National Aeronautics and Space Administration

EUROPA STUDY 2012 REPORT

EXECUTIVE SUMMARY

Europa Study Team, 1 May 2012, JPL D-71990

Task Order NMO711062 Outer Planets Flagship Mission

Cover art Michael Carroll

ES. EUROPA STUDY 2012 REPORT: EXECUTIVE SUMMARY

Contents

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, with contributions from the Applied Physics Laboratory, Johns Hopkins University.

The cost information contained in this document is of budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

ES. EUROPA STUDY 2012 REPORT: EXECUTIVE SUMMARY

ES.1 Executive Summary

ES.1.1 Introduction

Four hundred years ago, Galileo's discovery of Jupiter's four large moons forever changed humanity's view of the universe, helping to bring about the Copernican Revolution. Today one of these Galilean moons may again revolutionize science and our sense of place, for hidden beneath Europa's icy surface is the most promising home for extant extraterrestrial life within our reach.

This new appreciation began to unfold in 1995, when a spacecraft named in Galileo's honor arrived at the Jupiter system to follow up on earlier Voyager discoveries. As part of its mission, the Galileo spacecraft could provide only tantalizing samplings of data at Europa (Figure ES.1.1-1); nonetheless, it provided strong evidence for a deep global ocean beneath Europa's icy crust, leading to speculation on the potential for life within icy moons.

Figure ES.1.1-1. Europa's surface shows a landscape scarred by tectonic and icy volcanic events. This image of the Conamara Chaos region at 11 m per pixel implies that portions of the surface have been broken up into giant plates. This event is inferred to have happened in Europa's geologically recent past. The dark reddish material may be derived from the ocean.

Meanwhile, over the last quarter century we have learned that Jupiter-like planets are common around other stars, and perhaps many have icy moons like Europa. Understanding Europa—one of the most geophysically fascinating and astrobiologically promising bodies in our solar system—is therefore vital to understanding the habitability of worlds throughout the galaxy.

A mission targeting Europa would be needed to pursue these exciting discoveries using close-up observation with modern instrumentation designed to address the habitability of Europa. Over the last decade, NASA has considered several mission options for exploring Europa, convening a series of Science Definition Teams (SDTs), composed of experts from the scientific community, to hone the highest priority science objectives for Europa.

By 2008, technical studies culminated in a mature Pre–Phase A mission concept, the Jupiter Europa Orbiter (JEO), as part of a joint NASA–ESA Europa Jupiter System Mission (EJSM). The JEO concept was further refined throughout 2009 and 2010 in a pre–Phase A mode. The March 2011 Planetary Science Decadal Survey concluded that the science contribution of such a mission would be of paramount importance, comparable to the entire proposed Mars Sample Return campaign. It stated, "Because of this ocean's potential suitability for life, Europa is one of the most important targets in all of planetary science" (Space Studies Board 2011, p. 271).

However, because of serious concerns over mission cost, based on NASA's independent cost estimate, the Decadal Survey also recommended that "NASA should immediately undertake an effort to find major cost reductions for JEO, with the goal of minimizing the

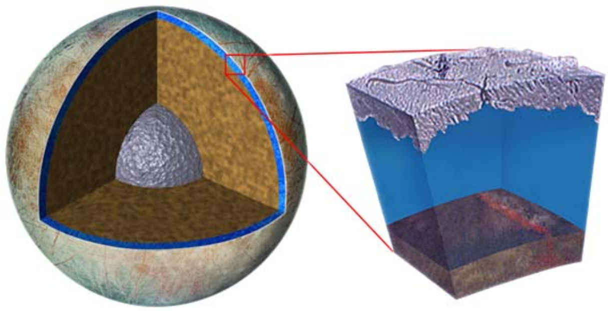


Figure ES.1.2-1. Europa is believed to have a relatively thin ice shell above a 100-km-thick global ocean—equivalent to twice the volume of all of Earth's oceans—in direct contact with a rocky mantle below. Oxidants from the surface above and chemicals from the rocky mantle below might be able to supply the ocean water with the required chemistry and energy for life.

size of the budget increase necessary to enable the mission" (Space Studies Board 2011, p. 5). To that end, NASA Headquarters promptly enlisted a new Europa SDT, and directed the Europa Study Team to examine a set of reduced-scope options for exploring Europa. Independent cost and technical reviews were to be performed on all study results. What follows is a summary of these results.

ES.1.2 Habitability of Europa as Motivation for Future Missions

Europa is a prime candidate in the search for present-day habitable environments in our solar system. Europa is unique among the large icy satellites (Figure ES.1.2-1) because it probably has a saltwater ocean today beneath an ice shell that is geodynamically active and relatively thin (several kilometers to several tens of kilometers thick). The combination of irradiation of its surface and tidal heating of its interior could make Europa a rich source of chemical energy for life. Perhaps most importantly, Europa's ocean is believed to be in direct contact with its rocky mantle, where conditions could be similar to those on Earth's biologically rich sea floor. Hydrothermal zones on Earth's seafloor are known to be rich with life, powered by energy and nutrients that result from reactions between the seawater and the warm rocky ocean floor.

Life as we know it depends on three principal "ingredients": 1) a sustained liquid water environment; 2) essential chemical elements (e.g., C, H, N, O, P, S) that are critical for building life; and 3) a source of energy that could be utilized by life (Figure ES.1.2-2). For Europa, current assessment of these three broad requirements for life can be summarized as: 1) a likely internal global ocean, which has likely existed for over 4 billion years, and potentially water pockets within the ice shell; 2) elements derived from the primordial chondritic composition of the satellites, plus delivery by asteroids and comets over time; and 3) oxidants at the surface, and possible hydrothermal activity at the ocean floor as driven by tidal heating, suggesting that the cycling of chemical energy into Europa's ocean over geological time is vital to understanding its habitability.

