consider the cost and schedule impact and the technical return on investment of code verification and validation before undertaking that activity.	Accept	Agreed and planned to be done in Phase A.	Phase A
17	Try to achieve a balanced approach to conservatism in the radiation-inclusive design.	Advisory	In plan. Will balance risk across the project to minimize overall risk as part of systems engineering effort to address mission hazards. Plan to work with the Radiation Advisory Board regularly on risk assessment, trades and status.	On going starting from Phase A
18	Give additional attention to the failed operations and recovery approach.	Accept	In plan	Phase A
19	Develop plans for handling ITAR concerns.	Accept	In plan	Phase A
20	Quantify large uncertainties and tailor the mission to deal with them.	Advisory	In plan, cannot quantify when complete	On going

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21	Present a bigger-picture view of the mission so that key players better understand and appreciate the scientific benefits, trade-offs, risks, and contingency plans.	Advisory	In plan, this is an on-going effort and presentation is constantly being refined as we get input on effectiveness	On going
RF1	Contact Barry Geldzahler and work out proof-of-concept scenario for end-to-end retrieval of data from Europa.	Reject	For Study, we have clear guidelines from HQ on approach to DSN capabilities. During subsequent efforts, we intend to work in normal channels and sign agreements with the appropriate parties.	
RF2	Scope out next level of details in facility. Look at time and effort required for ASIC design production, testing, and documentation.	Accept	Preliminary efforts will continue in Phase A, more detailed assessments will need to wait until Phase B	Phase B

8. DRAFT FLIGHT SYSTEM CHARGING REQUIREMENTS

8.1 Surface Charging Requirements

Each conductive layer of thermal blankets and all exposed conductive surfaces on the Flight system shall be grounded. All flight system exterior surfaces near plasma measuring instruments shall be conductive enough to prevent electrostatic fields disruption of the plasma measurements. Confirmation of meeting this requirement shall be made through test or analysis in accordance with design rules as described in NASA-TP-2361 (Design Guidelines for Assessing and Controlling Spacecraft Charging Effects).

8.2 Internal Charging Requirements

This requirement is driven by the high-energy electron environments of the mission. Some of the following design rules are universal, and some are specifically based on particular known mission environments; the two are made clear in context.

If the worst-case electron flux is less than 5×10^5 electrons per square centimeter per second at the dielectric or conductor in question, then the remaining specifications in this paragraph do not apply.

Design and analysis rules as described in NASA-HDBK-4002 (Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects) shall be used.

There shall be no ungrounded conductors (non-electrical and non-electronic without a conductive bleed path to chassis) of size greater than 3 cm^2 on most parts of the flight system and no ungrounded conductor areas greater than size 0.3 cm^2 on or near circuit boards or cabling or other electronics.

There shall be no ungrounded/unreferenced wiring (for example, spares or wiring isolated by switching activities or pulse transformers without a conductive bleed path to chassis) of length greater than 15 cm. No circuit, including input power leads (or non-circuit conducting elements, including structures) shall measure greater than 20 megohms to chassis.

Circuit boards, integrated circuit lids, transistor cans, and relay cans also shall be designed so that radiation spot shields over integrated circuits have a resistive bleed path to ground with resistance less than 10 megohms (zero ohms is acceptable). Additionally, any metal area greater than 0.3 cm^2 shall have a bleed path with the same Electrostatic Discharge (ESD) grounding limits of 0–10 megohms resistance to ground. Each open dielectric area (not covered by a grounded conductor) shall be verified to be able to store no more than 1 microjoule (1 uJ) of energy or no more than 2×10^{10} electrons accumulated in a 10 hour period.

Circuit boards shall be designed so that there will be no open dielectric surface areas greater than 0.3 cm^2 (assuming 80 mil thick FR4 type circuit board). Open dielectric surfaces with one dimension less than 3 mm need not be grounded. If there is an open dielectric surface area greater than 0.3 cm^2 , then place a grounded (by less than 10 megohms) metal patch on the region (a power plane over that region also meets the requirement). Alternatively, if there is a ground or power plane underneath the dielectric surface area, then the permitted dielectric surface area is increased in inverse proportion to the depth of the ground (or power) plane as shown in Figure below. This rule applies to both the front and rear surfaces of dielectric areas.

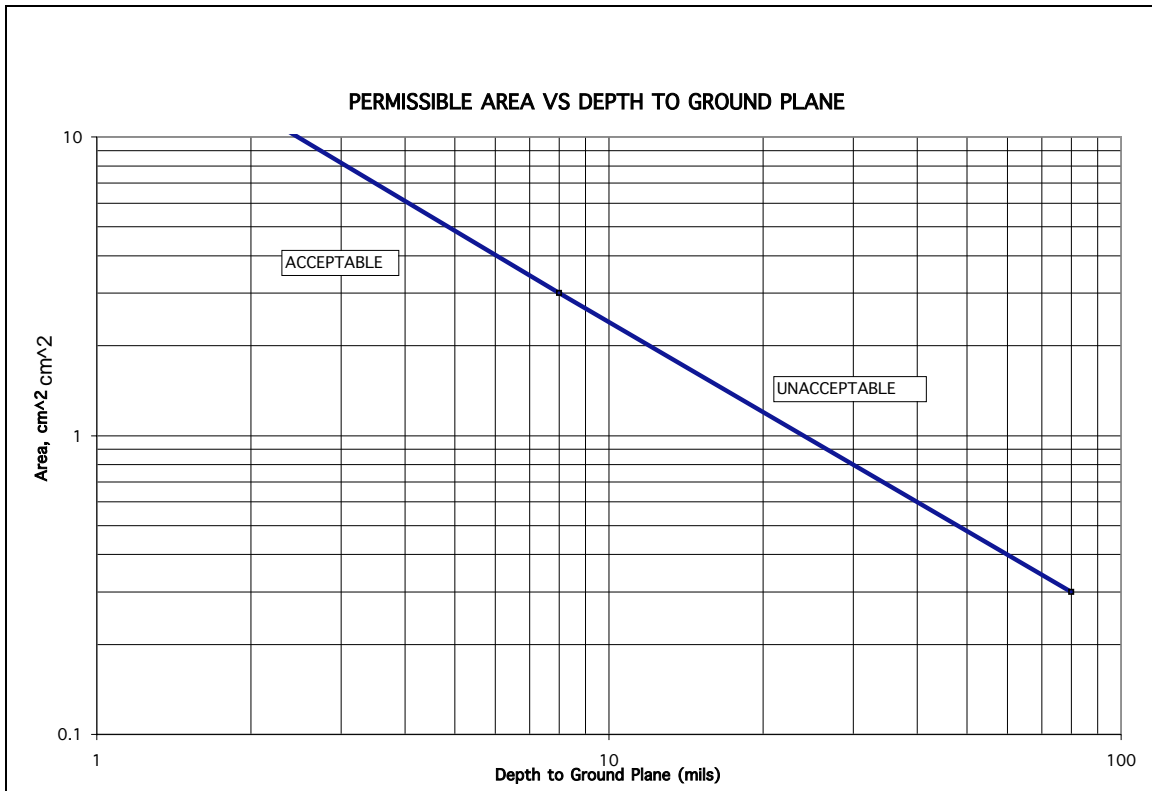


Figure - Permissible exposed dielectric area vs. depth to nearest ground/power plane.

8.2.1 Corona and High Voltage Breakdown

Assemblies and subsystem shall be designed to prevent corona or other forms of electrical breakdown at pressures between 50 to 5×10^{-4} torr and in Earth and Jupiter space plasma environments (see NASA-HDBK-4002 and NASA TP 2361). They all involve a loss of power from a source that has power; the subsequent energy flow can disturb or destroy materials at the location of the arc/discharge leading to a loss of dc power, signal, or RF, depending on the signal being affected by the breakdown.

As a minimum, design per JPL D-8208 Section 3.9, High Voltage Requirements.

Confirmation of meeting this requirement shall be made through test or analysis.

8.2.2 Electrical Isolation, Bonding and Grounding

8.2.2.1 Signal, Command, Data, and Telemetry

Electrical isolation of signal line, command, data, and telemetry interfaces shall exceed 1 megohm DC from chassis. Coupling capacitance shall be less than 400 picofarads per line for isolated interface circuits. Differential circuits shall be balanced with respect to chassis, both AC and DC.

8.2.2.2 Power Supply Input Lines

Electrical isolation of power supply input lines shall exceed 1 megohm DC from each line to chassis. Capacitance from each line to chassis shall be less than 0.1 microfarads.

8.2.2.3 Pyro Supply Lines

The pyro firing system shall be designed so that there can be less than 3 milliamps [TBR] direct chassis return currents as a result of pyro firings. This means that the firing unit itself must be isolated from the flight system power's ground reference, and it means that the firing unit's ground must be isolated from the spacecraft chassis. The firing unit return shall have a resistive reference to chassis such that no more than 3 milliamps of current may flow in the chassis due to a pyro firing event.

The concern is that squibs (EED's, pyros, etc.) have demonstrated that they can have a short circuit from their active pin to chassis in the pyro containment unit (pin-puller, valve actuator, cable cutter, separation nuts, etc.). The current may be as much as the firing unit can deliver through the wiring; this has been 17 amps or more in prior JPL spacecraft. This current may cause disruption of electronic circuits if they are unfortunate enough to have current induced voltages into nearby wiring. We can eliminate this possible problem by proper design of the pyro firing unit.

If the pyro firing system is not designed to prevent chassis return currents caused by pyro firing events, there shall be a system level test to simulate the effect of pyro firing-caused chassis currents.

The test shall consist of a complete flight system (configured as in flight), with simulated pyro ground fault currents. The ground fault current test shall be performed at least once for each pyro event that is planned in flight. The ground fault simulator shall have its return attached at the location of the chassis connection point for the pyro firing unit. The simulated ground fault current shall be injected into the flight system at the location of the each pyro device. The test shall consist of a pulse of current that is $1.25\times$ the maximum available pyro firing current at each location, and the time duration of the simulated current shall be $1.5\times$ the maximum duration of the switch that sends current to the pyro. For each location, the flight system operating mode shall be adjusted so that the operating mode matches that which would exist at the time of the firing event being simulated.

The criterion for a successful test is that no anomalies occur that would adversely interfere with the mission success.

8.2.2.4 Electrical Bonding

All conductive structural elements and conductive assemblies in the flight system shall be bonded together with an impedance not greater than 10 milliohms per joint (measured with a DC voltage). Bonding shall be done using the methods provided in NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment.

8.2.2.5 Electrical Grounding

All electrical/electronic circuitry shall be grounded by a single ground-wire to the chassis. Each electronic assembly may have a separate ground wire, but there shall be only one reference path from circuit to chassis for any given circuit. Ground wires shall not be used to carry current.

D. COST DETAIL

Details not available for public release.

E. EARTH-JUPITER INTERPLANETARY TRAJECTORY OPTIONS

E1. Introduction

The VEEGA trajectories were chosen for the EE baseline and backup missions because of their high delivered mass, moderate flight times, and frequent availability. There are, of course, many different combinations of gravity assists with Earth, Venus, and/or Mars that can deliver a mission to Jupiter. A search was performed for trajectories from Earth to Jupiter for launch dates ranging from 2015 through 2024. While the search was fairly thorough, it was certainly not exhaustive. In addition, many of the trajectories can be modified by trading flight time and ΔV ; this study did not have the resources to perform those types of options.

E2. Analysis Assumptions

The Atlas V 551 launch vehicle injected mass capabilities came directly from data on the NASA Launch Services Program Launch Vehicle Performance web site (<http://elvperf.ksc.nasa.gov/elvMap/index.html>). Post launch ΔV s are assumed to be accomplished with a high-thrust system with an Isp of 325 s, and only deterministic ΔV s are taken into account for the mass performance in these figures. The period of the orbit following

Jupiter Orbit Insertion (JOI) is 200 days, and we did not account for a satellite flyby on approach for these mass performances.

E3. Trajectory Results

Examples of the results are shown in **Figures E-1, E-2, and E-3**. **Figure E-1** shows that there is significant overlap between the performances of the different trajectory types. Loose groupings emerge after brief examination, however. The trajectories with the shortest time-of-flight (TOF) are the single Earth gravity assists, although those have poor delivered mass performance. While the largest delivered mass over the 10-year period studied is by a VEE trajectory, in all but that one case, the VEEGA, VVEE, and VEME trajectories produced better delivered mass performance for a given TOF than the VEE trajectories. In the category of performance > 3500 kg, the VEEGAs have a significant advantage in TOF over the otherwise similar delivery mass performance of the VEME and VVEE trajectories.

There is a wealth of information buried in these plots, but given the challenges of delivering sufficient mass to Jupiter, the VEEGAs generally offer the best performance for trajectories over 5.5 years in TOF to Jupiter.

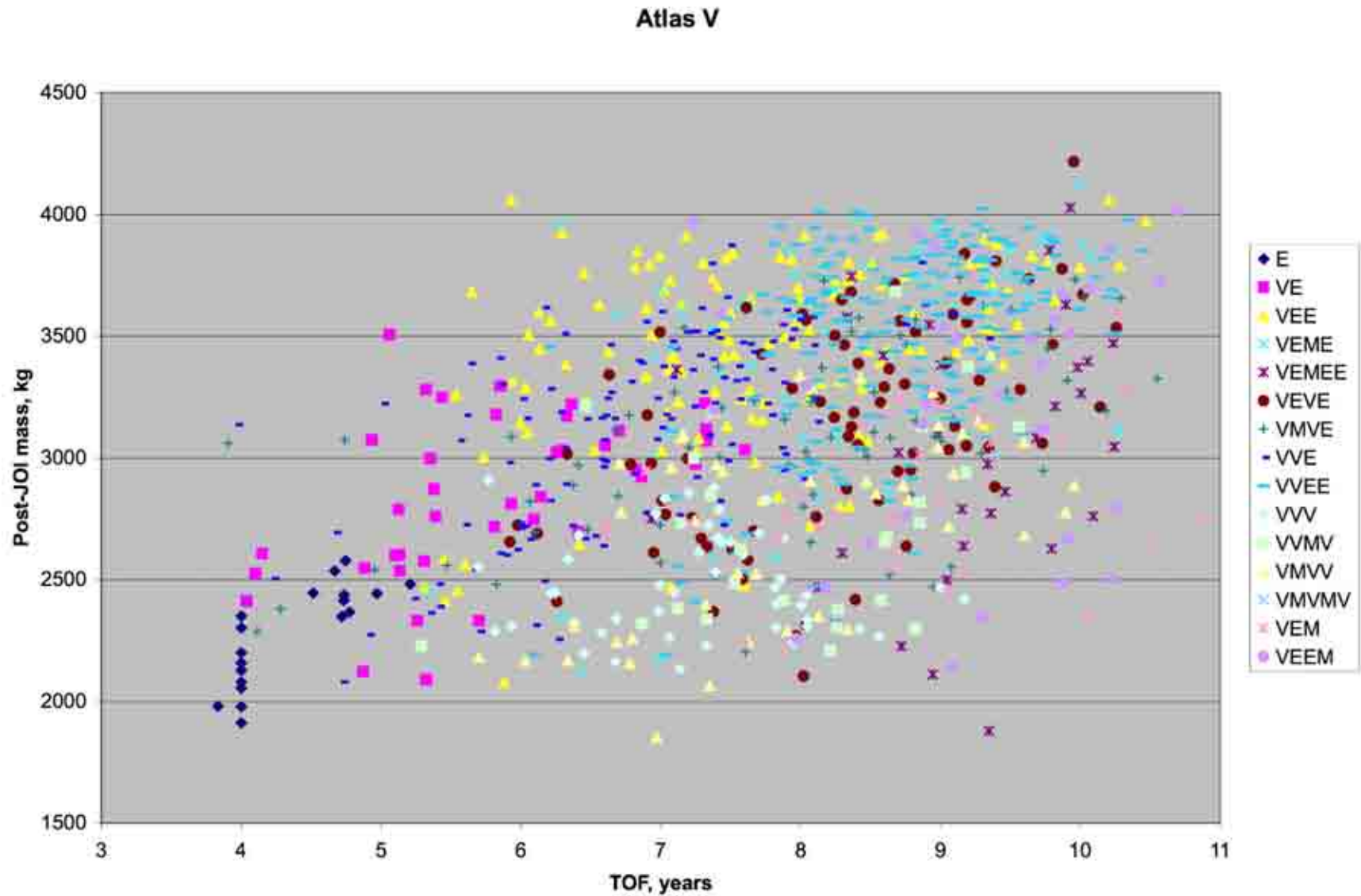


Figure E-1. Mass delivered to 200-day orbit around Jupiter versus flight time from Earth to Jupiter for an Atlas V 551 launch vehicle.

