National Aeronautics and Space Administration

Mission Concept Study

Planetary Science Decadal Survey Jupiter Europa Orbiter Component of EJSM

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Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

The data contained in this document may not be modified in any way.

Cost estimates described or summarized in this document were generated as part of a preliminary concept study, are model-based, assume a JPL in-house build, and do not constitute a commitment on the part of JPL or Caltech. References to work months, work years, or FTEs generally combine multiple staff grades and experience levels.

Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

Planetary Science Decadal Survey

Mission Concept Study Final Report

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Acknowledgments

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Executive Summary

(Taken directly from Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 1.)

Some 400 years ago, discovery of the four large moons of Jupiter by Galileo Galilei changed our view of the universe forever. Today Jupiter is the archetype for the giant planets of our solar system, and for the numerous giant planets now known to orbit other stars, and Jupiter's diverse Galilean satellites—three of which are believed to harbor internal oceans—are central to understanding the habitability of icy worlds.

By investigating the Jupiter system, and unraveling the history of its evolution from initial formation to the emergence of possible habitats and life, insight is gained into to how giant planets and their satellite systems form and evolve. Most important, new light is shed on the potential for the emergence and existence of life in icy satellite oceans.

Europa and Ganymede are believed to be internally active and harbor internal salt-water oceans. They are straddled by Io and Callisto (which may also harbor a deep ocean), key satellite end-members that tell of the origin and evolution of the Jupiter system. If extrasolar planetary systems are analogous, then icy satellites could be the most common habitats in the universe—probably much more abundant than Earth-like environments which require very specialized conditions to permit surface oceans.

In 1995, Galileo arrived at Jupiter to conduct its follow-up on the key Voyager discoveries, especially at Europa. Galileo made many discoveries in the Jovian system, and provided extremely strong evidence of a near-surface global ocean on Europa. The Juno mission, scheduled for launch in 2011, will focus on Jupiter's deep interior and magnetosphere but will not address key science questions for the Galilean satellites and the integrated Jupiter system. Thus, a new flagship-class mission to the Jupiter system and its satellites is required to address top priority scientific questions.

Background

Using the extensive experience gained from Galileo, Cassini, New Horizons, Juno and Mars Reconnaissance Orbiter, the 2008 NASA Pre-phase A effort focused on refining the mature Europa mission concept with very robust technical and cost margins, executing a detailed risk reduction plan and integrating the ESA portion of the mission concept.

In 2007, NASA performed two Jupiter mission concept studies: Europa Explorer and Jupiter System Observer. At the same time, an ESA Jupiter proposal, *Laplace*, was submitted to the Cosmic Vision Programme call. JPL and APL teamed in 2008 to address the next step in the NASA study of this mission concept. The primary focus of the NASA 2008 effort was threefold:

- Update the 2007 Europa Explorer with Jupiter system science (Jupiter Europa Orbiter, JEO),
- Begin executing risk reduction activities related to radiation and planetary protection, and
- Work with ESA to define a joint mission Europa Jupiter System Mission (EJSM) comprised of the JEO and the ESA *Laplace* orbiter (Appendix O).

The NASA contribution to EJSM, defined as JEO, is an Europa orbiter based in the previously studied line of Europa orbiters which culminated in 2007 as the Europa Explorer. The Ground Rules associated with the 2008 NASA study are summarized in Table ES-1. A summary of the 2008 effort for the JPL/APL team was to:

- Include Jovian *system science* as a Level 1 requirement (Section §2.4.6),
- Respond to NASA's 2007 TMC and Science panels, especially the Chemistry science objective, the radiation-induced effects on measurement quality and mitigation strategies (Appendix N),
- Refine the *radiation plan* described in the 2007 report and begin executing (§4.5, and Appendix F),

Table ES-1. NASA-provided ground rules provide framework for JEO study report.

Power options	Solar, MMRTG or ASRG—costs and characteristics supplied for radioisotope power options
Planetary Protection	JEO: ≤10^{-4} of contaminating the Europan ocean
Launch Vehicle (LV)	Delta IV-H, Ares and Atlas family—costs given including launch services and nuclear processing
Technology Philosophy	Be conservative
Launch Dates	Nominally 2020 but investigate 2018–2022
DSN Capability	Ka band downlink available, current 70m equivalent capability available, current 34m available, DSN ground system throughput of 100 Mbits/s
International Contributions	<$1B consistent with Cosmic Vision Proposals

- Define *baseline, floor and NASA-only* JEO mission concepts, (§4.1),
- Conduct an assessment of the science value of NASA-ESA and NASA only missions with respect to the science goals in the 2003 NRC Decadal Survey (§2.7, Appendix L).

The architecture of two free-flying, independent flight elements was a result of both the 2007 NASA and ESA studies. All studies of mission architectures performed over the past decade to address investigation of a putative Europan ocean have concluded that a Europa orbiter is an essential element. Thus, the NASA component was set as the Europa Explorer concept from 2007. The ESA component, Jupiter Ganymede Orbiter (JGO), was not pre-determined and was the result of decomposition of the science objectives.

A JPL/APL engineering team was formed to continue the evolution of the JEO mission and to execute the risk mitigation activities discussed in §4.5 and Appendix F. In addition, the JPL/APL engineering team supported the ESA engineering team to flesh out the ESA element (Appendix J). Also, an international science team was formed to define the highest priority science and to work with the engineering teams to refine the flight element implementations.

The main focus of this report is JEO. Discussion of the ESA element, JGO, is limited to Sections 1.0, 2.1, 2.6, 2.7 (Science), 3 (Architecture), and 4.11 (Management) to add context for the JEO mission element. Further details on the integrated EJSM and the JGO mission element are given in the EJSM Joint Summary Report [JPL D-48440], the ESA JGO "Assessment Study Report of Laplace—EJSM-JGO (*2008*), SRE-PA/2008.064/ASAW", and in Appendix J of this report.

Science Objectives

An extensive international effort involving scientists from more than half a dozen countries established the EJSM overarching theme as: The emergence of habitable worlds around gas giants.

The Joint Jupiter Science Definition Team (JJSDT) was chartered to define the goals and objectives for the EJSM. The JJSDT is an international group of 27 US, 15 European, and 5 Japanese scientists, which, during the last 8 months, evaluated the US National Research Council's Planetary Science Decadal Survey, the ESA Cosmic Vision, the NASA 2007 Europa Explorer [*Clark et al. 2007*] and Jupiter System Observer studies [*Kwok et al. 2007*], and the 2007 ESA Cosmic Vission Programme Laplace Proposal [*Blanc et al. 2007*] to establish a comprehensive and integrated set of goals and objectives for EJSM addressing the nature and origin of the Jupiter system, especially its satellites, to build on previous results and anticipated results from Juno.

To understand the Galilean satellites as a system, Europa and Ganymede are singled out for detailed investigation. This pair of objects provides a natural laboratory for comparative analysis of the nature, evolution, and potential habitability of icy worlds. The primary focus is on in-depth comparative analysis of their internal oceans, current and past environments, surface and near-surface compositions, and their geologic histories. Moreover, objectives for studying the other two Galilean satellites, Io and Callisto were also defined. To understand how gas giant planets and their satellites evolve, broader studies of Jupiter's atmosphere and magnetosphere would round out the Jupiter system investigation.

The JJSDT worked with the engineering teams to define a two flight element mission to Jupiter and the Galilean satellites, with each flight element ending their prime mission in orbit at a Galilean satellite, one at Europa and one at Ganymede. The JJSDT and engineering team developed extraordinary mission concepts which provide extensive Jovian system science as well as focused icy satellite science.

Europa is essentially a rocky world with an outer ~100 km layer comprised of a relatively thin icy shell above a saltwater ocean. Its ocean is in direct contact with the rocky mantle below, making it unique among icy satellites in having a plausible chemical energy source to support life. However, the details of the processes that shape Europa's ice shell, and fundamental question of its thickness, are poorly known.

The science goal for the JEO element of EJSM is: Explore Europa to investigate its habitability.

The objectives developed by the JJSDT to address this goal are:

- Characterize the extent of the ocean and its relation to the deeper interior,
- Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange (Figure ES-1),
- Determine global surface compositions and chemistry, especially as related to habitability.
- Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration.
- Understand Europa in the context of the Jupiter system.

Ganymede is believed to have a liquid ocean sandwiched between a thick ice shell above and high-density ice polymorphs below, more typical of volatile-rich icy satellites. It is the only satellite known to have an intrinsic magnetic field, which makes the Ganymede-Jupiter magnetospheric interactions unique in our solar system (Figure ES-2).

The science goals for the JGO element of EJSM are:

- How did the Jupiter System form?
- How does the Jupiter system work?
- Does the Jupiter system harbor a habitable world?

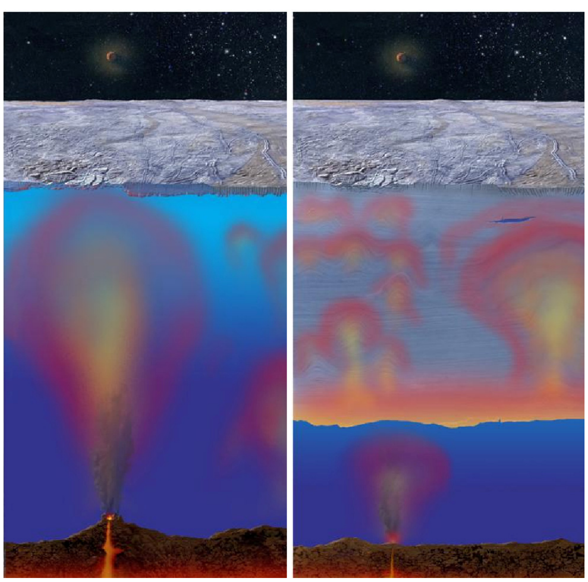

Figure ES-1. The NASA Jupiter Europa Orbiter would address the fundamental issue of whether Europa's ice shell is ~few km (left) or >30 km (right), with different implications for processes and habitability. In either case, the ocean is in direct contact with the rocky mantle below, which can infuse the chemical nutrients necessary for life.

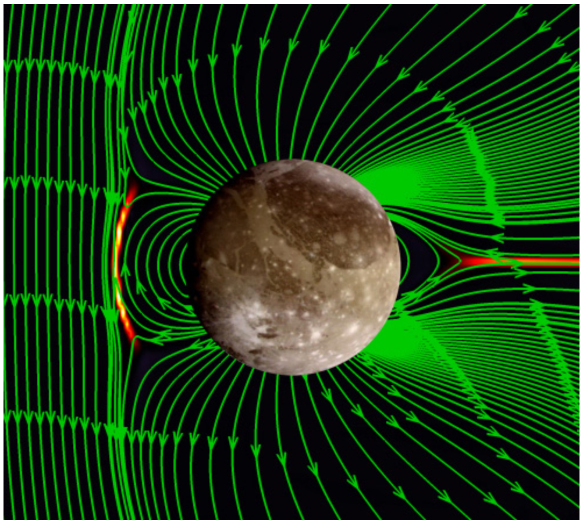

Figure ES-2. The ESA Jupiter Ganymede Orbiter would determine how Ganymede's unique magnetic field interacts with Jupiter's, how the interactions vary with time, and the role of a convecting core and internal ocean.

The objectives which the JJSDT have developed to address these goals are:

- Characterize Ganymede as a planetary object including its potential habitability,
- Study the Jovian satellite system,
- Study the Jovian atmosphere,
- Study the Jovian magnetodisk/magnetosphere,
- Study the interactions occurring in the Jovian system.

JEO Science Strategy

All-inclusive science objectives enable flexibility for the community to propose innovative techniques to address the science objectives without premature narrowing of potential instrumentation.

The JJSDT has taken the overall JEO science objectives and identified a set of investigations and measurements which would fully address the objectives. The full traceability matrix has been vetted with the science community and the approach is to be all inclusive. The JEO model payload presented uses only publicly available information and was selected to address the highest priority measurements without overly stressing the resources (cost, mass, power and risk). By taking this approach, the JJSDT acknowledges that not all measurements are fully addressed by the model payload.

This conservative strategy was taken intentionally for several reasons: 1) it allows those people with innovative or proprietary ideas to propose more capable instruments, 2) it balances the development risk and science value given publicly available information, 3) it demonstrates that the targets and mission are very exciting and scientifically rich, leaving room for innovative concepts, 4) it highlights how JEO would provide direct benefit to the complementary and synergistic JGO science objectives and 5) it provides NASA Headquarters with information to best evaluate the cost vs. risk posture for JEO once the instruments are actually proposed via the Announcement of Opportunity process.

