National Aeronautics and Space Administration

Mission Concept Study

Planetary Science Decadal Survey
Io Observer

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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.

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Planetary Science Decadal Survey

Mission Concept Study Final Report

Figures

Tables

Appendices

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Executive Summary

The Jovian moon Io is likely the most geologically active body in the solar system, offering insight into tidal heating, volcanic processes, and other phenomena. However, its location within Jupiter's radiation belt presents significant engineering challenges that must be addressed to enable future missions to Io. Under the direction of NASA, and with direct guidance from the National Research Council's (NRC's) Satellites Panel, the Jet Propulsion Laboratory's (JPL's) Advanced Project Design Team (Team X) looked at the feasibility of a remote observational mission to Io as a possible future New Frontiers concept. Per direction from the Satellites Panel, study options focused on four similar architectures to investigate the impacts of variations in payload, power systems, and mission duration. All of the options were targeted at New Frontiers–class mission constraints. The options included (1) an advanced stirling radioisotope generator (ASRG)-powered remote sensing spacecraft, (2) a solar-powered remote sensing spacecraft, (3) a solar-powered remote sensing spacecraft with one less instrument and a shorter observational period compared to Option 2, and (4) a solar-powered remote sensing spacecraft with one more instrument compared to Option 2. Launch dates were in line with NASA guidance on the next likely New Frontiers launch period. Trajectories to Jupiter and the observational tours were the same for all options with the exception of the previously mentioned shortened observational period.

For all options, the spacecraft would enter into a highly elliptical Jovian orbit and perform periodic flybys of Io. The orbits would be at high inclinations to reduce radiation exposure and to facilitate viewing of Io's polar regions, and would typically last approximately 60 days. The observational period for Options 1, 2, and 4 would span 10 flybys while Option 3 would span only 6. All options would include a redundant 3-axis stabilized spacecraft that would carry a narrow angle camera (NAC), a thermal mapper, and a pair of fluxgate magnetometers (FGMs). Options 1, 2, and 4 would also carry an ion and neutral mass spectrometer (INMS). Option 4 would also carry a fast-imaging plasma spectrometer (FIPS). In addition, the solar-powered options would require an instrument scan platform to enable continual sun pointing of the solar arrays during science data collection.

Radiation and power were the primary design drivers during the study, influencing the spacecraft, mission, and operational choices. Power generation and management trades, tour design, and radiation analysis work were carried out as part of this study. Solutions to both were influenced by the current Juno mission and an earlier Team X study done in 2008 for the Io Volcano Observer concept under the Discovery and Scout Mission Capabilities Expansion (DSMCE) program.

None of the options would require new technology. All options were around the expected New Frontiers cost cap (i.e., two slightly higher, one on the cap, and one slightly lower) and could be considered potential concepts for a future mission. However, the need for ASRG power could not be viewed as compelling and the technology did not appear enabling—a prerequisite for its usage.

1. Scientific Objectives

Science Questions and Objectives

The Io Observer mission concept is a New Frontiers–class mission designed to determine the internal structure of Io and mechanisms contributing to Io's volcanism. The science objectives of this study are summarized in Table 1-1. It is difficult to map Io because an Io orbiter would have to withstand more than a megarad/day of radiation due to the location of Io's orbit within the radiation belt surrounding Jupiter.

The Io Observer mission would utilize a high-inclination orbit of Jupiter to obtain multiple close flybys of Io with minimum accumulated radiation dose. A series of close flybys would enable the higher resolution mapping and details of the magnetic field and species in the atmosphere and plume required to understand the materials and processes that lead to Io's volcanic styles as well as put strong constraints on Io's internal structure.

Io is a fascinating, dynamic moon exhibiting widespread volcanic activity. Figure 1-1 shows surface deposits from active plumes (rings), active and recent hotspots (dark areas), and S and SO_2 deposits (ubiquitous with a range of colors arising from several mechanisms) on Io. The highest reported lava temperature, ~1800°C, is much higher than that seen in modern terrestrial activity—perhaps indicative of magma more primitive than that existing on Earth and a magma ocean in Io's interior.

The science mission requirements support an observational program that enables characterization of Io's volcanism. The high-radiation environment makes it impractical to map the full body at a range of time scales. However, the multiple flybys would support the acquisition of high-resolution data that is crucial to understanding current volcanism on Io and would allow long-term monitoring at lower resolution, which is sufficient given the extensive surface deposits created by Io's eruptions.

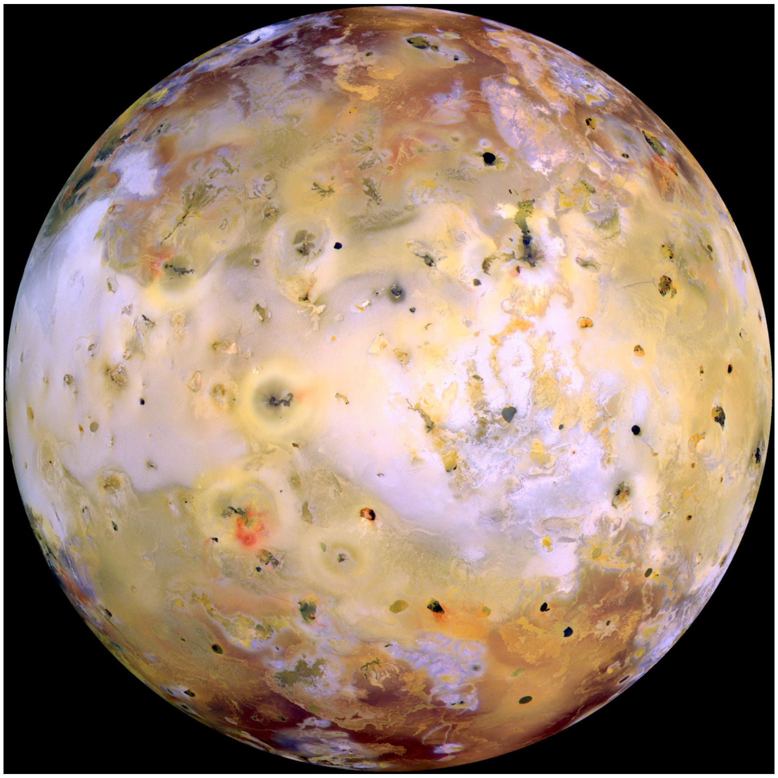

Figure 1-1. Image of the Jovian Moon Io

Table 1-1. Prioritized Io Science Objectives from Prior Decadal Survey

Primary Objectives	
A1	Test and revise models for active volcanic processes on Io
A2	Determine the state (melt fraction) of Io's mantle
A3	Test and revise models of tidal heating mechanisms
Secondary Objectives	
B1	Test and revise models for tectonic processes on Io
B2	Test and revise models for the interrelated volcanic, atmospheric, plasma torus, and magnetospheric mass- and energy-exchange processes
B3	Test and revise models for the state of Io's core via tighter constraints on whether Io is generating a magnetic field
B4	Improve our understanding of endogenic and exogenic processes controlling Io's surface composition
B5	Improve our understanding of Jupiter system science

Science Implementation

Measurements from the Galileo SSI imaging system suggested a very high peak lava temperature on Io, but from a single observation that is difficult to validate. Temperature measurements are challenging since the power received (brightness temperature) depends on the distribution of temperatures on the surface subtended by a single pixel. This difficulty is alleviated by measuring color temperature (i.e., the shape of the blackbody curve) in two or preferably three bands simultaneously. This requires a special camera design to enable simultaneity and high-imaging rates, which would be implemented for this mission.

Instruments

Brief descriptions of the key baseline instrument measurements are captured in Table 1-2. All instruments except the INMS would be considered science floor instruments (i.e., they are essential to the completion of the minimum science goals and cannot be descoped from the design). A more detailed description of each of the instruments is provided in Section 3.

Table 1-2. Study Instruments and Desired Measurements

Instrument	Measurement Objective
Narrow angle camera (NAC)	Measure peak lava temperatures with near-simultaneous (≤0.1 s; <0.01 s desired) color imaging (at least 2 wavelengths between 600 and 1000 nm) at ≤100 m/pixel to tightly constrain peak lava temperatures and test models of the state (melt fraction) of the mantle, monitor eruptions, and obtain stereo images for topography.
Thermal mapper (TM)	Map and monitor temperatures and heat-flow patterns related to the internal structure and tidal heating mechanisms; ≥3 bandpasses between 2–20 μm.
Ion and neutral mass spectrometer (INMS)	Determine compositional and spatial distribution of neutrals, which control energy input into the Io plasma torus; determine the composition of Io's atmosphere and volcanic plumes, providing constraints on Io's interior composition; and determine the composition and fluxes of low-energy ions picked up near Io.
Fluxgate magnetometer (FGM)	Detect magnetic induction and an internal field (if the latter is present).
Fast-imaging plasma spectrometer (FIPS)	Measure the energy, angular, and compositional distributions of the low-energy components of the ion distributions (<50 eV/charge to 20 keV/charge)

Orbital Activity

A typical orbit would consist of variants of the following example activity. During orbital cruise, the payload would monitor the Jovian system providing high-latitude views that are complementary to the Galileo (equatorial) dataset and with instrumentation that is different from the Juno mission. On Io approach, the entire illuminated hemisphere of Io would be imaged at less than 1 km/pixel in eight bands. Key features on Io's surface would be mapped at 10–100 m/pixel resolution in four bands and less than 10 m/pixel panchromatic. The liquid lava temperatures would be measured (the lavas are hot enough that this can be done on the illuminated hemisphere as well) at ~100 m/pixel in four bands, and regional thermal mapping would be obtained at 0.1–100 km/pixel. Both NAC stereo pairs and movies of active volcanism would be obtained (approximately two each per orbit). Imaging of Io in eclipse would be used to obtain global heat flow mapping at less than ~200 km/pixel and measurement of emissions from 200–1000 nm at less than 16 km/pixel. The magnetometers would be operated continuously and the mass spectrometer would obtain hundreds of mass spectra near closest approach as well as regular sampling at a distance from Io. The data return for the orbit would be the equivalent of approximately 5,000 images (at 12 megabits/image).

The science traceability matrix (Table 1-3) provides the flow down of science requirements. The imaging and thermal measurements must occur for mission success. While the mission would benefit from maximizing the number of flybys, the major science goals could be achieved with six close passes. The following science mission characteristics would enable the measurement of key parameters affecting Io's volcanic activity:

- High-inclination Jupiter orbit (>45° to Jupiter's equatorial plane) to lessen radiation exposure and improve polar coverage
- Several (>10) close (100–1000 km) Io flybys
- A minimum of three night-side and three day-side passes
- Two flybys at high but opposite magnetic latitudes (for magnetic induction measurements)
- Flybys that repeat coverage of about the same longitude for change detection
- A low flyby (~100 km)
- Possible pass through a plume (risk appears to be acceptable, particularly at the end of the mission)
- Many eclipse observations (occur every Io day—42.5 hours)
- Pointing stability of ~36 μrad/s or better to support imaging near closest approach and long-exposure eclipse observations

There are many other instruments that would be valuable for understanding Io's volcanism and its surrounding environment. However, this study used a minimal set in order to test the engineering and scientific feasibility of a focused mission to Io.

Science Traceability

The connectivity between the science goals of this study and the mission and instrument requirements are captured in the science traceability matrix (Table 1-3). This information was provided by the NRC Satellites Panel as part of the study's initial information package.

Table 1-3. Science Traceability Matrix

Science Goals[1]	IVO Science Objectives	Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Understand the eruption mechanisms for Io's lavas and plumes and their implications for volcanic processes on Earth, especially early in Earth's history when its heat flow was similar to Io's, and elsewhere in the solar system.	**A1.** Test and revise models for active volcanic processes on Io.	• Observe morphologies, temperatures, and temporal variability of lava flows, fountains, lakes, plumes, and vent regions. • Monitor at temporal and spatial scales of months to seconds and kilometers to tens of meters, as appropriate.	NAC: • Color imaging at 1 km/pixel over large regions of surface and limb each flyby and of specific features down to 10 m/pixel. 10 μrad/pixel to provide 1 km/pixel imaging (15 bandpasses) at 100,000 km range and 10 m/pixel at 1,000 km. • Acquire movies (<100 s time steps) of dynamic phenomena. • 100:1 SNR for 10 m/pixel color. Thermal mapper: • Repeat thermal mapping at 10 km/pixel or better each flyby via at least 3 bandpasses from 2-10 microns. 125 μrad/pixel to provide 12.5 km/pixel data (10 bandpasses) from range of 100,000 km or greater; 125 m/pixel from 1,000 km.	• At least 5 Io flybys with similar illumination at 1,000 km or less • At least 3 dayside C/A passes. S/C pointing flexibility is essential. • Pointing stability of 36 μrad/sec. Pointing accuracy to ~1 mrad (100 NAC pixels) for repeat imaging. • S/C must be able to store and return at least 10 Gb of data per flyby. • Camera(s) and Thermal mapper co-aligned to 1 mrad.

Science Goals[1]	IVO Science Objectives	Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Determine Io's interior structure, e.g., whether it has a magma ocean, and implications for the coupled orbital-thermal evolution of Io and Europa.	**A2.** Determine the state (melt fraction) of Io's mantle.	• Tightly constrain Io's lava eruption temperatures (a strong constraint on melt fraction or a "magma ocean" if melt fraction is high). • Search for induced magnetic signature of interconnected mantle melt. • Attempt to optically measure non-synchronous rotation. • Improve measurements of the shape of Io.	NAC: • Near-simultaneous (<0.1 s; <0.01 s desired) color imaging at 100 m/pixel or better. Minimal saturation and radiation noise. • At least 2 wavelengths of unsaturated data in 600–1000 nm range. • High data rate for high probability of observing at optimal times and places. • High-resolution (<100 m/pixel) repeat coverage of terminator and limb regions to measure or constrain rate of non-synchronous rotation and global shape.	• Slew spacecraft at rate ≥1.6 mrad/s (with 4-line filter sets) for measurement of peak temperatures. • At least 3 flybys on the night side of Io. • Plan identical orbits but with Io at magnetic latitudes near 9.6º and -9.6º.
Determine the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of Io's tidal heating.	**A3.** Test and revise models of tidal heating mechanisms.	• Global thermal mapping on multiple flybys, especially polar regions, at wavelengths that measure both magmatic and background heat flow.	Thermal mapper: • In addition to 2-10 µm region, ~20 µm mapping needed for background temperatures. ~200 km/pixel adequate. • Bandpasses at ~2, 5, 8, 15, and 20 µm. • Readout upper limit of 60 Hz. NEΔT ≤5 K in at least 1 band over T range 90–1000 K.	• Slew S/C at a rate ≤ 7.5 mrad/s. • Imaging while Io is in eclipse (Jupiter's shadow) to minimize re-radiated solar heat.

Science Goals[1]	IVO Science Objectives	Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Investigate the processes that form Io's mountains and the implications for tectonics under high heat-flow conditions that may have existed early in the history of other planets.	**B1.** Test and revise models for tectonic processes on Io.	• Imaging at 100 m/pixel or better of key structures. • Obtain ≤1 km/pixel topographic data with a vertical precision better than 1 km at a regional scale around key structures.	• NAC can re-image selected locations for stereo (~100 m/pixel) or include WAC for systematic pole-to-pole stereo imaging near C/A (~25 m/pixel at 200 km range). Supplement with limb imaging.	• Pointing accuracy to ~1 mrad (100 NAC pixels) for stereo overlap.
Understand the composition, structure, and thermal structure of Io's atmosphere and ionosphere, the dominant mechanisms of mass loss, and the connection to Io's volcanism.	**B2.** Test and revise models for the interrelated volcanic, atmospheric, and magnetospheric mass-loss processes.	• INMS measurements during C/A to Io and remote sensing of Na and other species, especially in eclipse (Io in Jupiter's shadow), to place INMS data into context. • FGM also constrains variations in composition of Io's exosphere and provides context. • Remote sensing of the atmosphere and torus in the UV. • Imaging of Io atmospheric emission in the visible and near-UV in Jupiter eclipse.	<u>INMS:</u> • Sufficient sensitivity and mass resolution to measure abundances of key species such as S, O, SO_2, SO, Na, Cl, and silicates. 1–300 amu; M/ΔM 300–1000 (increasing with mass). ~200 spectra per flyby. <u>NAC:</u> • Narrow spectral filters and combination of low read noise (~2 e^-), dTDI, and slew rates to remotely monitor escaping species. <u>UVS:</u> • 200–300 nm spectroscopy at <1-nm resolution for mapping of plume and atmosphere gases. Lyman-alpha imaging for global atmospheric distribution. 60–160 nm spectroscopy for auroral and torus emissions.	• Mount INMS orthogonal to remote sensing (point in ram direction near C/A with remote sensing pointed at Io). • Complete at least one flyby within 200 km of Io. • Away from C/A, slew S/C at ≤7.5 mrad/s to image Na and other species escaping Io.

Science Goals[1]	IVO Science Objectives	Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Determine whether Io has a magnetic field.	**B3.** Test and revise models for the state of Io's core via tighter constraints on whether Io is generating a magnetic field.	• Measure magnetic field vectors along IVO's trajectory.	FGM: • Detect variations with amplitudes of ~0.01 nT. Limited by S/C magnetic cleanliness: S/C interference has to be as low as possible. Use cruise phase to analyze remaining interference to allow removal by the gradiometer sensor arrangement. • Sensors need a thermally stabilized environment (MLI protected bracket).	• Mount one FGM near S/C and the other at the end of a 1-m bracket, and locate as far from ASRGs as possible. • Tweak flyby times by up to a few hours to occur when Io is at high magnetic latitudes.
Understand Io's surface chemistry, including volatiles and silicates, and derive magma compositions (and ranges thereof), crustal and mantle compositions and implications for the extent of differentiation, and contributions to the atmosphere, magnetosphere, and torus.	**B4.** Improve our understanding of endogenic and exogenic processes controlling Io's surface composition.	• Spectral remote sensing of Io's surface and INMS in situ sampling.	ThM: • 3–5 bandpasses to measure Christiansen emission peak and other silicate features. NAC: • 5–10 bandpasses to map color variations indicative of S, SO_2, and silicates; INMS data. INMS: • Data near C/A Near-IR spectrometer highly desirable: • 1–5 micron wavelength range.	• None beyond those listed above for NAC, Thermal Mapper, or INMS. • No additional requirements anticipated for near-IR spectrometer.