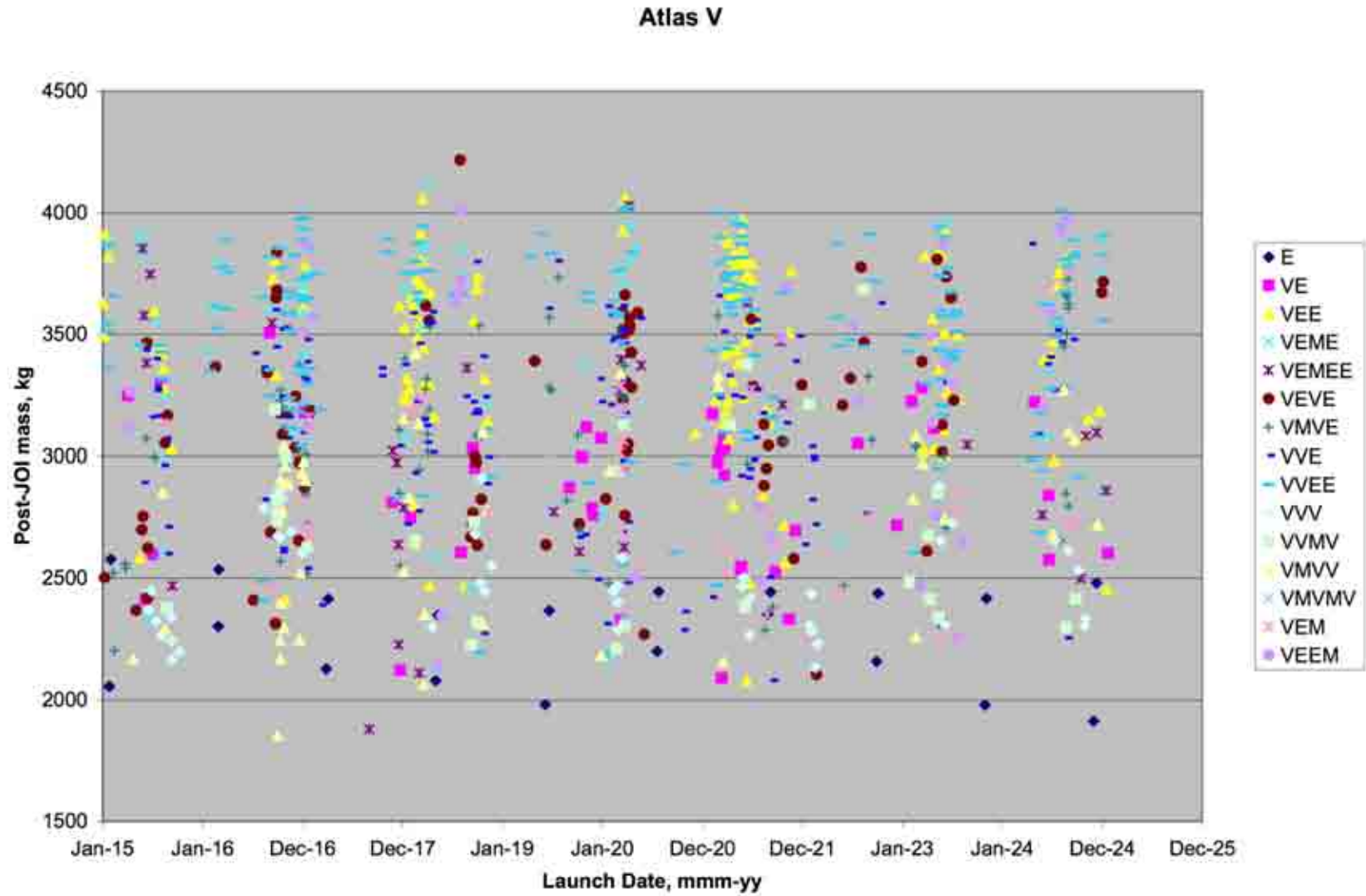


Figure E-2. Mass delivered to 200-day orbit around Jupiter versus launch date for an Atlas V 551 launch vehicle.

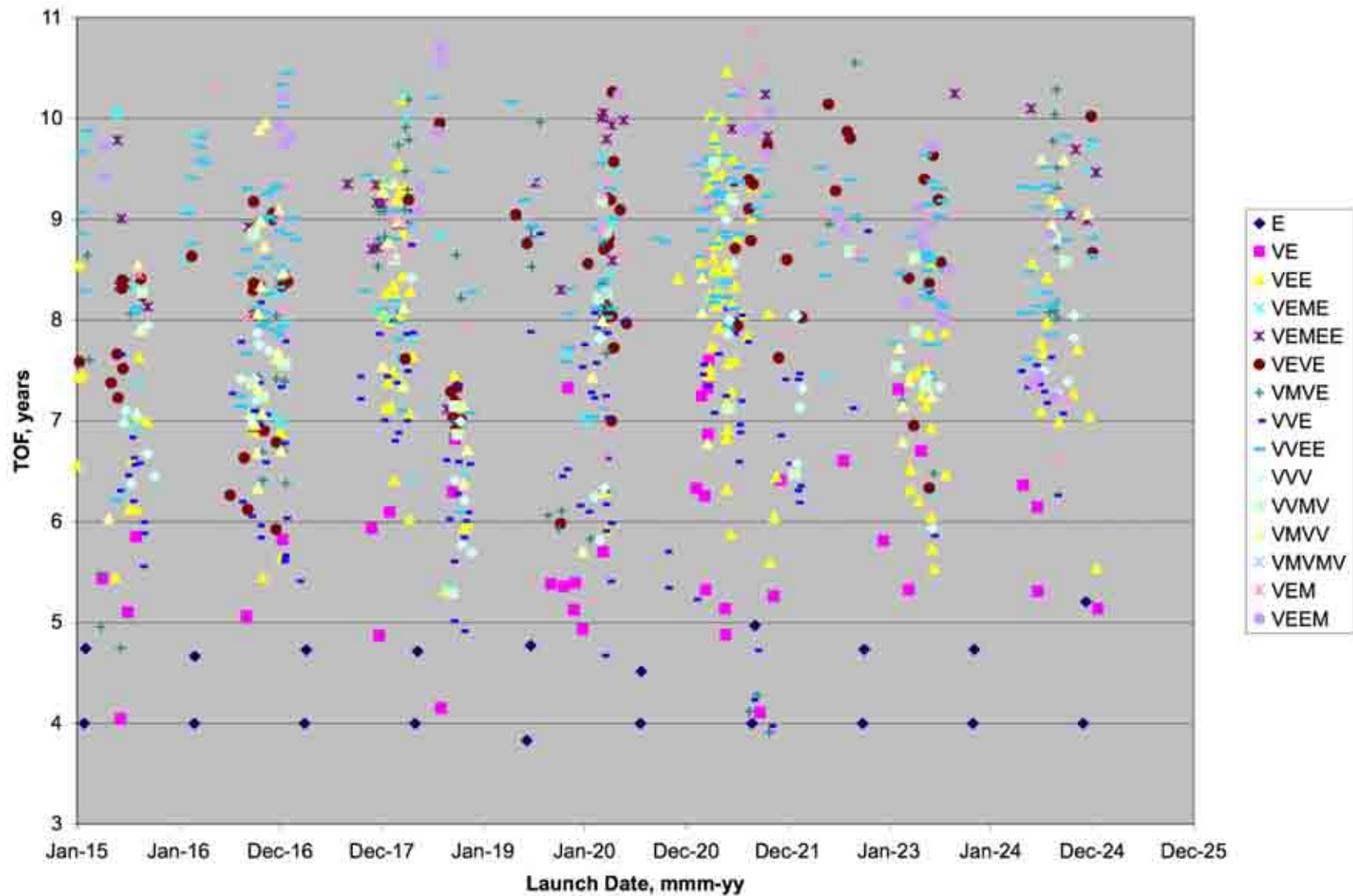


Figure E-3. Flight time from Earth to Jupiter versus launch date.

F. FLIGHT SYSTEM DESIGN SUPPORTING DETAIL

Details not available for public release.

G. OPERATIONS SCENARIO ANALYSIS

G1. Introduction

The purpose of Appendix G of the Europa Explorer (EE) study report is to document the work and methods used to develop the operations scenarios for the EE study and describe detailed operations context for several aspects of the mission. The key conclusions and summary descriptions of the baseline data acquisition and return scenarios and Jupiter system scenarios are included in the main body of the report. Tool and methodology descriptions and some key analysis results for the baseline science scenarios, floor science scenarios, and a quick look feasibility study for the Jupiter system tour are described in this appendix. Context descriptions including mission operations system architecture and DSN scheduling methods are also provided.

G2. Study Approach

The development of the operations scenarios was a central part of the EE Mission Concept Study from the start. The development was an interactive collaboration among all of the members of the Science Definition Team (SDT) led by Bob Pappalardo and Ron Greeley, the study lead, Karla Clark, and engineers from the operations scenario study team. The team members were Rob Lock, Greg Welz, Ken Klaasen, Rob Abelson, and Rob Sharrow at JPL and Nick Pinkine at APL.

The starting point for the operations scenarios development was the work done in the previous study (2006) since most of the key elements of the mission, including science payload, mission design, and flight system design, were similar to those from the previous study. The 2006 study did not develop detailed operations scenarios but did develop operations concepts for single orbits that dealt with challenges in collection and return of large data volumes with constrained on-board data storage. The results of the previous study directly supported the operations scenario development and can be found in [*Europa Explorer Data Return Issue Report 2006*].

Working in concert with the SDT, and in parallel with the SDT's development of the science value matrix, key mission capabilities and constraints were examined and challenged.

Science goals were discussed and options were considered for data collection scenarios.

The first scenarios to be considered were the floor mission scenarios. The SDT was developing the floor science goals and value matrix and the scenarios were needed to determine the science achievement and validate the science value estimates. Basic instrument operations constraints, interactions, and coverage estimates were developed and presented in the first sessions. Once the flight system capabilities were determined and orbit-by-orbit scenarios were developed, higher order scenarios for science campaigns were sketched out to estimate the progress of achievement of the science goals during the mission. This was needed for the science value matrix being developed separately by the SDT. Key system parameters estimated and traded were instrument power, mass and data rate, telecom rate, Solid State Recorder (SSR) capacity, instrument data volume allocations, operations timing constraints, co-observing issues, data reduction and compression factors and phasing of campaign goals.

Following the development of goals, operations scenarios and the science value matrix for the floor mission, the process was repeated for the baseline mission. During this process the strategy for data allocation for coordinated targets was developed based on coverage and resolution for the instruments rather than direct allocation of data volume. The baseline and floor scenarios were updated based on desired coordinated target strategy.

Due to the study guidelines to primarily focus on Europa science, a limited effort was made to understand the feasibility of, and constraints on, science data collection of the Jupiter system tour. Simple coordinated target observing strategies similar to those used for Europa science scenarios were used as place holders for imaging campaigns that might be used in a system tour. Trajectories for the tour which had been designed for minimum ΔV and radiation dose, were not optimized for tour science. The feasibility study used those trajectories as is to estimate the coarse science return for the mission. High-level conclusions and recommendations are given to indicate where deeper studies and system architecture modifications might be most beneficial.

G3. Ground System Architecture Context

The description of the ground system architecture in this appendix is intended to provide detailed information for the ground system elements, mission operations system, and the DSN scheduling rationale aspects of the mission not presented in the main body of the report. The descriptions of the mission design and flight system design are provided in §4 of the report and are not repeated here.

The ground system elements are the Deep Space Mission System (DSMS), which includes the DSN and several data processing and transport systems, and the mission operations system (MOS) for the project including the science planning, analysis, and archive functions. These descriptions are generic for JPL missions of the scope of EE and were used for cost estimation purposes. They are included for here for context.

The DSN scheduling rationale is described for all phases of the mission and is used for mission cost analysis and for Jupiter system tour and Europa science data return scenarios.

G3.1 Ground System

The ground system is illustrated in **Figure G-1**, and is made up of the people, processes,

software, and hardware necessary to successfully operate the mission. This figure shows the three major elements that make up the ground system, the NASA wide common services and capabilities provided through the DSMS; the project specific MOS with its underlying ground data system; and the science support elements.

G3.1.1 Deep Space Mission System

The DSMS handles the communication interface between the flight and ground systems. DSMS includes the DSN, the underlying interconnecting ground network, and the related services. The services support initial processing of the telemetry and the related data management and distribution of the telemetry data to specific interfaces, such as the science processing organization and spacecraft analysis teams.

The DSN will perform all tracking for this mission, starting shortly after launch. For launch support up through final injection burn the tracking system will consist of NASA Ground Network 9–12 m X-band ground stations used to support launches from Cape Canaveral Florida. The actual stations used depend significantly on the ascent trajectory. Once the DSN takes over the tracking duties it will follow a profile along the lines as described in **Table G-1**. The DSN currently consists of three complexes (Goldstone, USA; Canberra, Australia; Madrid, Spain), each with several 34 m stations and one 70 m station.

There is some concern about the availability of the 70 m stations during the science activities. The current 70 m stations were built in the 1960's and updated for many missions since then but have been, until recently, approaching their projected end-of-life. With the recent launch of New Horizons, funding has been provided to refurbish the 70 m stations, extending their projected end-of-life to 2025. In addition, there are plans in development to implement the 70 m equivalent capabilities, likely via arrays of smaller antennas, with implementation starting around 2010 with the goal of being operational by 2020. While opportunities will exist to increase mission performance using future capabilities, the operations scenarios assume only current or nearly delivered capabilities for the DSN.