Architectural Implementation

This year's study has refined the EJSM concept to identify two free-flying flight elements executing an intricately choreographed exploration of the Jupiter System before settling in at the intriguing end states of Europa and Ganymede.

EJSM's NASA-led JEO and ESA-led JGO have both unique and overlapping science objectives while being designed to stand alone if necessary. The JEO and JGO concepts are both orbital flight systems using conventional bi-propellant propulsion systems and capable of carrying 11 specifically selected instruments. Ka-band downlink systems on both orbiters would allow significant downlink capability while in the Jupiter system. The basic designs for the orbiters are very similar to previous large flight systems including Cassini, Mars Reconnaissance Orbiter and Rosetta. New technologies would not be required to execute either current mission concept though new developments would be required for JEO (radiation designs) and JGO (low-mass instruments). The development schedule for these missions is such that a technology developed by 2014/2015 could easily be incorporated if it enhances the mission capability. Current risk mitigation activities are under way to ensure that the radiation designs are implemented in the lowest risk approach. The robust baseline mission concepts includes mass and power margins well above what would be normal at this point. A summary of the flight elements is presented in Table ES-2.

JEO would encounter Io and spend significant time in the inner radiation belts at Jupiter. JGO's trajectory would allow it to stay outside the highest radiation areas and therefore has solar arrays for its power source. The higher radiation levels experienced by JEO while staying in the main radiation belts, would add significant challenge to designing a solar mission which could meet the science objectives. Previous studies (Appendix C) indicate that a radioisotope powered mission is a good technical solution. For purposes of this study, radioisotope power is baselined, though no final decision would be made until the appropriate National Environmental Policy Act (NEPA) and Launch Approval process is completed.

If NASA is forced to scale back on the scope of the mission, then a prioritized descope path has been developed in which the scientific and engineering capabilities can be resized to meet resources and programmatic needs. In this approach, a prioritized descope path (Table ES-3) was defined through the JJSDT, which reflects the combined insight of both the science and the engineering teams. Note that there are many reasons why it becomes necessary to take descopes. The actual order of descopes would be a function of the reasons a descope is required. If all descopes are taken, the NASA JEO floor mission would carry 7 instruments and would have more limited tour and Europa orbital phases. Because of the independence of the launches, the NASA-only mission is identical to the JEO baseline mission and the descope path would be the same. The comparison of the JGO, JEO baseline and the JEO floor are shown in Table ES-2.

While the ultimate goal of JEO would be to orbit Europa, its science scope is the entire Jovian system. Similarly, JGO would investigate the Jovian system, Callisto, and ultimately orbit Ganymede. Observations of the Jupiter system by the two flight elements would be both complementary and synergistic. A representative mission scenario is included in Figure ES-3.

Launched independently in early 2020, JEO and JGO would use chemical propulsion and Venus-Earth-Earth gravity assists to arrive at Jupiter ~6 years later. Although launch opportunities exist nearly every year, the mass delivered and flight times to Jupiter vary and can be traded (§5). After insertion into Jupiter orbit, both flight systems would perform tours of the Jupiter system using gravity assists of the Galilean satellites to shape their trajectories.

JEO would enter the Jupiter system, using Io for a gravity assist prior to JOI. This strategy increases in the delivered mass to Europa by significantly decreasing the required JOI propellant in trade for a modest increase in the radiation shielding of the flight system. The JEO baseline mission design features a 30-month Jupiter system tour which includes 4 Io flybys (including one at 75 km), 9 Callisto flybys (including one near-polar), 6 Ganymede flybys (including four at <1000 km), and 6 Europa flybys (including 3 early flybys at low altitude) along with ~2.5 years observing Io's volcanic activity, and Jupiter's atmosphere, magnetosphere, and rings. JEO would enter orbit around Europa and spends the first month in a 200 km circular orbit and then descends to a 100 km circular orbit for another 8 months (Figure ES-4). The mission would end with impact onto Europa.

JGO would use a Ganymede gravity assist prior to JOI, thereby avoiding the main radiation belts of Jupiter. JGO's initial orbit would be $13 \times 245\ R_J$. After a ~10-month tour through the Jupiter system with close flybys of Ganymede and a couple of Callisto flybys, measuring the Jovian magnetosphere, and monitoring Jupiter, JGO would begin a campaign of frequent, resonant flybys of Callisto for a total of 19 flybys. After ~1 year in this resonant orbit with Callisto, JGO would move to Ganymede and soon enter into an elliptical polar orbit (200 × 6000 km) for 80 days, collecting data and making measurements of Ganymede's magnetosphere. Afterward, JGO would enter a 200 km near-polar circular orbit for high resolution observations of Ganymede for 180 days (Figure ES-5). The mission would end with impact onto Ganymede.

Table ES-2. The robustness of the Europa Jupiter System Mission elements have significant science complementary capability.

	Jupiter Ganymede Orbiter	**Jupiter Europa Orbiter 2008 Baseline**	**Jupiter Europa Orbiter 2008 Floor**
Launch Vehicle	Ariane 5 ECA	Atlas V 551	Atlas V 541
Launch Month/Year	3/2020	2/2020	2/2020
Trajectory	VEEGA	VEEGA	VEEGA
Flight time to Jupiter (years)	6	6	6
Time in Jovian tour	28 months	30 months	20 months
Ganymede/Europa orbital lifetime	8.5 months	9 months	3.5 months
Number of Instruments including Radio science	11	11	7
Power source	Solar Arrays	5 MMRTG	5 MMRTG
Data volume	1.0 Tbits	4.5 Tbits	3.0 Tbits
Margins:			
Mass	>30%	43%	44%
Power	Not Available	33%	33%
Cost Reserve on Phases B-D	Not Available	37%	37%
Instruments:			
Laser Altimeter (LA)	X	X	X
Radio Science	X	X both ways Ka both ways USO	X both ways Ka down only
Ice Penetrating Radar (IPR)	X	X	X
Vis-IR Spectrometer (VIRIS)	X	X	Partial
Ultraviolet Spectrometer (UVS)	X	X	
Ion and Neutral Mass Spectrometer (INMS)	X	X	
Thermal Instrument (TI)	X	X	
Narrow Angle Camera (NAC)	-	X	
Wide-Angle Camera (WAC)	X	Combined	Combined
Medium-Angle Camera (MAC)	X		
Magnetometer (MAG)	X	X	X
Particle and Plasma Instrument (PPI)	X	X	Partial
Sub milliter Wave Sounder	X	-	-
Instrument Mass CBE (kg): (without shielding)	77 kg	106 kg	61 kg

Table ES-3. Final descope order based on science priorities identified by the JJSDT

Descope Order	Descope Item
1	Ka-band Up (Ka transponder req.)
2	Color on the Narrow Angle Camera
3	Energetic particle capability
4	Ultra Stable Oscillator
5	Ion and Neutral Mass Spectrometer
6	OpNav Functionality
7	Reduce Europa Science Phase by 5.5 month
8	6 Interdisciplinary scientists
9	Thermal Instrument
10	Ultra Violet Spectrometer
11	ATLAS V 551 to 541
12	Tour Phase reduced by 10mo
13	Hybrid Soldi State Recorder
14	Descope IR Capability (Reduce to 0.9 – 5 μm, with decreased spatial and spectral resolution)
15	Narrow Angle Camera

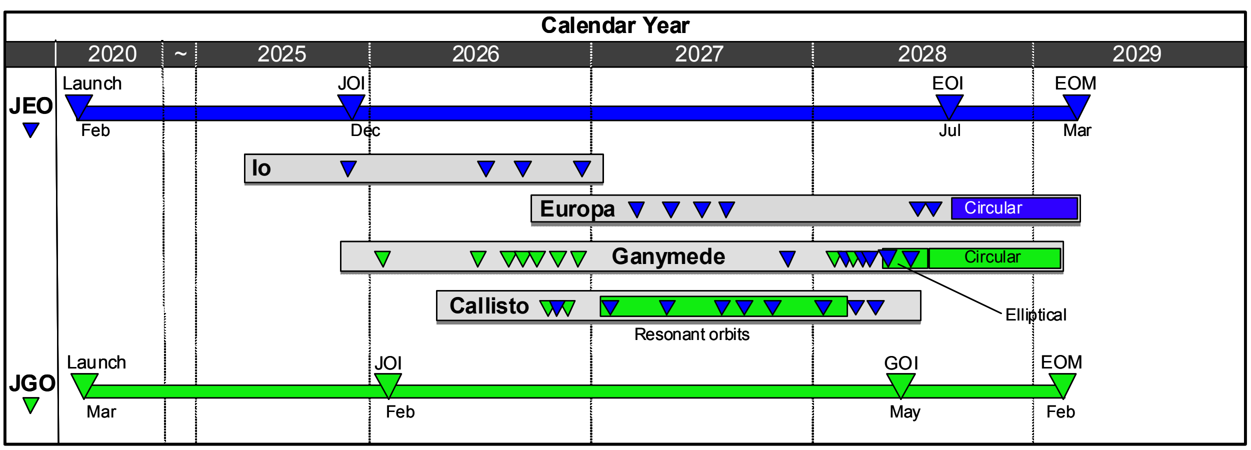

Figure ES-3. The notional timeline for EJSM assumes JEO and JGO would launch one month apart in 2020. The resulting possible synergistic observations of magnetospheric and other dynamic phenomena is unprecedented in planetary exploration.

Figure ES-4. The JEO flight system would use radioisotope power and deliver a complement of 11 instruments to explore Europa and the Jupiter System.

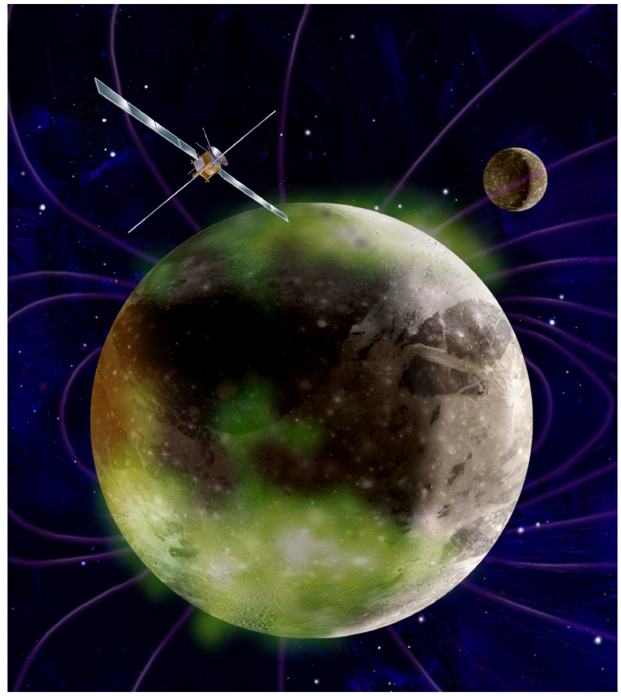

Figure ES-5. By staying away from the highest radiation areas in the Jupiter system, JGO would be able to use solar arrays to power a complement of 11 instruments and return ~1.0 Tbit of scientific data.

Launch Flexibility

Independent developments and launches create a very flexible implementation with multiple options for obtaining significant stand alone, complementary, and synergistic science to meet the science objectives.

The launches of JEO and JGO would *not* be dependent on each other. Moreover, numerous parameters in the trajectory designs provide flexibility to alter interplanetary flight times, Jupiter tour lengths, and orbital insertion timing to adjust the overlap of the two flight systems in orbit at Jupiter. If one partner is unable to deliver its flight element or runs into significant development schedule delay, then the other flight element could be launched without waiting for the other element and still deliver a rich and exciting science mission.

Cost and Schedule

An implementation with specific attention to designing for the radiation and planetary protection requirements balances risk, cost and science.

Both NASA and ESA have estimated the costs for their deliverable portions of the EJSM. The estimation methods used by each agency are specific to the mission concept development process within the agency. NASA has extensively studied a mission to the Jupiter system and Europa for several years and is able to provide a fairly high fidelity cost estimate with element costs provided by the implementation organizations and reviewed by independent cost review boards.

The JGO cost estimate is classified, according to the ESA Cost Engineering Chart of Services (Issue 3), as Class 4 of a Moderate Complexity project, performed in a Normal time frame.

NASA Costs

The current baseline JEO mission concept lifecycle cost estimate, Phase A through F, is $3.8B (RY) ($2.7B [FY07]). Reserves were applied to all costs, excluding the launch vehicle, at 10% for Phase A, 37% for Phases B–D, and 15% for Phases E and F. Early funding for additional support to the Instrument Announcement of Opportunity and radiation and planetary protection risk mitigation has been included in the Pre-Phase A risk mitigation and project formulation activities which are estimated at $38M (RY).

