National Aeronautics and Space Administration

EUROPA STUDY 2012 REPORT
INTRODUCTION

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

Task Order NMO711062 Outer Planets Flagship Mission

Cover art Michael Carroll

Europa Study 2012 Report: Introduction

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A. EUROPA STUDY 2012 REPORT: INTRODUCTION

A.1 NASA Headquarters Direction

The 2011 Planetary Decadal Survey recommended an immediate effort to find major cost reductions for a Europa mission by decreasing the mission scope. To that end, in April 2011, NASA's Planetary Science Division (PSD) directed the pre-project office to conduct a study to revise the JEO mission to meet the NASA cost target of $2.25B ($FY15). Science and technical descopes were to be utilized to achieve this goal in such a manner that the results could be validated via independent review on all study results.

The study was to abide by the following ground rules:

- Cost: All cost analyses shall use $FY15. An estimate of the cost for the minimum science mission is one of the objectives of this study. A discussion of the descopes and their cost impact if new technologies are utilized must also be provided.
- Science Objectives: The primary science objective of the mission concept is Europa. The science content of the EJSM JEO concept presented to the Decadal Survey is expected to be descoped. A science "floor" must be established for which any other descope(s) will make the mission not worthwhile to pursue.
- International Contributions: The study shall limit international contributions to no more than half of the payload.
- Launch Vehicle: The study shall delineate the cost of all potential launch vehicle options both presently available and projected to be available, but these costs are not to be included in the target.
- Power System: The study shall use the Advanced Stirling Radioisotope Generator (ASRG) as the power system for the spacecraft. The number of ASRG units is not specified but should be minimized. The study should assume ASRG cost of $50M per unit.
- Science Definition Team: The study shall utilize a small well focused Science Definition Team (SDT) to provide guidance on the scientific objectives, measurements, and priorities for the mission concept. The SDT shall be composed of US scientists only and shall be kept to a reasonable size. An ESA observer may be attending some meetings but is not expected to contribute.

For the remainder of FY11, the study team was to assess the feasibility of a limited number of mission concepts, including, but not limited to, a Europa orbiter that takes as its starting point the descope path in the 2008 final report (as recommended by the Decadal Survey) and a Jupiter orbiter with a large number of Europa flybys. NASA expects the product of this detailed study to consist of a final report that provides sufficient detail to undergo independent review. The PSD is expected select a single concept for detailed study in FY12.

A.2 Europa Science Overview

A.2.1 Background

Europa and her sibling satellites were discovered by Galileo in 1610, but nearly 400 years passed before any detailed views of their surfaces were seen and the uniqueness of the Galilean satellites was revealed. The physical and orbital properties of Europa are summarized in Table A.2.1-1. In the 1960s, ground-based telescopic observations determined that Europa's surface composition is dominated by water ice, as are most other solid bodies of the outer solar system.

The Pioneer 10 and 11 spacecraft flew by Jupiter in the 1970s, but the first spacecraft to

Table A.2.1-1. Properties of Europa.

Discovered	1610
Discoverers	Galileo Galilei, Simon Marius
Mean Distance from Jupiter	671,100 km
Radius	1560.8 ±0.5 km
Mass	(4.8017 ±0.000014) x 10^{22} kg
Density	3.014 ± 0.005 g/cm^3
Orbital Period	85 hours (3.551 Earth days)
Rotational Period	85 hours (3.551 Earth days)
Orbital Eccentricity	0.0094
Orbital Inclination	0.469 degrees
Visual Geometric Albedo (Avg.)	0.68
Escape Velocity	2.026 km/s
Spacecraft Visitors	Voyager 1 (March 1979) Voyager 2 (July 1979) Galileo (Jul 1994–Jan 2002)

image the surfaces of Jupiter's moons in significant detail were the Voyager 1 and 2 spacecraft. Voyager 1's closest approach to Jupiter occurred in March 1979, and Voyager 2's in July of the same year. Both Voyagers passed farther from Europa than any of the other Galilean satellites, with the best imaging resolution limited to 2 km per pixel. These images revealed a surface brighter than that of Earth's moon, crossed with numerous bands and ridges, and with a surprising lack of large impact craters or high-standing topography.