Science Goals[1]	IVO Science Objectives	Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Improve our understanding of Jupiter system science, including meteorology, aerosol structure, tropospheric composition, and auroral phenomena on Jupiter, composition and temporal variability of Europa's exosphere, Jovian magnetospheric processes, and small inner moons and rings of Jupiter.	**B5.** Improve our understanding of Jupiter system science.	• All instruments on IVO can acquire observations relevant to Jupiter system science, limited by observing time, data volume and other requirements for Io science.	• No additional requirements, but consider adding or tweaking spectral bandpasses of NAC and thermal mapper for Jupiter system science. • Near-IR spectrometer would enhance Jovian atmospheric science.	• No additional requirements, although there will be trades to consider.

Notes: This matrix describes the linkages between science objectives and how they are achieved. Note that functional requirements are requirements placed by science on the mission concept (e.g., requirements on the spacecraft, trajectory, mission architecture, etc.).

[1]Derived from Beebe et al., 2008.

2. High-Level Mission Concept

Overview

As part of NASA's support to the National Research Council (NRC) and its current Planetary Decadal Survey, JPL was assigned the task of developing a New Frontiers–class remote sensing mission to the Jovian moon Io. The initial prioritized science requirements, as well as the direction that the mission should be sized to fit within the likely constraints of the next New Frontiers call, were supplied by the Satellites Panel. Discussions in advance of the study settled on two options: an advanced stirling radioisotope generator (ASRG)-powered spacecraft and a solar-powered spacecraft. Both architectures were closely structured and similar to work carried out by the JPL Advanced Project Design Team (Team X) in 2008 under the Discovery and Scout Mission Capabilities Expansion (DSMCE) program. These options required no extensive up-front trade work and were considered mature enough to go directly into a Team X design study. This work was done in close coordination with the Satellites Panel with several panel members providing active guidance on the design process and decisions to Team X prior to, and during, the Team X study.

The Team X study was held February 16–18, 2010, with an additional session on April 19, 2010. The primary objective was to identify an Io observing mission design capable of meeting the likely New Frontiers proposal constraints. The study examined the feasibility of such a mission and did not look to maximize science return. As such, the instrument suite was modest: a narrow angle camera (NAC), an ion and neutral mass spectrometer (INMS), a thermal mapper, two fluxgate magnetometers, and a fast-imaging plasma spectrometer (FIPS). The two options studied were an ASRG-powered spacecraft and a solar-powered spacecraft. Both spacecraft concepts were 3-axis stabilized with Juno-heritage radiation vaults. Both were inserted in the same high-inclination, highly elliptical Jovian orbit with periodic flybys of Io. Orbits were approximately 60 days with the mission lasting ten orbits. The mission design leveraged earlier work done in the 2008 DSMCE study and was highly inclined to Jupiter's equatorial plane to minimize spacecraft exposure to the Jovian radiation belt as well as to facilitate observations of Io's poles. A radiation analysis of the current mission was performed as part of this study and is provided as Appendix C. Both options also borrowed the vault approach and the thruster-only attitude control system from the 2008 concept.

Following completion of both initial options, the NRC Science Champion requested a floor option be included. This third option was the same as the second option (i.e., solar-powered) except that the mission was to last only six orbits and the INMS was removed from the payload suite. In a follow-up session in April, a fourth option was studied, which was the same as the second option, with the addition of a FIPS instrument. The study designs were all developed based on the same set of assumptions and constraints. The first level of constraints was specified in the NASA-supplied *Ground Rules for Mission Concept Studies in Support of Planetary Decadal Survey* [1], which included details on cost reserves, ASRG performance and cost, Ka-band telecommunications usage, and launch vehicle costs—all of which were adhered to within the studies. The second level of constraints and assumptions was internal JPL best practices as specified in JPL documents *Design, Verification/Validation & Ops Principles for Flight Systems* [2] and *Flight Project Practices* [3]. These documents covered margin and contingency levels as well as redundancy practices. Finally, since a primary goal of the study was to look at the compatibility of the different options with a possible future New Frontiers announcement of opportunity (AO) call, a launch date some time after January 1, 2021 and before December 31, 2023, and a complete mission cost cap of approximately $1B were also assumed. The latter assumption came from adjusting the cost cap on the most recent New Frontiers AO for differences between the AO's cost assumptions and the current specified Decadal Survey assumptions (this number was later clarified by NASA as $1.056B FY2015). It should be viewed as an approximation of the eventual cost cap. Cost estimates that slightly exceed it should not be discounted as possible New Frontiers–class missions.

Key trades that contributed to the final point designs are described in detail later in this section and descriptions of the final designs are included in Section 3. Briefly, the options identified for detailed point designs and cost estimates are provided below.

1. ASRG-Powered Spacecraft—This architecture includes two ASRGs to power the mission. All instruments were body mounted. No reaction wheels were included; thrusters were considered adequate for the mission's pointing requirements. Data downlink used the Ka-band specified by NASA guidelines. A Juno-like titanium vault housed radiation-sensitive electronics where possible. Spot shielding was used elsewhere. This option was starved for power throughout the mission. A late subsystem power increase during the study made the loss of half an ASRG a mission-catastrophic failure. This made the design no longer redundant in the power subsystem; thus, a third ASRG was needed and identified as a lien on the design. The addition would add approximately $30M to the total cost of the mission; sufficient unused mass allocation exists to allow the addition without requiring a larger launch vehicle. Although all options were close in cost, this option was the most expensive at approximately $1.1B FY2015.
2. Solar-Powered Spacecraft (Figure 2-1)—The architecture for this option was similar to the first option but used Juno-like solar arrays for power generation. This mission required only about two-thirds of the Juno array area. Unlike Juno, this spacecraft would be 3-axis stabilized and must point a NAC at specific targets. Array inertia and array vibration posed a possible instrument-pointing issue upon closest approach. Ground tracking could also complicate the solar-array charging cycle. These issues were resolved with the inclusion of a 2-axis instrument scan platform. Since the array could be sized for the power need, there was no difficulty in managing the power demand as experienced in the study of the first option. This option was around the expected New Frontiers cost cap.
3. The Floor Option—The design of this option was similar to that of the second option except the mission was limited to six orbits and the INMS was dropped from the payload. The solar array decreased slightly due to the reduced payload. This option was below $1B FY2015.
4. Solar-Powered Spacecraft with Additional Instrument—The design of this option was the same as the second option, with the addition of a FIPS instrument. The solar array size increased slightly compared to the second option due to the power requirements of the added instrument. This option was comparable in cost to the first option at approximately $1.1 B FY2015.

None of the options would require new technology. All options were around the New Frontiers cap and could be considered potential architectures. However, with the existence of a viable solar-powered concept, the ASRG technology cannot be viewed as enabling, which is a prerequisite for its use.

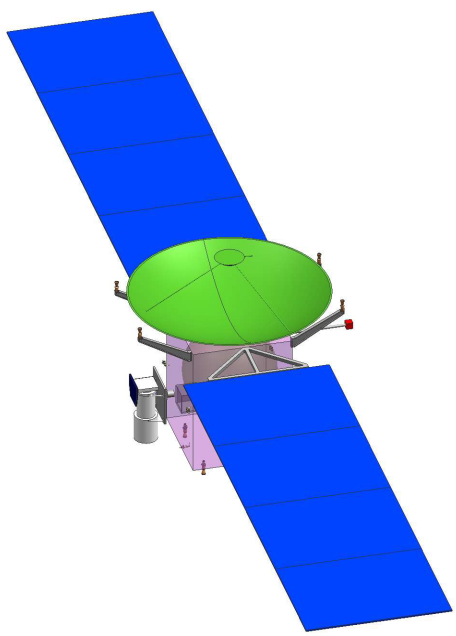

Figure 2-1. Solar-Powered Spacecraft (Conceptual Design)

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). Following the completion of this study, all options are considered to be at CML 4. The architectures studied by JPL's Team X were defined at the assembly level and estimated for mass, power, data volume, link rate, and cost using JPL's institutionally endorsed design and cost tools. Risks were also compiled as part of this study.

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

No technological developments were required to enable any of the options designed as part of this study. This is largely in keeping with the initial design goal of consistency with New Frontiers competitive missions. The studied missions leverage key technologies such as radiation protection and low-light solar power from the current Juno mission. Therefore, the determination that no new technologies would be needed or would require development is contingent on the successful development of the Juno mission.

Key Trades

Solar vs. ASRG—Both solar- and ASRG-powered missions were examined as part of this study. Solar-powered missions were slightly less costly and would have heritage (i.e., Juno) in time for this launch opportunity. Any issues with solar panel inertia interfering with instrument pointing were eliminated with a 2-axis instrument scan platform. A further analysis of solar panel vibration interaction with the payload should be considered, but, as of this study, there is no reason to consider ASRGs as enabling for this mission.

Orbital Period vs. Operational Considerations—Power and data management over the minimum orbital period requires balancing of the instrument operating cycles with the telecommunication downlink periods and battery recharge periods. The initial examination of a two-ASRG mission on a 30-day orbit was unable to show sufficient power generation to meet the overall power demand of the orbit. Therefore, the study chose a 60-day orbit, which did generate enough power on all options but added time and operations costs to the missions. Further analysis should be considered. Many alternatives exist and a better one may be determined.

3. Technical Overview

Instrument Payload Description

The payload would consist of a NAC, a thermal mapper, a pair of fluxgate magnetometers, and possibly an INMS, and a FIPS.

The NAC would measure peak lava temperatures with at least two color, near simultaneous (<0.1 s) imaging at <100 m/pixel. It would also be used to monitor eruptions, provide stereo images for topography, and possibly provide optical navigation capabilities. It is enabled by a 2k × 2k complementary metal oxide semiconductor (CMOS) detector. Detector pixel-level addressing permits windowing, framing and push-broom modes. Four color filters (e.g., >950 nm, >800 nm, 600–800 nm, and 400–600 nm) are planned, each of which covers just four lines with the set repeated 16 times. Digital time delay integration (dTDI) over multiple lines would provide nearly simultaneous color imaging to constrain peak lava temperatures and test models of the state (melt fraction) of the mantle. About half of the array is covered by up to 15 spectral filters from 200–1,000 nm, each filter covering ~64 lines for dTDI. Half of the array would provide clear panchromatic framing images for optical navigation and movies of dynamic phenomena. Charge-transfer efficiency can be maintained when a CMOS imager is subjected to high (1 Mrad) radiation environments. Transient noise would affect imagers. Two electrons of read noise would not likely be achieved within 20 Rj. This might impact the objective of remotely monitoring escaping species with the NAC. Data would be read off chip at 240 Mpixels/sec into a digital processing unit (DPU). Ten (10) microradian/pixel would be achievable with optics similar to the Lunar Reconnaissance Orbiter (LRO) NAC or New Horizons' Long Range Reconnaissance Imager.

The thermal mapper would map and monitor temperatures and heat-flow patterns related to the internal structure and tidal heating mechanisms via >3 bandpasses between 2–20 µm. The thermal mapper would be similar to THEMIS on Mars Odyssey. The architecture consists of a microbolometer array operated in push-broom mode with three filter strips across the detector array between 2–20 µm. The power estimate is driven by frame rate requirements.

The fluxgate magnetometers would detect magnetic induction and an internal field (if the latter is present). The instrument has heritage from Rosetta, Venus Express, and THEMIS missions. The estimate for the fully packaged mass of 1.5 kg is based on comparable missions. One magnetometer would be placed on the spacecraft and the other at the end of a ~1 m boom to calibrate effects of the spacecraft on the magnetometer measurements.

The INMS would determine 1) compositional and spatial distribution of neutrals, which control energy input into the Io plasma torus; 2) the composition of Io's atmosphere and volcanic plumes, providing constraints on Io's interior composition; and 3) the composition and fluxes of low energy ions picked up near Io. The Cassini quadrupole INMS has a narrower mass range (1–100 amu) than the desired performance for the Io Observer (1–300 amu) and less mass resolution (100 vs. 300–1,000, respectively). The ROSINA INMS on Rosetta has desired mass range (1–300 amu) and higher resolution (3000). However, ROSINA includes three sensors: a double-focusing mass spectrometer (DFMS), a reflection time-of-flight spectrometer (RTOF), and a comet pressure sensor (COPS). Performance comparable to the Io Observer desired performance may be achievable with only an RTOF-like sensor with a comparable mass, power, and cost to the Cassini INMS.

The FIPS measures the energy, angular, and compositional distributions of the low-energy components of ion distributions (<50 eV/charge to 20 keV/charge). This instrument would provide direct measurement of the plasma interaction with Jupiter and would provide context data for magnetometer measurements. The MESSENGER ESSP–based design detects H, ^{3}He, ^{4}He, O, Ne, Na, K, S, Ar, and Fe. The field of view is 1.4 pi steradians. The M/Q range is 1–40 amu/e.

The instruments would be operated simultaneously during Io flybys. Several Io flybys with similar viewing and lighting geometries are envisioned for repeat color imaging (<1 km/pixel) and regional thermal mapping (<10 km/pixel) with a return of >10 Gb of science data per flyby. Global, especially polar, mapping of heat-flow patterns at <200 km/pixel to test models of tidal heating mechanisms are planned. The Io plasma torus would be monitored before and after the Io flybys with the magnetometers and INMS. The magnetometers would operate continuously at a few vectors to characterize currents in the plasma torus. The INMS would determine in-situ density and composition of the plasma torus for a range of system III longitudes and would relate the measurements to Io activity.

Contingencies for the resources listed in Tables 3-1 through 3-6 are based on the following scale: build to print—2%, inherited design—15%, and new design—30%.

Table 3-1. Narrow Angle Camera

Item	Value	Units
Type of instrument	Camera	
Number of channels	20	bandpass
Size/dimensions (for each instrument)	$1 \times 0.3 \times 0.3$	m x m x m
Instrument mass **without** contingency (CBE*)	15	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	19.5	kg
Instrument average payload power **without** contingency	25	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	32.5	W
Instrument average science data rate^ **without** contingency	3000	kbps
Instrument average science data^ rate contingency	30	%
Instrument average science data^ rate **with** contingency	3900	kbps
Instrument fields of view (if appropriate)	~1	degrees
Pointing requirements (knowledge)	6×10^{-2}	degrees
Pointing requirements (control)	6×10^{-2}	degrees
Pointing requirements (stability)	2×10^{-3}	deg/sec

*CBE = Current best estimate

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

Table 3-2. Thermal Mapper

Item	Value	Units
Type of instrument	Thermal imager	
Number of channels	10	bandpass
Size/dimensions (for each instrument)	0.5 × 0.4 × 0.3	m x m x m
Instrument mass **without** contingency (CBE*)	12	kg
Instrument mass contingency	15	%
Instrument mass **with** contingency (CBE+Reserve)	13.8	kg
Instrument average payload power **without** contingency	15	W
Instrument average payload power contingency	15	%
Instrument average payload power **with** contingency	17.25	W
Instrument average science data rate^ **without** contingency	1000	kbps
Instrument average science data^ rate contingency	15	%
Instrument average science data^ rate **with** contingency	1150	kbps
Instrument fields of view (if appropriate)	3.5° x 4.6°	degrees
Pointing requirements (knowledge)	6×10^{-2}	degrees
Pointing requirements (control)	6×10^{-2}	degrees
Pointing requirements (stability)	2×10^{-3}	deg/sec

*CBE = Current best estimate

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

Table 3-3. Ion and Neutral Mass Spectrometer

Item	Value	Units
Type of instrument	Mass spectrometer	
Number of channels	1	
Size/dimensions (for each instrument)	0.20 (H) × 0.4 (L) × 0.4 (W)	m x m x m
Instrument mass **without** contingency (CBE*)	10.3	kg
Instrument mass contingency	2	%
Instrument mass **with** contingency (CBE+Reserve)	10.5	kg
Instrument average payload power **without** contingency	32	W
Instrument average payload power contingency	2	%
Instrument average payload power **with** contingency	32.64	W
Instrument average science data rate^ **without** contingency	1.5	kbps
Instrument average science data^ rate contingency	2	%
Instrument average science data^ rate **with** contingency	1.53	kbps
Instrument fields of view (if appropriate)	8	degrees (half angle)
Pointing requirements (knowledge)	1	degrees
Pointing requirements (control)	1	degrees
Pointing requirements (stability)	0.5	deg/sec

*CBE = Current best estimate

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

Table 3-4. Fluxgate Magnetometer (two units, all values PER unit)

Item	Value	Units
Type of instrument	Magnetometer	
Number of channels	3	axis
Size/dimensions (for each instrument)	0.01 × 0.01 × 0.01	m x m x m
Instrument mass **without** contingency (CBE*)	1.5	kg
Instrument mass contingency	15	%
Instrument mass **with** contingency (CBE+Reserve)	1.725	kg
Instrument average payload power **without** contingency	4	W
Instrument average payload power contingency	15	%
Instrument average payload power **with** contingency	4.6	W
Instrument average science data rate^ **without** contingency	1.4	kbps
Instrument average science data^ rate contingency	15	%
Instrument average science data^ rate **with** contingency	1.61	kbps
Instrument fields of view (if appropriate)	N/A	degrees
Pointing requirements (knowledge)	N/A	degrees
Pointing requirements (control)	N/A	degrees
Pointing requirements (stability)	N/A	deg/sec

*CBE = Current best estimate

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

Table 3-5. Fast Imaging Plasma Spectrometer

Item	Value	Units
Type of instrument	Ion spectrometer	
Number of channels	1	
Size/dimensions (for each instrument)	0.19 (H) x 0.17 (L) x 0.20 (W)	m x m x m
Instrument mass **without** contingency (CBE*)	1.4	kg
Instrument mass contingency	15	%
Instrument mass **with** contingency (CBE+Reserve)	1.5	kg
Instrument average payload power **without** contingency	1.9	W
Instrument average payload power contingency	15	%
Instrument average payload power **with** contingency	2.2	W
Instrument average science data rate^ **without** contingency	0.08	kbps
Instrument average science data^ rate contingency	15	%
Instrument average science data^ rate **with** contingency	0.09	kbps
Instrument fields of view (if appropriate)	1.4 pi	steradians
Pointing requirements (knowledge)	1	degrees
Pointing requirements (control)	1	degrees
Pointing requirements (stability)	0.5	deg/sec

*CBE = Current best estimate

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

Table 3-6. Payload Mass and Power

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Narrow angle camera	15	30	19.5	25	30	32.5
Thermal mapper	12	15	13.8	15	15	17.3
Ion and neutral mass spectrometer	10.3	2	10.5	32	2	32.6
Two flux gate magnetometers	3.0	15	3.45	8	15	9.2
Fast imaging plasma spectrometer	1.4	15	1.6	1.9	15	2.2
Total Payload Mass	41.7	17	48.9	81.9	14	93.8

Flight System

The flight system would consist of a single Jupiter orbiter that would enter into a highly elliptical Jovian orbit and perform periodic flybys of Io. The orbits would be at high inclinations to reduce radiation exposure and to facilitate viewing of the Io polar region. The orbiter concept is a mostly new design with some Juno heritage in radiation management and, with the solar options, in power generation. It would be dual (cold spare) redundant. The mission duration would be approximately eight years, including at least 10 Io flybys for Options 1, 2, and 4, and 6 Io flybys for Option 3. Both ASRG- and solar-powered design options for the orbiter were considered. Architectures for all options are summarized at the end of the section in Table 3-12.