The Project cost assumes it would be categorized as a Class A via NPR 8705.4, "Risk Classification for NASA Payloads", and as a Category 1 Project per NPR 7120.5D "NASA Space Flight Program and Project Requirements". The estimates represent the full life cycle and conservatively assume that all engineering and assemblies and individual instruments would be re-designed to mitigate radiation and planetary protection risks (no box heritage assumed). No offsets have been taken for potential domestic or foreign contributions. Approximately 32% of the total mission costs go directly into the science community.

ESA Costs

In the current configuration the JGO would be within the Cosmic Vision L-Class mission cost estimate of 650M€. This estimate includes costs for the JGO flight element, the Ariane 5 launch, and ground segment and operations. It excludes the cost for the scientific instruments which would be provided by industry or science institutes in ESA member states and funded nationally.

High Level Schedule

The development schedules for JEO and JGO are based on the standard development approaches used by NASA and ESA. The JEO schedule was developed in accordance with NPR7120.5D with specific considerations to reduce development risk associated with the challenging and time consuming radiation and planetary protection design developments. This schedule is shown in Figure ES-6.

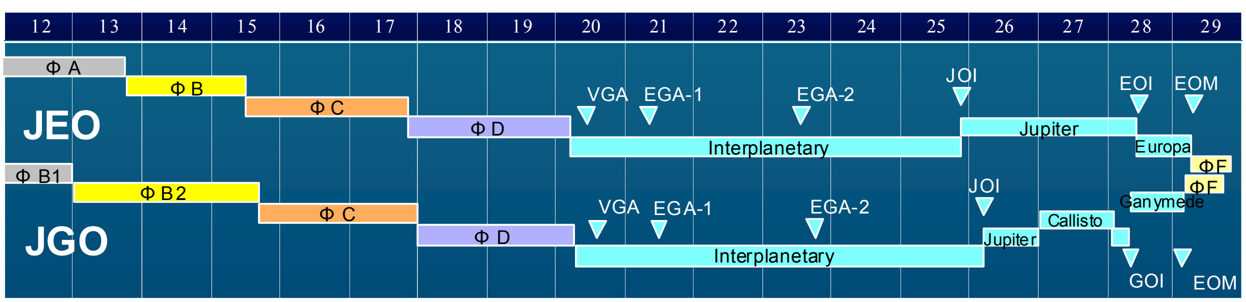

Figure ES-6. The concurrent but independent development of the JGO and JEO flight elements allow overlapping primary Jupiter System science enabling unprecedented observations of a single phenomenon from two different vantage points.

Scope of FY08 Phase II Studies

The 2008 NASA JEO study focused on three specific areas: refining the NASA mission concept, reducing risk and integrating with ESA. The JEO mission concept was reviewed and updated to incorporate additional Jupiter System science and to take advantage of technology maturation. The resulting concept provides a mature evolution from previous concepts which could provide scientists with a vast amount of information to address both the specific JEO Goal and Objectives and the Decadal Survey science. The model payload described herein only takes advantage of publically available information allowing innovative or proprietary concepts to only enhance the mission capabilities. The 2008 concept is mature and can only be summarized for this report. Because of space constraint, much of the detail has had to be left out of this report and the focus is on communicating the basic concepts and key results. To more fully understand the current concept, the reports from 2006 and 2007 should be examined as well as the reports discussed and referenced in the appendices.

The 2008 study risk reduction activity resulted in a detailed plan for a multi-year risk mitigation approach and in the delivery of 27 design documents and tutorials which potential providers can use to mitigate the risk to their designs (§4.5 and Appendix F). An Instrument Workshop was held in June 2008 to engage potential instrument providers in the aspects of design which are most important. Many of these deliverables have been made public via the Outer Planets Flagship Mission website http://opfm.jpl.nasa.gov. Several of the documents are ITAR sensitive and publically releasable versions are in the process of being made available. Additional, design information is planned for public release during Pre-Phase A activities to reduce risk early in the project development phases to contain cost growth and risk.

The final activity for 2008 was the integration of JEO with the ESA *Laplace* concept into the EJSM. The JJSDT found a very natural partitioning of science with the ESA flight element complementing JEO's science while concentrating on Callisto and Ganymede. The allocation of primary focus allows both organizations to develop mission concepts within their experience base which can be flown independently to achieve spectacular science, or in concert to achieve breathtaking science where the combination is greater than the sum of its parts.

Summary

The exploration of the Jupiter System is invaluable for providing insights our own solar system's evolution and into planetary architecture and habitability throughout the universe. For these reasons, both NASA's Solar System Exploration Decadal Survey and ESA's Cosmic Vision strategic document emphasize the exploration of the Jupiter system to investigate the emergence of habitable worlds.

Both the NASA-only and the NASA/ESA collaborative approach to Jupiter system and Europa/Ganymede exploration make the next giant leap in solar system understanding possible with a well-defined cost and risk posture for NASA. With better instruments, more focused tour objectives, extended time to study Io, Callisto, Europa, and Ganymede up close, and over three orders of magnitude more data return, JEO and JGO could provide the opportunity to radically advance the knowledge of the Jupiter System and its relationship to the emergence of habitable worlds around gas giants.

1. Scientific Objectives

Science Questions and Objectives

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 2.

Science Traceability

Table 1-1. Science Traceability Matrix

Science Objective		Science Investigation	Measurement	Instrument	Functional Requirement
A. Ocean	**Characterize the extent of the ocean and its relation to the deeper interior.**	**A1.** Determine the amplitude and phase of the gravitational tides.	A1a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A1a. Telecom system	Orbiter required, low altitude (~100–300 km, orbital inclination of ~40-85° (or retrograde equivalent) for broad coverage and cross-overs. Ground-tracks should not exactly repeat (while near-repeat is acceptable), so that different regions are measured. Requires a mission duration of at least several eurosols to sample the time-variability of Europa's tidal cycle. Near-continuous measurements near Europa, globally distributed, at altitudes ≤ 500 mk, for a duration of at least 1 – 3 months
			A1b. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1-m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A1b. Laser altimeter	
		A2. Characterize the magnetic environment (including plasma), to 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	
			A2b. Determine the plasma distribution function with 1 min resolution continuously for several months; detect electrons in the few keV to hundreds of keV with angular and time resolution	A2b. Particle and plasma instrument	
		A3. Characterize surface motion over the tidal cycle.	A3a. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1 m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A3a. Laser altimeter	
			A3b. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A3b. Telecom system	
		A4. Determine the satellite's dynamical rotation state.	A4a. Doppler shift from spacecraft tracking via two-way Doppler, to determine mean spin pole direction. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	A4a. Telecom system	
			A4b. Topographic differences at cross-over points from globally distributed topographic profiles to determine spin pole direction and libration amplitudes, with better than or equal to 1 m vertical accuracy.	A4b. Laser altimeter	
		A5. Investigate the core, rocky mantle, and rock-ocean interface.	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	
			A5d. Determine the distribution function of the plasma ions and electrons with continuous observations over several months	A5d. Particle and plasma instrument	
B. Ice	**Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.**	**B1.** Characterize the distribution of any shallow subsurface water.	B1a. Identify and locally characterize subsurface thermal or compositional horizons and structures related to the current or recent presence of water or brine, by obtaining sounding profiles of subsurface dielectric horizons and structures, with better than 50 km profile spacing over more than 80% of the surface, at depths of 100 m to 3 km at 10 m vertical resolution, and performing targeted subsurface characterization of selected sites at least 30 km in length.	B1a. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth)	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 of ≥ 80°.
			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 more than 80% of the surface, co-located with sounding profiles.	B1b. Wide-angle camera (stereo) and laser altimeter	
		B2. Search for an ice-ocean interface.	B2a. Identify deep thermal, compositional, or structural horizons by obtaining sounding profiles of subsurface dielectric horizons, with better than 50 km profile spacing over more than 80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution.	B2a. Radar sounder (nominally ~5 or 50 MHz, with ~1 MHz bandwidth)	
			B2b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over more than 80% of the surface, co-located with sounding data.	B2b. Wide-angle camera (stereo) and laser altimeter	
		B3. Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	B3a. Global identification and local characterization of subsurface dielectric horizons and structures, 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 over more than 80% of the surface, plus targeted characterization of selected sites at least 30 km in length.	B3a. Radar sounder (dual-frequency, nominally ~5 & ~50 MHz, with ~1 and ~10 MHz bandwidth)	
			B3b. Map thermal emission from the surface by measuring the albedo over more than 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 better than 2 K.	B3b. Thermal imager	
			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 microns (0.4–2.5 microns desirable), and better than 12 nm through a spectral range of at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	B3c. Vis-IR imaging spectrometer	
			B3d. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over more than 80% of the surface, co-located with sounding data.	B3d. Wide-angle camera (stereo) and laser altimeter	
			B3e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel, and topographic sampling of targeted sites with better than 1 m vertical accuracy.	B3e. Narrow-angle camera and laser altimeter	
			B3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over more than 80% of the surface.	B3f. Wide-angle camera, color	

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Science Objective		Science Investigation	Measurement	Instrument	Functional Requirement
B. Ice	**Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.**	**B3.** Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	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 microns, using profiles at better than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	B3g. UV imaging spectrometer	
			B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	B3h. Medium-angle camera	
			B3i. Doppler velocity of 0.1 mm/s over 60 s accuracy, to identify regions of density contrast within the ice crust. Multi-frequency communication (e.g., Ka & X) is best, but X is sufficient.	B3i. Telecom system	
		B4. Characterize regional and global heat flow variations.	B4a. Identify and map subsurface thermal horizons, by obtaining sounding profiles of subsurface dielectric horizons, with better than 50 km profile spacing over more than 80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution.	B4a. Radar sounder	
			B4b. Map thermal emission from the surface by measuring the albedo over more than 80% of the surface at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy.	B4b. Thermal imager	
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 and potential biosignatures.	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 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm spectral resolution (20 nm floor) through a spectral range of at least 2.5–5 microns, along profiles with less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C1a. Vis-IR imaging spectrometer	Solar phase angles of ≤ 45°, with orbital inclination of ≥ 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. As low an orbit as feasible is desired, for direct detection of sputtered particles.
			C1b. Characterize the composition of sputtered products from energetic particle bombardment of the surface, using ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C1b. Ion and neutral mass spectrometer	
			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 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C1c. UV imaging spectrometer	
		C2. Relate compositions to geological processes, especially material exchange 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 5 nm (10 nm floor) spectral resolution through a spectral range of at least 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm (20 nm floor) through a spectral range of at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C2a. Vis-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 microns.	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 better than 2 K, over more than 80% of the surface.	C2e. Thermal imager	
			C2f. Detailed morphological characterization of targeted features through imaging at better than or equal to 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 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	
		C3. Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, 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 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor), and better than 10 nm spectral resolution (20 nm floor) through a spectral range of at least 2.5–5 microns. SNR better than 128 for 0.9–2.6 microns and better than 32 for 2.6–5 microns.	C3a. Vis-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 to 3 nm spectral resolution, through a spectral range of at least 0.1–0.35 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C3b. UV imaging spectrometer	
			C3c. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm through a spectral range of at least 2.5–5 microns with SNR greater than 32, 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 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	C3c. Vis-IR imaging spectrometer and UV imaging spectrometer	
			C3d. Characterize the composition of sputtered products from energetic particle bombardment of the surface, through ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of more than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C3d. Ion and neutral mass spectrometer	
			C3e. Characterize the structure of the sputter-produced atmosphere using ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emissions, at equal to or better than 0.5 nm spectral resolution and 100 m/pixel scale through a spectral range of at least 0.1–0.20 microns.	C3e. UV imaging spectrometer	
			C3f. Determine the flux of trapped and precipitating ions (with composition) and electrons in the energy range 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute.	C3f. Particle and plasma instrument	