Despite the resolution limitations, the images were of high enough quality that researchers noted some of the dark bands had opposite sides that matched each other extremely well, like pieces of a jigsaw puzzle. These cracks had separated, and ductile dark icy material appeared to have flowed into the opened gaps, suggesting that the surface has once been mobile. The relative youth of Europa's surface was suggested by a lack of large impact craters—Voyager images showed only a handful—which are expected to build up over time as a planetary surface is constantly bombarded by meteorites over billions of years until the surface is covered in craters. A lack of craters implies that something has erased them—such as icy volcanic flows, or viscous relaxation of the icy crust. The patterns of some of the longest linear features on the surface did not fit with predicted simple models of global stresses that might arise from tidal interactions with Jupiter. However, if the shell was rotated back by several tens of degrees, the patterns fit exceptionally well to a model of "nonsynchronous rotation," by which the icy surface has slowly migrated with respect to the satellite's tidal axes. This mechanism probably requires a ductile or liquid layer between the surface ice and the deeper interior. Combined with the observations of dark bands, there were tantalizing hints that perhaps Europa had a warm interior at some time in the past, and perhaps still has today. Theoretical models of tidal heating of Europa suggested that a global subsurface ocean might exist within Europa today.

These intriguing findings led to a strong sense of anticipation for the Galileo mission, which launched from the Space Shuttle Atlantis in 1989 and entered orbit around Jupiter in 1995. The primary mission included observations of each the four Galilean satellites as the spacecraft passed by. Despite severe data rate limitations of the Galileo mission because its main antenna did not open, information from Galileo was so intriguing that the mission was extended to make 12 total close flybys of Europa. Data from the Galileo mission included images of Europa at a range of scales, and included magnetic measurements that strongly imply the presence of an induced magnetic field that implies a saltwater ocean beneath the surface today.

The ocean on Europa most likely formed early in the moon's evolution. During the formation of our solar system, the growing gas giant planet Jupiter pulled material from the solar nebula in nearly primordial form. Thus, the material incorporated into the Galilean satellites was probably similar in composition to the asteroids of the outer asteroid belt, containing ice, silicates, carbonaceous material, and nickel-iron metal. The Galilean satellites formed by aggregation of these solids, with the proportion of ice varying with distance from the warm protoplanet Jupiter.

Europa formed as a mostly rocky satellite (density = 3.0), able to accrete sufficient volatiles to form a ~100 km thick outer layer of H_2O. If the Jovian subnebula were cold enough, some lower-temperature condensates such as CO_2 could have been incorporated as Europa formed. Europa's early heat of accretion, combined with heat from radioactive decay, would have warmed the satellite's interior and formed a primordial ocean, which was likely reduced and sulfidic. Thermal and geochemical evolution would have caused some oxidation of the ocean through time, forming sulfates. Tidal heating of Europa—repeated squeezing as the satellite orbits its parent planet each 3.55 days (85.2 hours)—is sufficient to maintain Europa's liquid beneath a skin of ice ocean over the age of the Solar System.

A.2.2 Habitability of Europa—Motivation for Future Missions

Europa is a prime candidate in the search for present-day habitable environments in our solar system. It is probable that this planet-sized moon has a saltwater ocean today beneath a relatively thin and geodynamically active icy shell (Figure A.2.2-1). Europa is unique among the large icy satellites because its 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 sea floor 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 upon: 1) liquid water; 2) complex organic and inorganic compounds that contain nitrogen, phosphorus, sulfur, iron and certain trace elements; and 3) a photo- or chemical-energy source (Figure A.2.2-2). Europa appears to meet these minimum requirements for life, and it is distinguished among the bodies of our Solar System by the potential presence of enormous volumes of liquid water and geological activity that promote the exchange of surface materials with the sub-ice environment. However, 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.

A.2.2.1 Water

The likelihood that Europa has a global subsurface ocean hidden beneath a relatively young icy surface has profound implications in the search for past or present life beyond Earth. Europa is the natural target for the first focused spacecraft investigation of the habitability of icy worlds. Its candidate sources of chemical energy for life, direct ocean-mantle contact, a relatively thin ice shell, and potentially active geology that exchanges surface and oceanic material make it a recognized top

Figure A.2.2-1. Europa's surface shows a landscape marked by tectonic and icy volcanic events. This image shows ridges and bands that crisscross the icy surface, and spots that expose warm ice and/or water that erupted from below.