The extrapolation of the Juno solutions to the Io situation is viewed as relevant; early radiation dosage estimates have the Juno mission at about 400krad TID (100 mils of aluminum, RDF = 1) [4, 5], while the Io exposure by its tenth orbit would be about 180krad [Appendix C]. For the purpose of sizing the arrays, it was assumed that the arrays would experience similar degradation rates as seen in testing on Juno, so the arrays are likely conservative in their design. Since the Io titanium vault is of the same thickness as Juno's, and has been sized only for the reduced volume requirement, it too is likely conservative in design. Instrument sensors outside the vault are a different matter. Details of the instrument parts/shielding designs were beyond the scope of this study. However, both missions have a camera and a magnetometer. Juno radiation solutions are likely extendable to the Io mission for these instruments. The INMS detects charged particles, so it is likely not at risk to radiation exposure. The thermal mapper may need a more detailed analysis to verify a radiation solution.

A suite of four instruments was considered for the baseline mission—a NAC, an INMS, a thermal mapper, and a pair of fluxgate magnetometers. For the fourth option, a FIPS instrument was also included. The magnetometers would be mounted on a 1 m long deployable boom and the spacecraft. A 3 m diameter fixed high-gain antenna (HGA) would be mounted on one end of the spacecraft bus. The solar-powered options would also include a single 2-axis gimbaled scan platform affixed to the side of the bus for the instruments, so that observations could be conducted while the solar panels are continuously sun pointed. Table 3-7 provides a comparison of the primary differences between the requirements for the four options.

Tables 3-8 through 3-11 provide a mass and power summary for each option. The mass contingency policy is based on the subsystem- and system-level contingency factors. Each subsystem designer provides a contingency factor based on the assumed subsystem heritage and complexity. The total subsystem contingency is computed based on the sum of all subsystem masses. A systems contingency factor is applied to ensure that the total mass contingency is 43% (e.g., total subsystem contingency + system contingency = 43%). This 43% system contingency factor is based on JPL design principles. The power contingency policy is to add 43% contingency to the total power for each power mode. Unlike mass contingency policies, subsystem engineers do not add contingency for power at the subsystem level.

Table 3-7. Comparison of the Four Options

	Option 1	Option 2	Option 3	Option 4
Number of flybys	10	10	6	10
Instruments	NAC, INMS, thermal mapper, magnetometer	NAC, INMS, thermal mapper, magnetometer	NAC, thermal mapper, magnetometer	NAC, INMS, thermal mapper, magnetometer, FIPS
Power	ASRG	Solar	Solar	Solar

Table 3-8. Flight System Mass and Power—Option 1

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	226	30%	294	-	-	-
Thermal control	41	46%	60	27	43%	39
Propulsion (dry mass)	88	8%	95	25	43%	36
Attitude control	21	30%	27	39	43%	56
Command & data handling	24	7%	26	49	43%	70
Telecommunications	67	17%	78	75	43%	107
Power	148	30%	192	36	43%	51
Total Flight System Dry Bus Mass	**615**	**26%**	**772**	**251**	**43%**	**359**

Table 3-9. Flight System Mass and Power—Option 2

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	360	30%	468	-	-	-
Thermal control	36	35%	49	69	43%	99
Propulsion (dry mass)	88	8%	95	25	43%	36
Attitude control	23	28%	30	39	43%	56
Command & data handling	24	7%	26	49	43%	70
Telecommunications	67	17%	78	75	43%	107
Power	177	30%	230	52	43%	74
Total Flight System Dry Bus Mass	**775**	**26%**	**976**	**309**	**43%**	**442**

Table 3-10. Flight System Mass and Power—Option 3

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	346	30%	450	-	-	-
Thermal control	37	35%	50	67	43%	96
Propulsion (dry mass)	88	8%	95	25	43%	36
Attitude control	23	28%	29	39	43%	56
Command & data handling	24	7%	26	49	43%	70
Telecommunications	67	17%	78	75	43%	107
Power	152	30%	198	50	43%	72
Total Flight System Dry Bus Mass	**737**	**25%**	**926**	**305**	**43%**	**437**

Table 3-11. Flight System Mass and Power—Option 4

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	366	30%	475	-	-	-
Thermal control	37	35%	50	69	43%	99
Propulsion (dry mass)	88	8%	95	25	43%	36
Attitude control	23	28%	29	39	43%	56
Command & data handling	24	7%	26	49	43%	70
Telecommunications	67	17%	78	75	43%	107
Power	178	30%	231	54	43%	77
Total Flight System Dry Bus Mass	**783**	**26%**	**984**	**311**	**43%**	**445**

Structure

All four options in the study would include a 1.5 m × 1.5 m × 2 m central rectangular bus structure, containing a propellant tank, two pressurant tanks, and an electronics vault. The vault would be a scaled version of the Juno vault to fit the electronics volume for this design. This results in a 0.3 m cube with 12.7 mm thick titanium walls to reduce the radiation to 25 krad within the vault. All four options would also have a 3 m diameter fixed HGA on one end of the spacecraft bus and a magnetometer mounted on a 1 m long rigid deployable boom. Options 2, 3, and 4 would include a 2-axis articulated scanning platform for the instruments as well as two solar panel wings with four panels per wing. The total solar panel area would be 37 m^2 for Option 2, 35 m^2 for Option 3, and 38 m^2 for Option 4.

Thermal Control

The thermal subsystem design accounts for the variation in external environment of the orbiter caused by Venus and Earth flybys, as well as Jupiter/Io orbit. The thermal design consists of both passive and active elements. The passive elements for all four options would include multilayer insulation (MLI) on the bus and propulsion module, including stand-off MLI for micrometeoroid protection of the pressure tanks, thermal surfaces on the outer surface of the MLI mechanical surfaces and thermal radiator, thermal conduction control to conductively isolate some elements, and high conduction to couple high-power elements to the vault. A Venus flyby shield made of aluminized Kapton would be used in addition to the HGA to protect the spacecraft from solar and incident infrared (IR) energy from the planet during the Venus flyby. In Option 1, a capillary-pumped loop heat pipe system would utilize the ASRG waste heat to provide thermal energy to the vault, propulsion tanks, and some of the propellant lines, thus reducing the power requirements for thermal control. Electric heaters and thermostats would be used to heat the remaining propellant lines and radioisotope heater unit (RHUs) would be used to heat the thruster clusters.

In the solar-powered options, there would be no opportunity to utilize waste heat; therefore, the heating for propellant lines and valves would be provided by 22 electrical heaters. No RHUs would be used in Options 2, 3, and 4.

Propulsion

The propulsion subsystem would provide the propulsion for Jupiter orbit insertion (JOI), orbit maintenance, trajectory correction maneuvers (TCMs), and attitude control. The subsystem would be a hydrazine monopropellant system using bang-bang pressure regulation from a helium source. For all four options, the design includes a single off-the-shelf hydrazine propellant tank, two off-the-shelf He tanks, eight 267 N thrusters for large maneuvers, eight 4.5 N thrusters for orbit maintenance maneuvers and roll control during main engine burns, and twelve 0.7 N thrusters for attitude control. The design includes one spare for each major component, except tanks. The pressure transducers would be inside the vault. The radiation environment assumed in the study would be acceptable for the remainder of the propulsion subsystem.

Attitude Control

The attitude control subsystem (ACS) design for the orbiter provides 3-axis stabilization using thrusters in all of the design options, along with the ±36 μrad/s pointing stability required for long-eclipse observations and imaging upon closest approach, and boresight pointing of the HGA within 0.05 degrees. The ACS subsystem would include a star tracker assembly, inertial measurement unit (IMU) and sun sensors for attitude determination, and twelve 0.7 N MIT thrusters for fine-pointing control during observations. Two of the 0.7 N MIT thrusters would fire simultaneously to provide 180° slew in two minutes. No reaction wheels are included in the design.

For Options 2, 3, and 4, which include solar arrays, a 2-axis gimbaled instrument scan platform was added to the design to enable consistent orientation of the solar arrays at the sun. With this design, it would be possible to eliminate thruster firings during closest-approach imaging by pointing the scan platform using gimbal motors and letting the bus drift for a few minutes during flyby, thus reducing image smear.

Command & Data Handling

A data volume of 10 Gbits per 60 day orbit was assumed during this study. The command & data handling (C&DH) design assumes build-to-print MSAP components with no additional development requirements. The standard MSAP architecture is included in the design—RAD750 processor, critical relay control card (CRCC), non-volatile memory and camera card (NVMCAM) for data storage and camera control, telecommunication interface card (MTIF), serial interface assembly (MSIA), motor control and interface card (MCIC) for interface with the IMU, and remote engineering units (MREU). There would be no additional onboard data storage required beyond the NVMCAM as the data rate is low. All of the avionics would be housed inside the vault.

Telecommunications

The telecommunications subsystem is required to support a two-way link with Earth during the mission, including a science data downlink rate of 50 kbps from Io, a telemetry downlink rate of 2 kbps, and a commanding uplink rate of at least 2 kbps. The telecommunications system for all options would be a fully redundant X-band (for telemetry) and Ka-band (for science return) system. The design consists of one 3 m X-/Ka-band HGA, one X-band medium-gain antenna (MGA), and two X-band low-gain antennas (LGAs) along with two Ka-band 50 W TWTAs, two X-band 25-W TWTAs, and two X up/down, Ka-down SDST transponders. The design assumes that there would be no science data acquisition during downlinks, and thus the HGA is body-fixed for all options. The MGA would also be fixed with the boresight co-aligned with the HGA, while the two LGAs would be fixed on opposite sides of the spacecraft to enable near-Earth operations.

Power

The power subsystem design in Option 1 includes ASRGs, while the design in Options 2, 3, and 4 relies on solar panels based on Juno heritage. The arrays would use the same screening process as Juno with assumed acceptance rates based on Juno, and this is reflected in the overall power system cost estimate. All options assume that the power system would be tightly monitored with the operations plan adjusted as necessary to be consistent with available power output.

In Option 1, the power subsystem would consist of two ASRGs providing a total of 258 W of power nine years after launch. Li-ion batteries with a total capacity of 320 A-hr in seven 40 A-hr primary batteries and one redundant 40 A-hr battery would be included for energy balancing. Dual-string power electronics would also be included. The second electronics string would be cold and would not be brought online unless a fault occurred in the primary string. Excess generated energy would be shunted into space using shunt radiators provided by the thermal subsystem. The battery system would be sized to provide not-to-exceed depth of discharge of 70%, with discharges reaching that level fewer than 100 times in the mission. The system would include one additional battery to meet single fault-tolerant requirements. Initial analysis indicated that failure of one of the two pistons in either ASRG would result in a reduction in the science return. However, during this analysis, late increases in the subsystem power requirements reduced the power available following the single piston failure to a level where no science was achievable, making the failure mission-catastrophic. While it was too late to add a third ASRG to the design, the addition was viewed as necessary for redundancy and was identified as a lien against the design.

In Option 2, the power subsystem would consist of two deployed fixed rigid Ga-As solar array panels providing 348 W of power at the end of the mission. Li-ion batteries with a total capacity of 350 A-hr in six 50 A-hr primary batteries and one redundant 50 A-hr battery would be included for energy balancing. Dual-string power electronics would also be included. The second electronics string would be cold and would not be brought online unless a fault occurred in the primary string. Solar array string-switching electronics would be used to isolate excess electrical power on the array, eliminating the need for a shunt radiator. As in Option 1, the battery system would be sized to provide not-to-exceed depth of discharge of 70%.

Option 3 would have reduced power needs relative to Option 2 due to the absence of the INMS instrument. Similarly, the power subsystem would consist of two deployed fixed rigid Ga-As solar array panels providing 325 W of power at the end of the mission. Li-ion batteries with a total capacity of 264 A-hr in five 44 A-hr primary batteries and one redundant 44 A-hr battery would be included for energy balancing. As before, dual-string power electronics would also be included and the second electronics string would be a cold spare. Solar array string-switching electronics would be used to isolate excess electrical power on the array, eliminating the need for a shunt radiator.

Option 4 would have a similar power subsystem design as Option 2, with slightly higher power needs due to the addition of the FIPS instrument. The power subsystem design would consist of two deployed fixed rigid Ga-As solar array panels providing 350 W of power at the end of the mission. Li-ion batteries with a total capacity of 350 A-hr in six 50 A-hr primary batteries along with one redundant 50 A-hr battery would be included for energy balancing.

Table 3-12. Flight System Element Characteristics

Flight System Element Parameters (as appropriate)	Option 1	Option 2	Option 3	Option 4
General				
Design Life, months	101	101	93	101
Structure				

Flight System Element Parameters (as appropriate)	Option 1	Option 2	Option 3	Option 4
Structures material (aluminum, exotic, composite, etc.)	Aluminum, titanium, composites, titanium for vault			
Number of articulated structures	0	1	1	1
Number of deployed structures	1 (mag boom)	3 (mag boom+ 2 solar panel wings)	3 (mag boom+ 2 solar panel wings)	3 (mag boom+ 2 solar panel wings)
Aeroshell diameter, m	N/A			
Thermal Control				
Type of thermal control used	Active and passive			
Propulsion				
Estimated delta-V budget, m/s	1149	1124	1124	1124
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Monopropellant hydrazine			
Number of thrusters and tanks	(8) 267 N thrusters (large maneuvers) (8) 4.5 N thrusters (12) 0.7 N thrusters (ACS) 1 propellant tank			
Specific impulse of each propulsion mode, seconds	229			
Attitude Control				
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis			
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial			
Attitude control capability, degrees	0.05 degrees			
Attitude knowledge limit, degrees	0.025 degrees			
Agility requirements (maneuvers, scanning, etc.)	0.002 degree/sec (36 μrad/sec) stability requirement			
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	None	1 articulation, 2-axis (scan platform)	1 articulation, 2-axis (scan platform)	1 articulation, 2-axis (scan platform)
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	Sun sensors (radial accuracy < ±0.5 deg) Star trackers (pitch/yaw accuracy within ±18 arcsec) IMUs (bias stability within ± 0.015 arcsec/sec)			
	No scan platform electronics	2-axis gimbal drive electronics	2-axis gimbal drive electronics	2-axis gimbal drive electronics
Command & Data Handling				
Flight element housekeeping data rate, kbps	N/A			
Data storage capacity, Mbits	40 Gbytes			
Maximum storage record rate, kbps	10^4			
Maximum storage playback rate, kbps	10^4			

Flight System Element Parameters (as appropriate)	Option 1	Option 2	Option 3	Option 4
Power				
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	None (2 ASRGs)	Deployed fixed rigid	Deployed fixed rigid	Deployed fixed rigid
Array size, meters x meters	None	37.41	35.32	38.06
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	0	GaAs	GaAs	GaAs
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	320 (BOL) 258 (EOL)	348 (EOL)	325 (EOL)	350 (EOL)
On-orbit average power consumption, watts	370			
Battery type (NiCd, NiH, Li-ion)	Li-ion			
Battery storage capacity, amp-hours	320	350	264	350

Concept of Operations and Mission Design

This Io Observer mission would be implemented using two Venus gravity assists and one Earth gravity assist (EVVEJ) arriving at Jupiter approximately 6.5 years after launch. Figure 3-1 provides the trajectory schematic. The study considered four options and the mission design implications of each (Table 3-13). Ten Io flybys were considered for Options 1, 2, and 4, with the number of flybys reduced to six for Option 3. While no launch period analysis was performed, in general, allowing for a maximum C3 approximately two units higher than the nominal C3 (17.2 km^2/s^2) would facilitate a launch period of at least two to three weeks. Thus, a launch vehicle capability of 2360 kg was determined for the Atlas V 401, based on a C3 of 19.2 km^2/s^2.