These "ingredients" and the scientific issues surrounding them define three themes of *water*, *chemistry*, and *energy* that permeate discussions of Europa's potential habitability. Europa may meet these minimum require-

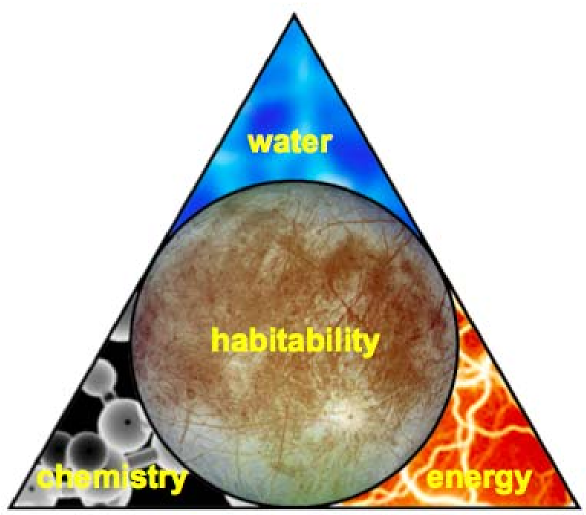


Figure ES.1.2-2. The three "ingredients" for life—water, chemistry, and energy—are key to understanding Europa's habitability, and they are developed into themes that permeate the Europa mission concepts.

ments, but the processes that shape Europa's ice shell, and the exchange processes between the surface and ocean, are poorly understood. Indeed, even the existence of a subsurface ocean, while suspected, is not yet proven. With this in mind, the four categories of scientific investigation most relevant to understanding Europa's habitability are:

***Ocean**:* Existence, extent, and salinity of the ocean and its relation to the deeper interior;

***Ice Shell**:* Existence and nature of any subsurface water within or beneath the ice shell, heterogeneity of the ice shell, and the nature of surface-ice-ocean exchange;

***Composition**:* The chemistry and distribution of salts, any organics, and other compounds, and their relationships to ocean composition;

***Geology**:* The characteristics and formation of surface features, including sites of recent or current activity, and implications for water reservoirs and satellite evolution.

ES.1.3 Europa Mission Study

To address and answer the key questions about Europa's habitability, a dedicated Europa mission would be required. To that end, a study was conducted starting in April 2011 to define options for Europa mission concepts. A Europa SDT guided the science definition, and a combined Jet Propulsion Laboratory (JPL) and Applied Physics Laboratory (APL) study team performed the technical work.

The SDT was tasked with reformulating the science of a Europa mission to achieve compelling science while ensuring reduced risk and scope from past studies. The SDT approached the task by identifying an overarching goal, key science objectives, and science investigations to best address those objectives, with examples of appropriate measurements that could be carried out at Europa to address the science investigations.

The SDT determined that there is a clear division among the key science questions and associated investigations (Table ES.1.3-1), where some are best conducted from Europa orbit, others best achieved through multiple flybys, and the remainder best addressed through a landed mission. To characterize the extent of the ocean and its relation to the deeper interior, scientists need systematic geophysical measurements of gravity, topography, and magnetic field: measurements best obtained from an orbital platform. An orbital platform also permits uniform geological mapping. In comparison, observations to characterize the ice shell, understand the surface composition, and perform high-

Table ES.1.3-1. Key Europa science questions and associated mission platforms.

Science Question	Orbiter	Multi-Flyby	Lander
1. What are the characteristics of Europa's ocean?	✓	*	✓
2. How thick is the icy shell?	✓	✓	✓
3. Is there near-surface water within the ice shell?		✓	✓
4. What is the global distribution of geological features?	✓	✓	
5. Is liquid water involved in surface feature formation?		✓	
6. Is the icy shell warm and convecting?		✓	✓
7. What does the red stuff tell us about ocean composition?		✓	✓
8. How active is Europa today?		✓	✓
9. What is the plasma and radiation environment at Europa?			
10. What is the specific nature of organics and salts at Europa?			✓

✓ Mission concept explicitly addresses the science question.
* Relevant science could be addressed with modest mission modifications.

resolution targeted geological observations are data-intensive and require high-mass, high-power instruments, so these are best carried out from a spacecraft that makes multiple flybys of Europa, transmitting data back to Earth during long orbital petals. Only a lander could accomplish evaluation of the detailed surface chemistry and mineralogy to best understand the detailed nature of near-surface organics and salts, as these investigations require *in situ* sample analyses.

Any of these three mission options would provide high caliber, compelling science that would change paradigms in our understanding of the nature and habitability of icy worlds. Each is intended to fly completely independently, without a requirement for any other mission.

Each mission option has a common goal:

Explore Europa to investigate its habitability.

A Europa *Orbiter* Mission would chiefly perform geophysical measurements ("water" science). A Europa *Multiple-Flyby* Mission would concentrate on performing remote measurements that address the "chemistry" and "energy" science. A Europa *Lander* Mission would concentrate on *in situ* "chemistry" science.

ES.1.4 Orbiter Concept

ES.1.4.1 Orbiter Science

The orbiter concept is tailored to the unique geophysical science that requires being in orbit at Europa. This includes confirming the existence of an ocean and characterizing that ocean through geophysical measurements of Europa's gravitational tides and magnetic induction response. It also includes mapping of the global morphology and topography of the satellite, to reveal its geological evolution.

The objectives, investigations, and model planning payload of the Orbiter Mission are

Table ES.1.4-1. Objectives, investigations, and model planning payload for a Europa Orbiter concept.

Goal	Objective		Investigation	Model Planning Payload	Theme		
					W	C	E
Explore Europa to investigate its habitability	Ocean	Characterize the extent of the ocean and its relation to the deeper interior.	Determine the amplitude and phase of gravitational tides.	Radio Subsystem, Laser Altimeter	✓		
			Determine Europa's magnetic induction response.	Magnetometer, Langmuir Probe	✓	✓	
			Determine the amplitude and phase of topographic tides.	Laser Altimeter, Radio Subsystem	✓		
			Determine Europa's rotation state.	Laser Altimeter, Mapping Camera	✓		
			Investigate the deeper interior.	Radio Subsystem, Laser Altimeter, Magnetometer, Langmuir Probe	✓	✓	✓
	Geology	Understand the formation of surface features, including sites of recent or current activity to understand regional and global evolution.	Determine the distribution, formation, and three-dimensional characteristics of magmatic, tectonic, and impact landforms.	Mapping Camera, Laser Altimeter	✓		✓

Note: Shaded check marks illustrate that the objectives directly address the themes of water (W), chemistry (C), or energy (E).

summarized in Table ES.1.4-1. Science objectives are listed in priority order, and the investigations within each objective are listed in priority order. The implied model planning payload are all low mass, low power, and low data rate, and thus well-matched to the technical demands of operating in Europa orbit. The Orbiter Mission concentrates on the water theme, as related to habitability, while addressing chemistry and energy themes as well.