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Science Objective		Science Investigation	Measurement	Instrument	Functional Requirement
C. Chemistry	**Determine global surface compositions and chemistry, especially as related to habitability.**	**C3.** Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.	C3g. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over more than 80% of the surface.	C3g. Wide-angle camera, color	
			C3h. Measure the surface albedo at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, over more than 80% of the surface.	C3h. Thermal imager	
			C3i. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	C3i. Narrow-angle camera	
		C4. Characterize the nature of exogenic materials.	C4a. Determine the ion (with composition) and electron precipitation flux at energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E$ = 0.1 and a time resolution of at least 1 minute.	C4a. Particle and plasma instrument	
			C4b. Ion and neutral mass spectrometry over a mass range of 300 Daltons, mass resolution of more than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C4b. Ion and neutral mass spectrometer	
			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 5 nm (10 nm floor) spectral resolution through a spectral range of 0.4–2.5 microns (1–2.5 microns floor) with SNR better than 128, and better than 10 nm resolution (20 nm floor) through a spectral range of at least 2.5–5 microns (SNR better than 32), along profiles with less than or equal to 25 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	C4c. Vis-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 microns, using profiles at less than or equal to 25 km spacing over more than 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 more than 80% of the surface.	C4e. Wide-angle camera, color	
D. Geology	**Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	**D1.** Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.	D1a. Determine the distributions and morphologies of surface landforms at regional and local scales, and the regional and global stratigraphic relationships among them, by determining surface color characteristics at ~100 m/pixel scale in at least 3 colors with near-uniform lighting conditions and solar phase angles less than or equal to 45 degrees, over more than 80% of the surface.	D1a. Wide-angle camera (color) and medium-angle camera	Near-replicating 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. Solar incidence angles of 45–80° 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 initial areal coverage, followed by improved resolution coverage at low altitude. Day-night repeat coverage required: afternoon orbit is desirable.
			D1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over more than 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 better than 50 km spacing over more than 80% of the surface, plus targeted characterization of selected sites.	D1d. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth)	
			D1e. Characterize 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 to 1 m.	D1e. Medium-angle camera or narrow-angle camera	
			D1f. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm resolution through a spectral range of at least 2.5–5 microns with SNR better than 32, 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 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	D1f. Vis-IR spectrometer and UV imaging spectrometer	
			D1g. 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 daytime and nighttime thermal observations at spatial resolution better than or equal to 250 m/pixel and temperature accuracy better than 2 K, over more than 80% of the surface.	D1g. Thermal imager	
			D1h. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D1h. Narrow-angle camera	
		D2. Determine sites of most recent geological activity and evaluate future landing sites.	D2a. Thermal mapping better than or equal to 250 m/pixel spatial resolution and temperature accuracy better than 2 K, over more than 80% of the surface, with the same regions observed in both the day and night.	D2a. Thermal imager	
			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 0.5 nm spectral resolution through a range of at least 0.1–0.2 microns.	D2b. UV imaging spectrometer	
			D2c. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	D2c. Medium-angle camera (stereo)	
			D2d. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D2d. Narrow-angle camera	
			D2e. Identify and map any age-sensitive chemical and physical indicators (e.g., H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9–2.5 microns (0.4–2.5 microns desirable) with SNR better than 128, and better than 12 nm through a spectral range of at least 2.5–5 microns with SNR better than 32, 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 microns, using profiles at less than or equal to 25 km spacing over more than 80% of the surface, plus targeting of selected sites.	D2e. Vis-IR spectrometer and UV imaging spectrometer	

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Science Objective		Science Investigation	Measurement	Instrument	Functional Requirement
D. Geology	**Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	**D2.** Determine sites of most recent geological activity and evaluate future landing sites.	D2f. Characterize the interaction between the surface and plasma to evaluate surface aging processes. Measure depth and temperature of the 1.65 micron water band (deeper for colder temperatures of crystalline (young) ice and nearly absent for pure amorphous (older) ice in addition to measurements at 3.1 and 4.53 microns. Determine the ion and electron precipitation flux with ion composition for energies of 1 eV to 1 MeV.	D2f. Particle and plasma instrument and Vis-IR imaging spectrometer	
		D3. Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris.	D3a. 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.	D3a. Thermal imager	
			D3b. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D3b. Narrow-angle camera	
			D3c. Characterize the interaction between the surface and plasma to evaluate surface aging processes. Measure depth and temperature of the 1.65 micron water band (deeper for colder temperatures of crystalline (young) ice and nearly absent for pure amorphous (older) ice in addition to measurements at 3.1 and 4.53 microns. Determine the precipitation flux of electrons and ions (with composition) in the eV to few MeV energy range.	D3c. Particle and plasma instrument and Vis-IR imaging spectrometer	
			D3d. 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, to constrain sputtering rates.	D3d. Magnetometer	
E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Satellite surfaces and interiors — **E1.** Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io.	E1a. Determine regional and global heat flow by 1) measuring global surface thermal emission at spatial resolution of 5 km/pixel to 10% radiometric accuracy at at least two wavelengths; 2) identifying thermally-controlled subsurface horizons within the ice shell by radar sounding at depths of 1 to 30 km at 100 m vertical resolution.	E1a. Thermal imager and radar sounder	Up to three flybys of Io with one at low altitude over an active volcano region; at least five flybys of Ganymede (altitudes <1000 km with at least four with altitude <200 km); at least five Callisto flybys including 1 polar (all with altitudes < 1000 km); closest approach distributed globally in latitude and longitude. Solar incidence angles of 45–80° are best for morphological imaging, while a solar phase angle ≤ 45° is best for color imaging.
			E1b. Thermal Mapping with 2K absolute accuracy, from ~80K to >160K, spatial resolution better than 10 km/pixel, preferably better than 500 m/pixel, within 30 degrees of the noon meridian and at night.	E1b. Thermal imager	
			E1c. Determine regional and global time-varying gravity and topography/shape of Io. Topographic differences at cross-over points with better than or equal to 10 m vertical accuracy. 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.	E1c. Telecom system and laser altimeter	
		E2. Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust).	E2a. Repeated (daily to monthly) monochromatic imaging of selected active volcanic features at ~1 km/pixel spatial resolution.	E2a. Narrow angle camera	
			E2b. IR imaging of volcanic thermal emission at better than 100 km/pixel spatial scale, absolute accuracy 2K, at silicate melt temperatures, over a range of temporal scales (e.g., hourly, daily, weekly, monthly). Desire better than 20 km/pixel spatial resolution.	E2b. IR imaging spectrometer	
			E2c. Frequent multispectral global mapping (minimum 3 colors) at better than or equal to 10 km/pix. Violet, green, NIR over a range of temporal scales (e.g., hourly, daily, weekly, monthly).	E2c. Narrow-angle camera	
			E2d. High-resolution visible imaging (better than 100 m spatial resolution) of selected volcanic features for change detection (e.g., with Galileo and Voyager data).	E2d. Narrow-angle camera	
			E2e. Global (>80%) monochromatic imaging at ~1 km/pixel spatial resolution at available opportunities.	E2e. Narrow-angle camera	
			E2f. IR imaging of volcanic thermal emission at better than 100 km/pixel spatial scale, absolute accuracy 2K, at silicate melt temperatures, over a range of temporal scales (e.g., hourly, daily, weekly, monthly). Desire better than 20 km/pixel spatial resolution.	E2f. IR imaging spectrometer	
			E2g. UV - VIS plume imaging: high phase angle plume monitoring (for dust and gas emissions) and low phase angle observations (for gas absorptions) over a range of temporal scales. Visible spatial resolution better than 20 km/pixel; UV spatial resolution better than 50 km/pixel.	E2g. UV imaging spectrometer and narrow-angle camera	
			E2h. Long-distance visible and thermal characterization (e.g., from Ganymede or Jupiter orbit) over a period of years. Desire close flybys of Io to characterize terrains/active features/change at high resolution.	E2h. Narrow-angle camera and thermal imager	
		E3. Investigate the presence and location of water within Ganymede and Callisto.	E3a. Determine Degree-2 dynamic gravity field and spin pole orientation. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency preferred. Many flybys.	E3a. Telecom system	
			E3b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT with multiple flybys at different orbital phases and closest approach of < 0.5 moon radii.	E3b. Magnetometer	
			E3c. Characterize the extent and location of water (including brines) in 3D by obtaining profiles at depths of 1 to 30 km at 100 m vertical resolution, and obtain simultaneous topography at better than or equal to 1 km/pixel spatial scale and better than or equal to 10 m range accuracy.	E3c. Radar sounder and laser altimeter	
		E4. Determine the composition, physical characteristics, distribution, and evolution of surface materials on Ganymede.	E4a. Identify globally distributed bulk material compositions, grain size, porosity, crystallinity, and physical state from the IR (0.8–2.5 microns) with a spectral resolution of 4 nm and an IFOV smaller than 100 m, to the thermal with 2K absolute accuracy, from ~80K to >160K and spatial resolution better than 10 km/pixel.	E4a. Vis-IR imaging spectrometer and thermal imager	
			E4b. Map global distribution of different materials, including radiolytic materials (e.g., SO_x, O_3, H_2O_2, OH, O_2), and document variability over a range of timescales in the IR (0.8–5 microns) with a spectral resolution better than 10 nm (4 nm in the 1–2.5 micron range) and IFOV less than 1 km, along with UV observations (0.1 to 0.4 microns) with spectral resolution of better than 2 nm and spatial resolution better than 1 km/pixel.	E4b. Vis-IR imaging spectrometer and UV imaging spectrometer	
			E4c. Determine origin and evolution of non-ice materials, including the role of geologic processes in the IR (0.8–5 microns; spectral resolution of better than 10 nm and IFOV smaller than 1 km) of representative features. Co-registered with higher-resolution panchromatic images.	E4c. Vis-IR imaging spectrometer and narrow-angle camera	
			E4d. Document composition, physical state, distribution, and transport of surface volatiles, e.g., sublimation, over the UV wavelength range of 0.1 to 0.4 microns with spectral resolution of 2 nm and spatial resolution better than 1 km/pixel. Spatial coverage of 50% to search for short-lived or mobile species and repeated coverage to look for changes. Visible wavelength mapping at 0.55–0.75 microns, spectral resolution of 1 nm. 50% global coverage with spatial resolution better than 1 km/pixel; repeated coverage to look for changes. IR coverage from 0.8–5 microns with spectral resolution better than 10 nm, IFOV smaller than 1 km. 50% global coverage with spatial resolution better than 1 km/pixel; repeated coverage to look for changes.	E4d. UV imaging spectrometer and Vis-IR imaging spectrometer	