Upon arrival, a 470 m/s JOI burn would be performed, which would place the spacecraft into a 200-day capture orbit. At apojove, the spacecraft would execute a perijove raise maneuver (PJR) of 300 m/s to set up the first Io flyby. Subsequent to the first Io flyby, only small maneuvers averaging around 10 m/s per flyby would be required to maintain the tour, with flybys roughly two months apart. Figure 3-2 illustrates the progression of the Io tour in Jupiter-centered sun-rotating coordinates.

Additional data on delta-V budgets, Io flyby characteristics, DSN tracking, mission design, mission operations, and ground system characteristics are captured in Tables 3-14 through 3-20.

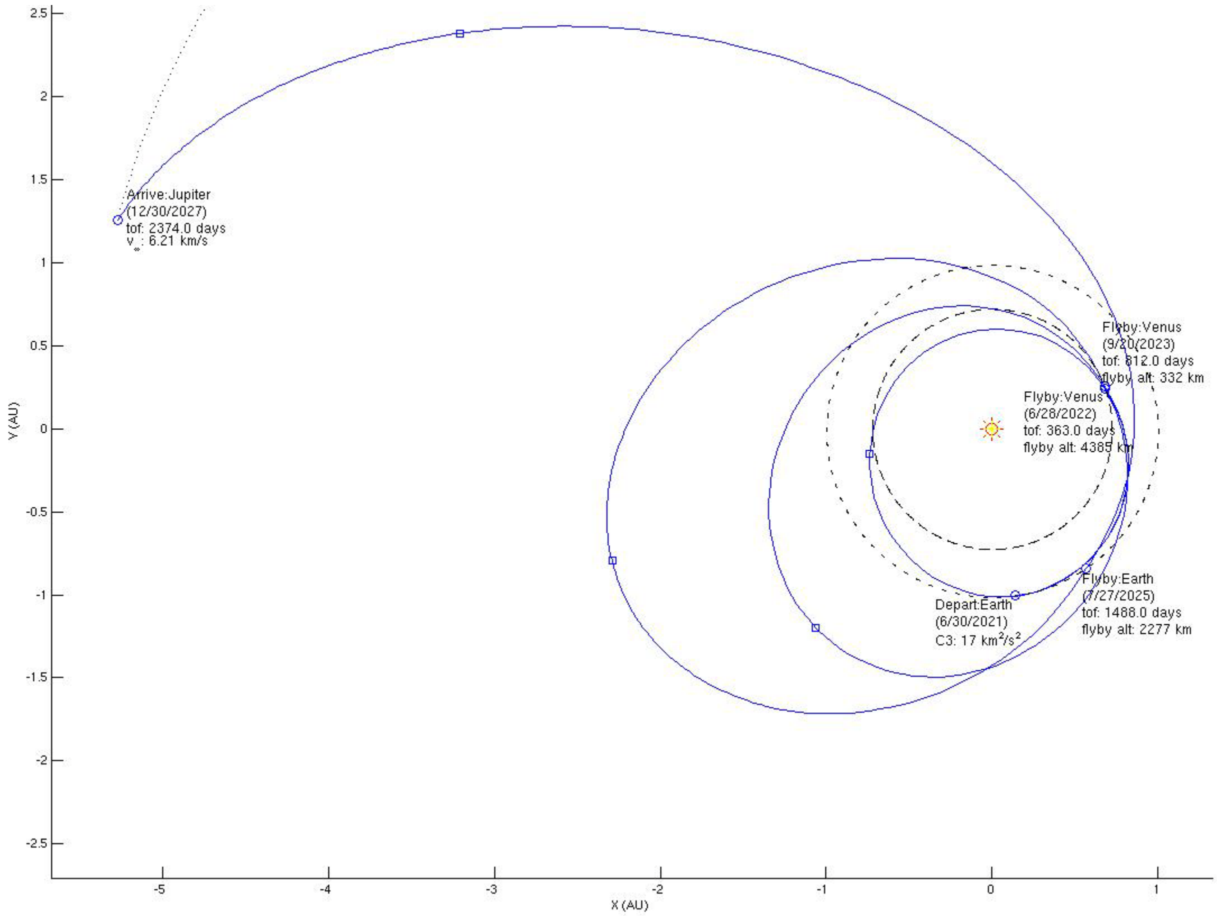

Figure 3-1. Earth-Venus-Venus-Earth-Jupiter (6.5-Year) Trajectory

Table 3-13. Four Options and Mission Design Effects

Option No.	Description	Mission Design Effects
1	Nuclear power (ASRGs) , 10 Io flybys	Bias Earth flyby (25 m/s)
2	Solar power, 10 Io flybys	No Earth biasing required
3	Solar power, 6 Io flybys	Reduced ΔV for tour ~10 m/s per flyby
4	Solar power, 10 Io flybys	No Earth biasing required

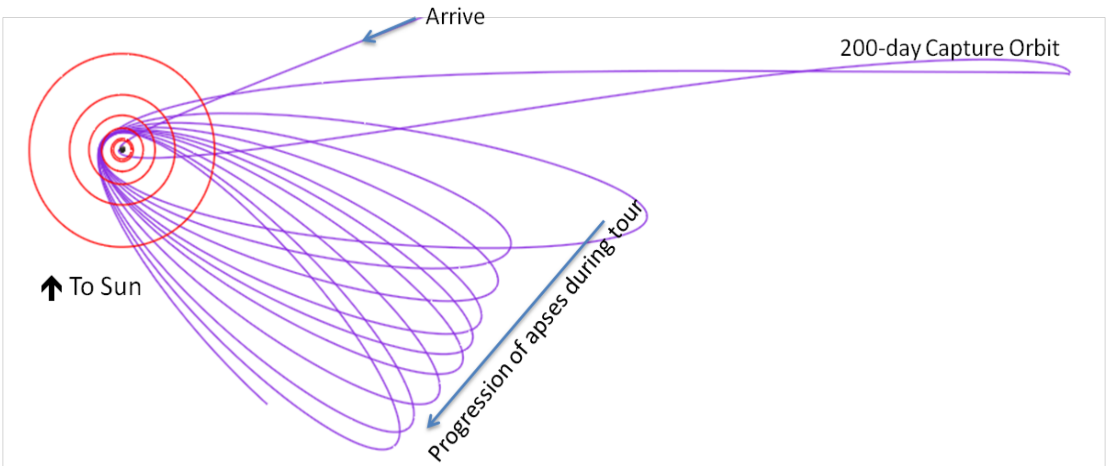

Figure 3-2. View from Jupiter North Pole of Arrival and Io Tour in Sun-Rotating Coordinates

Table 3-14. Key Events Timeline and ΔV Budget

Event	Date	L + mos	Opt. 1 ΔV (m/s)	Opt. 2 and Opt 4 ΔV (m/s)	Opt. 3 ΔV (m/s)	Comments
Launch	6/30/2021	–	30	30	30	Launch error correction, C3: 17–19 km^2/s^2
Venus flyby	6/28/2022	12.1	5	5	5	4300+ km altitude, statistical ΔV
Venus flyby	9/20/2023	27.1	5	5	5	300+ km altitude, statistical ΔV
Earth flyby	7/27/2025	49.6	30	5	5	1400+ km altitude, 5 statistical ΔV + 25 m/s Earth bias
JOI	12/30/2027	79.1	470	470	470	5000 km perijove, like Juno
Perijove raise	4/7/2028	–	300	300	300	Targets to first Io flyby
Statistical JOI/PJR	4/8/2028	–	25	25	25	3% of JOI + PJR
Io tour	7/17/2028 to 1/19/2030 (5/31/2029 Opt. 3)	–	105	105	65	~10 m/s per flyby (deterministic + statistical) ~58 days between flybys
Disposal	TBD		15	15	15	Impact on Io
Total	**–**	**–**	**985**	**960**	**920**	**–**

*Table 3-15. Io Flyby Details**

Encounter	Date	Alt (km)	Vinf (km/s)	Per(d)	Inc (deg)	Rp (RJ)	Lat	Lon	Beta Angle (deg)
Io Flyby 1	7/14/2028	509	17.3	86.8	45.7	5.8	0.39	-73.806	-22.128
Io Flyby 2	10/9/2028	250	17.4	58.4	46.0	5.7	6.489	-38.438	-51.957
Io Flyby 3	12/6/2028	95	17.5	58.4	46.0	5.7	8.715	-0.688	-84.676
Io Flyby 4	2/3/2029	93	17.5	58.4	46.0	5.7	10.777	-1.26	-79.2
Io Flyby 5	4/2/2029	108	17.4	58.4	46.2	5.7	-16.663	-179.387	75.638
Io Flyby 6	5/31/2029	108	17.4	58.4	46.4	5.8	-15.141	-179.314	71.072
Io Flyby 7	7/28/2029	92	17.6	58.4	46.6	5.7	9.997	-0.49	-65.861
Io Flyby 8	9/24/2029	92	17.6	58.4	46.6	5.7	12.015	-0.444	-61.487
Io Flyby 9	11/22/2029	105	17.6	58.4	46.9	5.8	-14.479	179.846	57.221
Io Flyby 10	1/19/2030	104	17.7	58.4	47.2	5.8	-11.372	179.719	52.876

* Please note that this flyby information refers to the representative orbit described in this report. This orbit is one of many that may be chosen and tailored to the science mission design requirements.

Table 3-16. DSN Tracking Schedule—Options 1, 2, and 4

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required
No.	**Name (Description)**					
1	Launch and Operations	34 BWG	2021	8	21.0	2.0
2	Launch and Operations	34 BWG	2021	8	14.0	2.0
3	Cruise 1—Cruise	34 BWG	2021	8	0.5	45.0
3	DDOR	34 BWG	2021	1	0.5	45.0
4	Venus Gravity Assist 1	34 BWG	2021	8	7.0	1.0
4	DDOR	34 BWG	2021	1	3.0	1.0
5	Venus Gravity Assist 1	34 BWG	2021	8	14.0	1.0
5	DDOR	34 BWG	2021	1	3.0	1.0
6	Venus Gravity Assist 1	34 BWG	2021	8	7.0	1.0
6	DDOR	34 BWG	2021	1	3.0	1.0
7	Post VGA	34 BWG	2021	8	3.0	3.0
7	DDOR	34 BWG	2021	1	1.0	3.0
9	Cruise 2—Cruise	34 BWG	2021	8	0.3	57.0
9	DDOR	34 BWG	2021	1	0.3	57.0
10	Cruise 2—TCMs	34 BWG	2021	8	7.0	1.0
11	Venus Gravity Assist 2	34 BWG	2021	8	7.0	1.0
11	DDOR	34 BWG	2021	1	3.0	1.0
12	Venus Gravity Assist 2	34 BWG	2021	8	14.0	1.0
12	DDOR	34 BWG	2021	1	3.0	1.0
13	Venus Gravity Assist 2	34 BWG	2021	8	7.0	1.0
13	DDOR	34 BWG	2021	1	3.0	1.0
14	Post VGA	34 BWG	2021	8	3.0	3.0
14	DDOR	34 BWG	2021	1	1.0	3.0
15	Cruise 3—Cruise	34 BWG	2021	8	0.3	90.0
15	DDOR	34 BWG	2021	1	0.3	90.0
16	Cruise 3—CMs	34 BWG	2021	8	7.0	1.0
17	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	7.0	1.0
18	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	14.0	1.0
19	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	7.0	1.0
20	Post EGA	34 BWG	2021	8	3.0	3.0
21	Cruise 4—Cruise	34 BWG	2021	8	0.3	112.0
21	DDOR	34 BWG	2021	1	0.3	112.0
22	Cruise 4—TCMs	34 BWG	2021	8	7.0	2.0
23	Cruise 4—Annual health checks	34 BWG	2021	8	7.0	1.0

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required
No.	Name (Description)					
24	JOI—Initial encounter	34 BWG	2021	8	7.0	6.0
25	JOI—Initial encounter	34 BWG	2021	8	7.0	1.0
25	DDOR	34 BWG	2021	1	3.0	1.0
26	JOI—Extended encounter	34 BWG	2021	8	14.0	1.0
26	DDOR	34 BWG	2021	1	3.0	1.0
27	JOI—Encounter	34 BWG	2021	8	7.0	1.0
27	DDOR	34 BWG	2021	1	3.0	1.0
28	Intermediate Orbit 1	34 BWG	2021	8	7.0	3.0
29	Intermediate Orbit 2	34 BWG	2021	8	3.0	1.0
29	DDOR	34 BWG	2021	1	1.0	1.0
30	Intermediate Orbit	34 BWG	2021	8	7.0	20.0
31	Intermediate Orbit End 1	34 BWG	2021	8	3.0	1.0
32	Intermediate Orbit End 2	34 BWG	2021	8	7.0	1.0
33	Intermediate Orbit End 3	34 BWG	2021	8	3.0	1.0
34	Science Orbit—DTE	34 BWG	2021	6	2.3	59.0
35	Science Orbit Navigation	34 BWG	2021	4	14.0	18.0

Table 3-17. DSN Tracking Schedule—Option 3

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required
No.	Name (Description)					
1	Launch and Operations	34 BWG	2021	8	21.0	2.0
2	Launch and Operations	34 BWG	2021	8	14.0	2.0
3	Cruise 1—Cruise	34 BWG	2021	8	0.5	45.0
3	DDOR	34 BWG	2021	1	0.5	45.0
4	Venus Gravity Assist 1	34 BWG	2021	8	7.0	1.0
4	DDOR	34 BWG	2021	1	3.0	1.0
5	Venus Gravity Assist 1	34 BWG	2021	8	14.0	1.0
5	DDOR	34 BWG	2021	1	3.0	1.0
6	Venus Gravity Assist 1	34 BWG	2021	8	7.0	1.0
6	DDOR	34 BWG	2021	1	3.0	1.0
7	Post VGA	34 BWG	2021	8	3.0	3.0
7	DDOR	34 BWG	2021	1	1.0	3.0
9	Cruise 2—Cruise	34 BWG	2021	8	0.3	57.0
9	DDOR	34 BWG	2021	1	0.3	57.0
10	Cruise 2- TCMs	34 BWG	2021	8	7.0	1.0
11	Venus Gravity Assist 2	34 BWG	2021	8	7.0	1.0
11	DDOR	34 BWG	2021	1	3.0	1.0
12	Venus Gravity Assist 2	34 BWG	2021	8	14.0	1.0
12	DDOR	34 BWG	2021	1	3.0	1.0
13	Venus Gravity Assist 2	34 BWG	2021	8	7.0	1.0
13	DDOR	34 BWG	2021	1	3.0	1.0
14	Post VGA	34 BWG	2021	8	3.0	3.0
14	DDOR	34 BWG	2021	1	1.0	3.0
15	Cruise 3—Cruise	34 BWG	2021	8	0.3	90.0
15	DDOR	34 BWG	2021	1	0.3	90.0
16	Cruise 3—TCMs	34 BWG	2021	8	7.0	1.0
17	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	7.0	1.0
18	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	14.0	1.0
19	Earth Gravity Assist—Initial encounter	34 BWG	2021	8	7.0	1.0
20	Post EGA	34 BWG	2021	8	3.0	3.0
21	Cruise 4—Cruise	34 BWG	2021	8	0.3	112.0
21	DDOR	34 BWG	2021	1	0.3	112.0

Support Period		Antenna Size (m)	Service Year	Hours per Track	No. Tracks per Week	No. Weeks Required
No.	Name (Description)					
22	Cruise 4—TCMs	34 BWG	2021	8	7.0	2.0
23	Cruise 4—Annual health checks	34 BWG	2021	8	7.0	1.0
24	JOI—Initial encounter	34 BWG	2021	8	7.0	6.0
25	JOI—Initial encounter	34 BWG	2021	8	7.0	1.0
25	DDOR	34 BWG	2021	1	3.0	1.0
26	JOI—Extended encounter	34 BWG	2021	8	14.0	1.0
26	DDOR	34 BWG	2021	1	3.0	1.0
27	JOI—Encounter	34 BWG	2021	8	7.0	1.0
27	DDOR	34 BWG	2021	1	3.0	1.0
28	Intermediate Orbit 1	34 BWG	2021	8	7.0	3.0
29	Intermediate Orbit 2	34 BWG	2021	8	3.0	1.0
29	DDOR	34 BWG	2021	1	1.0	1.0
30	Intermediate Orbit	34 BWG	2021	8	7.0	20.0
31	Intermediate Orbit End 1	34 BWG	2021	8	3.0	1.0
32	Intermediate Orbit End 2	34 BWG	2021	8	7.0	1.0
33	Intermediate Orbit End 3	34 BWG	2021	8	3.0	1.0
34	Science Orbit —DTE	34 BWG	2021	6	2.3	33.0
35	Science Orbit Navigation	34 BWG	2021	4	14.0	10.0

Table 3-18. Ground Data System Characteristics

Option	Data Volume	Passes (# / week, length [hrs])	Comments
Option 1	10 Gbit of science per 60 science orbit	Fifteen 6-hour passes per 60-day science orbit	ASRG power for the spacecraft at Jupiter
Option 2	10 Gbit of science per 60 science orbit	Fifteen 6-hour passes per 60-day science orbit	Solar power for spacecraft at Jupiter
Option 3	10 Gbit of science per 60 science orbit	Fifteen 6-hour passes per 60-day science orbit	Solar power for spacecraft at Jupiter, shorter science mission and remove one instrument compared to Options 1 and 2
Option 4	10 Gbit of science per 60 science orbit	Fifteen 6-hour passes per 60-day science orbit	Solar power for spacecraft at Jupiter and one additional instrument compared to Options 1 and 2

Table 3-19. Mission Design

Parameter	Value				Units
	Opt. 1	**Opt. 2**	**Opt. 3**	**Opt. 4**	
Orbit parameters (apogee, perigee, inclination, etc.)	Inclination ~45-47 degrees, Perijove 5.8 R_J				
Mission lifetime	101	101	93	101	mos
Maximum eclipse period	Brief; not a design driver				min
Launch site	KSC				
Total flight element #1 mass **with** contingency (includes instruments)	936	1167	1098	1177	kg
Propellant mass **without** contingency	1010	994	994	994	kg
Propellant contingency	–				%
Propellant mass **with** contingency	–				kg
Launch adapter mass **with** contingency	–				kg
Total launch mass	1946	2161	2092	2171	kg
Launch vehicle	Atlas V 401				Type
Launch vehicle lift capability	2360				kg
Launch vehicle mass margin	414	199	268	189	kg
Launch vehicle mass margin (%)	18%	8%	11%	8%	%

Table 3-20. Mission Operations and Ground Data Systems

Downlink Information	**Jovian Orbit / Io Flyby**
Number of contacts per week	(See Tables 3-16 and 3-17)
Number of weeks for mission phase, weeks	83
Downlink frequency band, GHz	Ka
Telemetry data rate(s), kbps	50
Transmitting antenna type(s) and gain(s), DBi	3 m HGA
Transmitter peak power, Watts	n/a
Downlink receiving antenna gain, DBi	34 m BWG - DSN
Transmitting power amplifier output, Watts	50
Total daily data volume, (MB/day)	27.2
Uplink Information	
Number of uplinks per day	3 uplinks per 58 day orbit
Uplink frequency band, GHz	X
Telecommand data rate, kbps	2
Receiving antenna type(s) and gain(s), DBi	3 m HGA

Planetary Protection

In accordance with NPR 8020.12C, the Io Observer mission is expected to be a Planetary Protection Category II mission. Accordingly, the Io Observer project would demonstrate that its mission meets the Category II planetary protection requirements per NPR 8020.12C, Appendix A.2. The planetary protection category of the mission would be formally established by the NASA Planetary Protection Officer (PPO) in response to a written request from the Io Observer project manager, submitted by the end of Phase A.