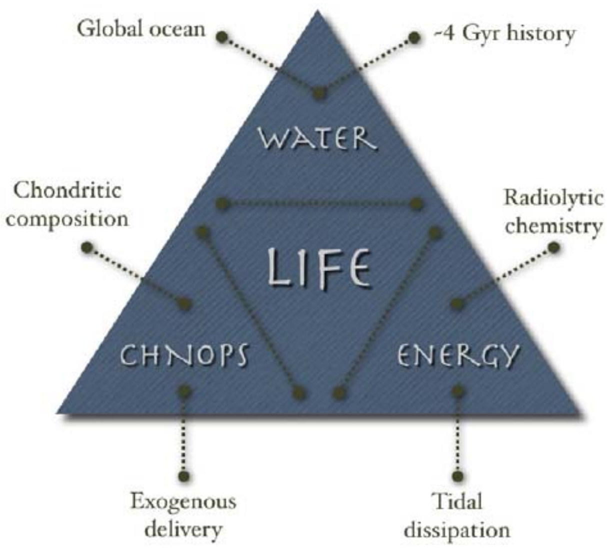

Figure A.2.2-2. Pyramid of habitability. Our present understanding of the conditions for life could be distilled down to three broad requirements: 1) a sustained liquid water environment (an internal global ocean, which has likely existed for over 4 billion years); 2) essential chemical elements (e.g., C, H, N, O, P, S) that are critical for building life (derived from primordial chondritic composition of the satellites, plus delivery by asteroids and comets over time); and 3) a source of energy that could be utilized by life (oxidants at the surface, and possible hydrothermal activity at the ocean floor as driven by tidal heating). The cycling of chemical energy into an icy satellite's ocean over geological time is key to understanding habitability of the satellite. Figure courtesy Kevin Hand.

priority for exploration.

Galileo observations confirmed Europa's surface as sparsely cratered and therefore young. Models for the formation of its abundant linear tectonic features suggest that the icy shell is relatively thin and responds to intense tidal flexing. Tidal deformation in Europa's ice could create briny pockets associated with salty impurities and partially melted zones.

These and other lines of evidence are consistent with an ocean many tens of kilometers deep beneath an ice shell a few to tens of kilometers thick, all underlain by a rocky seafloor in direct contact with ocean water, possibly supplied in chemical nutrients by hydrothermal activity. The potential for areas within the ice shell hosting salty fluids and the occurrence of hydrothermal systems driven by tidal heating make for a favorable environment for prebiotic chemistry or for microbial life. Cycling of water through and within the ice shell, ocean, and upper rocky mantle, could maintain an ocean rich with the chemistry conducive to life.

A.2.2.2 Chemistry

At present, Europa may hold the Solar System's best prospects for life beyond Earth, based on complementary surface and subsurface chemistry. Understanding Europa's chemistry relates to understanding its geophysical energy and the ability of Europa's water to serve as a medium for facilitating chemical reactions. These coupled interactions constitute the most likely source for elements essential for life, including C, H, N, O, P, and S.

Irradiation of Europa's icy surface is responsible for production of O_2, H_2O_2, CO_2, SO_2, and probably other oxidants yet to be discovered. At present, few constraints exist for mechanisms and timescales for delivery of these materials to the subsurface, where they could power life. Meanwhile, cycling of ocean water through seafloor minerals could replenish the water with biologically essential reductants, which are the other half of the necessary redox reaction for life. Combined geophysical and compositional factors, with a yet-uncertain role for tidal heating, may lead to ocean habitability.

A.2.2.3 Energy

Europa is unique for the extraordinary amount of tidal heat energy predicted to occur in its interior to drive interior geochemistry, coupled with energy in the form of Jupiter's intense radiation environment that generates an oxidant-rich surface chemistry. Physical cycling of energy at Europa is arguably the greatest uncertainty in assessing the satellite's habitability: the uncertain mechanisms of surface-ice-ocean exchange are critical to providing chemical energy to the ocean. Assessing the exchange processes between the ice shell, ocean, and underlying rocky interior is necessary for understanding Europan habitability.