ES.1.4.2 Orbiter Mission Concept

The Europa Orbiter Mission concept would deploy a highly capable, radiation-tolerant spacecraft (Figure ES.1.4-1) into orbit around Europa to collect a global data set to map the moon's surface morphology, its tidal cycle through gravity fluctuations, and its ocean induction signature through investigation of Europa's interaction with the Jovian magnetosphere. These measurements would be performed from a 100 km, 2- to 4-p.m. local solar time, near-polar orbit over the course of a 30 day science mission. The model planning payload assumed for the Europa Orbiter Mission (Table ES.1.4-2) consists of a notional set of remote-sensing instruments (Laser Altimeter and Mapping Camera), *in situ* instruments (Magnetometer and Langmuir Probe), and a telecommunications system that provides Doppler and range data for accurate orbit reconstruction in support of geophysical objectives.

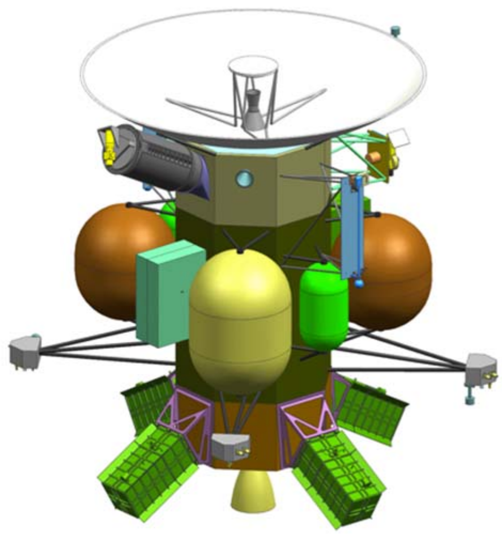


Figure ES.1.4-1. The Europa Orbiter Mission flight system provides a robust platform to collect and transmit science data.

ES.1.4.3 Orbiter Mission Design

The Orbiter Mission starts with the spacecraft launch on an Atlas V 551 that places it on a 6.5 year Venus–Earth–Earth Gravity Assist (VEEGA) interplanetary trajectory before performing the Jupiter Orbit Insertion (JOI) burn. After JOI, fifteen gravity-assist flybys of Ganymede and Calisto are used over the course of 18 months to reduce orbital energy and align the trajectory with Europa; this mission design balances total radiation dose for the spacecraft with the amount of ΔV required. A Europa Orbit Insertion (EOI) burn places the spacecraft directly into a 100 km, circular, near-polar science orbit. After a short checkout period, science observations are conducted for 30 days. This orbit and the mission duration were chosen to meet the science objectives for gravity science, laser altimetry, and mapping (Figure ES.1.4-2).

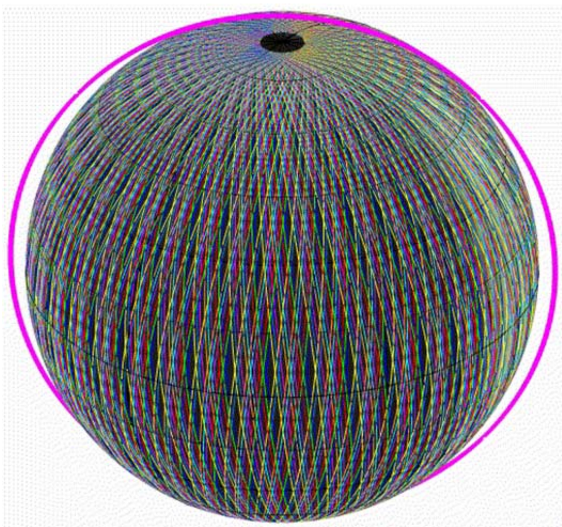
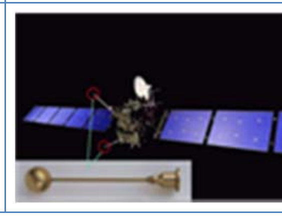


Figure ES.1.4-2. From a 100 km, circular, near-polar science orbit (pink circle), at the end of 30 days, the Orbiter Mission would create a dense network of Laser Altimeter profiles (equatorial spacing about 25 km), and it images essentially the entire surface in stereo (at about 100 m/pixel resolution). Each color represents those profiles obtained during a given 3.55 day orbit of Europa around Jupiter.

Table ES.1.4-2. Capable science instruments for the Europa Orbiter concept draw on previous flight designs.

Instrument	Characteristics	Similar Instruments	
Laser Altimeter (LA)	**Time-of-Flight Laser Rangefinder** Time-dependent topography as a function of Europa's position in its tidal cycle, along with tidal amplitude for ocean detection and ocean characteristics, at better than 1 m vertical resolution.	NEAR NLR; MESSENGER MLA; LRO LOLA	
Mapping Camera (MC)	**Pushbroom Imager with fixed color filters and along-track stereo channel** Imaging at better than 100-m/pixel spatial resolution and 30-m vertical resolution at better than 300 m/pixel spatial scale. Panchromatic plus three color bands.	MRO MARCI; Nozomi MIC; MPL/MSL/MARDI; MESSENGER MDIS; New Horizons MVIC	
Magnetometer (MAG)	**Dual 3-axis Fluxgate Magnetometer** Two sensors located on a 10-m boom to determine the induction response from the ocean. Measurement rate of 8 vectors/s and sensitivity of better than 0.1 nT.	MESSENGER MAG; Galileo MAG	
Langmuir Probe (LP)	**Dual Langmuir Probe** Characterization of the local plasma and electric field to support the MAG determination of Europa's magnetic induction response, using booms 1-m long oriented 180° apart over a full 4π steradian field.	Rosetta LAP; Cassini RPWS	

ES.1.5 Multiple-Flyby Concept

ES.1.5.1 Multiple-Flyby Science

The Europa Multiple-Flyby Mission concept concentrates on remote sensing science that can be accomplished through multiple close flybys of Europa. This includes exploring Europa's ice shell for evidence of liquid water within or beneath it, in order to understand the thickness of the ice shell and potential material pathways from the ocean to the surface and from the surface to the ocean. The mission concept also includes exploration of the surface and atmospheric composition of Europa, in order to address ocean composition and habitability. Detailed morphologic and topographic characterization of Europa's surface are included as well.