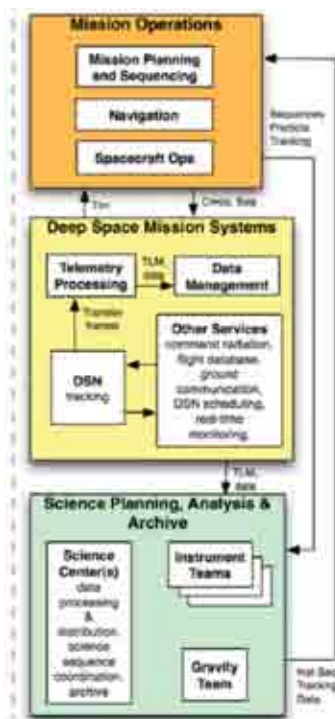


Figure G-1. Ground System Data Flow Diagram

Table G-1. Planned DSN coverage as a function of Mission Phase

DSN Coverage					
Description	Subnet	Year	Hours/ track	Tracks/ week	Duration (weeks)
Interplanetary Phase June 2015 to July 2021					
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				June/July 2015 30 day duration	
Launch to L+30	34m	2015	8	21	4
Cruise: Activities include science instrument calibrations, Venus and Earth gravity assist flyby science operations, trajectory correction maneuvers, and operations readiness testing.				July/August 2015 to December 2018	
Maneuvers & VEEGA	34m	2015–2019	8	10	11
Annual health checks	34m	2015–2019	8	7	5
Eng telemetry + Nav (through VEGA)	34m	2015–2016	8	3	41
Eng telemetry + Nav (till JOI – 30m)	34m	2016–2018	8	2	124
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 determine satellite ephemerides prior to pre-JOI Ganymede flyby.				January 2019 to JOI (July 2021)	
Eng telemetry + Nav (till JOI – 2m)	34m	2019–2021	8	3	123
JOI Approach Heavy tracking**	34m	2021	8	21	3
JOI Approach Light tracking**	34m	2021	8	14	3
JOI	34m	2021	8	20	2*
	70m		8	1.5	
Jovian Tour July 2021 to June 2023					
The phase is characterized by continuous science observations of the Jovian system and multiple (20+) flybys of major Jovian satellites. The final month of the phase is dedicated to targeting maneuvers in preparation for EOI.				JOI to EOI (July 2021 – June 2023)	
Jupiter System Science	34m	2021–2023	8	7	55
Fly-by Prep & Science	34m	2022–2023	8	14	44*
(22 fly-bys)	70m		8	3	
Europa Science June 2023 to June 2024					
Begins after achieving the primary science orbit and continues for 100 Eurosols (1 year). All high priority science goals are achieved in this phase.				June 2023 – June 2024 (1 year)	
EOI	34m	2023	8	20	2*
	70m		8	1.5	
Campaigns 1,2,3	70m	2023	8	21	13*
Ka-band Radio Science	34BWG		8	7	
Campaign 4	70m	2023–2024	8	7	39
Extended Europa Science June 2024 +					
Begins after the Focused Europa science phase ends. End date is dependent on negotiated funding period, flight system health, and remaining propellants.				June 2024 +	
Extended Orbital Science	70m	2024+	8	7	+
*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.					

In addition to the DSN, DSMS also provides services for working with the DSN. These services include telemetry processing and distribution, commanding, real-time monitoring and control, scheduling, and ground communications infrastructure. The

telemetry services will take the bit-stream as received at the DSN stations and convert it to level 0 formats (as the data appeared on the flight system prior to transmission). The telemetry system also performs additional processing to separate the instruments data

from the spacecraft data, stores the data in the project database for non-real-time analysis, and distributes telemetry data to the appropriate customers. The command service takes the command files generated by the MOS and radiates them to the flight system. The real-time monitoring and control team, also known as the mission control team, act as the interface between the mission and the DSN operations, and provide ongoing monitoring of the telemetry being received and of the command radiation activities, ensuring timely responses to problems in communications. Scheduling services ensure the project is able to get the DSN tracking resources needed routinely and for emergencies and are key to resolving conflicts with other missions over the limited resources of the DSN. Finally a critical, but often overlooked service is the ground communications network support. This final service provides as a minimum the communications between JPL and each of the DSN complexes and voicenet used by the project. More frequently this service is also extended to implement and support remote science or spacecraft operation centers. A key part of this support are network system administrators that ensure the continued

functioning of the network, network security, and voice communications.

G3.1.2 Mission Operation System

The MOS is made up of the project specific people, processes, software, and hardware used to operate the spacecraft and instruments, and for processing, storing and archiving the data associated with operating the spacecraft and instruments. Key elements of the project specific elements of the MOS include: the infrastructure support, spacecraft operations and analysis, navigation support, mission planning and sequence development, and training. **Figure G-2** shows the functions are flow of products among the MOS elements in the project.

The infrastructure support includes the system administrators, developers, and supporting hardware. Prior to launch the multi-mission Ground Data System (GDS) is adapted across all elements of the ground system to handle the mission specific functions and requirements. In addition, after launch the underlying multi-mission GDS undergoes periodic revision, about every 18 months, changes to the GDS will need to be made and tested as needed by supporting programmers. Typically every 3 to 4 years the GDS

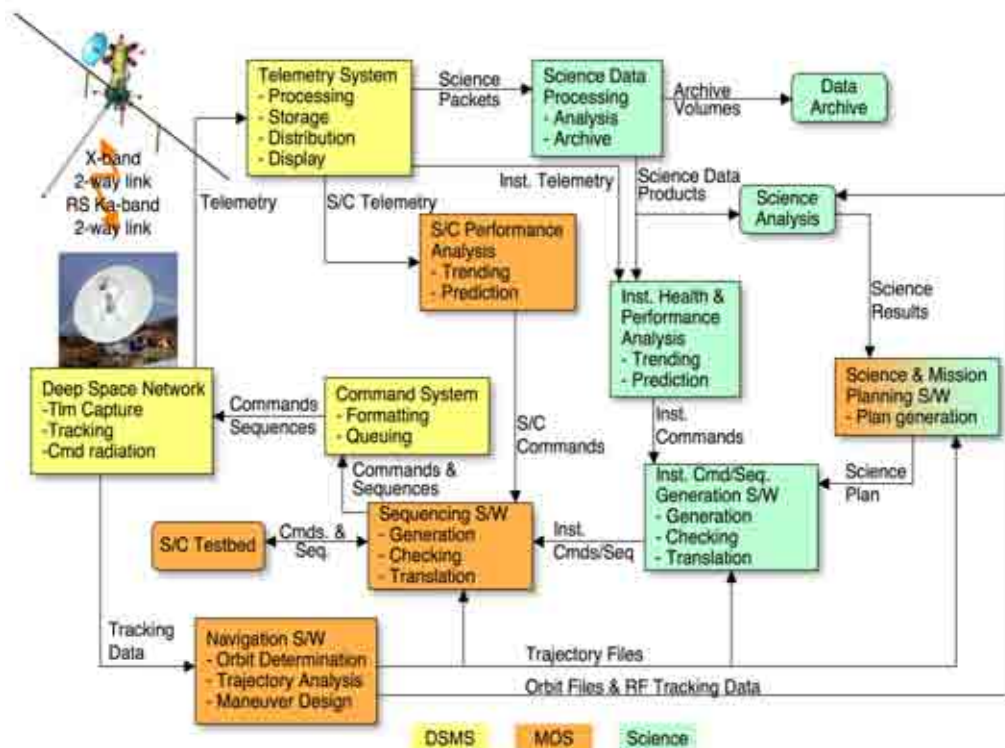


Figure G-2. MOS Function and Product Flow Diagram

computers and related hardware will need to be replenished to ensure that the hardware and operating systems support will be available during flight operations.

Spacecraft operations teams monitor spacecraft health and develop sequences for the spacecraft. The spacecraft subsystem engineers use the spacecraft engineering telemetry to perform general spacecraft health analysis and trending. The spacecraft subsystem engineers also participate in fault diagnosis, anomaly resolution, and prediction of future behavior, and sequence development and review.

The navigation team performs trajectory analysis and design, and will also support in the Europa Gravity mapping. The navigation team performs the orbit determination and trajectory analysis for the flight system using DSN RF data and, if needed, on-board imaging data. The navigation team also coordinates with instrument and spacecraft teams to implement planned propulsive maneuvers and reaction wheel de-saturation burns, predict flyby geometry and timing parameters, and plan future mission phase trajectories.

Mission planning is an ongoing function for the life of the mission and involves the cross-project coordination, planning and analysis of the trajectory design, mission timelines, and the major activities during each of the mission phases. This is performed with membership across the project including support from spacecraft, navigation, instrument and science teams. Once the flight system is operational, mission planning coordinates the refining of trajectories and activities to compensate for changing plans and evolving flight system characteristics, and to fine-tune specific events such as flybys, checkouts and instrument calibrations.

Training activities are required to maintain personnel skill levels and to prepare for mission operations. Activity planning, uplink product generation, flight and ground system software updates and testing, operations rehearsals and Operation Readiness Tests (ORT) support personnel training and readiness. These activities validate procedures and prepare the teams for upcoming critical events. During ATLO, missions typically conduct ORTs and other test and training

activities for launch, the first major maneuver, and for any mission critical event that could cause a loss of mission if done incorrectly. For the long duration of EE mission skill retention issues will necessitate additional training. Team training activities will be planned at regular intervals and will include post launch training activities and ORTs for each of the gravity assist encounters, the first Ganymede flyby, JOI, Europa approach, EOI, and Europa mapping campaigns.

Sequences will be developed by many teams and will be centrally integrated and tested. The spacecraft team develops the sequences for the spacecraft based on the mission plan, inputs from navigation, and the results of subsystem analysis and trends. The instrument operations teams create sequences for the instrument based on mission plans and science observation plans, coordinating with other instrument teams and the spacecraft team to ensure proper sharing of resources. These sequences are integrated together and tested to ensure that they do not violate flight rules, endanger the flight system, and will function correctly.

Science teams perform quick analysis of the returned science products within hours of data receipt. The quick analysis products would be used to support near term data collection strategies and to guide the longer-range observation plan updates.

The project science working group (PSG) leads science teams in setting up the overall science observation plan that will be used for the development and operation of the mission. Science observation planning is likely to evolve over the life of the mission as conditions change and spacecraft and instrument health change.

Instrument operations teams bridge the science teams and spacecraft operations. The science teams provide the direction for what the instrument observations are to be based on the mission and science plans. The spacecraft team provides the information on the spacecraft state and attitude, resources available, and any potential conflicts that may be encountered. The instrument operations team ensures that all instrument sequences meet science goals, are fully integrated, tested and successfully uplinked to the flight system.

G3.2 DSN Scheduling Rationale

The amount of tracking for this mission is significant due to the duration of the mission and the science volumes collected at Europa. The duration of 9 years is illustrated in [Figure G-3](#). The DSN tracking profile used for the current trajectory is summarized in [Table G-1](#). The profile, like the trajectory, is notional and provided only as a way of demonstrating the proof-of-concept, both will change and evolve over the course of project development.

Launch and Early Operations

Immediately after launch is an intense month of flight system deployment, checkout, and critical maneuvers. This period will use round-the-clock tracking by the DSN 34 m subnet to support the commanding, flight system telemetry, and RF navigation data needed for these tasks. During this phase the flight system developers are monitoring the deployments and performing their final in space tests and handing the flight system over to the flight team. The navigation team compares the actual launch performance versus the predicted, reviews RF data and alters the maneuver design to ensure the flight system will achieve the planned trajectory that will take it to Jupiter.

Cruise

The duration of cruise drives the tracking to be economical and still ensure safe delivery to Jupiter orbit. For the first year, three passes per week would provide the necessary tracking needed for navigation analysis and flight system characterization activities. For gravity assists or maneuvers the tracking will be augmented around the event to provide at least

twenty 8-hour passes for the 2 weeks surrounding the event. Fly-bys will also be used to test science and instrument operating procedures, in early preparation for the Jovian tour. After the first year tracking can generally be decreased to 2 or fewer 8-hour passes per week. With annual weeklong intensive spacecraft and instrument health checks, to ensure all is well. These health checks usually require 1 week of daily 8-hour passes. Though not explicitly called out, Δ DOR tracks will be scheduled periodically and prior to planet and satellite encounters.

About 18 months before JOI, tracking frequency is increased to handle the operational needs for JOI and the tour. This tracking will be used for flight software loads and provide RF tracking data to support increased orbit determination and trajectory analysis work for JOI, as well as some early Jovian system science. Approach to JOI is accompanied by significantly increased tracking including Δ DOR. At the time of JOI, 70 m tracking support will be used to augment 34 m tracking to provide the best reception available at burn attitudes.

Tour

Once in Jupiter orbit, tracking goes to a steady state of daily 8-hour 34 m passes, intended to support Jovian system science data collection and navigation. This routine is augmented around fly-bys to support the final navigation analysis and increased science. During and right after each fly-by, tracking is augmented with DSN 70 m antennas to maximize science return and improve navigation analysis accuracy.

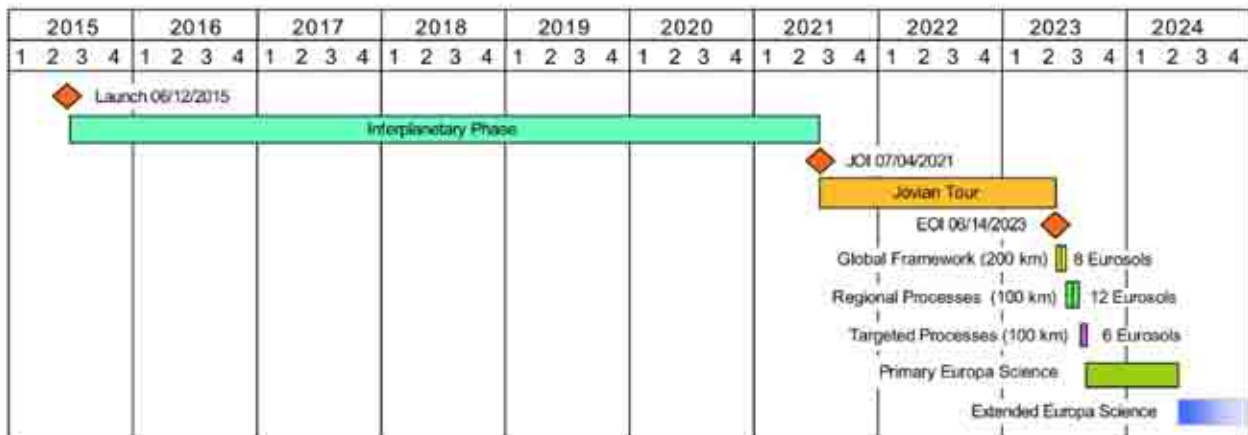


Figure G-3. Europa Explorer Mission Phase Timeline

Europa Mapping

The tour ends with Europa orbit insertion. Once in orbit, DSN tracking is increased to continuous 70 m tracking for 3 months to maximize science return. Focused Europa science will continue beyond the initial 3 months of science but with reduced tracking. The next 9 months will be targeted science and will provide key Europa science but use less tracking; one 70 m pass per day versus round the clock tracking.

In addition to the instrument based science observations, Europa gravity science will be performed during first 12 months in Europa orbit using the radio science capabilities of the flight system and DSN. Gravity science will use coherent, two-way Ka and X-band Doppler data. The 70 m can support the coherence X-band up and down, however, the Ka-band uplink passes currently require Goldstone's 34 m BWG, DSS-25, with the only Ka-band transmitter in the DSN.

Extended Europa Science (not costed)

At the end of the one-year prime Europa science activities the flight system will still have significant radiation margin available to enable months of additional operation around Europa. To make use of this opportunity, daily 8-hour 70 m passes could be used to support the continued observations (not yet planned or costed). These tracks would return the science observations made and support the navigation activities needed to maintain a stable orbit around Europa. This phase could continue until the flight system becomes inoperable or until the project is terminated. The present notional concept does not have additional Ka-band radio science and so the 34 BWG is not scheduled in this period.

G4. Scenario Analyses

The 2006 EE study examined operations concepts for the collection and return of large volumes of science data with highly constrained on-board data storage. The current study has a planning payload that can generate similar data volumes with a similar variety of data types and rates. Conclusions from the earlier study were applied as needed to the current study. The data collection tool used for the earlier study was updated and modified for the new planning payloads and used to

develop operations scenarios for science data collection and return.

The current study also has similar issues with mass memory depth. While emerging CDRAM memory components are somewhat less massive and power hungry than last year's baselined SRAM components, their performance is still unknown and they make large, massive and power hungry SSRs. The decision was made to allocate 1 Gb of SSR in the system design to science for data collection and return. Because of this, the operations constraints needed by the previous study were carried forward. They include (for the Europa Science phase):

- Downlink all data on the orbit collected
- Collect data mainly during downlink sessions
- Preclude mass memory allocations for data retransmission
- Schedule continuous DSN 70 m tracking (or equivalent)
- Use X-band for highest link reliability (based on weather)

These operations constraints remove consideration for data retransmission, discontinuous DSN coverage, and prioritizing and queuing of data products. On-the-fly data reduction, compression, processing, packetization and management can still be accommodated and is necessary in most cases. Analysis based on these recommendations showed that mass memory allocations of significantly less than one Gbit could be used while allowing considerable flexibility in data collection among instruments.