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Science Objective		Science Investigation			Measurement	Instrument	Functional Requirement
E. Jupiter System	Understand Europa in the context of the Jupiter system.	Satellite surfaces and interiors	E5.	Determine the composition, physical characteristics, distribution, and evolution of surface materials on Callisto.	E5a. Identify bulk material compositions, grain size, porosity, crystallinity, and physical state using globally-distributed hyperspectral IR imaging (0.8–2.5 microns). Spectral resolution of 4 nm, IFOV smaller than 100 m.	E5a. Vis-IR imaging spectrometer	
					E5b. Identify globally distributed bulk material compositions, grain size, porosity, crystallinity, and physical state from the IR (0.8–2.5 microns) with spectral resolution of 4 nm and IFOV smaller than 100 m, to the thermal with 2K absolute accuracy, from ~80K to >160K and spatial resolution better than 10 km/pixel.	E5b. Vis-IR imaging spectrometer and thermal imager	
					E5c. Map global distributions of different materials, including radiolytic materials (e.g., SO_x, O_3, H_2O_2, OH, O_2), and document variability over a range of timescales using global IR imaging (0.8–5 microns). Spectral resolution better than 10nm (4 nm in the 1–2.5 micron range), IFOV smaller than 1 km, along with UV observations (0.1 to 0.4 microns) with spectral resolution of better than 2 nm and spatial resolution better than 1 km/pixel.	E5c. Vis-IR imaging spectrometer and UV imaging spectrometer	
					E5d. Determine origin and evolution of non-ice materials, including the role of geologic processes in the IR (0.8–5 microns; spectral resolution of better than 10 nm and IFOV smaller than 1 km) of representative features. Co-registered with higher-resolution panchromatic images.	E5d. Vis-IR imaging spectrometer and narrow-angle camera	
			E6.	Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.	E6a. Measure the low order static gravity (J_2 and C_{22}) at 10^{-7} accuracy for the non-dimensional gravitational harmonics of both moons, via Doppler tracking.	E6a. Telecom system	
					E6b. Measure higher-order gravity to evaluate non-hydrostatic effects, via Doppler tracking.	E6b. Telecom system	
					E6c. Measure the dynamic degree-2 gravity signal to determine tidal k_2 to within 0.1, via Doppler tracking.	E6c. Telecom system	
					E6d. Measure the pole position to 0.1 deg accuracy to determine the obliquity of the spin axis.	E6d. Medium-angle camera	
					E6e. Globally distributed altimetry to 1 m vertical resolution and better than 1 km horizontal resolution (100 m horizontal resolution preferable, at least along specific spacecraft tracks if not globally)	E6e. Laser altimeter	
					E6f. Global (more than 80% coverage) visible imaging at 100 m/pixel spatial resolution. Additionally, desire ~10–20% coverage at 10 m/pixel.	E6f. Narrow-angle camera	
					E6g. Globally distributed profiling of thermal, compositional and structural horizons for Ganymede and Callisto's icy shells to depths from 1 up to 30 km at 100 m vertical resolution.	E6g. Radar sounder	
					E6h. Measurement of, or upper limit on, heat flow using thermal measurements in the 8 to 100 micron range with a spectral resolution of 2K and spatial resolution better than 30 km/pixel; observation collected several times of day and at night.	E6h. Thermal imager	
					E6i. Magnetic field. Determination of induction response at orbital (as well as Jupiter rotation) time scales to an accuracy of 0.1 nT but with the emphasis on looking for secular variation of the "steady" field or variation in the induction signal since Galileo.	E6i. Magnetometer	
		Satellite atmospheres	E7.	Characterize the composition, variability, and dynamics of Europa's atmosphere and ionosphere.	E7a. Perform UV imaging of Europa over the spectral range 100–200 nm at better than 0.5 nm resolution, better than 1 km spatial resolution, and better than 48 hr temporal resolution, including through the synodic cycle.	E7a. UV imaging spectrometer	≥10 radio occultation observations of the Galilean Satellites. Very close-to flybys (≤75 km) altitude strongly desired.
					E7b. Perform stellar occultations of Europa at UV wavelengths to search for water absorption and oxygen emission signatures. Cover 100–200 nm at better than 0.5 nm resolution, and latitude/longitude resolution of less than 30 deg.	E7b. UV imaging spectrometer	
					E7c. Scan perpendicular to the limb from ~5 km above the surface to the surface of the satellite at IR wavelengths to measure or search for emission from O_2 (1.27 microns), H_2O, CO_2 (4.26 microns) and other species in the Europa atmosphere.	E7c. IR imaging spectrometer	
					E7d. Perform radio occultations of Europa to measure its ionosphere.	E7d. Two-band radio communication system with USO	
					E7e. Determine the fluxes of positive ions and neutral particles, by ion mass spectrometry over a mass range of 300 Daltons, mass resolution of better than 500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	E7e. Ion and neutral mass spectrometer	
					E7f. Understand how sputtering generates an exosphere. Determine the flux and composition of the impacting charged particles (ions and electrons) between energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute.	E7f. Particle and plasma instrument	
			E8.	Understand the sources and sinks of Io's crustal volatiles and atmosphere.	E8a. Characterize volatile cycle, including composition, physical state, distribution, and transport of surface volatiles by global mapping of the surface at UV-IR wavelengths (e.g., for SO_2 frost variations) on a range of temporal scales (~days). IR (1–5 microns) at 20 nm spectral resolution and ~10–500 km/pixel; VNIR (0.35–1 microns) at 2 nm resolution; NUV (0.2–0.35 microns) with better than 20 nm spectral resolution and better than 100 km spatial resolution.	E8a. UV imaging spectrometer and Vis-IR imaging spectrometer	
					E8b. Dayside, nightside and eclipse coverage at UV wavelengths, 0.1–0.35 microns (for SO_2 and other gas density) at 0.5 nm spectral resolution, better than 500 km/pixel spatial resolution	E8b. UV imaging spectrometer	
					E8c. Determine roles and rates of sublimation, sputtering, and radiation darkening by global mapping of surface at UV-IR wavelengths at ~10–500 km/pix at better than 10 nm spectral resolution for 1–5 microns, and at ~2 nm for 0.1–1 microns, over a wide range of longitudes (i.e. to facilitate comparisons between leading and trailing hemispheres, especially in non-plume regions) and with thermal IR mapping with regional spatial resolution better than 10 km, including polar coverage.	E8c. Thermal instrument	
					E8d. Determine column densities of atmospheric/plume species across the globe and document correlations with plumes, geologic features and local albedo variations by global EUV - NIR (0.06–5 microns) surface and limb spectroscopy at better than 50 km resolution. UV spectral resolution of 0.3 nm. UV spatial resolution of better than 500 km/pixel. Visible imaging in eclipse.	E8d. UV imaging spectrometer, Vis-IR imaging spectrometer, and narrow-angle camera	
					E8e. UV stellar occultations (FUV-NUV) over a range of latitude/longitude space and a range of temporal scales/periodically throughout the mission. UV spectral resolution of 0.5 nm, 0.1–0.25 microns.	E8e. UV imaging spectrometer	
					E8f. Perform long-term and high-temporal-resolution monitoring of atmosphere, plumes, limb-glow, and equatorial spots via EUV - VNIR (0.06–1 microns) imaging limb observations of plumes, atmosphere, neutral clouds over a range of temporal scales (e.g., hourly, daily, weekly, monthly). UV spectral resolution of 0.5 nm, spatial resolution of <500 km/pixel. VNIR spatial resolution better than 10 km/pixel.	E8f. UV imaging spectrometer and Vis-IR imaging spectrometer	
					E8g. Determine the composition, distribution and physical characteristics (grain-size, crystallinity) of volatile materials on the surface, including SO_2 frost by vis-IR (0.4–5 micron) imaging on a global scale (better than 10 km/pixel for yellow and white-gray units), and at higher resolution for green and red units (~1 km/pixel).	E8g. Vis-IR imaging spectrometer	
					E8h. In situ neutral mass spectroscopy measurements of Io's atmosphere.	E8h. Ion and neutral mass spectrometer	

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

Science Objective		Science Investigation			Measurement	Instrument	Functional Requirement
E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Satellite atmospheres	**E9.**	Determine the sources and sinks of the Ganymede and Callisto atmospheres.	E9a. Determine column densities of atmospheric species across the globe at better than 1 km spatial resolution using IR limb scans, UV spectroscopy, and UV and visible-IR stellar occultations. UV spectral coverage 100–320 nm at 0.5 nm resolution. Perform long-term and high-temporal-resolution monitoring in context of magnetospheric variations.	E9a. UV imaging spectrometer and Vis-IR imaging spectrometer	
					E9b. Determine the composition, distribution and physical characteristics (grain-size, crystallinity, physical state) of volatile materials on the surface, including UV measurements of O_3, H_2O_2 and other species (100–320 nm at 2 nm resolution).	E9b. UV imaging spectrometer and Vis-IR imaging spectrometer	
					E9c. Investigate sputtering processes at high latitudes as compared with lower latitudes by measuring water ice grain sizes and products such as O_3, H_2O_2 and other species (UV observations over 100–320 nm at 2 nm resolution); measure flux of precipitating ions to representative satellite regions.	E9c. UV imaging spectrometer and particle and plasma instrument	
					E9d. Global FUV - IR (0.1–5 microns) spectroscopy at better than 50 km spatial resolution to measure SO_2, SO, S, O, Cl and other species in absorption and/or emission. UV spectral resolution of 0.5 nm; IR spectral resolution better than 10 nm.	E9d. UV imaging spectrometer and Vis-IR imaging spectrometer	
		Plasma and magnetospheres	**E9.**	Determine the sources and sinks of the Ganymede and Callisto atmospheres.	E9e. Perform stellar occultations at IR and UV wavelengths to search for water absorption and oxygen emission signatures. For UV, cover 100–200 nm at better than or equal to 0.5 nm resolution, and latitude/longitude resolution of better than 30 deg.	E9e. UV imaging spectrometer and Vis-IR imaging spectrometer	
					E9f. Scan perpendicular to the limb from ~5 km above the surface to the surface of the satellite at IR wavelengths to measure or search for emission from O_2 (1.27 microns), H_2O, CO_2 (4.26 microns) and other species in the Ganymede and Callisto atmospheres.	E9f. Vis-IR imaging spectrometer	
					E9g. Perform radio occultations of Ganymede and Callisto to measure the ionospheres.	E9g. Two-band radio communication system with USO	
			E10.	Characterize the neutral atoms and molecules escaping Europa's gravity.	E10a. Detect neutrals coming off Europa with a mass range up to 300 Daltons and a mass resolution of up to 500.	E10a. Ion and neutral mass spectrometer	
					E10b. Measure the flux of pickup ions in the tens to hundreds of eV energy range.	E10b. Plasma instrument	
					E10c. Determine the cold plasma temperature of the electrons to estimate ionization rates near Europa.	E10c. Plasma instrument	
			E11.	Characterize the composition of and transport in Io's plasma torus.	E11a. Perform EUV imaging spectroscopy (30–110 nm) of the Io plasma torus at 0.1 Rj/px and <0.5 nm spectral resolution over a range of timescales (e.g., hourly, daily, weekly, monthly) with emphasis on daily monitoring for > 30 days.	E11a. UV imaging spectrometer	Near-continuous measurements throughout the tour; dedicated campaign to observe the Io torus; broad distribution of Ganymede-magnetic latitude sampled on both leading and trailing hemispheres; near-continuous measurements near Europa during flybys, globally distributed, at altitudes < 500 km.
					E11b. Measure the flux and composition of charged particles (ions and electrons) between energies of 10 eV to 10 MeV at 15° angular resolution and $\Delta E/E = 0.1$ and a time resolution of at least 1 minute during passes of Io's torus. Magnetometer provides pitch angle distribution information. 8 vectors/s cadence is adequate. 0.1 nT resolution and 0.1 degree orientation knowledge.	E11b. Particle and plasma instrument and magnetometer	
			E12.	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.	E12a. Measure pickup ions in the tens to hundreds of eV energy range and energetic ions in the tens to few hundred keV/nuc energy range.	E12a. Ion and neutral mass spectrometer and particle and plasma instrument	
					E12b. Image neutral tori (e.g., H, O, S) at the orbits of Io, Europa, Ganymede, and Callisto.	E12b. UV imaging spectrometer	

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

Science Objective		Science Investigation		Measurement	Instrument	Functional Requirement
E. Jupiter System	**Understand Europa in the context of the Jupiter system.**	Plasma and magnetospheres	**E13.** Study the interactions between Jupiter's magnetosphere and Io, Ganymede, and Callisto (including characterize Ganymede's magnetic field).	E13a. Determine the trapped and precipitating fluxes of ions and electrons with energies between 10 eV and 10 MeV, 15° angular resolution or higher, $\Delta E/E=0.1$, and time resolution of 1 minute or higher.	E13a. Magnetometer and particle and plasma instrument	
				E13b. Investigate the generation of Ganymede's aurora with UV imaging (0.1–0.35 microns) of Ganymede (at 0.3 nm spectral resolution) at 1 km spatial resolution and at cadences of a minute or longer.	E13b. UV imaging spectrometer	
				E13c. Investigate the modification of surface composition and structure on open vs. closed field line regions by imaging of Ganymede at FUV-NIR wavelengths (100–350 nm and 0.8–2.5 microns) at 1 km spatial resolution.	E13c. UV imaging spectrometer and Vis-IR imaging spectrometer	
				E13d. Determine the flux and composition of precipitating ions and electrons between energies of 10 eV and 10 MeV and 15° angular resolution, $\Delta E/E=0.1$, and time resolution of at least 1 minute.	E13d. Magnetometer and particle and plasma instrument	
				E13e. UV and visible measurements at 1 min resolution of emission from moon magnetic footpoints in the Jovian auroral region.	E13e. UV imaging spectrometer and narrow-angle camera	
				E13f. Investigate effects of direct magnetospheric plasma, energetic particle, solar UV, and interplanetary dust interactions with the moon surfaces & atmospheres, search for hemispherical differences, and associated temporal variations with global UV-NIR measurements (0.1–3 microns) of hemispherical distributions of radiation products (sulfates, H_2O_2, O_2, CO_2) at 10 km resolution, and via repeated observations (timescale of months).	E13f. Particle and plasma instrument, UV imaging spectrometer, and Vis-IR imaging spectrometer	
			E14. Understand the structure, composition, and stress balance of Jupiter's magnetosphere.	E14a. Make continuous measurements of vector magnetic field (1 s resolution)	E14a. Magnetometer	
				E14b. Make continuous measurements of plasma and energetic charged particles (10 eV to 10 MeV), with full sky coverage and an angular resolution of 15°, $\Delta E/E=0.1$, and 10 s time resolution or higher.	E14b. Particle and plasma instrument	
			E15. Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.	E15a. Make continuous measurements of vector magnetic field (1 s resolution).	E15a. Magnetometer	
				E15b. Make continuous measurements of plasma and energetic charged particles (10 eV to 10 MeV), with full sky coverage and an angular resolution of 15°, $\Delta E/E=0.1$, and 10 s time resolution or higher.	E15b. Particle and plasma instrument	
		Jupiter Atmosphere	**E16.** Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa.	E16a. Measure the global distribution of water vapor humidity in the 2–8 bar region with 100 km spatial resolution. Use 5-micron imaging spectroscopy with spectral resolution R > 400.	E16a. Vis-IR imaging spectrometer	Coordinated feature-track observations using the entire suite of remote sensing instruments; sufficient time and resources for dedicated campaigns covering at least 2 full Jupiter rotations; solar, stellar and radio occultations covering as wide a range of latitudes as possible.
				E16b. Measure the global distribution of gaseous ammonia with 100 km horizontal spatial resolution at 2–6 bars (5 micron spectroscopy, R>400) and 200 km resolution at 0.1–0.4 bars (10 micron spectroscopy, R>400).	E16b. Vis-IR imaging spectrometer	
				E16c. Measure the vertical distribution of stratospheric water, 1–300 mbar (sub-mm sounding from 100–3000 GHz), 1–20 mbar with far-IR (R>400) spectroscopy.	E16c. Sub-mm wave sounder	
				E16d. Measure the global distribution of gaseous water and ammonia in the 10–100 bar region using passive microwave radiometry at 1–5 cm wavelength, possibly using the telecom antenna as a receiver for 1–5-bar region.	E16d. Microwave radiometer	
				E16e. Measure the 3-D distribution of disequilibrium species in the 0.1–4.0 bar region: measure PH_3, CO, AsH_3, GeH_4 at 100 km resolution using 5 micron spectroscopy at R>400. Measure PH_3, NH_3 in 100–600 mbar region at 200 km resolution at 10 microns with R>400 or at 1.0–4.0 microns with R>400. Measure at p<250 mbar in UV spectra.	E16e. Vis-IR imaging spectrometer, thermal imager, and UV imaging spectrometer	
				E16f. Determine the distribution of aerosols with altitude, latitude and longitude; investigate single scattering albedos, column abundances, topography of upper cloud layers, particles size distributions, IR opacities. Monitor changes in aerosol distribution associated with variations in atmospheric state (temperature, composition). Perform observations at multiple phase angles.	E16f. Vis-IR imaging spectrometer, wide- and medium-angle camera, and UV imaging spectrometer	