The objectives, investigations, and model planning payload of the Multiple-Flyby Mission are summarized in Table ES.1.5-1. Science objectives are listed in priority order, and investigations within each objective are listed in priority order. The Multiple-Flyby Mission instruments are heavy, require significant operating power, and generate large volumes of data. The multiple-flyby mission design allows for high-data-rate science collection followed by days of playback time, while greater mass margins afforded by foregoing Europa orbit insertion enable shielding to lower the radiation dose in the spacecraft avionics vault.

The Multiple-Flyby Mission concentrates on the chemistry and energy themes, as related to habitability. It also addresses the water theme by probing for water within the ice shell and investigating the relationship of surface chemistry and geology to subsurface water.

Table ES.1.5-1. Objectives, investigations, and model planning payload for the Europa Multiple-Flyby concept.

Goal		Objective	Investigation	Model Planning Payload	Theme W	Theme C	Theme E
Explore Europa to investigate its habitability	Ice Shell	Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.	Characterize the distribution of any shallow sub-surface water and the structure of the icy shell.	Ice-Penetrating Radar, Topographical Imager	✓		✓
			Search for an ice-ocean interface.	Ice-Penetrating Radar, Topographical Imager	✓		✓
			Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.	Ice-Penetrating Radar, IR Spectrometer, Topographical Imager	✓	✓	✓
			Characterize regional and global heat flow variations.	Ice-Penetrating Radar	✓		✓
	Composition	Understand the habitability of Europa's ocean through composition and chemistry.	Characterize the composition and chemistry of the Europa ocean as expressed on the surface and in the atmosphere.	IR Spectrometer, INMS	✓	✓	
			Determine the role of Jupiter's radiation environment in processing materials on Europa.	IR Spectrometer, INMS		✓	✓
			Characterize the chemical and compositional pathway's in Europa's ocean.	IR Spectrometer, INMS	✓	✓	
	Geology	Understand the forma-tion of surface features, including sites of recent or current activity, and characterize high science interest localities.	Determine sites of most recent geological activity, and characterize high science interest localities.	Topographical Imager	✓		✓

Note: Shaded check marks illustrate whether the objectives directly address the themes of water (W), chemistry (C), and energy (E).

ES.1.5.2 Multiple-Flyby Mission Concept

The Multiple-Flyby Mission concept (Figure ES.1.5-1) would deploy a highly capable, radiation-tolerant spacecraft into a long, looping orbit around Jupiter, performing repeated close flybys of Europa to collect information on ice shell thickness, composition, and surface geomorphology.

The model planning payload (Table ES.1.5-2) consists of four instruments: a Shortwave Infrared Spectrometer, an Ice-Penetrating Radar, a Topographical Imager, and an Ion and Neutral Mass Spectrometer (INMS). Except for calibration and maintenance, these instruments are operated during each Europa flyby. The nominal Multiple-Flyby Mission would perform 32 flybys of Europa at altitudes varying from 2700 km to 25 km.

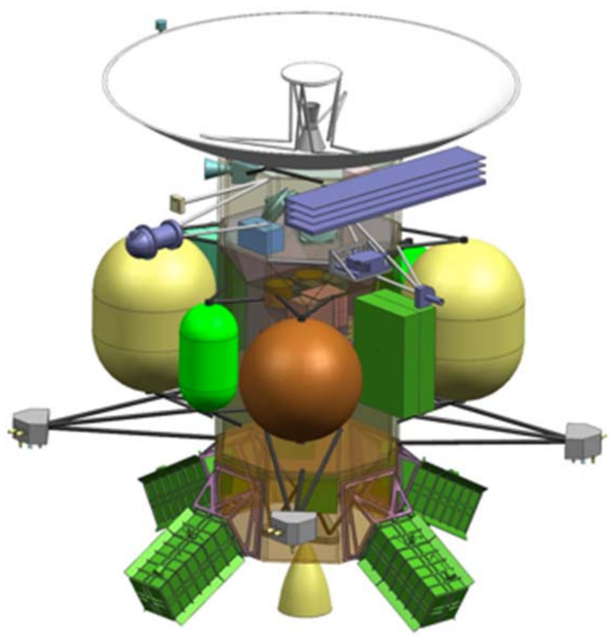
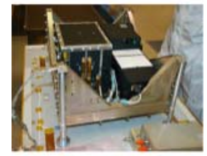
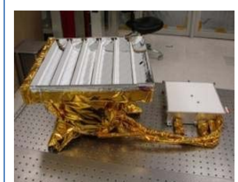
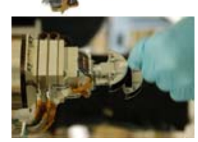


Figure ES.1.5-1. The Europa Multiple-Flyby Mission flight system provides a robust platform to collect, store, and transmit a high volume of science data.

Table ES.1.5-2. Capable science instruments for the Europa Multiple-Flyby concept draw on previous flight designs.