The simulation tool used for scenario analysis was adapted from the tool used last year. The planning payload instruments and instrument characteristics were incorporated and a second orbit was added to the minute-by-minute simulation. Methods for evaluating different orbit periods for different science campaigns, different data rates for each orbit, and data set asides for coordinated target data collection were incorporated.

G4.1 Floor Scenarios

During SDT meetings, science objectives were developed and instrument characteristics for the floor planning payload were developed.

Simulations were run to determine how well scenarios under discussion were performing. In this way, it was discovered that instrument data rates were too high for single orbit strategies but by alternating orbits for certain instruments, global imaging coverage and profile distribution would meet science goals. **Table G-2** shows the instrument characteristics of raw data rate, data reduction factor, observation duty cycle and generated data volumes per orbit for the floor planning payload. The example shown is for Campaign 1 at 200 km orbit altitude. Campaigns 2, 3, and 4 have similar characteristics but are at 100 km orbit altitude. Some instrument rates are twice as fast at the lower altitudes as the pixel rates are faster due to range and ground speed.

Figures G-4 through **G-6** show the floor data flow simulation results for Campaigns 1,

2 and 3. The red plot line shows the available accumulated downlink data volume (occultations are shown and include DSN lockup times). The green line shows the data collected as an accumulation to compare to the downlink capability. The dark blue line shows the state of the SSR at each minute. Each instruments data collection scenario is represented in the plot and the simultaneous and accumulated impacts are characterized.

The examples show accumulation in the SSR only during occultations. Operations constraints allow only a few low rate instruments to operate during occultations. These scenarios show only a 10–15% depth of use on the SSR and only during occultations. There is ample room for coordinated target data collection for either the ~400 Mb imaging type or the 900 Mb radar type on most orbits.

Table G-2. Floor Scenario Instrument Inputs – Rates, Reduction Factors, Duty Cycles

Inputs	WAC	MAC	IRS	IPR	TI	LA	PPI	MAG
Raw data rate (Mb/s)	0.1	1.5	0.03	30	0.004	0.002	0.002	0.0025
Mapping orbit duty cycle	40%	0%	40%	25%	100%	100%	100%	100%
Data reduction rate	4	4	2.5	215	2	1	1	1
Uncompressed Dvol (Mb)	336	0	99	62100	33	17	17	21
Compressed Rate (Mb/s)	0.025	0.38	0.012	0.140	0.002	0.0020	0.0020	0.0025
Total Dvol/Orbit #1 (Mb) (0.11)	84.0	0.0	40.3	0.0	16.6	16.6	16.6	20.7
Total Dvol/Orbit #2 (Mb) (0.11)	0.0	0.0	40.3	293.0	16.6	16.6	16.6	20.7
Total Dvol/2Orbit (Mb)	84.0	0.0	80.6	293.0	33.1	33.1	33.1	41.4

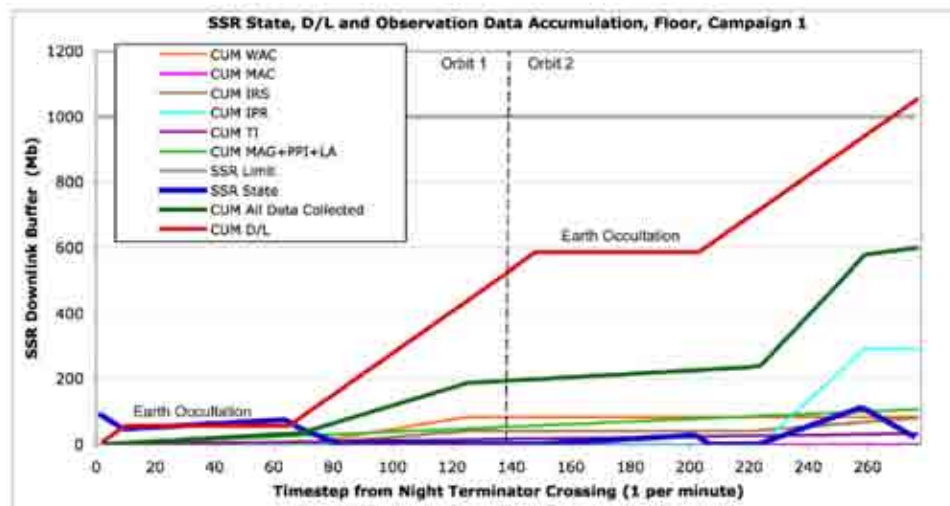


Figure G-4. Floor Data Flow Simulation Results for Campaign 1

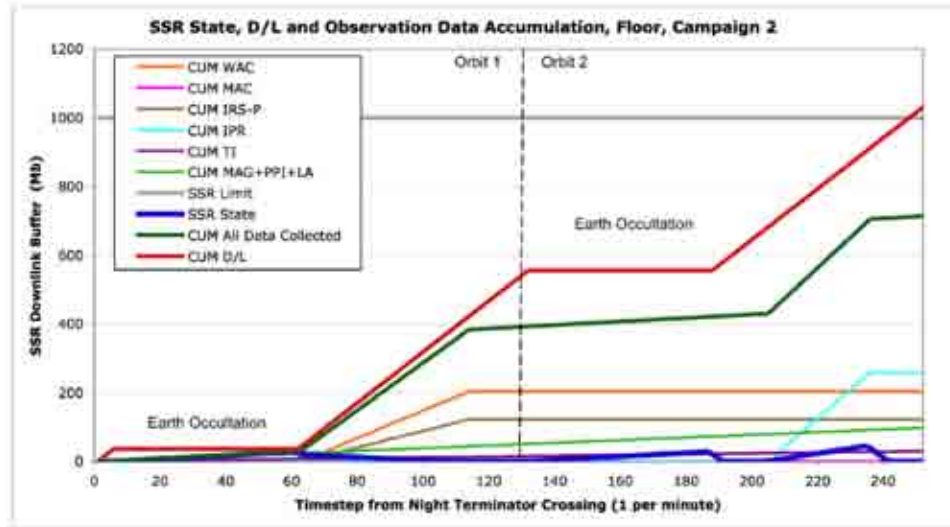


Figure G-5. Floor Data Flow Simulation Results for Campaign 2

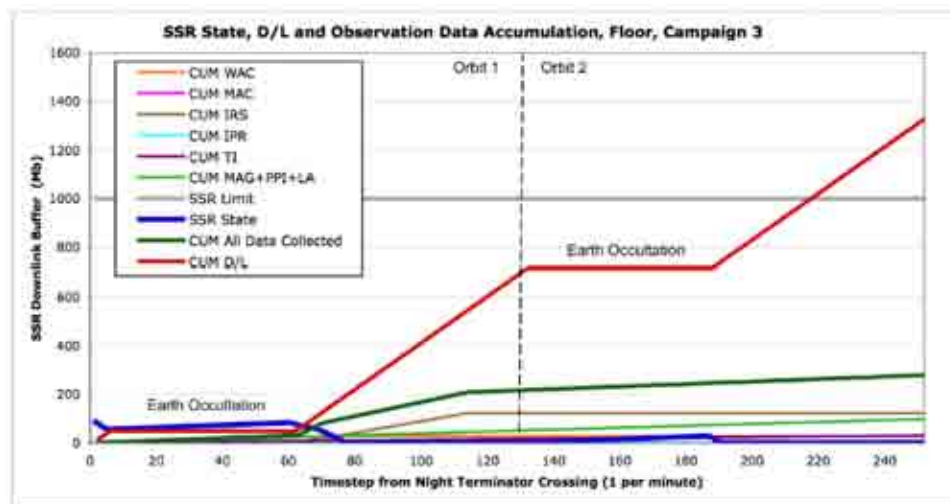


Figure G-6. Floor Data Flow Simulation Results for Campaign 3

The small difference between the downlink capacity and the accumulated data collected (red and green lines) shows that at the beginning of Campaign 2 (Figure G-5), few targets can be collected. This is due to the change in orbit period (from changing altitude from 200 km to 100 km) and occultation duration (they are relatively longer due to the lower period and closer orbit geometry). Campaign 3, on the other hand, shows most of its data as available for coordinated target observing. Campaign 4 was developed very late in the study and was not simulated. Its behavior is very similar to Campaign 3.

The mission performance of the floor mission is shown in Table G-3. Performance in this context is represented by measures of daily data volume for global mapping and profiling goals and for coordinated targets and the totals of same for each campaign. The number of targets per day and per campaign are also shown as are percentage distributions for the different representative instruments.

G4.2 Baseline Scenarios

After the floor scenarios were developed, the SDT began developing the baseline science scenarios. The planning payload and instrument characteristics were augmented to

be able to meet the baseline science goals. Simulations were run to determine how well scenarios under discussion were performing. **Table G-4** shows the instrument characteristics of raw data rate, data reduction factor, observation duty cycle and generated data volumes per orbit for the baseline planning payload. The example shown is for Campaign 1 at 200 km orbit altitude. Campaigns 2, 3, and 4 have similar

characteristics but are at 100 km orbit altitude. Some instrument rates are twice as fast at the lower altitudes as the pixel rates are faster due to range and ground speed.

Figures G-7 through **G-9** show the baseline data flow simulation results for Campaigns 1, 2 and 3. The red plot line shows the available accumulated downlink data volume (occultations are shown and include DSN lockup times). The green line shows the data

Table G-3. Floor Mission Performance – Data Volume and Number of Targets

Reference S/C (Floor)	Campaign 1						Campaign 2						Campaign 3						All Campaigns		
	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Total Targets	% total vol	Total Vol (Gb)
Data Volume	3.1	2.5				158	3.1	2.7				284	2.1	5.6							603
WAC	0.4		8%			12	0.4	0.0	7%			66	0.6		8%					15%	92
MAC¹	0.0	0.2	4%	11 T	295	7	0.0	0.3	5%	12 T	291	17	0.0	0.1	1%	1 T	21	1	606 T	4%	25
IRS²	0.4	1.4	32%	11 T	301	50	0.4	1.6	34%	12 T	295	67	0.7	0.1	11%	1 T	21	17	617 T	22%	135
IPR³	1.5	0.9	43%	1 T	28	68	1.5	0.9	42%	1 T	42	102	0.0	5.4	70%	6 T	126	113	196 T	47%	284
TI	0.2		3%			5	0.2		3%			7	0.2		2%			4		3%	16
LA	0.2		3%			5	0.2		3%			7	0.2		2%			4		3%	16
PPI	0.2		3%			5	0.2		3%			7	0.2		2%			4		3%	16
MAG	0.2		4%			6	0.2		4%			9	0.2		3%			5		3%	20

¹ MAC targets are 1 minute duration (71 km/min @200 km, 78 km/min @100 km)

² IRS targets are each 400x400 pixels, 128 Mb

³ IPR targets are each 30 Mb/s x 30 s, 900 Mb



Table G-4. Baseline Scenario Instrument Inputs – Rates, Reduction Factors, Duty Cycles

Inputs	WAC	MAC	NAC	IRS-P	IRS-I	IPR	TI	UVS-PL	UVS-I	LA	MAG	INMS	PPI
Raw data rate (Mb/s)	0.4	3	15	0.03	30	30	0.043	0.005	4	0.012	0.004	0.0015	0.002
Mapping orbit duty cycle	40%	0.0%	0.0%	40%	0.0%	45%	80%	100%	0.0%	100%	100%	100%	100%
Data reduction rate	4	4	4	2.5	2.5	107	2	1	2	1	1	1	1
Uncompressed Dvol (Mb)	1344	0	0	99	0	111780	285	41	0	99	33	12	17
Compressed Rate (Mb/s)	0.100	0.75	3.7500	0.012	12.000	0.280	0.022	0.0050	2.0000	0.0120	0.0040	0.0015	0.0020
Total Dvol/Orbit #1 (Mb) (0.32)	336.0	0.0	0.0	40.3	0.0	0.0	143.2	41.4	0.0	99.4	33.1	12.4	16.6
Total Dvol/Orbit #2 (Mb) (0.32)	0.0	0.0	0.0	40.3	0.0	1059.8	143.2	41.4	0.0	99.4	33.1	12.4	16.6
Total Dvol/2Orbit (Mb)	336.0	0.0	0.0	80.6	0.0	1059.8	286.4	82.8	0.0	198.7	66.2	24.8	33.1

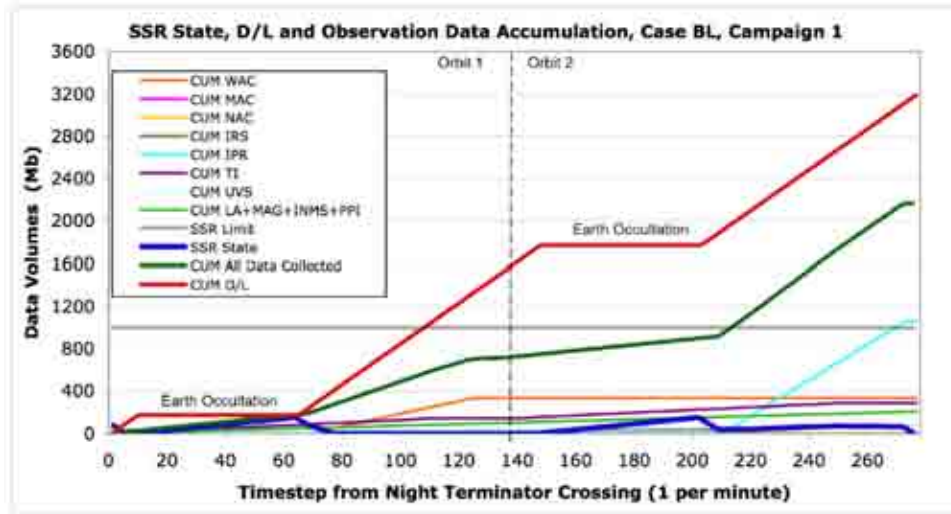


Figure G-7. Baseline Data Flow Simulation Results for Campaign 1

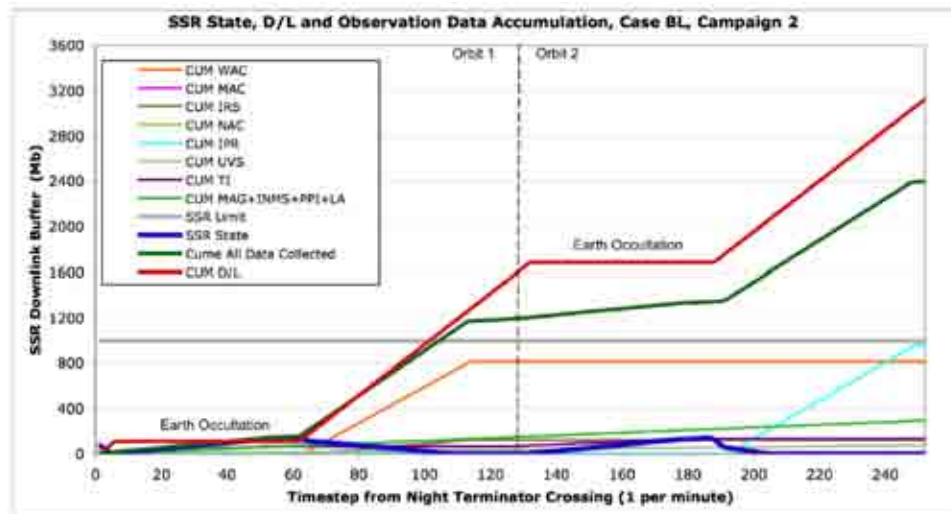


Figure G-8. Baseline Data Flow Simulation Results for Campaign 2

collected as an accumulation to compare to the downlink capability. The dark blue line shows the state of the SSR at each minute. Each instrument's data collection scenario is represented in the plot and the simultaneous and accumulated impacts are characterized.

The examples show accumulation in the SSR only during occultations when only a few low rate instruments are operating during. These scenarios show only a 10–15% depth of use on the SSR and only during occultations. There is ample room for coordinated target data collection for either the ~400 Mb imaging type or the 900 Mb radar type on most orbits.