Hydrothermal activity at Europa's seafloor may determine ocean chemistry and global cycling of ocean water. Tidal flexing and resultant energy input to Europa's ice shell are responsible for creating conditions that could drive solid-state convection in the ice, and fracturing and destabilization of brittle ice at Europa's surface. These geological processes may determine the nature and extent of chemical exchange between Europa's surface and its subsurface ocean.

A.3 Europa Mission Study

To address and answer the key questions about the Europa's habitability, a dedicated Europa mission is needed. To that end, this study report details work performed since April 2011 in defining Europa mission concepts. A Europa Science Definition Team (SDT) guided the science, and a combined Jet Propulsion Laboratory (JPL) and Applied Physics Laboratory (APL) study team performed the technical work. This document is a combined SDT and technical report of the mission concepts that were studied by the Europa Study Team.

The Europa Study Team initially converged on studying an orbiter and a multiple-flyby mission concept. In autumn 2011, NASA Headquarters directed that a lander mission concept also be investigated. Complete study results for the three mission concepts (Figure A.3-1) are contained in Section B (Orbiter), Section C (Multiple-Flyby) and Section D (Lander) of this report. Both the Orbiter and Multiple-Flyby Mission concepts are fully compliant with Decadal Survey and

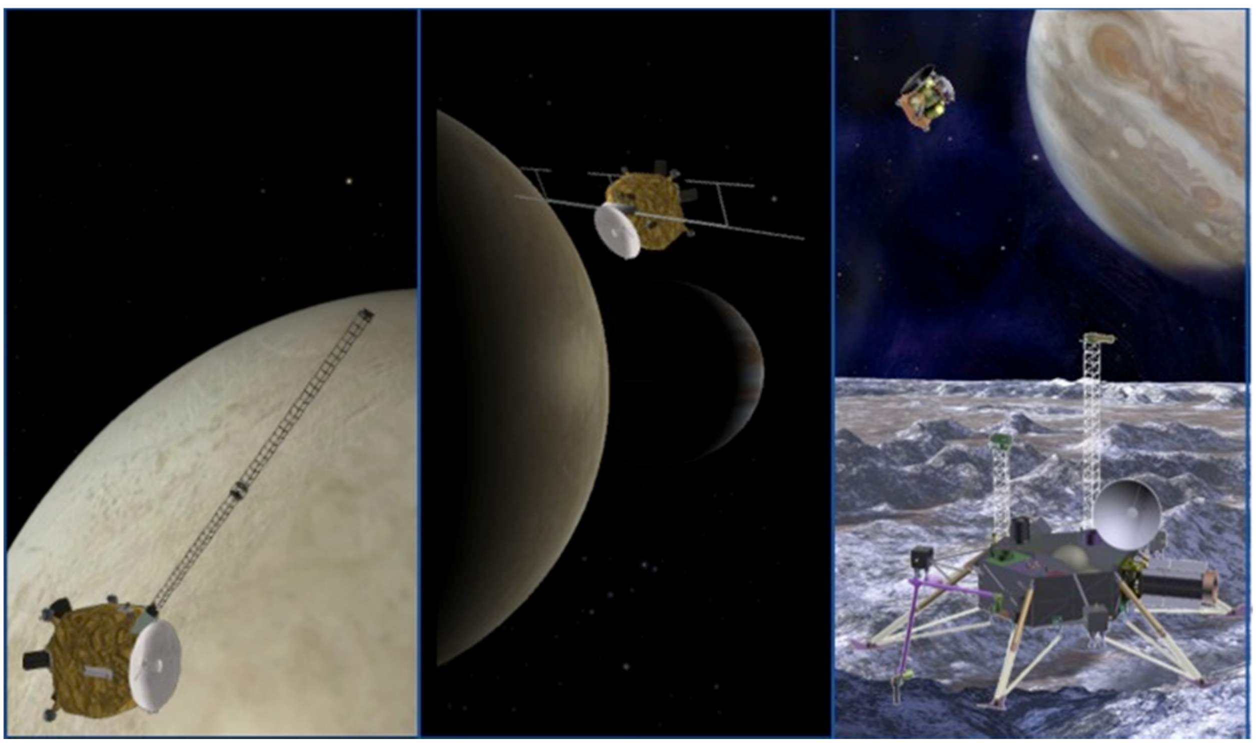

Figure A.3-1. Europa Orbiter Mission (left panel) would perform geophysical measurements ("water" science). The Multiple-Flyby Mission (middle panel) would concentrate on performing remote measurements that address the "chemistry" and "energy" science. The Europa landed mission (right panel) would perform detailed *in situ* characterization of a Europan landing site assessing key habitability science objectives.

NASA Headquarters direction. However, the Lander Mission concept was found to exceed the NASA total cost guideline and has associated mission risks that are deemed unacceptable at this time.

A.3.1 Science Definition Team Process

The NASA Headquarters tasked the Europa SDT with formulation and definition of the science goals, objectives, investigations, and example measurements for reduced-cost Europa mission concepts (flyby, orbiter, and lander) that maximize the science value per dollar. To carry out this task, SDT members and a chairperson were appointed from the scientific community to represent a broad range of Europa science interests (Table A.3.1-1). An initial group was assembled to evaluate concepts that achieve science objectives from Europa or Jupiter orbit, leading to the formulation of the Orbiter and Multiple-Flyby Mission concepts. When the scope of the study was expanded to include an evaluation of a lander concept, five additional members were added to the SDT for this study phase.