Instrument	Characteristics	Similar Instruments	
Ice-Penetrating Radar (IPR)	Dual-Mode Radar Sounder Radar sounding of the ice shell, with a higher-frequency band designed to provide high spatial resolution (footprint and depth) for studying the subsurface above 3 km depth at 10 m vertical resolution. A low-frequency band can penetrate much deeper to search for the ice-ocean interface or the hypothesized transition between brittle and ductile ice in the deep subsurface, at a depth of up to 30 km at 100 m vertical resolution.	Mars Express MARSIS; MRO SHARAD	 
Shortwave Infrared Spectrometer (SWIRS)	Pushbroom Spectrometer Reflectance spectra for surface composition at ~10 km/pixel resolution for global mapping, and scans at better than300 m/pixel. 10 nm spectral resolution from 0.85 to 5.0 µm.	Chandrayaan M3	
Ion and Neutral Mass Spectrometer (INMS)	Reflectron Time-of-Flight Mass Spectrometer Elemental, isotopic, and molecular composition of Europa's atmosphere and ionosphere by means of mass spectrometry during close flybys.	Rosetta ROSINA; Cassini INMS	 
Topographical Imager (TI)	Panchromatic Stereo Pushbroom Imager Stereo imaging to characterize geological landforms, and assistance in removal of clutter noise from Ice-Penetrating Radar off-nadir surface topography.	MRO MARCI; MESSENGER MDIS; New Horizons MVIC	  

ES.1.5.3 Multiple-Flyby Mission Design

The Multiple-Flyby Mission starts with the spacecraft launch on an Atlas V 551 that places it on a 6.5 year VEEGA interplanetary trajectory before performing the Jupiter Orbit Insertion (JOI) burn. After JOI, the spacecraft would perform four additional Ganymede gravity assists over 11 months to lower its orbital energy with respect to Jupiter and set up the correct flyby conditions (lighting and relative velocity) at Europa. The spacecraft would then embark on an 18 month Europa science campaign.

A unique multiple-flyby mission design allows for building up over time a regionally distributed network of flyby locations across Europa's entire globe (Figure ES.1.5-2, top). Remote-sensing instruments are able to observe Europa with flyby coverage similar to orbiting the body (Figure ES.1.5-2, bottom). This is analogous to how the Cassini mission at Saturn has been able to garner a global picture of Titan through repeated flybys.

This mission design achieves the science requirement of regionally-distributed global coverage of Europa with intersecting, daylit flyby trajectories. This results in 32 science flybys of Europa.

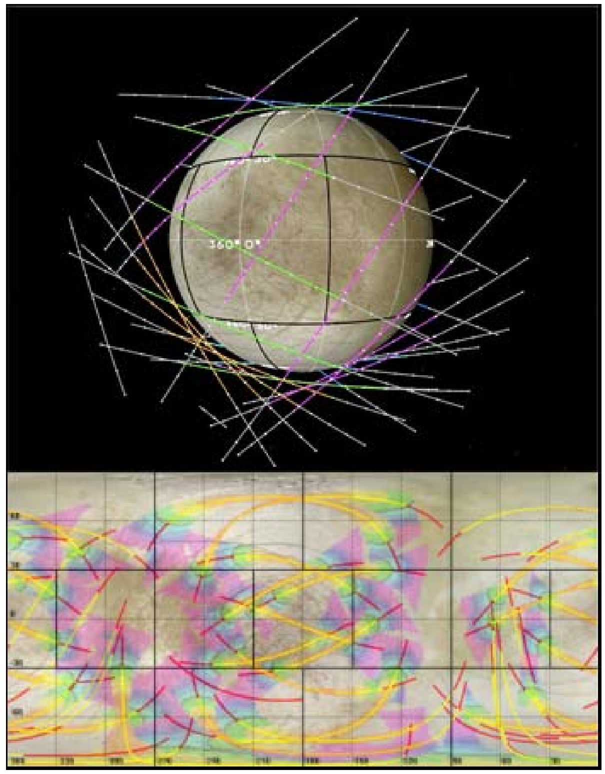


Figure ES.1.5-2. Unique mission design enables the Europa Multiple-Flyby Mission to obtain network-like mapping coverage approaching that of an orbiter. *Top:* Multiple fly-by paths envelop Europa after 32 spacecraft passes. *Bottom:* These multiple flybys provide globally distributed regional coverage by the instruments: arcing trajectory paths are shown for spacecraft altitudes of 25–400 km (red) and 400–1000 km, and pastel colors illustrate stereo imaging coverage by the Topographical Imager from 200 m/pixel (violet) down to 25 m/pixel (orange) for each daylit path.

ES.1.6 Lander Concept

ES.1.6.1 Lander Science

The Europa Lander Mission concept concentrates on science observations that can best be achieved by *in situ* examination of Europa from its surface. Chiefly, this means sampling Europa's dark reddish material (Figure ES.1.6-1) to understand its detailed composition and chemistry, to best understand the specific nature of salts, any organic materials, and other contaminants. It also means geophysical prospecting of Europa through seismology and magnetometry, in order to probe the satellite's ice shell and ocean. From the surface, it is possible to perform *in situ* characterization of the surface at a human scale, to "see" the surface as if standing upon it.

The objectives, investigations, and model planning payload of the Lander Mission are summarized in Table ES.1.6-1. Science objectives are listed in priority order, and investigations within each objective are listed in priority order. The highest priority composition objectives require a sampling and sample handling system to obtain icy material from the surface (0–2 cm depth) and near-surface (5–10 cm depth) and bring it to the instruments for analysis. Given the challenges of data return from and long-term survival on the surface, the

Table ES.1.6-1. Objectives, investigations, and model planning payload for the Europa Lander concept.

Goal	Objective		Investigation	Model Planning Payload	Theme W	Theme C	Theme E
Explore Europa to investigate its habitability	Composition	Understand the habitability of Europa's ocean through composition and chemistry	Characterize surface and near-surface chemistry, including complex organic chemistry to constrain ocean composition and understand the endogenic processes from which it evolves.	Mass spectrometer, Raman Spectrometer		✔	✔
			Characterize surface and near-surface chemistry, including complex organic chemistry to constrain the exogenic processes and material fluxes that affect ocean composition.	Mass spectrometer, Raman Spectrometer		✔	✔
			Constrain the context of compositional measurements.	Site Imager, (Reconnaissance Imager), Microscopic Imager	✔	✔	✔
	Ocean & Ice Shell	Characterize the local thickness, heterogeneity, and dynamics of any ice and water layers	Constrain the thickness and salinity of Europa's ocean.	Magnetometer, Multi-Band Seismometer Package	✔	✔	
			Constrain the thickness of ice and the thickness of any water layers in the region.	Magnetometer, Multi-Band Seismometer Package	✔		
			Search for local heterogeneity of the ice and any subsurface water.	Multi-Band Seismometer Package	✔	✔	
			Characterize Europa's seismic activity and its variation over the tidal cycle.	Multi-Band Seismometer Package	✔		✔
	Geology	Characterize a locality of high scientific interest to understand the formation and evolution of the surface at local scales	Constrain the processes that exchange material between the surface, near-surface, and subsurface.	Site Imager, (Reconnaissance Imager), Microscopic Imager	✔	✔	✔
			Constrain the processes and rates by which the surface materials (regolith and bedrock) form and evolve over time.	Site Imager, (Reconnaissance Imager), Microscopic Imager	✔	✔	✔
			Understand the regional and local context of the landing site.	Site Imager, (Reconnaissance Imager)	✔	✔	✔
			Constrain the physical properties of the surface and near-surface at the landing site to provide context for the sample.	(Reconnaissance Imager,) Microscopic Imager, Engineering data		✔	