The small difference between the downlink capacity and the accumulated data collected (red and green lines) shows that at the beginning of Campaign 2 (**Figure G-8**), few targets can be collected (once every other orbit). This is due to the change in orbit period (from changing altitude from 200 km to 100 km) and occultation duration (they are relatively longer due to the lower period and closer orbit geometry). By the middle of Campaign 2, data rate improvements (due to Earth Europa range reductions) and the completion of global color mapping, cause the available data volume to increase and the WAC data volume needs to decrease. Daily

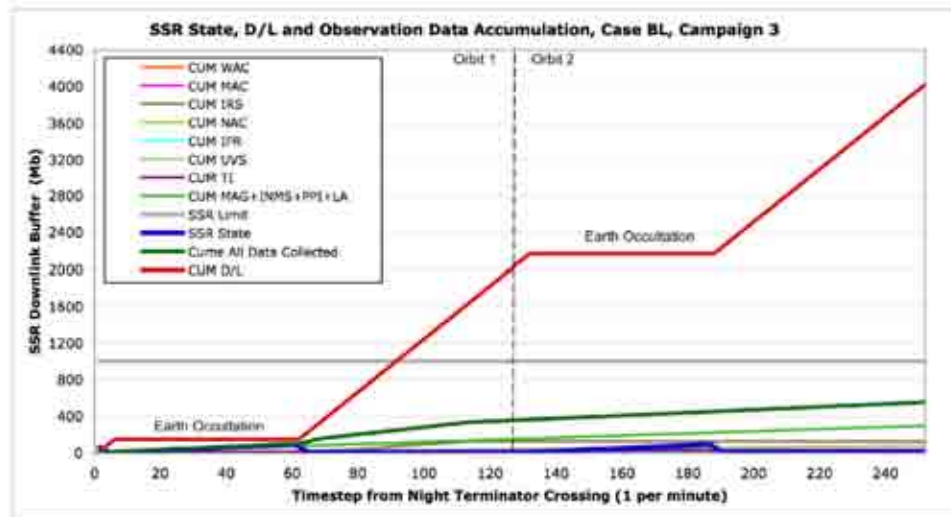


Figure G-9. Baseline Data Flow Simulation Results for Campaign 3

targeting will increase to an average more than one per orbit in this timeframe and beyond. Campaign 3 shows most of its data as available for coordinated target observing. Campaign 4 was developed very late in the study and was not simulated. Its behavior is very similar to Campaign 3.

Coordinated targets are collected only when analysis of upcoming data takes and downlink data volume shows there is sufficient data to collect one. Target locations will be selected based on lists of preselected targets by type and extent and can be automatically selected to fill data volumes as they become available. This planning occurs on the ground approximately with sequence uplink once per week, and with ephemeris updates several times per week.

The mission performance of the baseline mission is shown in [Table G-5](#). Performance in this context is represented by measures of daily data volume for global mapping and profiling goals and for coordinated targets and the totals of same for each campaign. The number of targets per day and per campaign are also shown as are percentage distributions for the different representative instruments. The totals column shows that the baseline scenario enables collection of data over more than the desired 1000 targets in the first 3 campaigns. The values for IPR, UVS and NAC are different reflecting different goals for their targets. IPR takes very large observations (900 Mb) and cannot collect at the same time as the imagers (a larger SSR would enable

simultaneous targeting for a subset of the total target set). UVS collects 2 stellar occultation targets at the limb of Europa each day. The NAC will collect high resolution target sets for characterizing potential future landing sites. This occurs in Campaign 3 and is likely to extend well into Campaign 4.

For both the floor and baseline missions (they have the same trajectory profile), the coverage of Europa is similar. Examples of global coverage for the WAC in baseline Campaign 1 is shown in [Figure G-10](#). Global color coverage is complete in 3 eurosols or about 10 days. Global stereo coverage can be achieved in another 10 days, leaving 8 days in Campaign 1 for margin. This margin is useful for orbiter and instrument checkout and trim maneuvers immediately after EOI. A delay in mapping startup of several days can be tolerated and still achieve the Campaign 1 science goals.

The WAC coverage for Campaign 2 is shown in [Figure G-11](#). Because the WAC swaths are narrower due to lower orbit altitude, 7 eurosols are needed to achieve global coverage. Global stereo goals can be achieved in the remainder of Campaign 2. Small gaps in coverage are planned into the data allocations for Campaign 3.

[Figure G-12](#) shows the ground track coverage for the 200 km orbit used in Campaign 1. This notional orbit has a 4 eurosol repeat pattern. This can be seen in the narrow spacing between adjacent ground

tracks in the figure. Other repeat patterns will be considered in future studies. The ground track pattern can be used as a surrogate for LA, TI, IR spectral profiles, UV spectral profiles and IPR observations. The white box in the figure represents 10×10 degrees on the

surface. Each degree on the surface is about 27 km in distance for both latitude and longitude near the equator. The ground track separation in the first campaign will be 60–70 km at the widest points.

Table G-5. Baseline Mission Performance – Data Volume and Number of Targets

Reference S/C (Baseline)	Campaign 1: Global Framework						Campaign 2: Regional Processes						Campaign 3: Targeted Processes						Total Targets	% total vol	Total 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)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Avg Targ per day	Cam Tot Targ	Cam Tot 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			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	1026 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, 76 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

¹ MAC targets are 1 minute duration (71 km @200 km, 78 km @100 km)
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³ IRS targets are each 400x400 pixels, 128 Mb
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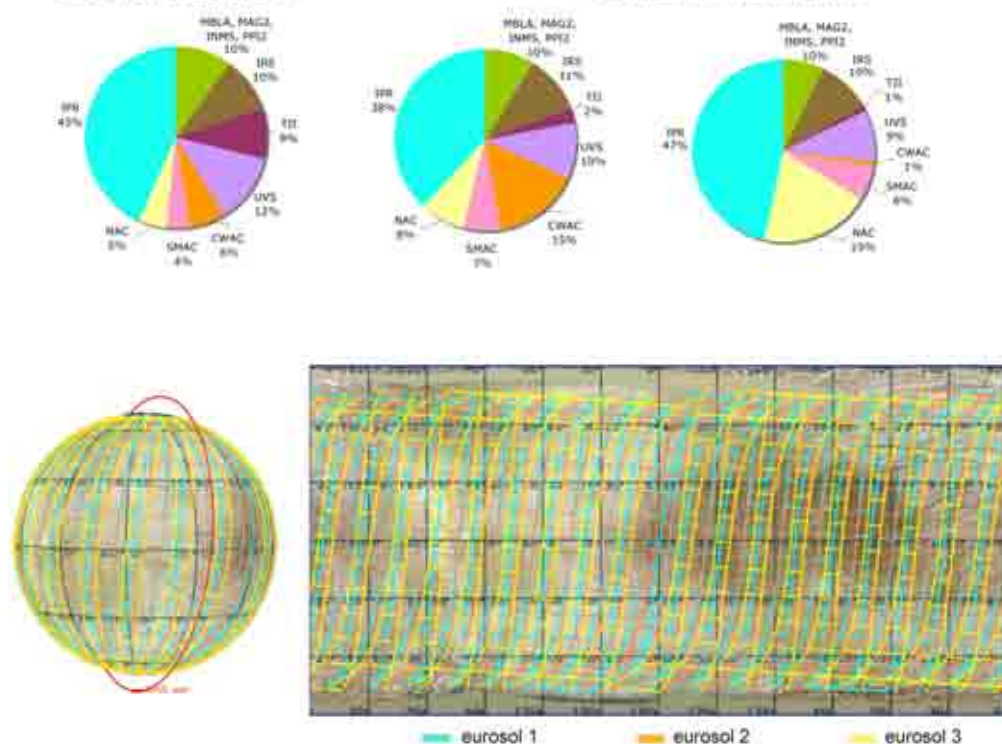


Figure G-10. WAC Coverage for 3 Eurosols in Campaign 1

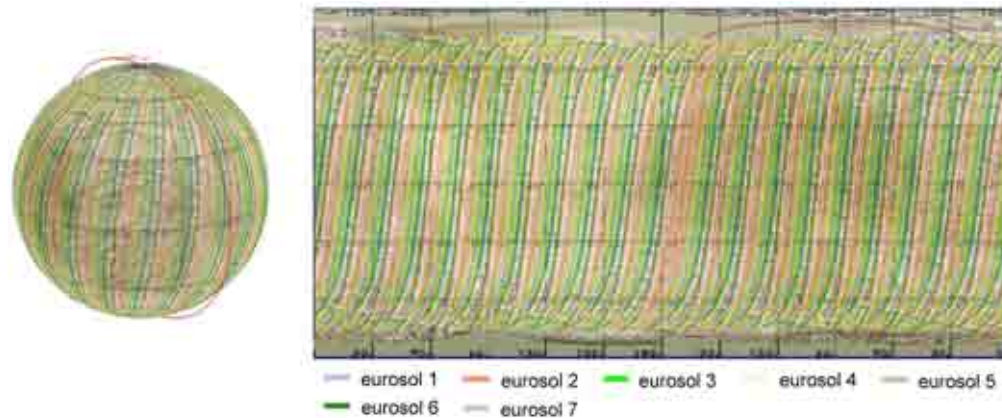


Figure G-11. WAC Coverage for 7 Eurosols in Campaign 2

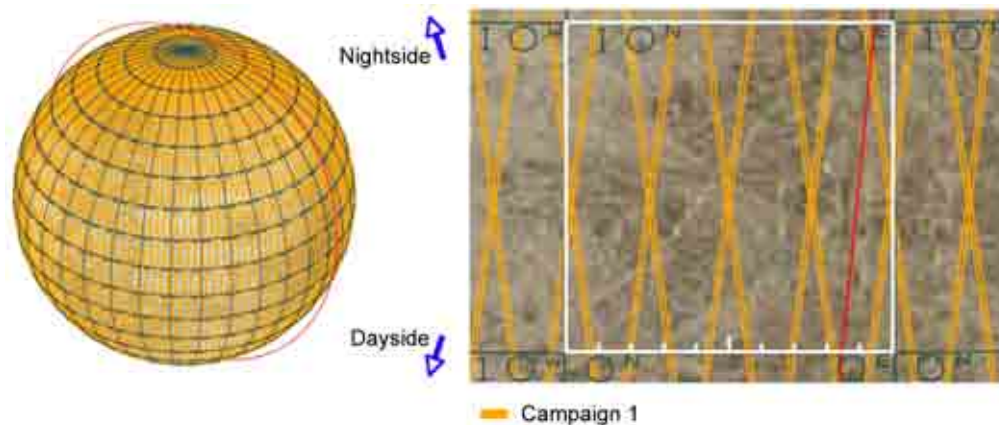


Figure G-12. Ground-track Coverage in Campaign 1

By the end of Campaign 3, the ground tracks will be densely scattered across Europa. Laser altimeter, thermal and spectral profiles will have grids finer than 1 degree on the surface and the radar sounder will have grids about half as fine. **Figure G-13** shows the ground track spacing for Campaigns 1–3. The colors show how the ground tracks build up by campaign.

Other repeat cycles will have considerably better performance as these have very close spacing at the repeat intervals. This allows for larger gaps in the grid. Other repeat cycles can be devised to reduce the gap size with small impacts to orbit altitude and period. Other considerations include alternating orbit repeat patterns vs repeat geometry for swath coverage and gap fill, and ideal repeat patterns for repeat pass stereo coverage.

G4.3 Jupiter System Science Analysis

The Jupiter system science opportunities exist as a result of the trajectory needed to reduce the required ΔV for EOI to feasible levels. The trajectory gradually reduces the flight system's orbital energy through 2 years of gravity assist flyby maneuvers at Ganymede, Callisto, and Europa. While not fully optimized, the tour portion of the end-to-end trajectory is typical of trajectories that have been optimized to minimize ΔV and radiation total dose. No consideration for encounter geometry for science was made. The resulting trajectory contains encounters with Callisto, Ganymede and Europa that can be considered typical for such trajectories. It is very likely that future studies will be able to design science optimized targeted and non-

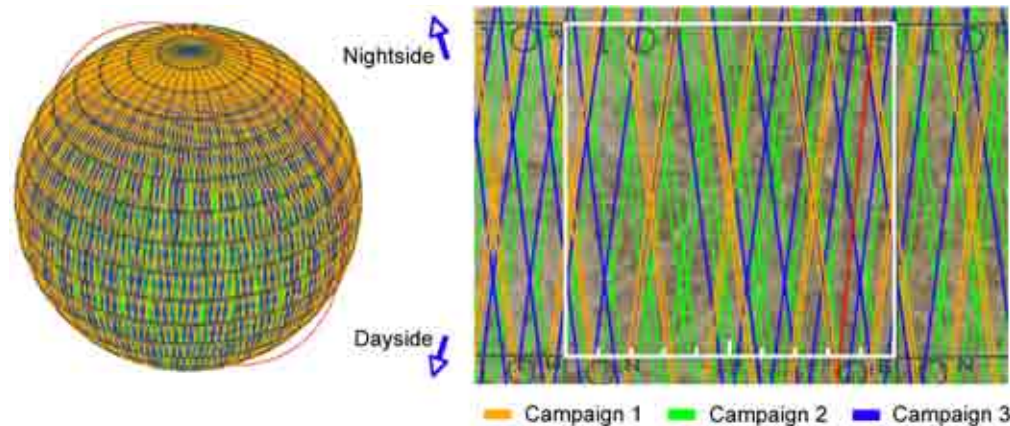


Figure G-13. *Ground-track Coverage in Campaigns 1–3*

targeted encounters for a small penalty of ΔV , radiation dose, and/or trip time.

The following analysis is representative of the types of geometries that could be used for observing during a Tour. The analysis is a cursory look at typical geometries and how they might be used with the EE planning payload to survey Jupiter and the Jovian satellite system. While the flight system is in Jupiter orbit during the tour, each gravity assist flyby typically happens within a day or two of a Jupiter closest approach. EE's ability to collect tour science is determined by the planning payload, on-board storage space, downlink rate, and DSN time. Gravity assist flybys have additional DSN tracking coverage scheduled, including 70 m stations, to increase data volume returned and navigation accuracy during an encounter. While the additional data volume is increased, the close ranges and high resolutions occur over such a short time period that on-board data storage becomes the most significant limiting constraint.

Around any given satellite encounter, the range to the surface will be less than 10,000 km for about 1 to 3 hours depending on the range and relative speed of the flight system to the target. At 10,000 km the narrow angle camera (NAC), for example will get 100m/pixel resolution, similar to the WAC in a 100 km Europa orbit. **Figure G-14** shows the pixel resolution vs range for the three imaging payloads.

During the closest approach portions of the encounter, where ranges of less than 10,000 km occur, the 1 Gb SSR science data allocation can support collection and return of

around 2–3 Gb. In a week where a satellite encounter and Jupiter flyby occurs, the tracking coverage and associated telecom rates typically support downlink of 10–30 Gb for the entire week.

In addition to the data volume that can be collected during the closest approach, the remaining downlink data volume capacity over the week 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, where NAC can get resolutions of 1–5 km/pixel. “Non-targeted” means that they are geometrically opportunistic and have no impact on the vehicle flight path.

Table G-6 summarizes the number and characteristics of the Jupiter observing, gravity assist encounter, and not-targeted observing opportunities during the tour.

Jupiter Opportunities

The Jupiter opportunities are well distributed across the Tour, facilitating observation of changing phenomena that span the length of the 2-year tour. Jupiter observing opportunities at less than 1 million km are relatively evenly spaced in time and occur on every orbit whether there is a satellite encounter or not. **Table G-7** summarizes the characteristics of 40 Jupiter opportunities during the tour that have range less than one million km.