The SDT approached the task by identifying an overarching goal, key science objectives, science investigations to best address those objectives, and examples of appropriate measurements that could be carried out by each platform to address the science investigations. Presentations were heard from the SDT members, and from the other members of the scientific and engineering communities invited to provide complementary expertise. To perform its tasks, the SDT was organized into Objective Working Groups (Ocean and Ice Shell, Composition, and Geology), each with a lead and a deputy, who served as principal points of contact for formulating the science traceability for the Orbiter and Multiple-Flyby Mission concepts. For the Lander Mission concept, Cross-Cutting Working Groups were also formed, for the topical areas of Astrobiology, Instruments, and Landing Sites. Each of these cross-cutting groups was composed of members from each of the three Objective Working Groups, to ensure full cross-communication.

Table A.3.1-1. Europa Science Definition Team.

Member	Inst.	Role
Fran Bagenal	U. Colorado	Plasma
Amy Barr	Brown U.	Geophysics
Bruce Bills	JPL	Geophysics
Diana Blaney	JPL	Composition
Don Blankenship	U. Texas	Ice shell
Will Brinckerhoff*	GSFC	Astrobiology
Jack Connerney	GSFC	Magnetometry
Kevin Hand*	JPL	Astrobiology
Tori Hoehler*	Ames	Astrobiology
William Kurth	U. Iowa	Plasma
Melissa McGrath	MSFC	Atmosphere
Mike Mellon*	SWRI	Ice Physics
Jeff Moore	Ames	Geology
Robert Pappalardo	JPL	Chair, Study Scientist
Louise Prockter	APL	Deputy, Geology
David Senske	JPL	Deputy, Geology
Everett Shock*	ASU	Geochemistry
David Smith	MIT	Geophysics

SDT augmentations for the lander mission study.

Table A.3.1-2. Europa Science Definition Team meetings 2011–2012.

Date		SDT Activity	Location
2011	2-3 May	Considered Europa objectives and mission design trades, and converged on Orbiter and Multiple-Flyby Mission concepts	Pasadena, CA
	23–24 Jun	Provided feedback on initial Orbiter and Multiple-Flyby mission designs, and iterated on model payloads and mission requirements	Pasadena, CA
	22-23 Aug	Finalized Orbiter and Multiple-Flyby Mission science traceability, model payloads, and mission requirements	Pasadena, CA
	17-18 Oct	Developed initial objectives and investigations for Lander Mission	Pasadena, CA
	29-30 Nov	Derived preliminary lander model payload and science mission requirements	Boulder, CO
2012	31 Jan–2 Feb	Determined baseline vs. floor science and finalized Lander Mission model payload and mission requirements	Pasadena, CA

The 2011-2012 activities of the SDT are summarized in Table A.3.1-2, which provides an overview of the meetings convened during the study phase, from the spring 2011 through May 2012. Throughout the study, technical team members worked closely with the SDT to understand and iterate on mission requirements imposed by science. This process aimed for mission concepts that were realistic within the target resources while preserving the high-level scientific objectives.