Note: Shaded check marks illustrate whether the objectives directly address the themes of water (W), chemistry (C), and energy (E).

Lander science is accomplished by instruments with low data volume requirements, along with data editing and compression. The Lander Mission concentrates on the chemistry theme, as related to habitability, while addressing water and energy themes as well.

ES.1.6.2 Lander Mission Concept

The lander mission concept (Figure ES.1.6-1 and Figure ES.1.6-2) would deploy a robust, highly capable, radiation-tolerant soft Lander to the surface of Jupiter's moon Europa to perform *in situ* investigation of surface and near-surface composition and chemistry, seismological and magnetic study of local and regional ice and ocean thickness and dynamics, and high-resolution imagery of landing site and sample morphology. The model planning payload on the landed element (Table ES.1.6-2) consists of six instruments: a Mass Spectrometer, a Raman Spectrometer, a Magnetometer, a Multiband Seismometer Package, a Site Imaging System, and a Microscopic Imager.

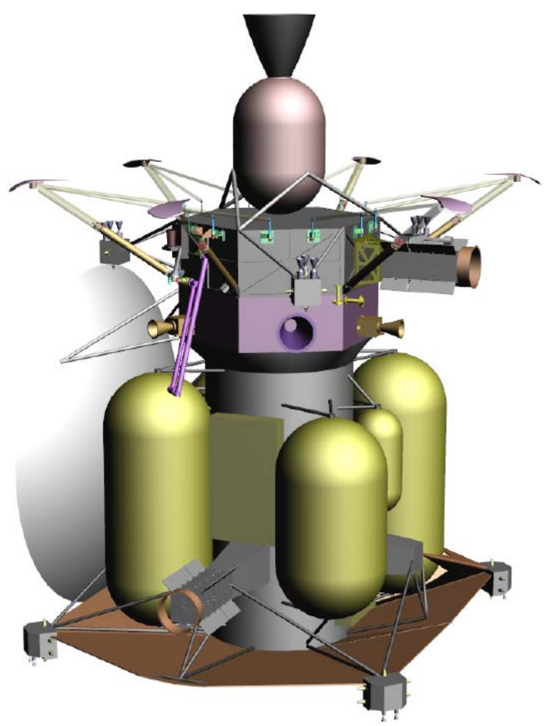
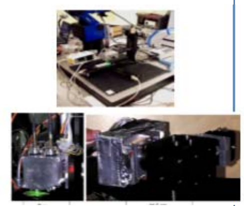
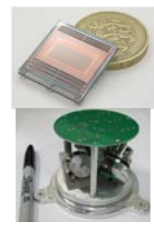
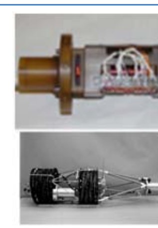
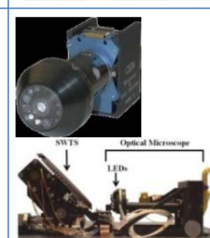


Figure ES.1.6-1. The integrated spacecraft with Carrier and Lander elements provides reconnaissance, safe landing, and *in situ* science in a single mission.

Table ES.1.6-2. Capable science instruments for the Europa Lander concept draw on previous flight designs.

Instrument	Characteristics	Similar Instruments	
Mass Spectrometer (MS)	**Quadrupole mass spectrometer** Evolved gas analysis, pyrolysis, and gas chromatography for determining the composition of the Europa's surface and near surface, through measurement of two obtained samples. Abundances will be retrieved of organics (as low as 1 ppb) and inorganics (as low as 1 ppm).	Huygens GCMS; MSL SAM; Rosetta COSAC	
Raman Spectrometer (RS)	**Raman infrared line spectrometer** Characterization of surface and near-surface chemistry, including complex organic chemistry, through measurement of shift in the wavelength of the scattered laser light due to vibrations in mineral structure, across a spectral range of 900 nm–1.5 µm.	New development; some similarity to ExoMars RS and MMRS	
Multiband Seismometer Package (MBS)	**Six 3-axis MEMS seismometers** Thickness of ice and water layers through seismic analysis, and characterization of seismic activity level and its variation over the tidal cycle.	New development; some similarity to ExoMars SP sensors and COTS seismome-ters	
Magnetometer (MAG)	**3-axis fluxgate magnetometer** Ocean thickness and salinity though measurement of the magnetic induction signal generated in Europa's ocean as a response to Jupiter's magnetic field.	MESSENGER MAG; Galileo MAG	
Site Imaging System (SIS)	**Dual stereo color imagers** Stereo landform mapping of the landing site from near the Lander to the horizon, including the sample acquisition location.	MER Pancam	
Microscopic Imager (MI)	**Wide-angle close-focus camera** Wide-angle, close-focused camera to provide high-resolution images of the collected samples to characterize ice grains and non-ice materials within the samples.	MSL MAHLI; Phoenix MECA; MER Microscopic Imager; Beagle 2 Microscope	
Reconnais-sance Camera (RC)	**Engineering panchromatic narrow-angle camera** Camera on the Carrier element for high-resolution imagery of candidate landing sites from Europa orbit prior to Lander deployment, and to image Lander on surface to provide context for the landed measurements. Resolution 0.5 m/pixel from 200-km altitude.	MRO HiRISE	

These investigations would be performed during a 30 day science campaign from a single location on the surface of Europa. There is also one instrument on the Carrier element: a Reconnaissance Camera to aid landing site selection. The information needed to select a safe landing site is not available from the Galileo and Voyager database. Without a precursor mission, the science landing zones would be selected from several candidates identified before launch and narrowed to one zone after a 30 day on-orbit landing site reconnaissance campaign and site selection process determines the preferred landing site for safe Lander deployment (Figure ES.1.6-2).