Planned DSN coverage allows about 1.8 Tb to be downlinked during the tour. Of this, about half of the downlink is focused around

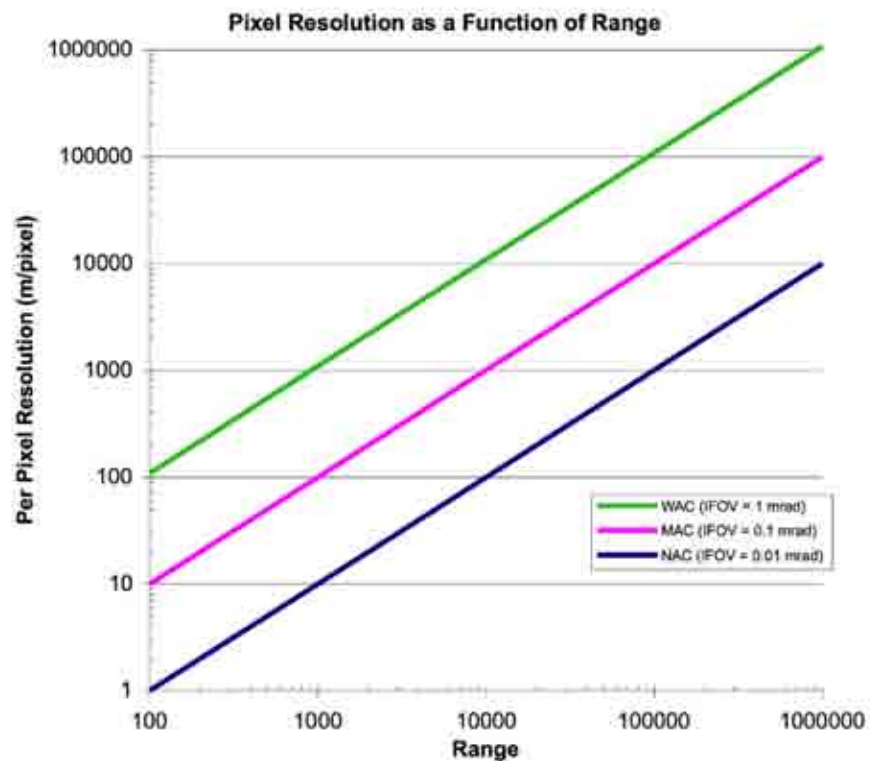


Figure G-14. Pixel Resolution as a Function of Range

Table G-6. System Science Observing Opportunities

	Opportunities	Ranges (km)	Phase angles (deg)	Ground Speeds (km/s)
Jupiter	40	560,000 – 1,000,000	10 – 100	
Encounters				
<i>Callisto</i>	4	370 – 3,600	80 – 120	2.8 – 4.7
<i>Europa</i>	5	100 – 2,800	60 – 100	0.4 – 1.9
<i>Ganymede</i>	14	450 – 8,050	70 – 170	1.2 – 6.9
Non-Targetted				
<i>Callisto</i>	1	325,000	70	
<i>Europa</i>	13	107,000 – 460,000	5 – 135	
<i>Ganymede</i>	7	28,000 – 430,000	55 – 114	
<i>Io</i>	17	276,000 – 490,000	8 – 174	

Table G-7. Summary of opportunities to observe Jupiter at less than 1 million km

Date	Closest Approach (km)	SC Speed wrt Jupiter (km/s)	Closest Approach Latitude	West Longitude of Closest Approach	Closest approach East Longitude	phase angle sun-body-sc (deg)
7/4/21	821906	140.6	1.7	90.24	269.8	70.9
1/6/22	781700	133.5	0.6	99.70	260.3	61.3
3/19/22	719104	122.5	0.2	215.14	144.9	67.2
4/17/22	687226	116.4	-4.2	334.34	25.7	70.7
5/8/22	709349	120.8	0.5	285.48	74.5	65.6
6/2/22	708185	120.6	0.5	343.49	16.5	62.3
7/5/22	831104	143.1	2.4	277.07	82.9	70.6
8/10/22	857370	148.1	-0.1	325.13	34.9	69.8
9/15/22	808258	139.2	-4.0	240.20	119.8	76.4
10/6/22	796495	137.4	-0.1	252.16	107.8	78.1
10/25/22	922784	160.6	-0.4	116.27	243.7	64.6
11/18/22	922222	160.5	-0.4	129.41	230.6	62.2
12/2/22	862301	149.9	-3.1	115.65	244.3	41.8
12/16/22	899888	155.9	-7.5	27.46	332.5	47.8
12/30/22	930657	162.8	-0.5	32.88	327.1	38.3
1/14/23	954224	167.1	-0.5	247.04	113.0	36.9
1/24/23	894137	156.7	-0.6	258.37	101.6	10.8
2/4/23	894673	156.8	-0.6	233.01	127.0	9.4
2/11/23	736722	128.2	-0.3	145.63	214.4	44.7
2/16/23	566657	96.2	0.1	79.73	280.3	84.0
2/21/23	566703	96.2	0.1	254.27	105.7	83.4
2/27/23	567210	96.3	0.1	60.85	299.2	84.5
3/4/23	561412	95.3	0.5	340.74	19.3	90.4
3/10/23	562689	95.5	0.5	294.37	65.6	91.3
3/15/23	557309	94.6	0.8	30.60	329.4	97.3
3/20/23	557445	94.6	0.8	168.69	191.3	96.7
3/25/23	570145	97.1	0.8	336.05	24.0	96.5
3/28/23	994399	179.1	-0.2	175.28	184.7	97.6
3/31/23	700706	122.0	-2.3	255.58	104.4	67.8
4/6/23	701205	122.1	-2.4	205.86	154.1	67.6
4/12/23	699964	121.8	-2.4	147.39	212.6	68.2
4/17/23	699502	121.7	-2.4	88.71	271.3	68.6
4/23/23	699191	121.7	-2.5	29.55	330.5	68.6
4/28/23	595786	101.2	-0.3	64.58	295.4	83.1
5/4/23	593902	101.6	-0.6	301.45	58.6	94.3
5/9/23	598058	102.3	-0.5	273.39	86.6	94.2
5/14/23	598832	102.5	-0.2	49.30	310.7	74.3
5/20/23	592948	101.8	-0.1	356.32	3.7	68.6
5/25/23	601298	103.5	-0.1	147.29	212.7	69.1
5/29/23	600973	103.4	-0.1	308.18	51.8	69.9

flybys at high resolutions. During the rest of the tour the data volume can be used to downlink data of non-targeted opportunities of Jupiter and its satellites as they become available within suitable ranges.

Non-Targeted Encounters

Non-targeted encounters are opportunities to observe satellites in the Jupiter system at

less than 500,000 km range. These opportunities are not specifically targeted in the mission design and the timing and number of encounters could be adjusted at varying cost in ΔV . The details of these non-targeted encounters are shown below in [Table G-8](#) through [Table G-10](#).

Table G-8. Summary of Europa non-targeted opportunities at < 500,000 km

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Europa	7/4/21	233126	2.1	8.3	167.48	84.0
Europa	7/5/22	262308	3.7	8.5	206.77	41.8
Europa	8/10/22	337577	5.5	1.0	218.80	22.9
Europa	9/14/22	227714	3.4	-12.9	198.77	56.1
Europa	10/6/22	341508	6.0	0.3	229.75	10.7
Europa	12/29/22	382669	8.6	-0.9	200.85	4.8
Europa	2/15/23	458108	2.7	-0.1	73.73	57.6
Europa	2/18/23	400261	12.2	0.1	163.20	66.9
Europa	3/19/23	364031	2.6	1.8	78.01	73.1
Europa	3/21/23	341080	10.7	-3.0	165.16	57.3
Europa	3/31/23	107362	2.7	-16.2	170.55	58.8
Europa	4/9/23	383542	11.3	14.0	187.43	135.6
Europa	4/19/23	344411	10.3	-9.6	171.18	75.2

Table G-9. Summary of Ganymede and Callisto non-targeted opportunities at < 500,000 km

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Ganymede	7/6/22	47984	5.5	50.0	68.38	111.2
Ganymede	8/10/22	119666	5.6	-0.1	25.72	114.1
Ganymede	12/16/22	184608	3.4	-78.1	0.43	104.3
Ganymede	2/15/23	351931	7.0	0.1	341.57	57.2
Ganymede	3/9/23	428925	9.4	0.7	358.26	75.9
Ganymede	5/17/23	27507	2.0	10.1	189.90	96.0
Ganymede	6/1/23	112068	0.8	1.5	353.39	54.6
Callisto	12/5/22	327140	3.4	68.8	325.59	68.9

Table G-10. Summary of Io non-targeted opportunities at < 500,000 km

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Io	2/10/23	437398	22.1	-0.1	190.41	95.1
Io	2/15/23	423989	22.4	0.1	199.48	174.0
Io	3/19/23	460398	24.8	1.0	194.12	145.3
Io	3/24/23	392239	20.9	2.7	196.20	163.1
Io	4/1/23	455307	23.3	-14.0	172.36	22.8
Io	4/6/23	364381	18.6	-10.9	174.74	41.0
Io	4/11/23	367361	19.1	4.3	186.69	104.6
Io	4/16/23	465107	23.8	12.7	191.12	152.0
Io	4/24/23	483054	25.0	-13.0	174.92	29.0
Io	4/29/23	439731	23.5	3.0	166.15	10.9
Io	5/5/23	435073	23.2	3.0	165.66	9.4
Io	5/10/23	393818	20.9	-0.3	166.03	16.4
Io	5/15/23	363469	19.1	-0.4	164.17	7.7
Io	5/21/23	340247	18.1	0.4	163.81	16.8
Io	5/23/23	441646	23.9	-0.3	190.22	165.3
Io	5/26/23	488939	26.6	0.3	174.96	73.4
Io	5/29/23	276099	14.4	-0.4	189.52	116.7

Encounter Opportunities

Several feasibility level analyses were conducted to explore the usefulness of EE payloads during gravity assist flybys or encounters. The EE payload is intended to collect data in a low altitude, near-circular orbit of Europa where ground speed, altitude and lighting conditions are very similar orbit-to-orbit. In the tour, however, ground speeds, altitudes, and lighting conditions vary drastically through each encounter. For most encounters, these conditions are within reasonable limits for the types of instruments in the planning payload, particularly if they have been designed for the expected ranges. To effectively use some of the instruments, flight system slews may be needed. Two bounding case flyby examples were studied to determine how, generally, the observations might be acquired. For the two representative cases, slew rates to maintain tracking of the ground with the instruments and the gimbal rates needed to keep the HGA pointed on the Earth were also within reasonable limits

compared to conditions in Europa orbit. Because of data volume storage constraints, a strategy of alternating imaging and IPR sub-surface sounding was employed to ensure reasonable observations of each type. This only becomes an issue when the flyby range was close enough to use the IPR and there are many encounter geometries with poor lighting that are useful for radar coverage.

Table G-11 summarizes the dates and geometry of the flyby encounters. Details of these encounters with potential for science observations are provided including latitude and longitude, closest approach altitude, ground speed, and lighting phase angle.

Figures G-15 through **G-17** show 30-minute ground tracks centered on closest approach for the targeted encounters of Callisto, Europa, and Ganymede. In total there are 14 Ganymede encounters, 4 Callisto Encounters, and 5 Europa encounters before EOI.

Table G-11. Summary of the dates and geometry of the flyby encounters

Satellite Encounter	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	East Longitude of Closest approach	phase angle sun-body-sc (deg)	Ground Speed (km/s)
G0	4-Jul-2021	500	8.15	0.15	235.80	81.0	6.8
G1	6-Jan-2022	1500	7.00	30.70	242.70	70.0	4.4
G2	18-Mar-2022	120	7.00	8.00	251.00	72.0	5.5
G3	16-Apr-2022	100	7.00	64.60	269.80	87.7	6.7
G4	7-May-2022	100	6.95	-75.40	89.24	93.0	6.7
G5	14-Sep-2022	100	5.70	48.60	251.60	93.0	5.6
G6	5-Oct-2022	1190	5.40	-77.85	228.53	88.0	3.9
G7	19-Nov-2022	958	4.38	-12.00	298.70	141.0	1.8
G8	3-Dec-2022	100	4.55	-73.35	193.70	98.0	4.2
G9	15-Jan-2023	2695	3.34	2.30	300.77	172.0	1.7
G10	5-Feb-2023	1312	3.51	3.69	275.69	156.0	2.3
G11	12-Feb-2023	2594	3.34	3.03	248.50	127.2	1.7
G12	28-Mar-2023	1139	3.17	-55.84	33.24	70.0	2.9
G13	25-Apr-2023	200	3.16	47.00	340.70	101.0	1.2
C1	4-Jun-2022	400	6.51	44.00	83.00	82.0	4.7
C2	8-Jul-2022	1909	6.37	-86.00	12.00	87.0	2.8
C3	23-Oct-2022	3095	5.38	2.30	100.80	119.0	2.8
C4	27-Dec-2022	1159	4.23	-66.10	133.70	109.0	4.0
E1	27-Feb-2023	6069	2.70	33.40	309.20	77.0	0.5
E2	10-Mar-2023	8773	2.70	24.40	307.70	69.0	0.4
E3	28-Apr-2023	1451	2.45	-7.30	357.00	99.0	1.8
E4	9-May-2023	1500	2.39	22.10	175.82	86.0	1.9
E5	20-May-2023	669.5	1.96	15.50	213.00	46.0	0.6

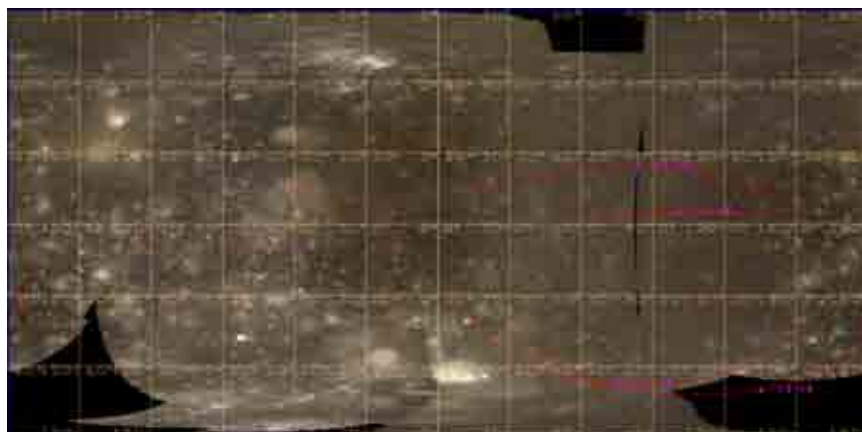


Figure G-15. Callisto Flyby encounters



Figure G-16. Europa Flyby encounters

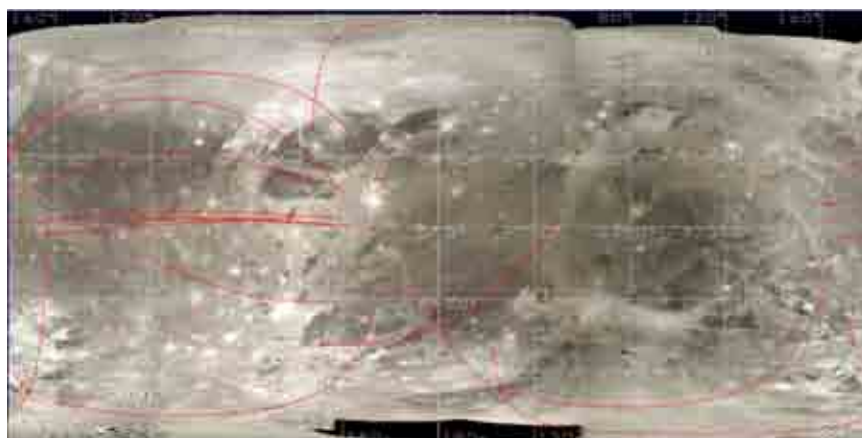


Figure G-17. Ganymede Flyby encounters

Representative Encounter Data Collection Strategy

Depending on flight system speed relative to the encounter body, time between 10,000–100,000 km, varies but there is generally sufficient time below 10,000 km to empty and drain the 1 Gb science allocation two to three times.