The SDT was requested to reformulate a Europa mission, using JEO as a basis of comparison, that achieves compelling science but represents a descope from past studies. It became clear that there is a division between the key science investigations best conducted from Europa orbit and those best achieved through multiple flybys. To characterize the extent of the ocean and its relation to the deeper interior, systematic geophysical measurements of gravity, topography, and magnetic field are needed, and are 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-resolution targeted geological observations are quite data intensive and require high-mass, high-power instruments, so these are best carried out from a spacecraft that makes multiple flybys of Europa, broadcasting data back 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, requiring the *in situ* sample analyses. All three of these mission options could provide high caliber, compelling science that would change paradigms in our understanding of the nature and habitability of icy worlds.

A.3.2 Independent Review Process

The science and technical overviews of the Orbiter and Multiple-Flyby Mission concepts were presented to at an open community meeting of the Outer Planets Assessment Group (OPAG) on October 19th, 2011. Both concepts were received very favorably and enthusiastically endorsed by OPAG. The science and a technical overview of the lander concept were presented at open meeting of OPAG on March 29th, 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 additional technology maturation.

An independent review board was formed to provide a technical assessment, including risks, of the proposed mission concepts. In making this assessment, the board was asked to consider:

- Ability of the mission element to satisfy the science objectives
- Mission design approach
- Robustness of the mission element and the associated system architectures
- Robustness of mission element and system margins and compliance with JPL design principles
- Proposed scope, including available options, as consistent with the funding target value to complete the mission element
- Cost risk
- Project planning risks, including design, environment mitigation plans, integration and test plans, schedule, and margins

Members of the review board are listed in Table A.3.2-1. The Board provided written reports detailing the findings of their independent technical and cost reviews, including any requests for actions as recommended by the board. The board met on November 15, 2011 to review both the orbiter and flyby concepts. The board again met on March 15, 2012 to review the lander concept and to consider responses to previous requested actions. The science, technical, and manage-

Table A.3.2-1. Independent Review Board.

Review Board Member	Institution and Role
Scott Hubbard	NASA (Ret.), Chair
Orlando Figueroa	NASA (Ret.), former Director for Mars Exploration
Mark Saunders	NASA (Ret.), Former Director of NASA Independent Program Assessment Office
Dave Nichols	JPL, Systems Engineering
Jeff Srinivasan	JPL, Telecommunications
Barry Goldstein	JPL, Avionics
Cindy Kahn	JPL, Mechanical Systems
Gentry Lee	JPL, Solar System Chief Engineer
Will Devereux	APL, Head of Engineering
Douglas Eng	APL, System Engineering
Rosaly Lopes	JPL, Science (Orbiter & Flyby)
Leslie Tamppari	JPL, Science (Lander)

ment 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 deemed the lander concept as a challenging assignment to the study team in that a large amount of work was completed in short amount of time, and they commended the study team in exposing the challenges and risks of a Europa lander, but they 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 unknown terrain is too risky to fly the lander mission. The board written reports are contained in Sections B.4.5, C.4.5, and D.4.5.

Aerospace Corporation was contracted to perform an Independent Cost Estimate (ICE) 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. In addition, the Europa Study Team populated a data package provided by the Aerospace Corporation, detailing mission technical and programmatic information. The Europa Study Team interacted with the Aerospace Corporation to assure that any misunderstandings were clarified and reconciled. The results of the Aerospace Corporation ICE results showed excellent correlation with the Europa Study Team estimated costs. The Aerospace Corporation's written reports are contained in Sections B.4.4, C.4.4, and D.4.4.

A.4 References

Space Studies Board, 2011. Visions and Voyages for Planetary Science in the Decade 2013–2022. The National Academies Press, Washington, DC.