The Io Observer project would prepare all planetary protection documents and hold all reviews as required by the NASA PPO. The Io Observer project plans to demonstrate compliance with the non-impact requirements during the prime mission for Mars, Europa, Ganymede, and Callisto by a combination of trajectory biasing and analyses performed by the navigation team. After the prime mission, the spacecraft would be disposed into Io or Jupiter. In the event that the spacecraft is unable to be disposed into Io or Jupiter, the Io Observer project would use the same approach to demonstrate contamination avoidance as is being used by Juno. The probability of contamination would be estimated based on the results of the following: probabilistic risk assessment (PRA) analysis; radiation transport analysis; total bioburden estimation over the time period required to sterilize the spacecraft by radiation; trajectory analysis to estimate the accidental impact of Europa, Ganymede, and Callisto over the time period required to sterilize the spacecraft by radiation; and a spacecraft impact analysis. If the probability of contamination exceeds the requirement(s), then the spacecraft would be cleaned/microbially reduced as needed to meet the requirements (note: this is not included in the cost estimate). The results of all of these analyses would be documented in the planetary protection pre-launch report.

Risk List

No major risks were identified during the study. Seven moderate risks and nine minor risks were identified that spread across the four options that were analyzed. Figure 3-3 provides a 5 × 5 risk chart that describes the distribution of the identified risks.

Table 3-21 provides a detailed summary of the moderate risks and mitigations identified. Table 3-22 provides the definitions of the risk impact and likelihood ranges used. Option 1 was found to have the most moderate risks.

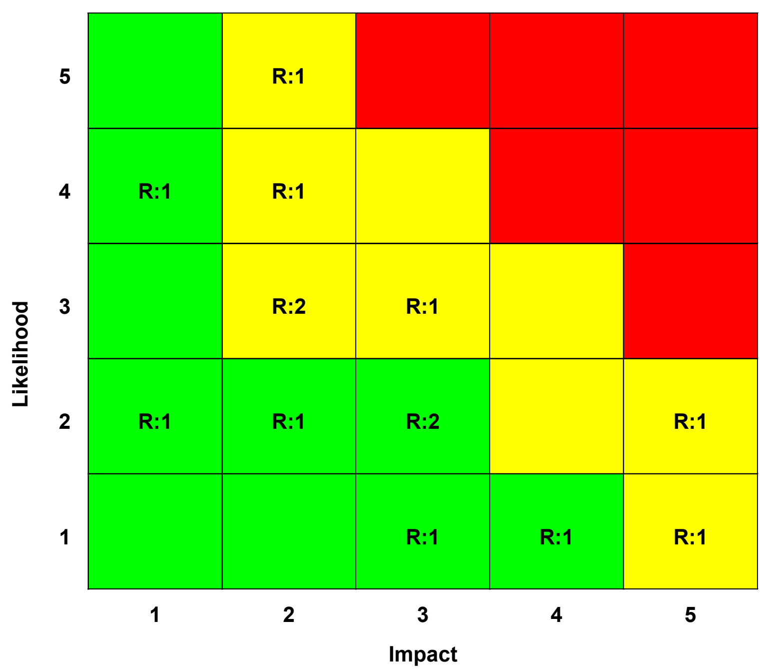

Figure 3-3. Risk Chart

Table 3-21. Summary of the Moderate Risks

Risk	Level	Description	Impact	Likelihood	Mitigation	Mitigated Impact	Mitigated Likelihood
ASRG failure mode adequacy (Option 1)	M	Mission assumes two ASRGs. If one ASRG loses one piston, ASRG performance degrades to less than required for the minimum power mode: "battery recharge."	5	2	Carry one complete spare ASRG	1	1
Analysis of Vis pushbroom thermal (Option 3 and 4)	M	Pushbroom-style measurements may be difficult to analyze. Data quality is strongly tied to sharpness of thermal boundaries, stability of spacecraft, and for low altitudes, change in resolution. Represents an analysis cost risk.	2	5	Additional instrument early design / implementation; instrument design / implementation crucial	3	2
Inadequate thermal mapper exposure time (Option 1, 2, 3, and 4)	M	High frame rate from thermal imager may preclude sufficient integration time to make measurement with the required accuracy.	3	3	No immediately identified mitigation	-	-
Radiation effects on instrument performance (Option 1, 2, 3, and 4)	M	The total radiation dose, rate of exposure, and/or single event radiation effects experienced in the Jovian environment could significantly impact the onboard instrument's performance. This could significantly impact the likelihood of mission success	2	4	Shielding, EEE parts	2	3
Vrel high for INMS (Option 1, 2, and 4)	M	Neutrals and molecules are converted to other forms (mostly plasma) on entry to the INMS as Vrel increases. Supposedly, the conversion at 17 km/s is adequate, but on the high side	3	5	Change the look direction	2	3
Plasma-based instrument failure (Option 4)	M	Assuming build-to-print, but instrument was previously used in a very different environment. Expect the fluxes to be different, which could saturate the instrument. Estimate a 50/50 chance instrument will totally fail. The instrument would contribute 10–20% of the science value for the Option 4 mission.	2	3	Redesign instrument for environment	1	1
Plutonium availability (Option 1)	M	If the supply of plutonium continues to be limited, then the Io mission may not be possible for architectures dependent on ASRGs.	5	1	No immediately identified mitigation	-	-

Note: Highest-priority thermal-mapper data is not acquired at closest approach, so will not be strongly affected by limits on integration time during the fastest part of the flybys.

Table 3-22. Risk Level Definitions

Levels	Mission Risk		Implementation Risk	
	Impact	**Likelihood of Occurrence**	**Impact**	**Likelihood of Occurrence**
5	Mission failure	Very high, >25%	Consequence or occurrence is not repairable without engineering (would require >100% of margin)	Very high, ~70%
4	Significant reduction in mission return (~25% of mission return still available)	High, ~25%	All engineering resources would be consumed (100% of margin consumed)	High, ~50%
3	Moderate reduction in mission return (~50% of mission return still available)	Moderate, ~10%	Significant consumption of engineering resources (~50% of margin consumed)	Moderate, ~30%
2	Small reduction in mission return (~80% of mission return still available)	Low, ~5%	Small consumption of engineering resources (~10% of margin consumed)	Low, ~10%
1	Minimal (or no) impact to mission (~95% of mission return still available)	Very low, ~1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very low, ~1%

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

Figure 4-1 provides a feasible schedule for all Io Observer mission options. The mission complexity is consistent with a New Frontiers basic mission. The reference schedules used for this study are derived from the JPL mission schedule database, which extends back to the Voyager mission.

There are no major schedule drivers or long lead items that need to be addressed beyond the proposed schedule. Table 4-1 provides the key phase durations. The Io Observer mission is being proposed as a New Frontiers–competed mission; therefore, all instruments and flight elements are planned to be delivered at the beginning of system-level integration and test. All options analyzed have the same schedule except Option 3, which has a slightly shorter Phase E. A possible Phase F was not included in the study.

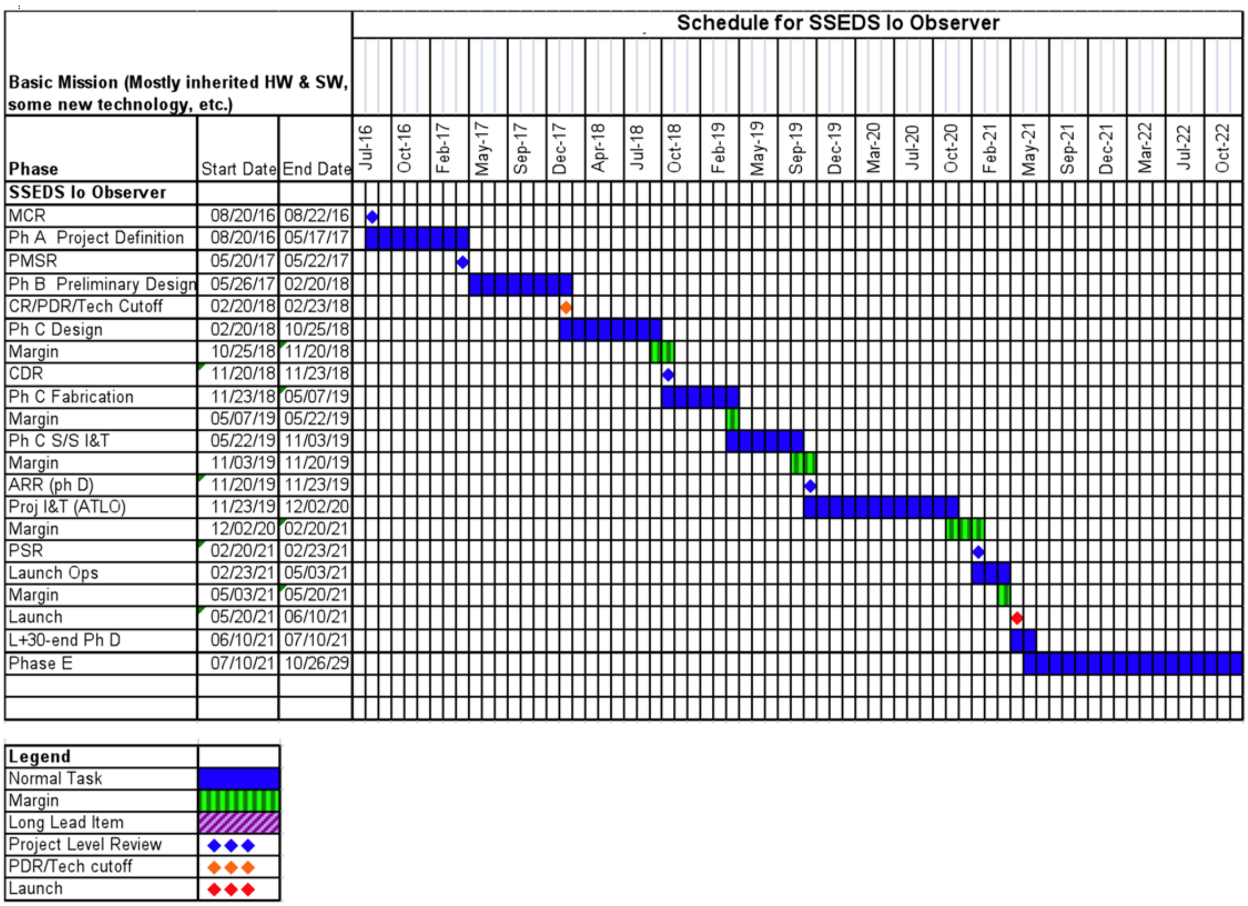

Figure 4-1.Baseline Mission Schedule

Table 4-1. Key Phase Duration

Project Phase	Duration (Months)
Phase A—Conceptual design	9
Phase B—Preliminary design	9
Phase C—Detailed design	21
Phase D—Integration & test	19
Phase E—Primary mission operations	101 (Option 3 is 93)
Phase F—Extended mission operations	TBD
Start of Phase B to PDR	9
Start of Phase B to CDR	18
Start of Phase B to delivery of all instruments	30
Start of Phase B to delivery of all flight elements	30
System-level integration & test	15 (plus 3 months at launch site and 1 month checkout)
Project total funded schedule reserve	5
Total development time Phase B–D	49

Technology Development Plan

No technology development plan would be required since there are no new technologies in any of the architectures examined in this study. Radiation vault design and low-light solar technology will be developed by the Juno mission currently underway. By NASA guidelines, ASRGs are presumed to be available for the purpose of this study; therefore, no technology development is assumed.

Development Schedule and Constraints

As the mission was designed to fit into a New Frontiers–class mission, no major schedule issues were identified.

5. Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

The cost estimates provided in this report were generated by JPL's Team X. Team X generates a most likely cost using the JPL standard work breakdown structure (WBS) that may be tailored to meet the specific needs of the mission being evaluated. These estimates are generated to WBS levels 2 and 3 (subsystem) and are based on various cost estimating techniques. These methods are not exclusive to each other and are often combined. The various estimating techniques consist of grassroots techniques, parametric models, and analogies. The models for each station (subsystem) in Team X (total of about 33) have been built, validated, and are owned by each responsible line organization. The models are under configuration management control and are utilized in an integrated and concurrent environment, so that the design and cost parameters are linked. These models are customized and calibrated using actual experience from completed JPL planetary missions. In applying these models, it has been found that the resultant total estimated Team X mission costs have been consistent with mission actual costs.

The cost estimation process begins with the customer providing the base information for the cost estimating models and defining the mission characteristics, such as:

- Mission architecture
- Payload description
- Master equipment list (MEL) with heritage assumptions
- Functional block diagrams
- Spacecraft/payload resources (mass [kg], power [W], …)
- Phase A−F schedule
- Programmatic requirements
- Model specific inputs

Most of the above inputs are provided by the customer through a technical data package.

The following costing requirements were also specified in the Decadal Survey study ground rules:

- Reserves were set at 50% for Phases A through D
- Reserves were set at 25% for Phase E
- The launch vehicle cost was specified in the ground rules
- ASRG costs were also specified in the ground rules

Cost Estimates

Science workforce estimates are summarized in Tables 5-1, 5-2, and 5-3. Table 5-1 summarizes the science team for Options 1 and 2, which would both include the same suite of four science instruments and 10 Io flybys. Table 5-2 summarizes the science team for Option 3, which is a descoped option that would include only three science instruments and 6 Io flybys. Table 5-3 summarizes the science team for Option 4, which is similar to Option 2 but with the addition of a FIPS instrument. Phase E1 begins three months prior to the start of science operations and ends at the completion of science operations (22.9 months total for Options 1, 2, and 4; 14.9 months total for Option 3).