Europa Explorer Themes:					
	Origins	Evolution	Processes	Habitability	Life

Science Objective		Science Investigation		Measurement	Instrument	Functional Requirement
E. Jupiter System	Understand Europa in the context of the Jupiter system.	Jupiter Atmosphere	E17. Characterize Jovian atmospheric dynamics and structure.	E17a. Global visible/near-IR dayside imaging at 30 km/pixel to characterize dynamics. Imaging should include repeated coverage of the same regions at ~2 hour intervals for cloud tracking (necessary to obtain winds). Wavelengths should include visible and/or near-IR continuum as well as one or more methane absorption band (e.g., 889 nm and other) to obtain vertical structure of winds and clouds. Imaging strategy must characterize behavior over a range of timescales, including short (1–3 days), medium (~1 month), and long (~1 year) timescale variability. Strategy ideally should involve global or near-global daily coverage for periods of weeks-to-months.	E17a. Wide/medium-angle camera and Vis-IR imaging spectrometer	
				E17b. Obtain global temperature maps (100 km resolution) for vertical temperature structure and horizontal gradients (for deriving thermal wind shears). Pressure ranges 1–10 mbar and 100–500 mbar for 7–250 micron spectroscopy, 5–300 mbar for sub-mm spectroscopy. Limb spectroscopy with 20–40 km vertical spatial resolution for vertical distribution.	E17b. Thermal imager and sub-mm spectrometer	
				E17c. Make repeated radio occultations to obtain vertical temperature profiles closely spaced in space and time (e.g., at the same latitude ±10 degrees, once every 2 weeks) to investigate wave propagation in the stratosphere and upper troposphere, in addition to investigating the temporal behavior of the Jovian ionosphere.	E17c. Two-band radio communication system with USO	
				E17d. Perform stellar and solar occultations over a wide range of latitudes to obtain high vertical resolution temperature structure and composition in the upper stratosphere (1 km at 20 K per measurement).	E17d. Vis-IR imaging spectrometer, thermal imager, and UV imaging spectrometer	
				E17e. Measure the 3-D distribution of stratospheric hydrocarbons and other molecules in the stratosphere, at 100 km spatial resolution with global coverage and spectral resolution R > 2000 in the mid-IR (8–16 microns) and FUV (110–200 nm). Limb spectroscopy with 20–40 km vertical spatial resolution for vertical distribution.	E17e. Mid-IR spectrometer and UV imaging spectrometer	
				E17f. Measure Jovian aurora on timescales of minutes, hours, and days at IR (0.8–2.5 microns) and UV (0.1–0.2 microns) wavelengths.	E17f. Vis-IR imaging spectrometer and UV imaging spectrometer	
		Rings	E18. Characterize the properties of the small moons, ring source bodies, and dust.	E18a. Conduct a comprehensive search for embedded moons within the ring system, down to a limiting size of ~100 m (~14th magnitude). Conduct multiple surveys of the ring region at low phase angles to ensure completeness of coverage. Each object should be detected at least ~20 times over a time frame of ~1 year to enable a precise determination of its orbit; astrometric precision of better than 30 km is required.	E18a. Narrow-angle camera with a clear or very broad-band filter	At least one shadow passage from long range; ≥3° inclination off of the ring plane.
				E18b. Search for km-sized moons throughout the Jovian system (from the rings to beyond the orbit of Callisto) with a detection threshold of ~1 km (~10th magnitude). This requires repeated, complete mosaics of the system taken at low phase angles and using a medium- or a wide-angle camera. After discovery, each previously unknown object should be targeted with a narrow-angle camera ~ 20 times over a time frame of ~1 year to provide a precise determination of its orbit. Astrometric precision of better than 30 km is required.	E18b. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter	
				E18c. Search for dust belts throughout the Jovian system (from the rings to beyond the orbit of Callisto) down to optical depths of $\sim10^{-9}$ (or reflectivities of $\sim10^{-8}$). Emphasize high phase angles and edge-on viewing geometry to achieve the most stringent detection limits. Study any belts detected from at least 10 phase angles, ranging from less than 10 degrees to greater than 170 degrees, to constrain particle sizes. At a few phase angles, measure the color in the visual and near-IR for additional limits on size and composition.	E18c. Wide-, medium- and/or narrow-angle cameras with several very broad-band filters	
				E18d. Profile the radial structure of the entire ring system (from the inner halo to beyond the orbit of Thebe) down to a spatial resolution of ~10 km and a sensitivity to reflectivities of 10^{-8}. Obtain at least 10 phase angles from less than 10 degrees to greater than 170 degrees, and use several visual and near-IR broad-band filters. Requires a viewpoints at least a few degrees out of the ring plane.	E18d. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter (especially CH_4)	
				E18e. Determine ring and inner moon surface composition with a sensitivity to reflectivities of $\sim10^{-7}$. Obtain this level of sensitivity in each of more than 200 spectral bands from the visual to beyond ~ 3 microns. Observe near backscatter to emphasize the surface composition of the larger embedded bodies in the system.	E18e. Vis-IR imaging spectrometer	
			E19. Identify the dynamical processes that define the origin and dynamics of ring dust.	E19a. Determine the ring's 3-D structure, including the vertical structure of the halo and gossamer rings, via imaging from a variety of viewing geometries. Requires complete mosaics of the system from Jupiter out to beyond the orbit of Thebe, with resolution of better than 100 km/pixel. Images of the faintest ring components must be sensitive to reflectivities below 10^{-8}. Images must be obtained at a variety of opening angles and phase angles in order to decouple the ring's variations depending on radius, vertical distance from the ring plane, and phase angle. Note that imaging of the halo along the boundary of Jupiter's shadow provides optimal vertical resolution.	E19a. Wide-, medium- and/or narrow-angle cameras with a clear or very broad-band filter (especially CH_4)	
				E19b. Identify and characterize time-variable phenomena, including clump formation and evolution, via repeated, complete rotational profiles of the main ring with a resolution of better than 100 km/pixel. Obtain at least 20 complete profiles, sampling a wide variety of time scales from ~ days to ~ 1 year.	E19b. Narrow-angle camera with a clear or very broad-band filter	
				E19c. Search for warps and asymmetries on scales of 10–30 km via imaging of the system from nearly and exactly edge-on perspectives. Encompass the entire region from the halo out to beyond the orbit of Thebe, using cameras that are matched to the spatial scales of each region.	E19c. Wide-, medium- and/or narrow-angle cameras with appropriate filters (especially CH_4)	

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

2. High-Level Mission Concept

Overview

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). The Jupiter Europa Orbiter Mission concept is between concept maturity levels (CMLs) 5 and 6. Detailed science traceability, defined relationships, and dependencies are all completed for the planning payload. The basic implementation mode has been selected and major partnerships are established. Technologies and risks have been defined. Mitigation plans are in place and some early mitigation activities are being executed. The basic verification and validation (V&V) approach has been defined for the planetary protection and radioisotope power source requirements, and testbeds/software and integration and test (I&T) approaches are story-boarded. The development schedule has been developed through to the subsystem levels (in some cases below that) and integrated into a master schedule. This schedule was used to develop a quasi-grassroots cost estimate. The spacecraft, planetary protection, project integration and test, and mission design are a grassroots estimate, but other areas are model-based. In two areas (mission assurance and education and public outreach), the costs are rules-of-thumb based.

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Technology Maturity

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.4.

Key Trades

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.4.5.

3. Technical Overview

Instrument Payload Description

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.2.

Table 3-1. Instrument Specifications

	Units	Laser Altimeter	Ice Penetrating Radar	VIS-IR Spectrometer	UV Spectrometer	Ion and Neutral Mass Spectrometer	Thermal Instrument	Narrow-Angle Camera	Wide and Medium Angle Camera	Magnetometer	Particle and Plasma Instrument
Instrument mass **without** contingency (CBE*)	kg	9.7	31	27.5	9.5	15.1	5	13.4	7.9	3.2	16.4
Instrument mass contingency	%	30	30	30	30	30	30	30	30	30	30
Instrument mass **with** contingency (CBE+Reserve)	kg	12.6	40.3	35.8	12.4	19.6	6.5	17.4	10.2	4.1	21.3
Instrument average payload power **without** contingency	W	15	45	25	5	33	5	14	7	4	13
Instrument average payload power contingency	%	30	30	30	30	30	30	30	30	30	30
Instrument average payload power **with** contingency	W	20	59	33	6.5	43	6.5	18	9	5	17
Instrument average science data rate^ **without** contingency	kbps	2	140	11,400	10	2	15	10,700	1,065	4	2
Instrument average science data^ rate contingency	%	0	0	0	0	0	0	0	0	0	0
Instrument average science data^ rate **with** contingency	kbps	2	140	11,400	10	2	15	10,700	1,065	4	2
Instrument fields of view (if appropriate)	degrees	0.029	5.7	9.17 x 0.014	3.67 x 0.057	20 x 40	3 x 0.14	1.17 x 1.17	58 x 0.057	N/A	360 x 90

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-2. Payload Mass and Power

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Laser altimeter	9.7	30	12.6	15	30	20
Ice penetrating radar	31.0	30	40.3	45	30	59
VIS-IR spectrometer	27.5	30	35.8	25	30	33
UV spectrometer	9.5	30	12.4	5	30	6.5
Ion and neutral mass spectrometer	15.1	30	19.6	33	30	43
Thermal instrument	5	30	6.5	5	30	6.5
Narrow-angle camera	13.4	30	17.4	14	30	18
Wide and medium-angle camera	7.9	30	10.2	13	30	17
Magnetometer	3.2	30	4.1	4	30	5
Particle and plasma instrument	16.4	30	21.3	13	30	17
Science electronics chassis	26.6	30	34.6	–	–	
Total Payload Mass	**165.3**	–	**214.9**	**172**	–	**225**

Flight System

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.4.