ES.1.6.3 Lander Mission Design

The Lander Mission would start with the spacecraft launch on a Delta IVH Launch Vehicle that places it on a 6.5 year VEEGA interplanetary trajectory before performing the Jupiter Orbit Insertion (JOI) burn. After JOI, the spacecraft would perform eleven gravity-assist flybys of Ganymede and Calisto over about 1.5 years to lower its energy with respect to Europa, at which point a Europa Orbiter Insertion (EOI) is performed. This mission design was selected to reduce the total radiation dose on the lander, which minimizes lander mass. This is important because additional lander mass penalizes the lander wet mass and the carrier wet mass. The spacecraft is placed into a 200 km circular, near-polar, orbit, for landing sight reconnaissance. After 30 days, a safe landing site is selected and the landing sequence is initiated. Then the periapsis is lowered to 5 km, where the Lander is released to perform its deorbit, descent, and landing sequence. After separation, the Carrier returns to the 200 km circular orbit to perform data-relay functions and to take images of the resultant landing site. The Carrier remains in orbit for the mission duration (nominally 30 days).

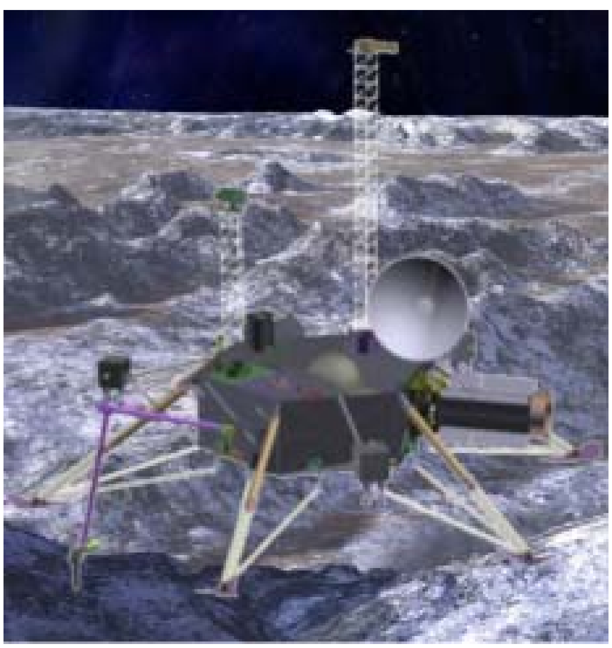


Figure ES.1.6-2. The Lander (deployed surface configuration) provides a reliable platform for completing the baseline science objectives. (Background artwork by Michael Carroll.)

ES.1.7 Key Architectural Concepts

The Europa spacecraft would employ a modular configuration (Figure ES.1.7-1), which provides distinct programmatic advantages. Implementation flexibility is gained through parallel integration paths, module-level integration during Phase C testing, and isolation of implementation issues at the module level. A modular approach minimizes peaks in the project funding profile and allows greater flexibility in phasing of module implementation schedules.

The spacecraft design uses a nested shielding configuration (Figure ES.1.7-2) that reduces the radiation dose at critical electronic components to existing geosynchronous part tolerances. The spacecraft design uses a radiation design factor of two (thus assuming that the end-of-life radiation experience by components is twice as great as the modeling predicts). Upon flight system assembly, the avionics vault is placed into a cavity within the propulsion module. The components in the avionics vault gain shielding from neighboring

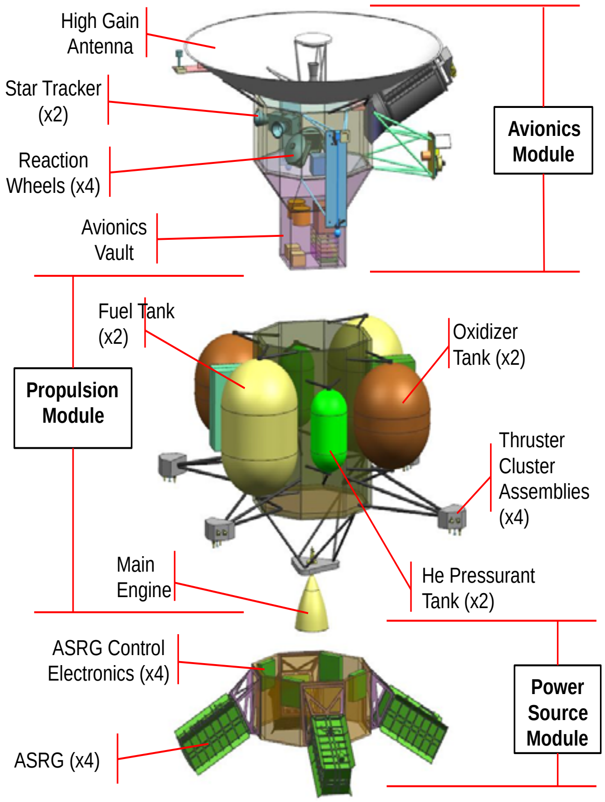


Figure ES.1.7-1. The Europa modular design simplifies integration and test (Orbiter spacecraft shown).

components and structure, while the propellant provides additional radiation shielding.

An additional benefit of the nested configuration is an efficient thermal design, which uses waste heat from the avionics vault to warm the propellant without additional heaters.

For electrical power, each spacecraft would utilize Advanced Stirling Radioisotope Generators (ASRGs), which are a NASA technology development to advance the efficiency of radioisotope power systems (RPS). The ASRGs would provide stable power output throughout all mission phases and life, while reducing the amount of plutonium-238 fuel required as compared to previous RPS designs.