Since some encounter closest approaches do not get close enough to get meaningful data from the radar (~2000 km altitude), and other closest approaches occur partially or completely during eclipse, there are ample opportunities to alternate the primary focus for data volume collection of the various flybys between the IPR sub-surface soundings and the imaging payloads. Representative target strategies for Jupiter system encounters showing both an imaging focused flyby and a radar focused flyby are shown in [Table G-12](#). They are similar in data volume to comparable target strategies used in orbit with the addition of a WAC image for context on the imaging focused encounters, and a MAC image to provide context to the radar driven encounters.

Analysis of several Ganymede flybys was performed to look at two bounding cases: a fast, close encounter with 70 km closest approach and 6.7 km/s speed with respect to Ganymede; and a distant, slow encounter with 2700 km closest approach and 3.2 km/s speed with respect to Ganymede. These provide bounding cases are representative of encounters at Ganymede.

For the first case of closest approach of 70 km, the range is less than 100,000 km for about 11 hours, while the closest approach is less than 10,000 km for only a little over one hour. At less than 100,000 km, the NAC and MAC can image with resolutions of 1 km/pixel and 10 km/pixel, respectively. At 10,000 km the resolution has improved to 100 m/pixel for the NAC and 1 km/pixel for the MAC. [Figure G-18](#) shows a timeline of the observing strategy and [Figure G-19](#) shows example coverage during a flyby with 15 minutes centered on encounter where range is below 2000 km using only imaging focused targets.

Table G-12. Representative target strategies for encounters for both imaging focused and radar focused observations

Payload	Duration	Volume (compressed)
WAC	70 s	7 Mb
MAC	60 s	45 Mb
NAC	6 s	60 Mb
IRS	10 s	128 Mb
UVS	8 s	120 Mb
Total		360Mb

Payload	Duration	Volume (compressed)
MAC	60 s	45 Mb
IPR	30 s	900 Mb
Total		945Mb

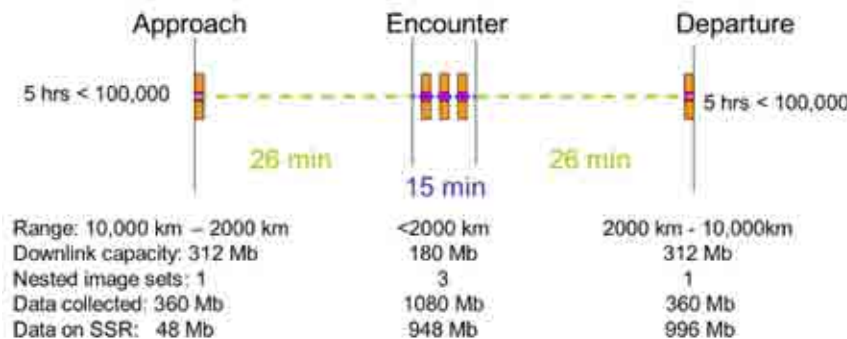


Figure G-18. Shows the general imaging strategy during a 70 km altitude closest approach for ranges less than 10,000 km using imaging coordinated targets

Figure G-19 shows how this strategy described would cover the surface using only the imaging coordinated targets at encounter. NAC is shown with purple swaths, MAC with orange swaths, and WAC with white swaths. The 15 minutes centered around closest approach is shown projected nadir as a ground trace in the dashed blue line. The star shaped patterns from the WAC are due to the projection of the edges of the square FOV onto the curved surface. The oval shaped MAC FOVs occur when the edges of the square FOV are above the limb of Ganymede. A constant pitch rate of 0.1 deg/s has been applied to the flight system to get reasonable ground speeds and keep the target in the FOV around closest approach.

These close encounter ranges are also favorable for the radar so both observation

strategies were examined. **Figures G-20** and **G-21** show how a similar encounter with closest approach at 70 km could be modified to focus the closest approach altitudes below 2000 km on radar measurements. **Figure G-20** shows the target spacing with radar targets used at altitudes less than 2000 km. During approach and departure, imaging coordinated targets are shown.

Figure G-21 shows how the strategy would cover the surface for imaging focused encounter. NAC is shown with purple swaths, MAC with orange, and WAC with white swaths. In the center of the ground track shown in blue there is a long narrow radar measurement shown. The same constant pitch rate of 0.1 deg per second has been applied here.

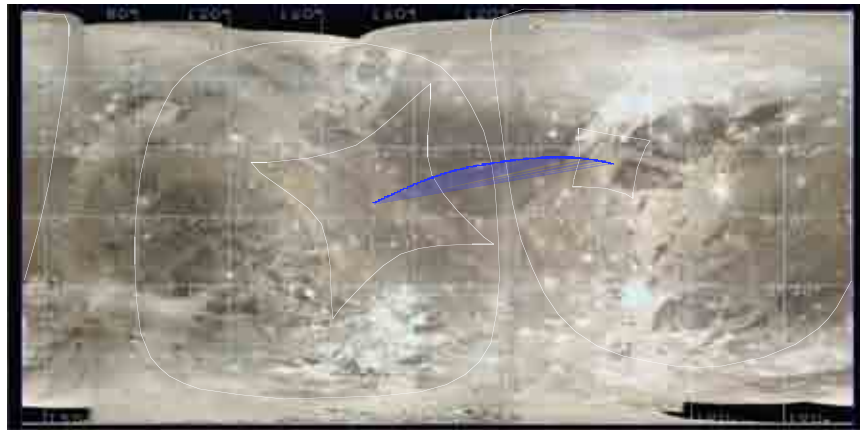


Figure G-19. Representative Coverage of Ganymede during a close flyby using the imaging coordinated targets

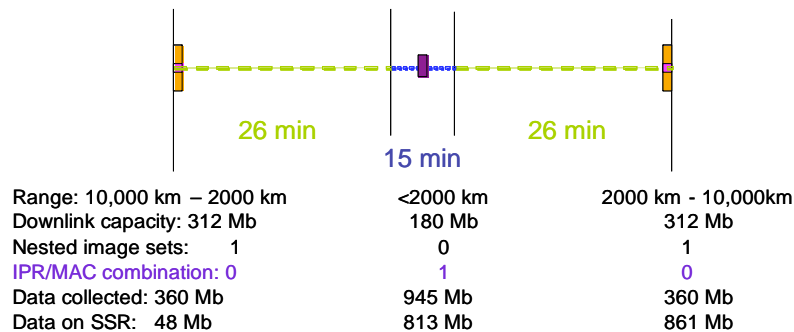


Figure G-20. Shows the general imaging strategy during closest approach where ranges are less than 10,000 km for IPR targets during closest approach



Figure G-21. Representative Coverage of Ganymede during a close flyby using imaging coordinated targets at ranges greater than 2000 km, and the radar sub-surface sounding target during closest approach at ranges of less than 2000 km

The other bounding case showing the more distant approach of 2700 km has slower relative velocity with respect to Ganymede and is too far away for meaningful radar observations. The imaging focused closest approach analysis resulted in a similar representative data collection strategy for ranges less than 10,000 km, though the lower speeds permit more targets since there is more time to downlink data.

The range is less than 100,000 km for over 20 hours and closest approach ranges of less than 10,000 km lasts for almost 2.5 hours. Assuming the SSR is emptied of stored data before reaching 10,000 km on approach, and nearly full at 10,000 km on departure, a total of seven 360 Mb coordinated imaging targets can be collected, totaling about 2.5 Gb. **Figure**

G-22 shows a representative strategy for how the seven image sets could be spread out at altitudes of less than 10,000 km.

During the 60-minute approach, assuming an average downlink rate of 200 kbps, two 360 Gb image sets, totaling 720 Mb, are taken and downlinked. The empty SSR is then filled completely during the 20-minute encounter. During departure, as storage capacity on the SSR is made available, additional targets are collected. The 18 hours between 10,000 km and 100,000 km allows up to about 13 Gb more to be collected for a total of 15.5 Gb. A constant pitch rate of 0.015 deg/s has been assumed for this encounter to keep a constant tracking angle throughout the flyby and keep ground speeds and lighting conditions within reasonable limits.

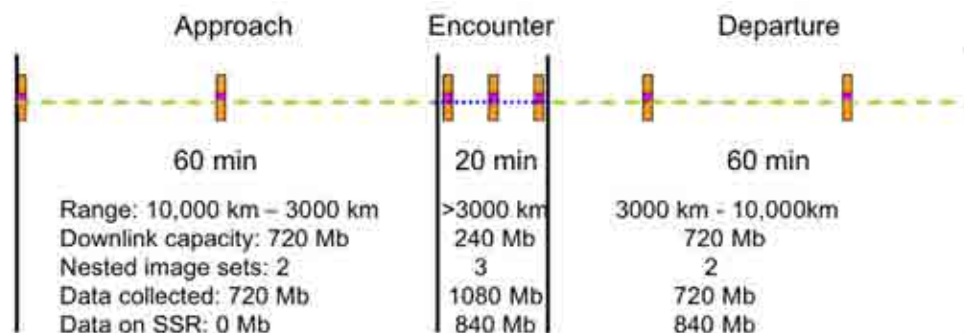


Figure G-22. Shows the general imaging strategy during a 2700 km altitude closest approach for ranges less than 10,000 km using imaging coordinated targets

This map of Ganymede in **Figure G-23** shows that during encounter there is excellent coverage at less than 10,000 km range. NAC is shown with purple swaths, MAC with orange, and WAC with white swaths.

Jupiter System Science Conclusions

The EE tour of the Jupiter System (required for propulsive reasons) provides ample opportunities to respond to the Priority 2 science objectives (§2) to determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons. Dozens of opportunities exist to observe Jupiter and each of its Galilean satellites. These opportunities are important for placing Europa in the context of the Jovian satellite system. This larger context directly applies to interpreting measurements obtained at Europa, but it also allows measurements at Europa to be understood in the broader context as a member of the Jupiter system.

The planning payload instruments would provide strong capability for accomplishing Jupiter system science. The SDT has not optimized the EE payload nor resources to achieve Priority 2 science objectives during the tour, but assuming coverage strategies similar to Galileo's, EE could expect a typical satellite flyby or perijove pass to achieve optical remote sensing with about an order of magnitude higher resolution. Instruments not included in the Galileo payload would be trained on the satellites, notably the radar sounder. As a result, the composition, structure, origin, history, and present dynamics of Jupiter and its system would be addressed

over a 2-year time scale. Moreover, fields and particles instruments operate continuously, allowing study of the interactions between Jupiter's magnetosphere and its satellites. Processes controlling satellite habitability are better understood as a result of the science accomplished during this Jupiter System tour.

For improved areal coverage of the surface at the highest resolutions during the relatively brief encounters, a larger capacity SSR would significantly increase the amount of data collected over a short period of time, which could then be downlinked over the following DSN contacts. For example, assuming data is also downlinked during the 30–60 minute satellite encounter, a tripling of the science SSR allocation to 3 Gb would about double the amount of areal coverage at less than 10,000 km range (which could be shared by the optical remote sensing instruments). For the brief duration at the closest ranges and highest resolutions, the time available to downlink is small, so the areal coverage would increase linearly with the increase in science SSR memory available.

G4.4 Trade Studies

G4.4.1 DSN Trades

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 mission phase with particular emphasis on the goals for the first 92 days. Primary consideration was given to options to reduce 70 m tracking needs. The cases considered are shown in **Table G-13**. In each tracking case, the 2 scenarios examined

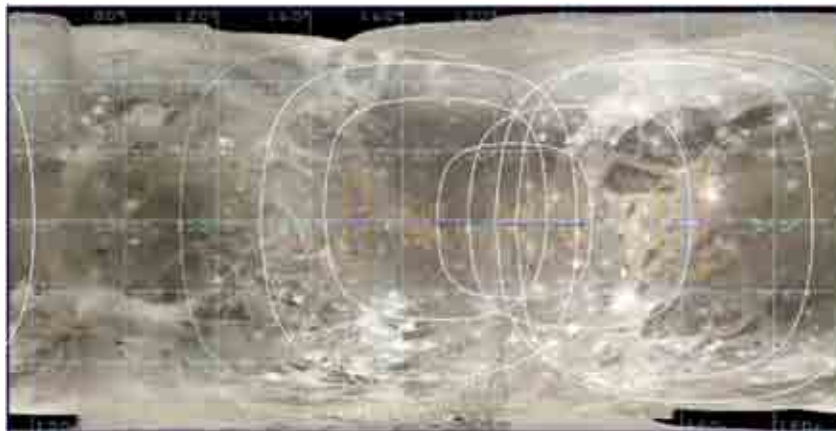


Figure G-23. 2700 km encounter

improvements to the flight system or increases to the mission duration.

The study showed (**Table G-14**) that operations scenarios are unaffected by short term scheduling issues. In the event of planned short term outages, 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 the Focused Science campaign (after 92 days) 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.

Table G-13. DSN trade study cases

Case	Tracking Schedule	Description
Baseline	70 m × 3 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka) Doppler only	35 W TWTA 1 Gb SSR 92-day scenario
Case 1A	70 m × 2 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler & Telemetry	Increase TWTA power Increase SSR capacity 92-day scenario
Case 1B	70 m × 2 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler & Telemetry	35 W TWTA Increase SSR capacity Increase Mission Duration
Case 2A	70 m × 1 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler & Telemetry	Increase TWTA power Increase SSR capacity 92-day scenario
Case 2B	70 m × 1 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler & Telemetry	35 W TWTA Increase SSR capacity Increase Mission Duration

Table G-14. DSN Trade Study Results

CASE	Baseline	Case 1A	Case 2A	Case 1B	Case 2B
DSN Tracking (Passes/day)	4 (3x70m + 1x34m)	3 (2x70m + 1x34m)	2 (1x70m + 1x34m)	3 (2x70m + 1x34m)	2 (1x70m + 1x34m)
Mission Duration (days)	92	92	92	119	190
Data rate @5.5 AU to 70m (kb/s)	320	414	590	320	320
Needed science SSR allocation (Gb)	1	4.5	9.2	4.6	9.4
Needed SSR cards	1	3	5	3	5
Needed average power increase (W)	-	18	46	8	16
Avg Daily downlink (Gb)	19.3	19.3	19.3	14.9	9.3
Mission Data Volume (Tb)	1.8	1.8	1.8	1.8	1.8
Total Number of Targets	1030	1030	1030	1030	1030
Comments			Doppler tracking gaps		Campaign 2 will stretch out due to low daily volume. Doppler tracking gaps

Red text indicates a dependent parameter

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.

G4.4.2 Mass Memory Trades

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. Each card added to the SSR adds 3 kg and 11 W.

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

Tracking gaps of two hours, four hours, and increments of eight hours were considered as representing one orbit, two 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 sensitivity to increased target size was not considered. No incremental improvements in satellite encounter science were analyzed other than the general position that more is better and SSRs in the 8–10 Gb size range are considered adequate.

The operability improvements are generally considered to be retransmission of data lost in downlink due to flight system or ground system mishap, the capability to post process data on-board for data editing or prioritization. These issues were lumped together and treated as retransmission. Retransmission has large latencies due to light time, DSN complexity, and decision making process times. The best retransmission schemes that make maximum use of automation and limited decision points take as little as 8 hours.