Table 5-1. Science Team Workforce for Options 1 and 2

(Four science instruments and 10 Io flybys)

			A	B	C	D	E1	F
		Phase:	**A**	**B**	**C**	**D**	**E1**	**F**
		Duration (Months)	**9**	**9**	**21**	**19.0**	**22.9**	**6**
WBS Element		**(Work-Months)**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**
4		Science	**10.3**	**43.6**	**339.4**	**146.0**	**1280.1**	**96.1**
4.1		Science Management	2.6	13.6	36.4	31.5	120.7	13.7
	4.1.1	Science Office	2.6	13.6	36.4	31.5	120.7	13.7
4.2		Science Implementation	6.8	29.1	300.9	112.6	1086.5	76.3
	4.2.1	Participating Scientists	3.2	3.2	28.9	27.2	283.9	29.6
	4.2.T	Teams Summary	3.6	26.0	272.0	85.5	802.7	46.6
4.3		Science Support	0.9	0.9	2.1	1.9	72.8	6.1
	4.3.1	Science Data Visualization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.2	Science Data Archiving	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.3	Instrument Support	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.4	Science Environmental Characterization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.5	Operations Support	0.9	0.9	2.1	1.9	72.8	6.1
		Equivalent FTEs:	**1.04**	**4.74**	**16.06**	**7.58**	**52.72**	**15.00**

Table 5-2. Science Team Workforce for Option 3

(Descoped mission: Three science instruments and 6 Io flybys)

			A	B	C	D	E	F
		Phase:	**A**	**B**	**C**	**D**	**E**	**F**
		Duration (Months)	**9**	**9**	**21**	**19.0**	**14.9**	**6**
WBS Element		**(Work-Months)**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**
4		Science	**7.4**	**32.0**	**239.8**	**98.6**	**720.2**	**57.2**
4.1		Science Management	2.3	11.7	29.7	26.9	82.6	11.8
	4.1.1	Science Office	2.3	11.7	29.7	26.9	82.6	11.8
4.2		Science Implementation	4.3	19.4	208.1	69.9	590.6	41.1
	4.2.1	Participating Scientists	1.8	1.8	15.0	14.6	118.4	14.2
	4.2.T	Teams Summary	2.5	17.6	193.0	55.2	472.2	26.9
4.3		Science Support	0.9	0.9	2.1	1.9	47.0	4.4
	4.3.1	Science Data Visualization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.2	Science Data Archiving	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.3	Instrument Support	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.4	Science Environmental Characterization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.5	Operations Support	0.9	0.9	2.1	1.9	47.0	4.4
		Equivalent FTEs:	**0.73**	**3.46**	**11.32**	**5.09**	**29.40**	**8.80**

Table 5-3. Science Team Workforce for Option 4

(Similar to Option 2, but with added FIPS instrument)

			A	B	C	D	E	F
		Phase:	**A**	**B**	**C**	**D**	**E**	**F**
		Duration (Months)	**9**	**9**	**21**	**19.0**	**22.9**	**6**
WBS Element		**(Work-Months)**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**	**W-M**
4		Science	**12.2**	**52.2**	**419.0**	**177.5**	**1567.4**	**116.9**
4.1		Science Management	2.9	15.1	41.1	35.4	131.4	14.9
	4.1.1	Science Office	2.9	15.1	41.1	35.4	131.4	14.9
4.2		Science Implementation	8.3	36.3	375.9	140.3	1352.8	95.1
	4.2.1	Participating Scientists	3.8	3.8	35.8	33.4	349.5	36.8
	4.2.T	Teams Summary	4.5	32.4	340.0	106.8	1003.3	58.3
4.3		Science Support	0.9	0.9	2.1	1.9	83.3	6.9
	4.3.1	Science Data Visualization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.2	Science Data Archiving	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.3	Instrument Support	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.4	Science Environmental Characterization	0.0	0.0	0.0	0.0	0.0	0.0
	4.3.5	Operations Support	0.9	0.9	2.1	1.9	83.3	6.9
		Equivalent FTEs:	**1.25**	**5.70**	**19.85**	**9.24**	**64.81**	**18.32**

Phase A duration is estimated at 9 months for this mission, nominally beginning at the end of August 2016 (i.e., one month of Phase A during FY 2016 and eight months of Phase A during FY 2017). The Team X tools estimate a total Phase A cost of approximately $14.6M in RY dollars for Options 1, 2, and 4, and $11.7M for Option 3. Typical Phase A activities would include architecture and design trades, development of design requirements, and detailed concept development in preparation for implementation. No new technologies would be required for this mission; therefore, there would be no technology development efforts (or costs) during Phase A.

Tables 5-4 through 5-7 show the total mission cost profile for each option. These costs assume that the mission would be totally funded by NASA and that all significant work would be performed in the US. Note, also, that the distribution of Phase E costs is assumed by the models to be fairly uniform, which is not a good approximation for this mission (which has a lengthy quiet cruise followed by a comparatively short period of intense science operations).

Table 5-4. Total Mission Cost Funding Profile—Option 1

Item	Prior	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	FY2034	FY2035	FY2036	Total (Real Yr.)	Total (FY2015)
Cost																								
Phase A concept study (included below)		0.9	7.0																				7.9	7.5
Technology development																								
		Phase A - D																						
Mission PM/SE/MA		0.1	4.0	16.8	22.1	24.8	19.2																87.0	77.3
Pre-launch science		0.02	0.8	3.3	4.3	4.8	3.7																16.9	15.1
Instrument PM/SE		0.01	0.4	1.7	2.3	2.5	2.0																8.9	7.9
Narrow Angle Camera (NAC)		0.02	0.9	3.6	4.7	5.3	4.1																18.5	16.5
Thermal Mapper (TM)		0.02	0.7	2.8	3.6	4.1	3.1																14.3	12.7
Ion and Neutral Mass Spectrometer (INMS)		0.03	1.4	5.9	7.7	8.6	6.7																30.4	27.0
Flux Gate Magnetometer (FGM)		0.01	0.4	1.7	2.3	2.6	2.0																9.0	8.0
Flight Element PM/SE		0.05	2.1	8.9	11.7	13.1	10.2																46.0	40.9
Flight Element (Orbiter)		0.3	11.0	46.0	60.6	67.9	52.6																238.4	211.9
MSI&T 2		0.03	1.2	4.9	6.4	19.0	16.3																47.8	41.9
Ground data system dev		0.02	1.0	4.3	5.6	6.3	4.9																22.1	19.7
Navigation & mission design		0.02	0.8	3.3	4.4	4.9	3.8																17.3	15.4
Total dev. w/o reserves		0.6	24.7	103.1	135.8	163.9	128.6																556.7	494.2
Development reserves		0.3	12.9	53.6	70.6	79.1	61.3																277.8	246.9
Total A–D development cost		0.9	37.6	156.7	206.4	242.9	190.0																834.4	741.1
Launch services				35.1	61.3	68.7	53.3																218.4	193.0
							Phase E																	
Phase E science							1.4	5.6	5.8	5.9	6.1	6.2	6.4	6.6	6.8	1.7							52.5	39.6
Other Phase E cost							3.3	13.3	13.6	14.0	14.4	14.8	15.2	15.6	16.0	4.1							124.3	93.7
Phase E reserves							1.1	4.5	4.6	4.7	4.8	5.0	5.1	5.2	5.4	1.4							41.7	31.5
Total Phase E							5.8	23.4	24.0	24.6	25.3	26.0	26.7	27.4	28.1	7.1							218.5	164.8
Education/outreach		0.00	0.08	0.34	0.45	0.50	0.39	0.67	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.20							7.8	6.3
Other (specify)																							0.0	0
Total Cost	**$**	**$ 0.9**	**$ 37.7**	**$ 192.1**	**$ 268.2**	**$ 312.1**	**$ 249.4**	**$ 24.0**	**$ 24.7**	**$ 25.3**	**$ 26.0**	**$ 26.7**	**$ 27.5**	**$ 28.2**	**$ 29.0**	**$ 7.3**							**$ 1,279**	**$ 1,105**
																Total Mission Cost								**$ 1,105**

(FY costs1 in Real Year Dollars, Totals in Real Year and 2015 Dollars)

1 Costs should include all costs including any fee

2 MSI&T - Mission System Integration and Test and preparation for operations

Table 5-5. Total Mission Cost Funding Profile—Option 2

Item	Prior	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	FY2034	FY2035	FY2036	Total (Real Yr.)	Total (FY2015)
Cost																								
Phase A concept study (included below)		0.8	6.6																				7.4	7.0
Technology development																								
		Phase A - D																						
Mission PM/SE/MA		0.1	2.9	12.0	15.9	17.7	13.8																62.3	55.4
Pre-launch science		0.02	0.8	3.3	4.3	4.8	3.7																16.9	15.1
Instrument PM/SE		0.01	0.4	1.7	2.3	2.5	2.0																8.9	7.9
Narrow Angle Camera (NAC)		0.02	0.9	3.6	4.7	5.3	4.1																18.5	16.5
Thermal Mapper (TM)		0.02	0.7	2.8	3.6	4.1	3.1																14.3	12.7
Ion and Neutral Mass Spectrometer (INMS)		0.03	1.4	5.9	7.7	8.6	6.7																30.4	27.0
Flux Gate Magnetometer (FGM)		0.01	0.4	1.7	2.3	2.6	2.0																9.0	8.0
Flight Element PM/SE		0.05	2.1	8.9	11.7	13.1	10.2																46.1	41.0
Flight Element (Orbiter)		0.2	10.6	44.3	58.4	65.4	50.7																229.7	204.1
MSI&T 2		0.03	1.2	4.9	6.4	19.2	16.5																48.2	42.3
Ground data system dev		0.02	1.0	4.3	5.6	6.3	4.9																22.2	19.7
Navigation & mission design		0.02	0.8	3.3	4.4	4.9	3.8																17.3	15.4
Total dev. w/o reserves		0.5	23.2	96.7	127.4	154.6	121.5																523.8	464.9
Development reserves		0.3	12.1	50.4	66.4	74.4	57.7																261.3	232.2
Total A–D development cost		0.8	35.3	147.1	193.8	228.9	179.1																785.0	697.1
Launch services				32.4	56.6	63.4	49.1																201.4	178.0
							Phase E																	
Phase E science							1.4	5.6	5.7	5.9	6.0	6.2	6.4	6.5	6.7	1.7							52.1	39.3
Other Phase E cost							3.3	13.4	13.7	14.1	14.5	14.9	15.3	15.7	16.1	4.1							124.9	94.2
Phase E reserves							1.1	4.5	4.6	4.7	4.8	5.0	5.1	5.2	5.4	1.4							41.7	31.5
Total Phase E							5.8	23.4	24.0	24.7	25.3	26.0	26.7	27.4	28.2	7.2							218.8	165.0
Education/outreach		0.00	0.08	0.32	0.43	0.5	0.4	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.2							7.5	6.0
Other (specify)																							0.0	0
Total Cost	**$**	**$ 0.8**	**$ 35.4**	**$ 179.8**	**$ 250.8**	**$ 292.8**	**$ 234.4**	**$ 24.0**	**$ 24.7**	**$ 25.3**	**$ 26.0**	**$ 26.7**	**$ 27.5**	**$ 28.2**	**$ 29.0**	**$ 7.3**							**$ 1,213**	**$ 1,046**
																	Total Mission Cost							**$ 1,046**

(FY costs1 in Real Year Dollars, Totals in Real Year and 2015 Dollars)

1 Costs should include all costs including any fee

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Table 5-6. Total Mission Cost Funding Profile—Option 3

Item	Prior	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	FY2034	FY2035	FY2036	Total (Real Yr.)	Total (FY2015)
Cost																								
Phase A concept study (included below)		0.8	6.0																				6.8	6.5
Technology development																								
		Phase A - D																						
Mission PM/SE/MA		0.1	2.8	11.6	15.3	17.2	13.3																60.3	53.6
Pre-launch science		0.01	0.6	2.4	3.1	3.5	2.7																12.2	10.8
Instrument PM/SE		0.01	0.3	1.1	1.4	1.6	1.2																5.4	4.8
Narrow Angle Camera (NAC)		0.02	0.9	3.6	4.7	5.3	4.1																18.5	16.5
Thermal Mapper (TM)		0.02	0.7	2.8	3.6	4.1	3.1																14.3	12.7
Flux Gate Magnetometer (FGM)		0.01	0.4	1.7	2.3	2.6	2.0																9.0	8.0
Flight Element PM/SE		0.05	2.1	8.9	11.7	13.1	10.2																46.0	40.9
Flight Element (Orbiter)		0.2	10.6	44.4	58.5	65.5	50.8																230.0	204.4
MSI&T 2		0.03	1.2	4.9	6.4	18.9	16.3																47.7	41.8
Ground data system dev		0.02	1.0	4.2	5.5	6.2	4.8																21.6	19.2
Navigation & mission design		0.02	0.8	3.2	4.2	4.7	3.7																16.6	14.8
Total dev. w/o reserves		0.5	21.3	88.6	116.7	142.5	112.1																481.7	427.6
Development reserves		0.3	11.1	46.3	61.1	68.4	53.0																240.1	213.4
Total A–D development cost		0.8	32.4	135.0	177.8	210.9	165.1																721.9	641.0
Launch services				32.4	56.6	63.4	49.1																201.4	178.0
							Phase E																	
Phase E science							0.9	3.7	3.8	3.9	4.0	4.1	4.2	4.3	2.5								31.4	23.9
Other Phase E cost							3.2	12.9	13.3	13.7	14.0	14.4	14.8	15.2	8.9								110.4	84.1
Phase E reserves							1.0	3.9	4.0	4.1	4.2	4.4	4.5	4.6	2.7								33.4	25.4
Total Phase E							5.1	20.5	21.1	21.7	22.3	22.9	23.5	24.1	14.2								175.3	133.5
Education/outreach		0.0	0.1	0.3	0.4	0.4	0.3	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.4								6.6	5.4
Other (specify)																							0.0	0
Total Cost	**$**	**$ 0.8**	**$ 32.4**	**$ 167.6**	**$ 234.8**	**$ 274.7**	**$ 219.6**	**$ 21.2**	**$ 21.7**	**$ 22.3**	**$ 22.9**	**$ 23.5**	**$ 24.2**	**$ 24.8**	**$ 14.6**								**$ 1,105**	**$ 958**
																	Total Mission Cost							**$ 958**

(FY costs1 in Real Year Dollars, Totals in Real Year and 2015 Dollars)

1 Costs should include all costs including any fee

2 MSI&T - Mission System Integration and Test and preparation for operations

Table 5-7. Total Mission Cost Funding Profile—Option 4

Item	Prior	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	FY2032	FY2033	FY2034	FY2035	FY2036	Total (Real Yr.)	Total (FY2015)
Cost																								
Phase A concept study (included below)		0.9	6.8																				7.7	7.3
Technology development																								
		Phase A - D																						
Mission PM/SE/MA		0.1	2.9	12.2	16.1	18.0	14.0																63.3	56.2
Pre-launch science		0.02	0.9	3.9	5.2	5.8	4.5																20.4	18.2
Instrument PM/SE		0.01	0.5	2.0	2.7	3.0	2.3																10.5	9.4
Narrow Angle Camera (NAC)		0.02	0.9	3.6	4.7	5.3	4.1																18.5	16.5
Thermal Mapper (TM)		0.02	0.7	2.8	3.6	4.1	3.1																14.3	12.7
Ion and Neutral Mass Spectrometer (INMS)		0.03	1.4	5.9	7.7	8.6	6.7																30.4	27.0
Flux Gate Magnetometer (FGM)		0.01	0.4	1.7	2.3	2.6	2.0																9.0	8.0
Fast Imaging Plasma Spectrometer		0.01	0.4	1.6	2.1	2.4	1.9																8.4	7.5
Flight Element PM/SE		0.05	2.1	8.9	11.7	13.1	10.2																46.2	41.0
Flight Element (Orbiter)		0.3	10.7	44.8	59.0	66.1	51.3																232.3	206.4
MSI&T 2		0.03	1.3	5.3	7.0	19.9	17.1																50.5	44.3
Ground data system dev		0.02	1.0	4.3	5.7	6.3	4.9																22.2	19.8
Navigation & mission design		0.02	0.8	3.3	4.4	4.9	3.8																17.3	15.4
Total dev. w/o reserves		0.6	24.1	100.4	132.3	160.2	125.9																543.4	482.4
Development reserves		0.3	12.5	52.3	68.9	77.2	59.8																271.1	240.9
Total A–D development cost		0.9	36.6	152.7	201.2	237.4	185.7																814.5	723.3
Launch services				32.4	56.6	63.4	49.1																201.4	178.0
							Phase E																	
Phase E science							1.7	6.8	6.9	7.1	7.3	7.5	7.7	7.9	8.1	2.1							63.2	47.7
Other Phase E cost							3.5	14.1	14.5	14.9	15.3	15.7	16.1	16.6	17.0	4.3							132.1	99.7
Phase E reserves							1.2	5.0	5.1	5.2	5.4	5.5	5.7	5.8	6.0	1.5							46.4	35.0
Total Phase E							6.4	25.8	26.5	27.3	28.0	28.7	29.5	30.3	31.1	7.9							241.7	182.3
Education/outreach		0.0	0.1	0.3	0.5	0.5	0.4	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.2							7.9	6.3
Other (specify)																							0.0	0
Total Cost	**$**	**$ 0.9**	**$ 36.7**	**$ 185.4**	**$ 258.2**	**$ 301.2**	**$ 241.6**	**$ 26.5**	**$ 27.2**	**$ 28.0**	**$ 28.7**	**$ 29.5**	**$ 30.3**	**$ 31.1**	**$ 31.9**	**$ 8.1**							**$ 1,265**	**$ 1,090**
																	Total Mission Cost							**$ 1,090**

(FY costs1 in Real Year Dollars, Totals in Real Year and 2015 Dollars)

1 Costs should include all costs including any fee

2 MSI&T - Mission System Integration and Test and preparation for operations

Appendix A. Acronyms

AO	announcement of opportunity
ACS	attitude control system
ASRG	advanced stirling radioisotope generator
BOL	beginning of life
C/A	closest approach
CBE	current best estimate
C&DH	command & data handling
CML	concept maturity level
CMOS	complementary metal oxide semiconductor
COPS	comet pressure sensor
CRCC	critical relay control card
DSMCE	Discovery and Scout Mission Capabilities Expansion
DFMS	double-focusing mass spectrometer
dTDI	digital time delay integration
EVVEJ	Earth-Venus-Venus-Earth-Jupiter
EOL	end of life
ESSP	Earth System Science Pathfinder
FGM	fluxgate magnetometer
FIPS	fast-imaging plasma spectrometer
FY	fiscal year
HGA	high-gain antenna
IR	infrared
JPL	Jet Propulsion Laboratory
IMU	inertial measurement unit
INMS	ion and neutral mass spectrometer
LGA	low-gain antenna
MEL	master equipment list
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MEV	maximum expected value
MGA	medium-gain antenna
MIT	minimum impulse thruster
MLI	multilayer insulation
MCIC	motor control and interface card
M/Q	mass-to-charge ratio
MREU	MSAP remote engineering unit
MSAP	Multi Mission System Architectural Platform
MSIA	MSAP serial interface assembly
MTIF	MSAP telecom interface card
NAC	narrow angle camera
NRC	National Research Council
NVCAM	non-volatile memory and camera card
PJR	perijove raise maneuver
RHU	radioisotope heater unit
SSI	solid-state imaging
TID	total incident dose
TCM	trajectory correction maneuver
TM	thermal mapper
UHF	ultra-high frequency

Appendix B. References

[1] National Aeronautics and Space Administration. *Ground Rules for Mission Concept Studies in Support of Planetary Decadal Survey, Revision 2.* Released 10 November 2009.