Table 3-3. Flight System Element Mass and Power

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	320	31	420	15	57	24
Thermal control	68	30	88	23	57	36
Propulsion (dry mass)	159	28	203	1	57	2
Attitude control	69	33	91	90	57	141
Command & data handling	34	17	40	52	57	81
Telecommunications	56	27	70	82	57	129
Power	55	30	72	10	57	16
Cabling	83	30	108	24	57	38
Radiation monitoring system	8	30	10	4	57	6
RPS system	226	0	226	–	–	–
Radiation shielding	132	30	172	–	–	–
Total Flight Element Dry Bus Mass	**1,210**	**25**	**1,500**	**301**	**57**	**473**

Table 3-4. Flight System Element Characteristics

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design life, months	70 months, cruise 30 months, Jovian tour 9 months, Europa
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum, graphite composite, aluminum honeycomb
Number of articulated structures	2; HGA and main engine
Number of deployed structures	2; HGA and magnetometer
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	Surfaces, heaters louvers, heat pipes, RHUs, MLI
Propulsion	
Estimated delta-V budget, m/s	2,260
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Bipropellant (hydrazine and nitrogen tetroxide) main engine, monopropellant (hydrazine) reaction control thrusters
Number of thrusters and tanks	2 tanks, 1 main engine, 16 RCS thrusters
Specific impulse of each propulsion mode, seconds	Main 323 lbf-sec/lbm
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Solar
Attitude control capability, degrees	1 mrad
Attitude knowledge limit, degrees	10 μrad/s
Agility requirements (maneuvers, scanning, etc.)	
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	2 axis for both HGA and main engine
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	4 reaction wheels with 25 Nms of angular storage, 16, 4.5 N RCS thrusters
Command & Data Handling	
Flight Element housekeeping data rate, kbps	
Data storage capacity, Mbits	17,000 jovian tour; 1,000 Europa orbit
Maximum storage record rate, kbps	200,000
Maximum storage playback rate, kbps	280
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	5 MMRTGs
Array size, meters x meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	625, 540
On-orbit average power consumption, watts	539
Battery type (NiCd, NiH, Li-ion)	Li-Ion
Battery storage capacity, amp-hours	2 12 Amp-hours

Concept of Operations and Mission Design

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.3 and Section 4.4.2.7.3.

Table 3-5. Mission Design

Parameter	Value	Units
Orbit parameters (apogee, perigee, inclination, etc.)	0.7 – 5.5 95° incl, Europa	AU
Mission lifetime	109	mos
Maximum eclipse period	120	min
Launch site	KSC	
Total flight element #1 mass **with** contingency (includes instruments)	1,714	kg
Total flight element #2 mass **with** contingency (includes instruments)	N/A	kg
Propellant mass **without** contingency	2,681	kg
Propellant contingency	0	%
Propellant mass **with** contingency	2,681	kg
Launch adapter mass **with** contingency	123	kg
Total launch mass	4,745	kg
Launch vehicle	Atlas V 541	type
Launch vehicle lift capability	5,040	kg
Launch vehicle mass margin	295	kg
Launch vehicle mass margin (%)	6	%

Table 3-6. Mission Operations and Ground Data Systems

Down link Information	Cruise	Jovian Tour	Europa Orbit
Number of contacts per week	1–3	7–14	7–21
Number of weeks for mission phase, weeks	347	139	41
Downlink frequency band, GHz	8.4	32	32
Telemetry data rate(s), kbps	0.04	82.9	82.9
Transmitting antenna type(s) and gain(s), DBi	MGA	3 m HGA, 57.46	3 m HGA, 57.46
Transmitter peak power, Watts	45	56	56
Downlink receiving antenna gain, DBi	74.27	78.78	78.78
Transmitting power amplifier output, Watts	25	22.5	22.5
Total daily data volume, (MB/day)	**0.3**	**3,600**	**7,600**
Uplink Information			
Number of uplinks per day	0.14 – 1	0.28	1
Uplink frequency band, GHz	7.150	7.150	7.150
Telecommand data rate, kbps	0.008	2	2
Receiving antenna type(s) and gain(s), DBi	MGA, 18.11	3 m HGA, 44.44	3 m HGA, 44.44

Planetary Protection

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.7.

Risk List

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.10.

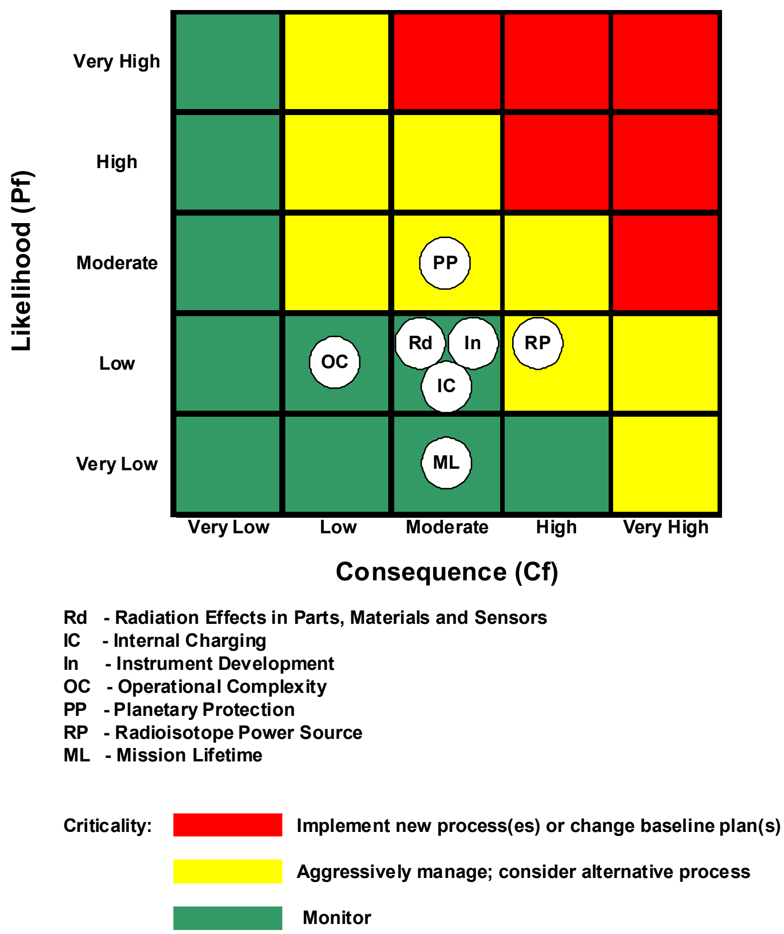

Figure 3-1. Jupiter Europa Orbiter Risk Evaluation

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.11.6.

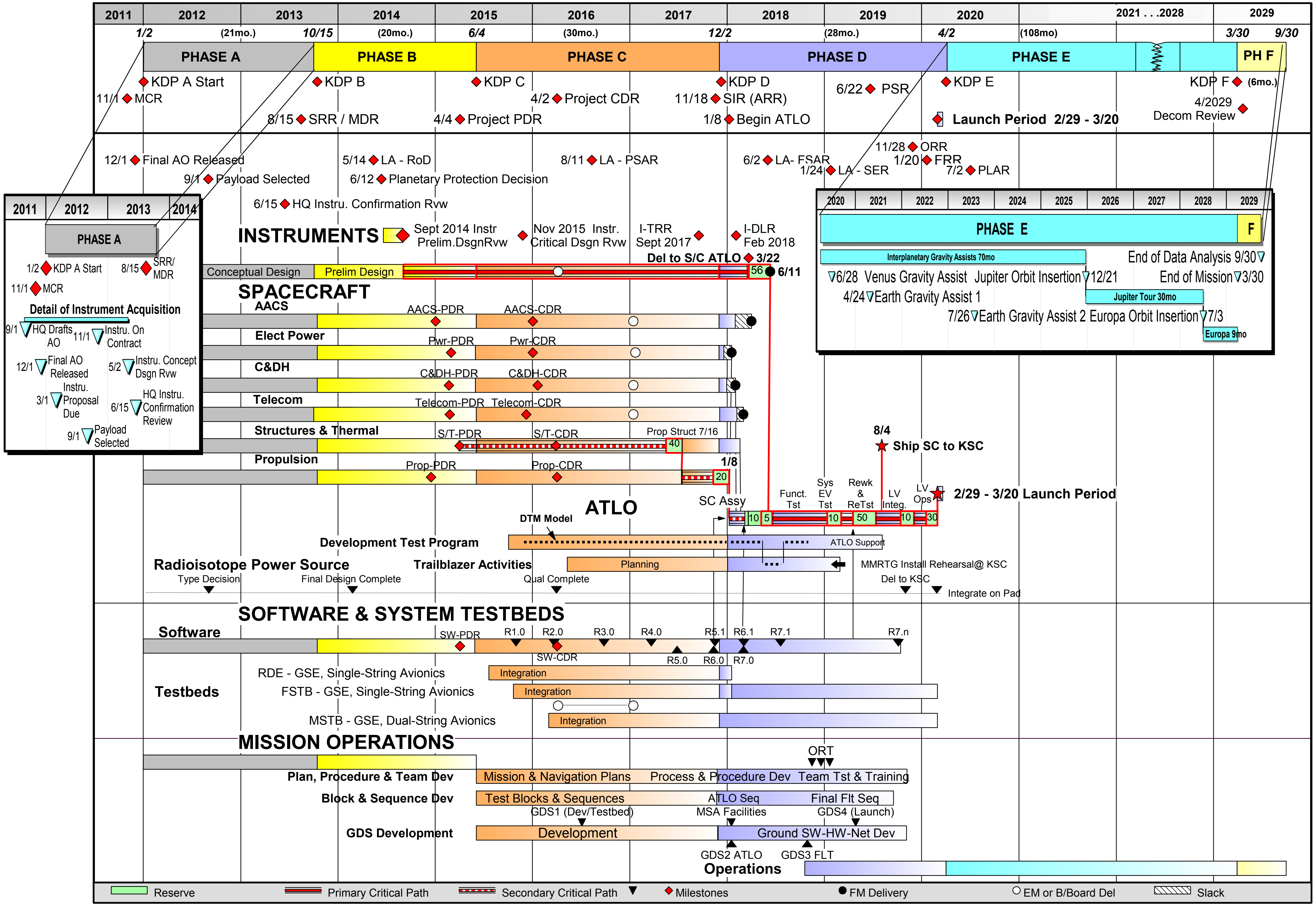

Figure 4-1. Mission Schedule

Table 4-1. Key Phase Duration

Project Phase	Duration (Months)
Phase A – Conceptual Design	21
Phase B – Preliminary Design	20
Phase C – Detailed Design	30
Phase D – Integration & Test	28
Phase E – Primary Mission Operations	108
Phase F – Extended Mission Operations	6
Start of Phase B to PDR	18
Start of Phase B to CDR	30
Start of Phase B to Delivery of Instruments	56
Start of Phase B to Delivery of Subsystems	54
System-level integration & test	21
Project total funded schedule reserve	8
Total development time Phase B–D	78

Technology Development Plan

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 4.9.

Development Schedule and Constraints

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Section 3.3.2 and Section 4.4.4.2.

5. Mission Life-Cycle Cost

See JEO Study 2008: Final Report [1], Section 4.11.7 and Appendix D.

Costing Methodology and Basis of Estimate

The NASA portion of the EJSM cost estimate presented here is the total mission cost for the complete project life cycle from Phase A through Phase F as presented in Table 5-1. Notice that the real year (RY) cost profile is provided for an assumed 2020 launch. The total costs per year and by phase are also presented in 2015 then-year dollars. Note that the total costs per year at the bottom of the table shows costs based on the reserve posture determined in the 2008 study as well as the reserve requirements specified in the NASA ground rules (50% cost reserves for Phases A–D and 25% cost reserves for Phase E).

Cost Estimates

See Jupiter Europa Orbiter Mission Study 2008: Final Report [1], Appendix D.