The results of the trades study (see [Figure G-24](#)) are that for the addition of a single card, bringing the science data allocation to 3 Gb, the simultaneous collection of imaging and radar targets and the accommodation of 2-hour tracking gaps is enabled. With 2 added cards

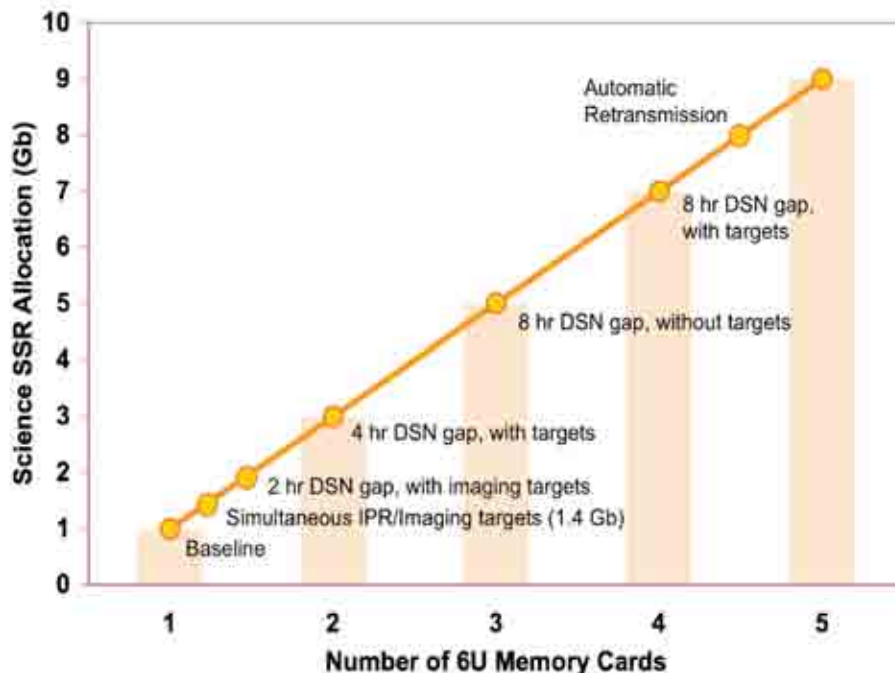


Figure G-24. Benefits of Adding Memory Cards

(5 Gb), the mission can perform routine mapping and accommodate a planned gap of 8 hours (one full DSN pass). Another added card brings the science allocation to 7 Gb and allows routine mapping and full target data acquisition in the presence of an 8 hour tracking gap. The maximum case of 5 cards in the SSR gives a 9 Gb science allocation. This enables retransmission of data.

G5. Findings

The science objectives set by the SDT can be easily met with the flight and ground system design set in the study. With the 26 eurosol, 92-day mission for which the analysis was performed, the science goals are met with margin. For the impacts of a 100 sol mission, aging 70 m subnet, and emerging CRAM high volume SSR design, the mission design has many options to improve science performance or balance the flight system design and resources for a longer mission with smaller DSN apertures, potentially Ka-band telecom, and deeper on-board storage.

The science scenarios developed by the SDT meet all science goals with margin. The highest priority goals are met in the first weeks of the mission. Higher resolution data sets and finer profile grids in later mission campaigns exceed the stated science goals. Future studies can trade performance for such issues as

ground track repeat patterns, instrument FOV, alternating orbit strategies, observation duty cycles to optimize performance against goals or re-work the goals for strategic needs.

The scenario studies have shown that floor and baseline missions can be considered with the developed tools and science performance can be optimized across the flight and ground system scope.

G6. Next Steps

For future studies, anticipated changes in study goals should be factored into the operations scenarios, such as:

- Longer mission life capability
- Planning payload changes
- Tour science goals
- More mature SSR concept performance
- Additional Telecom system design trades (X-Ka vs DSN optimization)

The interaction between telecom, C&DH (throughput, compression, and mass memory), instrument characteristics (rates, compression, timing) and ground resources like DSN stations and retransmission, suggest that further optimization should be performed. The operations scenarios should inform and respond to those design iterations.

H. TELECOMMUNICATIONS LINK ANALYSIS

H1. Introduction

This appendix contains the performance estimates for the EE telecommunication links. The telecommunications subsystem is described in §4.4. The following paragraphs detail the assumptions within the link analysis, as well as present the results of the analysis with charts and link design control tables where appropriate.

H2. Requirements

The link shall provide for Command, Telemetry, and Radiometric Navigation:

Radiometric Navigation Performance

1. Doppler: < 0.1 mm/sec in 60 sec
2. Ranging: 4 m in 10 min
3. ΔDOR (VLBI): 0.12 ns

Command Performance at BER < 1E-5

4. Minimum rate: 7.8 bps
5. Maximum rate: 2000 bps

Engineering Telemetry Performance BER < 1E-6

6. Minimum rate: 10 bps
7. Maximum rate: ~800 kbps at EOI +6 mo

Key Functions

8. Initial Acquisition
9. Safemode Telecom & Command
10. Critical Event Data & Monitoring
11. Single fault immunity

H3. Telecommunications Subsystem Overview

The maximum range is 5.5 AU for the Europa science phase since it is constrained to > 50 deg SEP angle for Doppler quality (science requirement).

In order to minimize transmit circuit losses, the telecom hardware is mounted on the back of the HGA which reduces the loss between the output of the high-power amplifiers and the 3 m, X/Ka-band HGA.

Flight system communication is primarily via X-band, with limited use of Ka-band for carrier-only science. Dual string, cross-strapped SDSTs and 35-W TWTAs provide X up/X down command and telemetry capability. In addition, a single string Ka-band transponder and 3.5 W SSPA provides a Ka up/Ka-down carrier-only reference signal for gravity and radio science experiments. If the

Ka-band transponder fails, the SDST can provide a Ka-band downlink (referenced to the X-band uplink) which can be used for somewhat lower sensitivity gravity science as compared to Ka/Ka, but still better than X/X alone. The Ka band link can only be operated with the HGA, but the X-band link can be operated with the HGA, MGA, or either LGA.

The high rate links are designed to communicate to DSN 70 m antennas. Link performance for cruise and Jupiter system tour does not constrain the design. The MGA link example is for safe modes during Europa science phase to a 70 m antenna. The MGA 13 deg ½ angle is larger than the Jupiter SEP angle of ~11 deg. The 200 b/s rate shows excess margin above the required 3 dB design margin at 40 b/s.

H4. Assumptions

Assumptions made for the link analysis include:

- 90% Cumulative Weather Distribution
- 15 deg station elevation (20 deg Ka-band)
- 40K receiver noise temperature
- Jupiter Hot body noise in the antenna field of view (13K)
- QPSK suppressed carrier modulation
- Turbo 1/6 encoding
- 8920 bit frame length
- Ranging is OFF for QPSK modulation

H5. Link Design Control Tables

The link Design Control Tables (DCT) were derived from the telecom concept and design assumptions. Because the detailed design has not yet been determined, some parameters, such as circuit losses, were assumed based on actual designs from previous projects. In this case, parameter assumptions were derived from the MRO Telecom design, which has a very similar design concept, configuration and operations scenario. [Tables H5-1](#) through [H5-3](#) show the DCTs adapted from the 2006 Europa Explorer Study [Europa Explorer Design Team Report, JPL D-34109, April 27, 2006]. The Telecom subsystem design concept is nearly identical to the current study with the exception of the TWTA power. The previous analysis used a 50 WRF TWTA whereas the current concept specifies a 35 WRF TWTA.

Table H5-1. 35 W X-band TWTA, 3 m HGA, 70 m DSN, Turbo 1/6, 3 mradian pointing

[illegible]

Table H5-2. 35 W X-band TWTA, MGA, 70 m DSN

35 W TWTA							Range, km	
X-Band MGA, 13.0° off-point							6,2240-69	Range, AU
DSN #1 (noise configuration: XX)							0.7%	ORBIT, km
Antenna 13 deg elevation/90% EIR Weather (Year Average)							13.00	MPL, deg
Hot body noise = 13 K							13	From Angle, deg
1 way								
Block V function includes carrier noise/13 M.23 Model								
Two channel B: 7.4-12.5-BB (0-10) FFB (0-10) 4								
Carrier Loop Bandwidth = 3.0 Hz							RF band	
Symbol Rate to the DSN = 40 sps							Freq, MHz	
Data Bit Rate (actual) = 10 sps							X	
Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	8	RF band
TRANSMITTER PARAMETERS								
1) SC RF Power Output	dBm	45.44	0.20	0.20	45.44	0.0087	T	38.8
2) Total Circuit Loss	dB	-2.40	0.50	0.50	-2.40	0.0835	U	13.00
3) Antenna Gain (on bore sight)	dB	19.24	0.30	0.30	19.24	0.0217	T	13.00
4) Ant Pointing Loss	dB	-5.74	0.52	0.52	-5.74	0.0297	U	13.00
5) EIRP (1+2+4)	dBm				56.63	0.2016		
PATH PARAMETERS								
6) Space Loss	dB	-289.26	0.00	0.00	-289.26	0.0000	D	
7) Atmospheric Att	dB	-0.22	0.00	0.00	-0.22	0.0000	D	
RECEIVER PARAMETERS								
8) DSN Antenna Gain	dB	74.36	0.10	0.10	74.36	0.0017	T	
9) Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	
10) Polarization Loss	dB	-0.09	0.00	0.00	-0.09	0.0000	U	
TOTAL POWER SUMMARY								
11) Total Rcvd Pwr (Pt)	dBm				-158.85	0.2033	G	
12) Noise Spec Dens	dBm/Hz	-182.22	-0.10	0.10	-182.22	0.0010	G	
System Noise Temp	K	43.42	-1.00	1.00			G	
Vacuum, zenith	K	14.89	-1.00	1.00			T	
Elevation	K	2.28	0.00	0.00			G	
Atmosphere	K	13.69	0.00	0.00			G	
Hot Body Noise	K	13.00	0.00	0.00			G	
13) Received P/N ₀	dB-Hz				23.57	0.2044	G	
14) Received P/N ₀ - 2 sigma	dB-Hz				22.87			
CARRIER PERFORMANCE (actual)								
15) Tim Carrier Supp	dB	-4.96	0.24	0.25	-4.96	0.0101	T	
16) Ping Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	
17) DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	
18) Required P/N ₀ (12+14+15+16)	dB-Hz				15.90	0.2145	T	
19) Carrier Loop Bandwidth, B	dB-Hz	4.77	0.00	0.00	4.77	0.0000	T	
20) Carrier Loop SNR	dB				11.13	0.2145	U	
21) Required Carrier Loop SNR	dB				19.00	0.0000	D	
22) Carrier Loop SNR Margin	dB				1.19	0.2145	U	
SUBCARRIER PERFORMANCE at Rec. P/N ₀								
23) SubCar. L. SNR	dB				22.48			
24) Required Loop SNR	dB				20.00			
25) SubCarrier Loop SNR Margin	dB				2.48			
SYMBOL LOOP PERFORMANCE at Rec. P/N ₀								
26) Sym. Loop SNR	dB				23.48			
27) Required Loop SNR	dB				15.00			
28) Symbol Loop SNR Margin	dB				5.49			
TELEMETRY PERFORMANCE at Required P/N ₀								
29) Tim Data Supp	dB	-11.87	0.11	0.12	-11.87	0.0022	T	
30) Ping Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	
31) DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	
32) Data Rate	dB	15.77	0.00	0.00	15.77	0.0000	D	
33) Radio Loss	dB	-0.46			-0.46		T	
34) SubCarrier Demod. Loss	dB	-0.36			-0.36		T	
35) Symbol Sync. Loss	dB	-0.10			-0.10		T	
36) Mismatch Distortion Loss	dB	-0.15			-0.15		T	
37) Threshold Eb/N ₀	dB				2.28		G	
38) Required Eb/N ₀	dB				3.43		G	
39) Required P/N ₀	dB-Hz				29.87	0.3047	U	
40) Performance Margin (29-13)	dB				2.71			
41) Sigma	dB				3.11			
42) Margin - 2 sigma	dB				1.28			
Wind Loading Loss	dB	0.00	0.00	0.00	0.00	0.0000	U	
Pointing Loss due to Wind (BWG)	dB	0.00	0.00	0.00	0.00	0.0000	U	
Adjusted Performance Margin	dB				2.71			

Table H5-3. 3.5 W Ka-band SSPA, HGA, 34 m DSN, carrier only

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. S/C Transmitter Power	dBm	35.44	0.1	-0.1	35.44	0.0017
2. S/C Xmit Circuit Loss	dB	-1.5	0.5	-0.5	-1.5	0.0833
3. S/C Antenna Gain	dBi	57.52	0.5	-0.5	57.52	0.0417
4. Degrees-off-boresight (DOFF) Loss	dB	0	0	0	0	0
5. S/C Transmit Pointing Loss	dB	-10.82	0	0	-10.82	0
6. EIRP (1+2+3+4+5)	dBm	80.64	1.07	-1.07	80.64	0.1267
PATH PARAMETERS						
7. Space Loss	dB	-300.92	0	0	-300.9	0
8. Atmospheric Attenuation	dB	-1.18	0	0	-1.18	0
RECEIVER PARAMETERS						
9. DSN Antenna Gain	dBi	78.84	0.3	-0.3	78.84	0.015
10. DSN Antenna Pnt Loss	dB	-0.11	0.1	-0.1	-0.11	0.0033
11. Polarization Loss	dB	-0.03	0.1	-0.1	-0.03	0.0033
TOTAL POWER SUMMARY						
12. Tot Rcvd Pwr (6+7+8+9+10+11)	dBm	-142.76	-1.16	1.16	-142.8	0.1483
13. SNT in Vacuum	K	21.33	-1	2	21.66	0.3889
14. SNT due to Elevation	K	1.47	0	0	1.47	0
15. SNT due to Atmosphere	K	66.08	0	0	66.08	0
16. SNT due to the Sun	K	0	0	0	0	0
17. SNT due to other Hot Bodies	K	37.27	0	0	37.27	0
18. SNT (0+14+15+16+17)	K	126.15	-1	2	126.65	0.25
19. Noise Spectral Density	dBm/Hz	-177.59	-0.03	0.07	-177.6	0.0003
20. Received Pt/No (12-19)	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
21. Received Pt/No, mean-3 dB	dB-Hz	31.81	0	0	31.81	0
CARRIER PERFORMANCE						
25. Recovered Pt/No (20+[AGC+BPF])	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
26. Telemetry Carrier Suppression	dB	0	0	0	0	0
27. Ranging Carrier Suppression	dB	0	0	0	0	0
28. DOR Carrier Suppression	dB	0	0	0	0	0
29. Carrier Power (AGC) (12+26+27+28)	dBm	-142.76	-1.16	1.16	-142.8	0.1483
30. Received Pc/No (25+26+27+28)	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
31. Carrier Loop Noise BW (this loop BW is very wide)	dB-Hz	10	0	0	10	0
32. Carrier Phase Error Var (from 30,31,xpond,solar)	rad^2	0.0048	0	0	0.0048	0
33. Carrier Loop SNR (CNR) (from 32)	dB	23.23	1.16	-1.16	23.23	0.1486
34. CNR, mean-3 dB	dB	20.23	0	0	20.23	0
35. Recommended CNR	dB	10	0	0	10	0
36. CNR Margin (33-35)	dB	13.23	1.16	-1.16	13.23	0.1486
37. CNR Margin, mean-3 dB (34-35)	dB	10.23	0	0	10.23	0

I. NASA ASTROBIOLOGY INSTITUTE LETTER

Dear Karla, Bob, Ron, and Mitch:

In a Dec. 12, 2001 letter to Dr. Michael Belton (Chair of the NRC Steering Committee developing the decadal strategy for Solar System Exploration), the NASA Astrobiology Institute placed a Europa orbiter in its highest priority mission category. The envisioned orbiter featured a payload capable of confirming the presence of a subsurface ocean, characterizing the subsurface, and obtaining remote sensing observations pertinent to Europa's surface composition, geological history, and biological potential.

The current concept for the Europa Explorer mission, as presented on May 8, 2007 to the NAI Executive Council by Mitch Sogin for the mission Science Definition Team, appears to meet these measurement objectives.

The NAI Executive Council reaffirms that such a mission is in its highest priority mission category for advancing the astrobiological goals of Solar system exploration.

Sincerely,

Carl Pilcher, Director of the NAI
for the NAI Executive Council