[2] Jet Propulsion Laboratory. 11 December 2006. *Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles), Revision 3.* Document number 43913.

[3] Jet Propulsion Laboratory. 30 September 2008. Flight Project Practices, Revision 7. Document number 58032.

[4] "Juno Concept Study Report," New Frontiers Phase A Concept Study AO-03-OSS-03. March 2005.

[5] JPL IOM 5132-2006-038, "Documentation of the Juno CSR Radiation Environment," Martin Ratliff to William McAlpine, 18 May 2006.

Appendix C. Radiation Analysis

Io Observer Radiation Environment Summary

This document describes how the dose-depth plot for the Io Observer was calculated.

–Michael Kokorowski, 10-March-2010

1. Trajectory

   The trajectory of the Io Observer spacecraft was defined by the spk file io_scpse.bsp provided by Nathan Strange. This file ranges in time between 2027 Nov 01 00:01:05.182 and 2030 APR 17 00:01:05.185. This file does not contain the cruise portion of the mission, but it does contain the entire trajectory within the Jovian system.

   The range of time for which the electron and proton flux was calculated is 2027 Dec 1 to 2030 Feb 1, as suggested by Nathan Strange. The cumulative dose was calculated for each orbit. The end of each orbit was taken to be:

   - Orbit 1: 2028-APR-07
   - Orbit 2: 2028-AUG-27
   - Orbit 3: 2028-NOV-07
   - Orbit 4: 2029-JAN-05
   - Orbit 5: 2029-MAR-04
   - Orbit 6: 2029-MAY-01
   - Orbit 7: 2029-JUN-29
   - Orbit 8: 2029-AUG-26
   - Orbit 9: 2029-OCT-23
   - Orbit 10: 2029-DEC-21
   - Orbit 10: 2030-FEB-17

   Again, these times were suggested by Nathan Strange. The end of each orbit occurs when the spacecraft is near apoapsis.

2. Electron and Proton Flux Calculation

   The Jupiter radiation environment assumed for this study is defined by the GIRE radiation model (JPL Publication 03-006) and is freely available online (http://www.openchannelsoftware.com/). In this case, we assumed an offset, tilted dipole (OTD) magnetic field model. Other, more complex magnetic field models exist (e.g., VIP4 and Khurana). The Jovian magnetic field near 6 RJ is reasonably approximated with an OTD. Additionally, using an OTD provides a significant speed advantage when calculating B and L coordinates. As a check, flux values for a previous study using the VIP4 model (Io Volcano Observer, IOM 5132-08-037) were within several percent (<10%) for most cases. Differences are due to both trajectory and the magnetic field model.

   The dose accumulated during the cruise stage was neglected. The cruise dose is expected to be minimal. In the Io Volcano Observer study, the cruise dose contributed ~2.5% of the total dose behind 100 mils of Al.

3. Dose-Depth Calculation

   The dose-depth curves were obtained using NOVICE radiation transport code. The shielding was assumed to be a spherical shell (standard JPL practice). The reported dose-depth is given for a Radiation Design Factor of 1 (RDF=1).

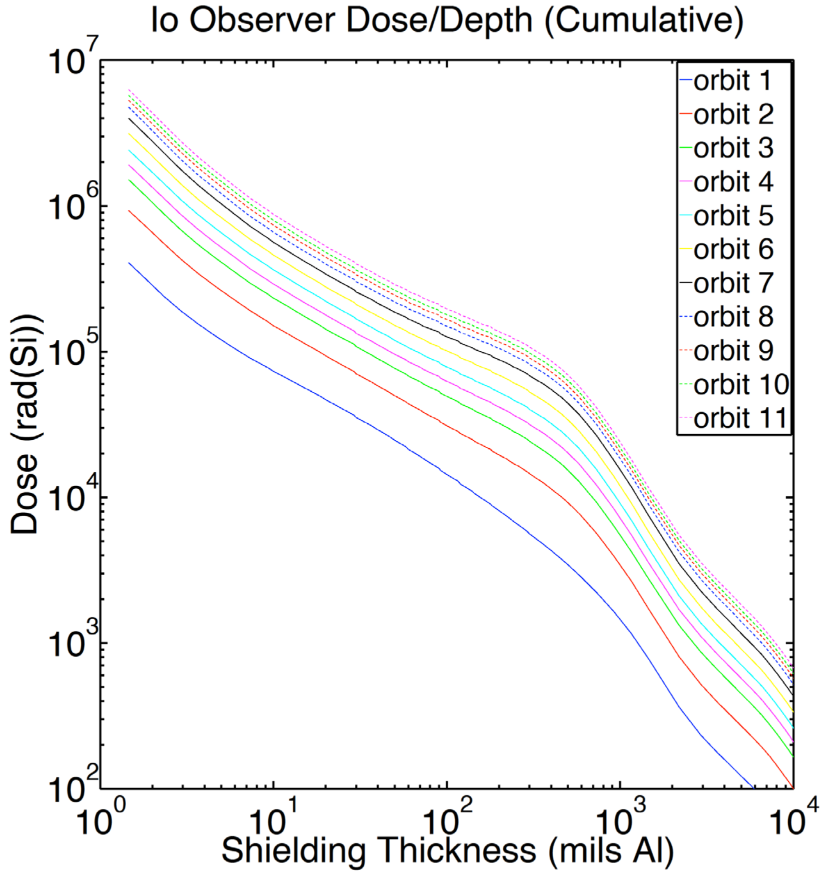

Figure C-1. Io Observer Radiation Exposure Estimate

Appendix D. Master Equipment Lists

The following MELs are included in this appendix:

- Option 1
- Option 2
- Option 3
- Option 4

Option 1 MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.
			1664.3 kg
Launch Vehicle PLA			0.0 kg
Stack (w/ Wet Element)			1664.3 kg
Useable Propellant			985.6 kg
Stack (w/ Dry Element)			678.8 kg
Carried Elements			0.0 kg
Dry Element			678.8 kg
			1664.3 kg
Useable Propellant			985.6 kg
System 1: Monoprop			985.6 kg
Dry Element			678.8 kg
System Contingency			134.7 kg
Subsystem Heritage Contingency			157.1 kg
Payload			40.3 kg
Instruments		5	40.3 kg
Narrow Angle Camera (NAC)	15.0 kg	1	15.0 kg
Thermal Mapper (TM)	12.0 kg	1	12.0 kg
Ion and Neutral Mass Spectrometer (INMS)	10.3 kg	1	10.3 kg
Flux Gate Magnetometer (FGM)	1.5 kg	2	3.0 kg
Additional Payload		0	0.0 kg
Bus			638.5 kg
Attitude Control		13	21.0 kg
Sun Sensors	0.0 kg	8.0	0.0 kg
Star Tracker	2.5 kg	2.0	5.0 kg
IMUs	4.0 kg	2.0	8.0 kg
Shielding:	8.0 kg	1.0	8.0 kg
Command & Data		22	23.6 kg
Processor: RAD750	0.6 kg	2	1.1 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg
Power: CEPCU	1.2 kg	4	4.6 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg
Power		26	148.1 kg
No Solar Panels	0.0 kg	0	0.0 kg
Li-CFx (Primary Battery)	0.0 kg	0	0.0 kg
Li-ION (Secondary Battery)	10.3 kg	8	82.3 kg
Thermal Battery (Thermal Battery)	0.0 kg	0	0.0 kg
Advanced Stirling (ASRG-850C)	24.0 kg	2	48.0 kg
Chassis	4.6 kg	1	4.6 kg
Array Segment Switches* Boards	0.8 kg	0	0.0 kg
Load Switches Boards	0.8 kg	2	1.6 kg
Thruster Drivers* Boards	0.8 kg	2	1.6 kg
Pyro Switches* Boards	0.8 kg	2	1.6 kg
Houskeeping DC-DC Converters* Boards	1.0 kg	2	2.0 kg
Power/Shunt Control* Boards	1.0 kg	2	2.0 kg
High Voltage Down Converter* Boards	20.0 kg	0	0.0 kg
Battery Control Boards	0.8 kg	4	3.2 kg
ARPS (Stirling) Controller* Boards	0.8 kg	0	0.0 kg
Diodes* Boards	0.0 kg	0	0.0 kg
Shielding	1.2 kg	1	1.2 kg

				CBE Mass Per Unit	# of Units	Current Basic Est.
Propulsion					**97**	**112.0 kg**
	System 1: Monoprop				97	112.0 kg
		Hardware			97	87.9 kg
			Gas Service Valve	0.3 kg	3	0.9 kg
			HP Latch Valve	0.4 kg	6	2.1 kg
			HP Transducer	0.3 kg	1	0.3 kg
			Gas Filter	0.1 kg	1	0.1 kg
			NC Pyro Valve	0.2 kg	2	0.4 kg
			NO Pyro Valve	0.2 kg	1	0.2 kg
			Press Regulator	0.7 kg	2	1.5 kg
			Temp. Sensor	0.0 kg	8	0.1 kg
			Liq. Service Valve	0.4 kg	1	0.4 kg
			LP Transducer	0.3 kg	3	0.8 kg
			Liq. Filter	0.5 kg	1	0.5 kg
			LP Latch Valve	0.4 kg	4	1.4 kg
			Temp. Sensor	0.0 kg	32	0.3 kg
			Lines, Fittings, Misc.	4.5 kg	1	4.5 kg
			Monoprop Main Engine	0.7 kg	8	5.9 kg
			Monoprop Thrusters 1	0.2 kg	12	2.0 kg
			Monoprop Thrusters 2	0.3 kg	8	2.6 kg
			Pressurant Tanks	9.5 kg	2	18.9 kg
			Fuel Tanks	45.0 kg	1	45.0 kg
		Pressurant				4.5 kg
		Residuals				19.7 kg
Mechanical					**10**	**226.1 kg**
	Struc. & Mech.				8	168.6 kg
		Primary Structure		108.4 kg	1	108.4 kg
		Secondary Structure		8.1 kg	1	8.1 kg
		Vault		40.0 kg	1	40.0 kg
		ASRG Adapter		1.3 kg	2	2.5 kg
		Mag Boom		1.0 kg	1	1.0 kg
		Mag Boom Launch Lock and Deploy Mechanism		1.0 kg	1	1.0 kg
		Integration Hardware		7.6 kg	1	7.6 kg
	Adapter, Spacecraft side			14.8 kg	1	14.8 kg
	Cabling Harness			42.7 kg	1	42.7 kg
Telecom					**38**	**66.9 kg**
	X/Ka-HGA 3.0m diam Parabolic High Gain Antenna			33.7 kg	1	33.7 kg
	X-MGA (19dB) MER			0.6 kg	1	0.6 kg
	X-LGA			0.5 kg	2	0.9 kg
	SDST X-up/X&Ka-down			3.2 kg	2	6.4 kg
	X-band TWTA, RF=25W			3.0 kg	2	6.0 kg
	Ka-band TWTA, RF<100W			2.9 kg	2	5.8 kg
	Coax Transfer Switch (CXS)			0.1 kg	1	0.1 kg
	Waveguide Transfer Switch (WGTS)			0.4 kg	5	1.9 kg
	X-band Diplexer, high isolation			0.8 kg	1	0.8 kg
	Hybrid Coupler			0.0 kg	2	0.0 kg
	Filter, high power			0.4 kg	1	0.4 kg
	Coax Cable, flex (190)			0.2 kg	8	1.3 kg
	WR-112 WG, rigid (Al)			1.3 kg	7	8.9 kg
	WR-28 WG, rigid (Al)			0.0 kg	3	0.1 kg
	Shielding				0	0.0 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.
Thermal		**281**	**40.6 kg**
Multilayer Insulation (MLI)	0.4 kg	45	16.9 kg
Thermal Surfaces		27	0.7 kg
General	0.0 kg	27	0.7 kg
Paints/Films	0.0 kg	0	0.0 kg
Chemical Processes	0.0 kg	0	0.0 kg
Thermal Conduction Control		1	0.5 kg
General	0.0 kg	0	0.0 kg
Isolation (G-10)	0.5 kg	1	0.5 kg
High Conductance	0.0 kg	0	0.0 kg
Heaters		47	2.7 kg
Catalogue	0.0 kg	0	0.0 kg
Custom	0.1 kg	40	2.0 kg
Propulsion Tank Heaters	0.1 kg	1	0.1 kg
Propulsion Line Heaters	0.1 kg	6	0.6 kg
Temperature Sensors		60	1.2 kg
Thermistors	0.0 kg	60	1.2 kg
PRT's	0.0 kg	0	0.0 kg
Thermostats		60	1.2 kg
Mechanical	0.0 kg	60	1.2 kg
Electronic	0.0 kg	0	0.0 kg
Relay Switches (Heater Control)	0.0 kg	0	0.0 kg
Thermal Louvers	1.0 kg	4	3.9 kg
Thermal Radiator (Area=m2)	0.0 kg	0	0.0 kg
Heat Pipes		30	5.0 kg
CCHP (Straight)	0.2 kg	20	3.0 kg
CCHP (2-D Bends)	0.0 kg	0	0.0 kg
VCHP	0.0 kg	0	0.0 kg
Loop HP	0.2 kg	10	2.0 kg
Cryogenic HP	0.0 kg	0	0.0 kg
Phase Change Material		0	0.0 kg
Wax	0.0 kg	0	0.0 kg
Water	0.0 kg	0	0.0 kg
Cryogenic Coolers		0	0.0 kg
Passive (1 Stage)	0.0 kg	0	0.0 kg
Passive (2 Stage)	0.0 kg	0	0.0 kg
Passive (3 Stage)	0.0 kg	0	0.0 kg
Passive (Contrator)	0.0 kg	0	0.0 kg
Mechanical (Stirling)	0.0 kg	0	0.0 kg
Mechanical (Sorption)	0.0 kg	0	0.0 kg
Mech. (Gas-Standing Wave)	0.0 kg	0	0.0 kg
Thermal Switch	0.0 kg	0	0.0 kg
Mechanical Pump Loop System	0.0 kg	0	0.0 kg
RHU's	0.0 kg	0	0.0 kg
Instrument Thermal Control	0.0 kg	0	0.0 kg
Other Components		7	8.5 kg
Thermal Radiator (Area=m2)	3.0 kg	2	6.0 kg
Thermal Transfer Plates	0.5 kg	4	2.0 kg
Venus Shield	0.5 kg	1	0.5 kg

Option 2 MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.
Launch Mass			**1813.6 kg**
Launch Vehicle PLA			**0.0 kg**
Stack (w/ Wet Element)			**1813.6 kg**
Useable Propellant			**989.1 kg**
Stack (w/ Dry Element)			**824.5 kg**
Carried Elements			**0.0 kg**
Dry Element			**824.5 kg**
Wet Element			**1813.6 kg**
Useable Propellant			**989.1 kg**
System 1: Monoprop			**989.1 kg**
Dry Element			**824.5 kg**
System Contingency			**154.0 kg**
Subsystem Heritage Contingency			**200.5 kg**
Payload			**40.3 kg**
Instruments		**5**	**40.3 kg**
Narrow Angle Camera (NAC)	15.0 kg	1	15.0 kg
Thermal Mapper (TM)	12.0 kg	1	12.0 kg
Ion and Neutral Mass Spectrometer (INMS)	10.3 kg	1	10.3 kg
Flux Gate Magnetometer (FGM)	1.5 kg	2	3.0 kg
Additional Payload		**0**	**0.0 kg**
Bus			**784.2 kg**
Attitude Control		**15**	**23.0 kg**
Sun Sensors	0.0 kg	8.0	0.0 kg
Star Tracker	2.5 kg	2.0	5.0 kg
IMUs	4.0 kg	2.0	8.0 kg
Scan Platform Gimbal Drive Electronics	1.0 kg	2.0	2.0 kg
Shielding:	8.0 kg	1.0	8.0 kg
Command & Data		**22**	**23.6 kg**
Processor: RAD750	0.6 kg	2	1.1 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg
Power: CEPCU	1.2 kg	4	4.6 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg
Power		**26**	**163.2 kg**
GaAs TJ Rigid Solar Array (37.73 m^2)	33.7 kg	2	67.3 kg
Li-CFx (Primary Battery)	0.0 kg	0	0.0 kg
Li-ION (Secondary Battery)	12.7 kg	6	75.9 kg
Thermal Battery (Thermal Battery)	0.0 kg	0	0.0 kg
Advanced Stirling (ASRG-850C)	0.0 kg	0	0.0 kg
Chassis	5.2 kg	1	5.2 kg
Array Segment Switches* Boards	0.8 kg	2	1.6 kg
Load Switches Boards	0.8 kg	2	1.6 kg
Thruster Drivers* Boards	0.8 kg	2	1.6 kg
Pyro Switches* Boards	0.8 kg	4	3.2 kg
Houskeeping DC-DC Converters* Boards	1.0 kg	2	2.0 kg
Power/Shunt Control* Boards	1.0 kg	1	1.0 kg
High Voltage Down Converter* Boards	20.0 kg	0	0.0 kg
Battery Control Boards	0.8 kg	3	2.4 kg
ARPS (Stirling) Controller* Boards	0.8 kg	0	0.0 kg
Diodes* Boards	0.0 kg	0	0.0 kg
Shielding	1.4 kg	1	1.4 kg