All three mission concepts have good–to-excellent technical margins for this stage of the development process (Table ES.1.7-1).

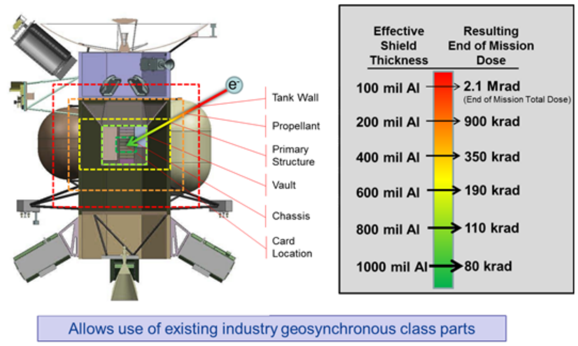


Figure ES.1.7-2. The nested shield approach reduces the radiation dose seen by the electronics and allows the use of heritage hardware (Orbiter spacecraft shown).

ES.1.8 Cost Estimating Methodology

To estimate the cost of each mission concept, JPL used its institutional cost estimation process applicable for the design maturity of a concept study in early formulation. This process focuses on using parametric cost models, analogies, and other non-grassroots estimating techniques. For the three mission concepts, the tools and methods used include the following:

- SEER and PRICE, commercial off-the-shelf (COTS) tools that have been calibrated to the most relevant JPL planetary missions
- NASA Instrument Cost Model (NICM) for the payload (at 70% confidence level, to be conservative)
- NASA Space Operations Cost Model (SOCM)
- Institutional wrap factors based on analogous historical planetary missions

Table ES.1.7-1. All three spacecraft have excellent (blue) or good (green) technical margins.

Technical Parameter	Orbiter	Multi-Flyby	Lander
Mass Margin	42%	48%	29%
Power Margin	39%	39%	38%
Data Return Margin	39%	80%	86%
Radiation Design Factor	2	2	2

- 40% reserves applied for Phases A–D and 20% for Phases E–F

The Europa Study Team vetted the integrated cost rollup and detailed basis of estimate (BOE), and reviewed the results for consistency and reasonableness with the mission design, WBS, and NASA requirements to ensure that technical and schedule characteristics were accurately captured and a consistent cost-risk posture utilized. Analog missions were used as an additional cross-check. Table ES.1.8-1 summarizes the cost estimate for each mission option. The results are reasonable and conservative, as deemed by the independent review board and by the Aerospace Corporation, as described next.

Table ES.1.8-1. Cost Elements for Each Mission Option

Mission Option	Cost Estimate (FY15$, No LV)
Orbiter	$1.6B
Multiple-Flyby	$1.9B
Lander	$2.8B

ES.1.9 Independent Review

An independent review board was formed to provide a technical assessment, including risks, of the proposed mission concepts. The board had a broad range of expertise and was led by Scott Hubbard (Chair), Orlando Figueroa, and Mark Saunders, who are each retired NASA Headquarters personnel. The board met on November 15, 2011 to review both the orbiter and flyby concepts, and then on March 15, 2012 to review the lander concept and to consider responses to previous requested actions. The science, technical, and management details of the three mission concepts were presented in detail at these reviews. The board deemed both the orbiter and flyby concepts as viable within the cost estimate with low risk. The board concluded that a landed mission is not viable without a precursor mission that would first determine Europa landing surface characteristics; otherwise, active sample acquisition combined with landing safely on an unknown terrain was deemed to be too risky.

The science and technical overviews of the Orbiter and Multiple-Flyby Mission concepts were presented to an open community meeting of the Outer Planets Assessment Group (OPAG) on October 19, 2011. Both Orbiter and Multiple-Flyby options were received very favorably and were enthusiastically endorsed by OPAG.

The science and technical overview of the Lander Mission concept were presented at open meeting of OPAG on March 29, 2012. OPAG viewed the lander science as exciting science; however, the concept was considered infeasible in the short term due the cost magnitude and the need for technology maturation.

The Aerospace Corporation was contracted to perform an independent cost verification. They performed an Independent Cost Estimate (ICE) and a Cost and Technical Evaluation (CATE) for each mission concept, to serve as an independently derived check against the Europa Study Team estimates. Members of the Aerospace Corporation attended both independent review team sessions in order to gather data for their cost estimates. The Europa Study Team interacted with the Aerospace Corporation to assure that any misunderstandings were clarified and reconciled. The results of the Aerospace Corporation results showed excellent correlation with the Europa Study Team estimated costs. The Aerospace Corporation review showed no schedule or cost threats for the Orbiter and Multiple-Flyby mission options. The Lander mission option was determined to have minimum cost and schedule threats. The Aerospace ICE and CATE results are summarized in Table ES.1.9-1.

Table ES.1.9-1. Aerospace ICE and CATE estimates for each mission option.

Mission Option	Aerospace Independent Cost Estimate (ICE) (FY15$, No LV)	Aerospace Cost and Technical Evaluation (CATE) (FY15$, No LV)
Orbiter	$1.7B	$1.8B
Multiple-Flyby	$2.1B	$2.1B
Lander	$2.8B	$3.0B

ES.1.10 Summary

Three unique science mission concepts were examined in detail by a joint science and engineering team. Any of the three would be a scientifically compelling mission that would change paradigms in our understanding of the workings and potential habitability of icy worlds, in our Solar System and beyond.

These mission options use superb architectural concepts, which utilize a nested shielded design to enable the use of standard space equipment and parts, minimize the number of instruments necessary to achieve outstanding science, have significant margins to accommodate risk, and employ a modularity approach that increases schedule and test flexibility.

The Lander Mission concept is believed to be unaffordable in the current federal budget environment and has associated mission risks that are deemed unacceptable without further development. Both the Orbiter Mission and Multiple-Flyby Mission concepts are found to be fully consistent with Decadal Survey and NASA Headquarters direction. The independent review board concluded: "Both the Orbiter and Multiple-Flyby mission concepts satisfied the 'existence proof' test as missions that met Europa science requirements, could be conducted within the cost constraints provided and have substantial margins." Overall, we conclude that the Multiple-Flyby Mission concept has the greatest science return per dollar, and it is our recommended option.