Table 5-1. Total Mission Cost Funding Profile

(FY costs in Real Year Dollars, Totals in Real Year and 2015 Dollars)

	Phase A			Phase B			Phase C/D							Phase E											Phase F		Total ($M RY)	Total ($M FY15)
	FY 2012	FY 2013	Total	FY 2014	FY 2015	Total	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	Total	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	Total	FY 2029	Total	All Phases	All Phases
01 Project Management	**2.3**	**11.0**	**13.3**	**19.3**	**11.8**	**31.2**	**7.4**	**20.0**	**16.1**	**14.9**	**14.6**	**6.9**	**80.0**	**2.9**	**4.8**	**3.9**	**4.2**	**4.2**	**4.9**	**5.7**	**5.9**	**6.0**	**2.9**	**45.4**	**1.7**	**1.7**	**171.7**	**157.3**
02 Project System Engineering	**1.5**	**3.5**	**5.0**	**5.1**	**3.7**	**8.8**	**2.4**	**7.6**	**8.3**	**8.9**	**9.5**	**5.1**	**41.8**														**55.5**	**53.1**
03 Safety & Mission Assurance	**0.5**	**2.0**	**2.5**	**9.3**	**8.7**	**18.0**	**7.4**	**23.1**	**22.9**	**12.8**	**6.0**	**2.9**	**75.0**	**0.5**	**0.8**	**0.6**	**0.7**	**0.6**	**1.2**	**1.7**	**1.7**	**1.7**	**0.8**	**10.2**	**0.4**	**0.4**	**106.1**	**100.2**
04 Science	**0.9**	**1.5**	**2.4**	**5.7**	**4.0**	**9.7**	**3.6**	**11.4**	**11.8**	**8.6**	**8.0**	**4.1**	**47.5**	**3.1**	**6.3**	**6.2**	**6.4**	**9.7**	**30.5**	**40.1**	**37.9**	**39.2**	**20.0**	**199.3**	**11.7**	**11.7**	**270.6**	**213.3**
04.01 Science Management	0.9	1.5	2.4	2.0	1.4	3.4	0.7	2.1	2.2	2.3	2.4	1.2	10.9	1.1	2.2	2.0	2.1	2.7	3.4	4.0	4.1	4.2	2.2	27.9	1.5	1.5	**46.0**	**38.4**
04.02 Science Implementation				2.9	2.0	4.9	2.6	8.2	8.5	5.1	4.4	2.2	31.0	1.5	3.0	3.1	3.2	4.4	21.9	30.7	28.2	29.2	14.8	140.0	8.7	8.7	184.6	143.7
04.03 Science Support				0.8	0.6	1.4	0.3	1.0	1.0	1.3	1.3	0.7	5.6	0.5	1.1	1.1	1.2	2.5	5.3	5.5	5.6	5.8	2.9	31.5	1.5	1.5	40.0	31.2
05 Payload System	**1.6**	**3.5**	**5.1**	**28.2**	**18.8**	**47.0**	**54.6**	**167.2**	**169.6**	**99.9**	**4.2**	**2.1**	**497.6**														549.7	529.2
05.01 PL Mgmt	0.9	1.2	2.0	1.2	0.8	2.0	0.5	1.5	1.5	1.6	1.6	0.8	7.5														11.5	11.2
05.02 PL Sys Eng	0.7	2.3	3.1	3.8	2.1	5.9	1.2	2.5	2.4	2.5	2.6	1.3	12.5														21.5	20.9
05.06 Laser Altimeter (LA)				1.2	0.8	2.0	2.7	8.2	8.3	4.8			24.0														26.0	25.0
05.07 Ice Penetrating Radar (IPR)				5.8	4.0	9.8	13.2	40.8	41.3	23.9			119.3														129.1	124.2
05.08 Vis-IR Imaging Spectrometer (VIRIS)				3.9	2.7	6.6	8.9	27.5	27.8	16.1			80.3														86.9	83.6
05.09 UV Spectrometer (UVS)				2.0	1.4	3.4	4.6	14.2	14.4	8.3			41.5														44.9	43.2
05.10 Ion and Neutral Mass Spectrometer (INMS)				1.4	1.0	2.4	3.2	10.0	10.1	5.8			29.1														31.5	30.3
05.11 Thermal Instrument (TI)				1.8	1.2	3.0	4.1	12.5	12.7	7.3			36.6														39.6	38.1
05.12 Narrow Angle Camera (NAC)				2.5	1.7	4.2	5.7	17.4	17.7	10.2			51.0														55.2	53.1
05.13 Wide Angle & Meduim Angle Camera (WAC + MAC))				2.4	1.6	4.1	5.5	16.9	17.2	9.9			49.6														53.6	51.6
05.14 Magnetometer (MAG)				0.8	0.5	1.3	1.8	5.4	5.5	3.2			15.8														17.1	16.5
05.15 Particle and Plasma Instrument (PPI)				1.4	1.0	2.4	3.3	10.1	10.3	6.0			29.7														32.1	30.9
05.30 Science Instrument Purge SS					0.0	0.0	0.0	0.2	0.4	0.1			0.7														0.7	0.7
06 Spacecraft System	**1.6**	**16.0**	**17.6**	**115.6**	**124.1**	**239.7**	**72.0**	**233.1**	**230.9**	**82.5**	**28.8**	**11.0**	**658.4**														**915.7**	**891.1**
06.01 S/C Mgmt		0.5	0.5	1.1	0.8	1.9	0.4	1.2	1.2	1.3	1.3	0.5	5.9														8.2	7.9
06.02 SC Sys Eng		0.9	0.9	4.5	4.8	9.3	2.5	7.4	5.5	3.1	2.6	0.9	22.0														32.2	31.3
06.03 SC Prod Assur (Included in WBS 03 SMA)																												
06.04 Power SS	0.2	2.0	2.2	5.8	19.9	25.7	3.1	22.2	10.6	2.8	1.5	0.6	40.8														68.7	67.4
06.05 C&DH SS	0.1	0.5	0.6	40.9	20.7	61.6	10.6	21.4	9.1	1.7	0.5	0.2	43.6														105.8	105.7
06.06 Telecom SS	0.2	2.0	2.2	15.4	5.2	20.6	10.4	16.4	8.1	2.9	0.9	0.5	39.3														62.1	61.4
06.07 Mech SS	0.2	1.7	1.9	7.3	13.5	20.8	8.4	36.1	60.5	7.1	4.6	1.5	118.2														140.9	135.9
06.08 Thermal SS		0.9	0.9	1.7	1.9	3.6	0.9	2.4	3.0	5.8	1.9	0.5	14.6														19.0	18.2
06.09 Prop SS		2.4	2.4	13.4	6.1	19.5	6.4	13.6	7.7	4.8	2.2	1.4	36.1														58.0	57.0
06.10 GN&C SS	0.9	4.4	5.3	7.2	15.0	22.2	9.7	30.8	22.6	3.5	1.6	0.6	68.8														96.4	94.4
06.11 Harness				0.5	1.0	1.4	0.5	2.5	5.0	2.0	1.9	0.7	12.6														14.0	13.2
06.12 Flt SW		0.4	0.4	2.0	3.3	5.3	2.6	12.2	12.5	9.6	5.1	1.8	43.8														49.5	47.1
06.13 SC Materials & Proc		0.0	0.0	0.2	1.0	1.1	0.3	1.1	1.1	0.8	0.3		3.6														4.8	4.6
06.14 SC Testbeds				0.1	0.7	0.8	0.6	2.7	3.7	3.8	3.7	1.2	15.8														16.6	15.5
06.16 Radiation Monitoring SS	0.0	0.2	0.2	0.9	0.5	1.4	0.3	0.9	0.8	0.9	0.7	0.6	4.2														5.9	5.6
06.17 Radioisotope Power Source (5 MMRTGs)				14.6	29.9	44.5	15.0	61.4	78.9	32.5			187.8														232.2	224.4
06.18 Trailblazer							0.2	0.7	0.6				1.5														1.5	1.5
07 Mission Ops Sys	**0.4**	**1.1**	**1.5**	**1.8**	**2.1**	**3.9**	**2.0**	**6.6**	**7.7**	**12.0**	**17.0**	**12.8**	**58.1**	**15.8**	**27.1**	**17.3**	**24.3**	**17.5**	**22.7**	**40.7**	**40.5**	**40.8**	**18.1**	**264.6**	**5.2**	**5.2**	**333.4**	**265.5**
07.03 Gnd Station Trckng												3.4	3.4	0.8	1.6	1.5	1.6	0.8	0.8	11.6	10.0	36.7	5.1	70.5			**73.9**	**54.2**
08 Launch Sys (Atlas 551 LV + Nuclear processing)								**5.3**	**65.5**	**105.6**	**90.5**		**266.9**														**266.9**	**246.1**
09 Ground Data Sys	**0.2**	**0.7**	**1.0**	**1.6**	**1.5**	**3.1**	**2.0**	**7.9**	**9.3**	**11.3**	**12.4**	**6.5**	**49.3**	**1.7**	**3.0**	**2.7**	**2.7**	**2.4**	**2.6**	**3.0**	**4.5**	**4.2**	**1.6**	**28.4**	**0.8**	**0.8**	**82.6**	**72.3**
10 Project System I&T		**0.3**	**0.3**	**4.0**	**5.7**	**9.7**	**2.6**	**5.7**	**3.1**	**16.5**	**26.4**	**10.9**	**65.2**														**75.2**	**69.7**
11 Educ and Pub Outreach	**0.1**	**0.2**	**0.3**	**0.9**	**0.8**	**1.7**	**0.7**	**2.1**	**2.0**	**1.2**	**0.6**	**0.3**	**6.9**	**0.5**	**0.8**	**0.6**	**0.7**	**0.7**	**1.2**	**1.7**	**1.7**	**1.7**	**0.8**	**10.4**	**0.4**	**0.4**	**19.6**	**16.7**
12 Mission Design	**1.1**	**3.2**	**4.4**	**4.4**	**2.9**	**7.3**	**1.4**	**3.6**	**3.7**	**3.6**	**3.5**	**1.7**	**17.4**														**29.1**	**28.4**
Subtotal before Reserves	**10.1**	**43.1**	**53.3**	**196.0**	**184.1**	**380.1**	**156.1**	**493.6**	**550.8**	**377.9**	**221.5**	**67.8**	**1,867.6**	**25.2**	**44.4**	**32.8**	**40.6**	**35.8**	**63.9**	**104.6**	**102.1**	**130.3**	**49.2**	**628.9**	**20.1**	**20.1**	**2,950.0**	**2,697.2**
Reserves as determined in 2008 study	**1.0**	**4.3**	**5.3**	**72.2**	**67.8**	**140.0**	**57.5**	**179.9**	**178.8**	**100.3**	**48.2**	**23.7**	**588.4**	**3.6**	**6.3**	**4.6**	**5.7**	**5.1**	**9.3**	**13.7**	**13.6**	**13.8**	**6.5**	**82.2**	**3.0**	**3.0**	**818.9**	**770.9**
Total NASA Phase A-F Cost	**11.2**	**47.4**	**58.6**	**268.2**	**251.9**	**520.1**	**213.6**	**673.4**	**729.6**	**478.2**	**269.8**	**91.4**	**2,456.0**	**28.8**	**50.7**	**37.4**	**46.4**	**40.9**	**73.2**	**118.2**	**115.7**	**144.1**	**55.7**	**711.1**	**23.1**	**23.1**	**3,768.9**	**3,468.1**
Contributions																												
Combined Toal (NASA + Contributions)																												
Euiropa Jupiter Systrem Mission estimate updated with new reserve requirement (50% Phase A-D, 25% Phase E-F)																												
Subtotal before Reserves	**10.1**	**43.1**	**53.3**	**196.0**	**184.1**	**380.1**	**156.1**	**493.6**	**550.8**	**377.9**	**221.5**	**67.8**	**1,867.6**	**25.2**	**44.4**	**32.8**	**40.6**	**35.8**	**63.9**	**104.6**	**102.1**	**130.3**	**49.2**	**628.9**	**20.1**	**20.1**	**2,950.0**	**2,697.2**
Reserves of 50% A-D and 25% E as required by NASA SS2012 PS Decadal Survey Study Ground Rules	**5.1**	**21.6**	**26.6**	**98.0**	**92.0**	**190.1**	**78.1**	**246.8**	**275.4**	**188.9**	**110.8**	**33.9**	**933.8**	**6.3**	**11.1**	**8.2**	**10.2**	**8.9**	**16.0**	**26.1**	**25.5**	**32.6**	**12.3**	**157.2**	**5.0**	**5.0**	**1,312.7**	**1,200.2**
Total NASA Phase A-F Cost	**15.2**	**64.7**	**79.9**	**294.0**	**276.1**	**570.2**	**234.2**	**740.3**	**826.2**	**566.8**	**332.3**	**101.6**	**2,801.4**	**31.5**	**55.6**	**41.0**	**50.8**	**44.7**	**79.9**	**130.7**	**127.6**	**162.9**	**61.5**	**786.1**	**25.1**	**25.1**	**4,262.7**	**3,897.4**
Contributions																												
Combined Toal (NASA + Contributions)																												

Appendix A. Acronyms

ASRG	advanced stirling radioisotope generators
CDR	Critical Design Review
CML	concept maturity level
EJSM	Europa Jupiter System Mission
ESA	European Space Agency
FY	fiscal year
I&T	integration and test
JEO	Jupiter Europa Orbiter
JJSDT	Joint Jupiter Science Definition Team
JGO	Jupiter Ganymede Orbiter
LV	launch vehicle
MEV	maximum expected value
MMRTGs	multimission radioisotope thermoelectric generator
NRC	National Research Council
PDR	Preliminary Design Review
RWA	reaction wheel assembly
RY	real year
SNR	signal-to-noise ratio
USO	ultra-stable oscillator
UV	ultraviolet
VIS-IR	visible infrared
V&V	verification and validation

Appendix B. References

[1] National Aeronautics and Space Administration, and European Space Agency. *Jupiter Europa Orbiter Mission Study 2008: Final Report—The NASA Element of the Europa Jupiter System Mission (EJSM).* 30 January 2009.