				CBE Mass Per Unit	# of Units	Current Basic Est.
Propulsion					**97**	**111.7 kg**
	System 1: Monoprop				97	111.7 kg
		Hardware			97	87.9 kg
			Gas Service Valve	0.3 kg	3	0.9 kg
			HP Latch Valve	0.4 kg	6	2.1 kg
			HP Transducer	0.3 kg	1	0.3 kg
			Gas Filter	0.1 kg	1	0.1 kg
			NC Pyro Valve	0.2 kg	2	0.4 kg
			NO Pyro Valve	0.2 kg	1	0.2 kg
			Press Regulator	0.7 kg	2	1.5 kg
			Temp. Sensor	0.0 kg	8	0.1 kg
			Liq. Service Valve	0.4 kg	1	0.4 kg
			LP Transducer	0.3 kg	3	0.8 kg
			Liq. Filter	0.5 kg	1	0.5 kg
			LP Latch Valve	0.4 kg	4	1.4 kg
			Temp. Sensor	0.0 kg	32	0.3 kg
			Lines, Fittings, Misc.	4.5 kg	1	4.5 kg
			Monoprop Main Engine	0.7 kg	8	5.9 kg
			Monoprop Thrusters 1	0.2 kg	12	2.0 kg
			Monoprop Thrusters 2	0.3 kg	8	2.6 kg
			Pressurant Tanks	9.5 kg	2	18.9 kg
			Fuel Tanks	45.0 kg	1	45.0 kg
		Pressurant				4.4 kg
		Residuals				19.4 kg
Mechanical					**14**	**359.3 kg**
	Struc. & Mech.				12	295.9 kg
		Primary Structure		100.5 kg	1	100.5 kg
		Secondary Structure		16.2 kg	1	16.2 kg
		Solar Array Structure		56.0 kg	2	112.1 kg
		Solar Array Latch/Release, Hinges, and Booms		5.0 kg	2	10.0 kg
		Scan Platform Structure		2.0 kg	1	2.0 kg
		Scan Platform Actuator		6.0 kg	1	6.0 kg
		Vault		40.0 kg	1	40.0 kg
		Mag Boom		1.0 kg	1	1.0 kg
		Mag Boom Launch Lock and Deploy Mechanism		1.0 kg	1	1.0 kg
		Integration Hardware		7.0 kg	1	7.0 kg
	Adapter, Spacecraft side			14.6 kg	1	14.6 kg
	Cabling Harness			48.8 kg	1	48.8 kg
Telecom					**38**	**66.9 kg**
	X/Ka-HGA 3.0m diam Parabolic High Gain Antenna			33.7 kg	1	33.7 kg
	X-MGA (19dB) MER			0.6 kg	1	0.6 kg
	X-LGA			0.5 kg	2	0.9 kg
	SDST X-up/X&Ka-down			3.2 kg	2	6.4 kg
	X-band TWTA, RF=25W			3.0 kg	2	6.0 kg
	Ka-band TWTA, RF<100W			2.9 kg	2	5.8 kg
	Coax Transfer Switch (CXS)			0.1 kg	1	0.1 kg
	Waveguide Transfer Switch (WGTS)			0.4 kg	5	1.9 kg
	X-band Diplexer, high isolation			0.8 kg	1	0.8 kg
	Hybrid Coupler			0.0 kg	2	0.0 kg
	Filter, high power			0.4 kg	1	0.4 kg
	Coax Cable, flex (190)			0.2 kg	8	1.3 kg
	WR-112 WG, rigid (Al)			1.3 kg	7	8.9 kg
	WR-28 WG, rigid (Al)			0.0 kg	3	0.1 kg
	Shielding				0	0.0 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.
Thermal		**275**	**36.4 kg**
Multilayer Insulation (MLI)	0.4 kg	53	19.7 kg
Thermal Surfaces		29	0.7 kg
General	0.0 kg	29	0.7 kg
Paints/Films	0.0 kg	0	0.0 kg
Chemical Processes	0.0 kg	0	0.0 kg
Thermal Conduction Control		1	0.5 kg
General	0.0 kg	0	0.0 kg
Isolation (G-10)	0.5 kg	1	0.5 kg
High Conductance	0.0 kg	0	0.0 kg
Heaters		65	4.5 kg
Catalogue	0.0 kg	0	0.0 kg
Custom	0.1 kg	40	2.0 kg
Propulsion Tank Heaters	0.1 kg	3	0.3 kg
Propulsion Line Heaters	0.1 kg	22	2.2 kg
Temperature Sensors		60	1.2 kg
Thermistors	0.0 kg	60	1.2 kg
PRT's	0.0 kg	0	0.0 kg
Thermostats		60	1.2 kg
Mechanical	0.0 kg	60	1.2 kg
Electronic	0.0 kg	0	0.0 kg
Relay Switches (Heater Control)	0.0 kg	0	0.0 kg
Thermal Louvers	1.0 kg	4	3.9 kg
Thermal Radiator (Area=m2)	10.5 kg	0	2.1 kg
Heat Pipes		1	2.0 kg
CCHP (Straight)	0.0 kg	0	0.0 kg
CCHP (2-D Bends)	0.0 kg	0	0.0 kg
VCHP	0.0 kg	0	0.0 kg
Loop HP	2.0 kg	1	2.0 kg
Cryogenic HP	0.0 kg	0	0.0 kg
Phase Change Material		0	0.0 kg
Wax	0.0 kg	0	0.0 kg
Water	0.0 kg	0	0.0 kg
Cryogenic Coolers		0	0.0 kg
Passive (1 Stage)	0.0 kg	0	0.0 kg
Passive (2 Stage)	0.0 kg	0	0.0 kg
Passive (3 Stage)	0.0 kg	0	0.0 kg
Passive (Contrator)	0.0 kg	0	0.0 kg
Mechanical (Stirling)	0.0 kg	0	0.0 kg
Mechanical (Sorption)	0.0 kg	0	0.0 kg
Mech. (Gas-Standing Wave)	0.0 kg	0	0.0 kg
Thermal Switch	0.0 kg	0	0.0 kg
Mechanical Pump Loop System	0.0 kg	0	0.0 kg
RHU's	0.0 kg	0	0.0 kg
Instrument Thermal Control	0.0 kg	0	0.0 kg
Other Components		3	0.5 kg
Thermal Radiator (Area=m2)	0.0 kg	2	0.0 kg
0	0.0 kg	0	0.0 kg
Venus Shield	0.5 kg	1	0.5 kg

Option 3 MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.
Launch Mass			**1768.5 kg**
Launch Vehicle PLA			**0.0 kg**
Stack (w/ Wet Element)			**1768.5 kg**
Useable Propellant			**989.1 kg**
Stack (w/ Dry Element)			**779.4 kg**
Carried Elements			**0.0 kg**
Dry Element			**779.4 kg**
Wet Element			**1768.5 kg**
Useable Propellant			**989.1 kg**
System 1: Monoprop			**989.1 kg**
Dry Element			**779.4 kg**
System Contingency			**145.3 kg**
Subsystem Heritage Contingency			**189.9 kg**
Payload			**30.0 kg**
Instruments		**4**	**30.0 kg**
Narrow Angle Camera (NAC)	15.0 kg	1	15.0 kg
Thermal Mapper (TM)	12.0 kg	1	12.0 kg
Flux Gate Magnetometer (FGM)	1.5 kg	2	3.0 kg
Additional Payload		**0**	**0.0 kg**
Bus			**749.4 kg**
Attitude Control		**15**	**23.0 kg**
Sun Sensors	0.0 kg	8.0	0.0 kg
Star Tracker	2.5 kg	2.0	5.0 kg
IMUs	4.0 kg	2.0	8.0 kg
Scan Platform Gimbal Drive Electronics	1.0 kg	2.0	2.0 kg
Shielding:	8.0 kg	1.0	8.0 kg
Command & Data		**22**	**23.6 kg**
Processor: RAD750	0.6 kg	2	1.1 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg
Power: CEPCU	1.2 kg	4	4.6 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg
Power		**26**	**141.2 kg**
GaAs TJ Rigid Solar Array (35.64 m^2)	31.8 kg	2	63.6 kg
Li-CFx (Primary Battery)	0.0 kg	0	0.0 kg
Li-ION (Secondary Battery)	11.2 kg	5	56.2 kg
Thermal Battery (Thermal Battery)	0.0 kg	0	0.0 kg
Advanced Stirling (ASRG-850C)	0.0 kg	0	0.0 kg
Chassis	5.5 kg	1	5.5 kg
Array Segment Switches* Boards	0.8 kg	2	1.6 kg
Load Switches Boards	0.8 kg	2	1.6 kg
Thruster Drivers* Boards	0.8 kg	2	1.6 kg
Pyro Switches* Boards	0.8 kg	4	3.2 kg
Houskeeping DC-DC Converters* Boards	1.0 kg	2	2.0 kg
Power Bus Monitor and Control Boards	1.0 kg	2	2.0 kg
High Voltage Down Converter* Boards	20.0 kg	0	0.0 kg
Battery Control Boards	0.8 kg	3	2.4 kg
ARPS (Stirling) Controller* Boards	0.8 kg	0	0.0 kg
Diodes* Boards	0.0 kg	0	0.0 kg
Shielding	1.5 kg	1	1.5 kg

				CBE Mass Per Unit	# of Units	Current Basic Est.
Propulsion					**97**	**111.7 kg**
	System 1: Monoprop				97	111.7 kg
		Hardware			97	87.9 kg
			Gas Service Valve	0.3 kg	3	0.9 kg
			HP Latch Valve	0.4 kg	6	2.1 kg
			HP Transducer	0.3 kg	1	0.3 kg
			Gas Filter	0.1 kg	1	0.1 kg
			NC Pyro Valve	0.2 kg	2	0.4 kg
			NO Pyro Valve	0.2 kg	1	0.2 kg
			Press Regulator	0.7 kg	2	1.5 kg
			Temp. Sensor	0.0 kg	8	0.1 kg
			Liq. Service Valve	0.4 kg	1	0.4 kg
			LP Transducer	0.3 kg	3	0.8 kg
			Liq. Filter	0.5 kg	1	0.5 kg
			LP Latch Valve	0.4 kg	4	1.4 kg
			Temp. Sensor	0.0 kg	32	0.3 kg
			Lines, Fittings, Misc.	4.5 kg	1	4.5 kg
			Monoprop Main Engine	0.7 kg	8	5.9 kg
			Monoprop Thrusters 1	0.2 kg	12	2.0 kg
			Monoprop Thrusters 2	0.3 kg	8	2.6 kg
			Pressurant Tanks	9.5 kg	2	18.9 kg
			Fuel Tanks	45.0 kg	1	45.0 kg
		Pressurant				4.4 kg
		Residuals				19.4 kg
Mechanical					**14**	**345.9 kg**
	Struc. & Mech.				12	285.5 kg
		Primary Structure		96.7 kg	1	96.7 kg
		Secondary Structure		15.9 kg	1	15.9 kg
		Solar Array Structure		53.1 kg	2	106.2 kg
		Solar Array Latch/Release, Hinges, and Booms		5.0 kg	2	10.0 kg
		Scan Platform Structure		2.0 kg	1	2.0 kg
		Scan Platform Actuator		6.0 kg	1	6.0 kg
		Vault		40.0 kg	1	40.0 kg
		Mag Boom		1.0 kg	1	1.0 kg
		Mag Boom Launch Lock and Deploy Mechanism		1.0 kg	1	1.0 kg
		Integration Hardware		6.8 kg	1	6.8 kg
	Adapter, Spacecraft side			14.7 kg	1	14.7 kg
	Cabling Harness			45.7 kg	1	45.7 kg
Telecom					**38**	**66.9 kg**
	X/Ka-HGA 3.0m diam Parabolic High Gain Antenna			33.7 kg	1	33.7 kg
	X-MGA (19dB) MER			0.6 kg	1	0.6 kg
	X-LGA			0.5 kg	2	0.9 kg
	SDST X-up/X&Ka-down			3.2 kg	2	6.4 kg
	X-band TWTA, RF=25W			3.0 kg	2	6.0 kg
	Ka-band TWTA, RF<100W			2.9 kg	2	5.8 kg
	Coax Transfer Switch (CXS)			0.1 kg	1	0.1 kg
	Waveguide Transfer Switch (WGTS)			0.4 kg	5	1.9 kg
	X-band Diplexer, high isolation			0.8 kg	1	0.8 kg
	Hybrid Coupler			0.0 kg	2	0.0 kg
	Filter, high power			0.4 kg	1	0.4 kg
	Coax Cable, flex (190)			0.2 kg	8	1.3 kg
	WR-112 WG, rigid (Al)			1.3 kg	7	8.9 kg
	WR-28 WG, rigid (Al)			0.0 kg	3	0.1 kg
	Shielding				0	0.0 kg

							CBE Mass Per Unit	# of Units	Current Basic Est.
			Thermal					**274**	**37.0 kg**
				Multilayer Insulation (MLI)			0.4 kg	52	19.4 kg
				Thermal Surfaces				28	0.7 kg
					General		0.0 kg	28	0.7 kg
						Paints/Films	0.0 kg	0	0.0 kg
						Chemical Processes	0.0 kg	0	0.0 kg
				Thermal Conduction Control				1	0.5 kg
					General		0.0 kg	0	0.0 kg
						Isolation (G-10)	0.5 kg	1	0.5 kg
						High Conductance	0.0 kg	0	0.0 kg
				Heaters				65	4.5 kg
					Catalogue		0.0 kg	0	0.0 kg
					Custom		0.1 kg	40	2.0 kg
					Propulsion Tank Heaters		0.1 kg	3	0.3 kg
					Propulsion Line Heaters		0.1 kg	22	2.2 kg
				Temperature Sensors				60	1.2 kg
					Thermistors		0.0 kg	60	1.2 kg
					PRT's		0.0 kg	0	0.0 kg
				Thermostats				60	1.2 kg
					Mechanical		0.0 kg	60	1.2 kg
					Electronic		0.0 kg	0	0.0 kg
				Relay Switches (Heater Control)			0.0 kg	0	0.0 kg
				Thermal Louvers			1.0 kg	4	3.9 kg
				Thermal Radiator (Area=m2)			10.5 kg	0	3.2 kg
				Heat Pipes				1	2.0 kg
					CCHP (Straight)		0.0 kg	0	0.0 kg
					CCHP (2-D Bends)		0.0 kg	0	0.0 kg
					VCHP		0.0 kg	0	0.0 kg
					Loop HP		2.0 kg	1	2.0 kg
					Cryogenic HP		0.0 kg	0	0.0 kg
				Phase Change Material				0	0.0 kg
					Wax		0.0 kg	0	0.0 kg
					Water		0.0 kg	0	0.0 kg
				Cryogenic Coolers				0	0.0 kg
					Passive (1 Stage)		0.0 kg	0	0.0 kg
					Passive (2 Stage)		0.0 kg	0	0.0 kg
					Passive (3 Stage)		0.0 kg	0	0.0 kg
					Passive (Contrator)		0.0 kg	0	0.0 kg
					Mechanical (Stirling)		0.0 kg	0	0.0 kg
					Mechanical (Sorption)		0.0 kg	0	0.0 kg
					Mech. (Gas-Standing Wave)		0.0 kg	0	0.0 kg
				Thermal Switch			0.0 kg	0	0.0 kg
				Mechanical Pump Loop System			0.0 kg	0	0.0 kg
				Aero-Shell TPS				0	0.0 kg
					Heatshield		0.0 kg	0	0.0 kg
					Backshell		0.0 kg	0	0.0 kg
				Parachute				0	0.0 kg
					Viking		0.0 kg	0	0.0 kg
					MER		0.0 kg	0	0.0 kg
				RHU's			0.0 kg	0	0.0 kg
				Instrument Thermal Control			0.0 kg	0	0.0 kg
				Other Components				3	0.5 kg
					Thermal Radiator (Area=m2)		0.0 kg	2	0.0 kg
					0		0.0 kg	0	0.0 kg
					Venus Shield		0.5 kg	1	0.5 kg

Option 4 MEL

	CBE Mass Per Unit	# of Units	Current Basic Est.
Launch Mass			**1835.9 kg**
Launch Vehicle PLA			**0.0 kg**
Stack (w/ Wet Element)			**1835.9 kg**
Useable Propellant			**989.1 kg**
Stack (w/ Dry Element)			**846.7 kg**
Carried Elements			**0.0 kg**
Dry Element			**846.7 kg**
Wet Element			**1835.9 kg**
Useable Propellant			**989.1 kg**
System 1: Monoprop			**989.1 kg**
Dry Element			**846.7 kg**
System Contingency			**157.1 kg**
Subsystem Heritage Contingency			**207.0 kg**
Payload			**41.7 kg**
Instruments		**6**	**41.7 kg**
Narrow Angle Camera (NAC)	15.0 kg	1	15.0 kg
Thermal Mapper (TM)	12.0 kg	1	12.0 kg
Ion and Neutral Mass Spectrometer (INMS)	10.3 kg	1	10.3 kg
Flux Gate Magnetometer (FGM)	1.5 kg	2	3.0 kg
Fast Imaging Plasma Spectrometer	1.4 kg	1	1.4 kg
Additional Payload		**0**	**0.0 kg**
Bus			**805.0 kg**
Attitude Control		**15**	**23.0 kg**
Sun Sensors	0.0 kg	8.0	0.0 kg
Star Tracker	2.5 kg	2.0	5.0 kg
IMUs	4.0 kg	2.0	8.0 kg
Scan Platform Gimbal Drive Electronics	1.0 kg	2.0	2.0 kg
Shielding:	8.0 kg	1.0	8.0 kg
Command & Data		**22**	**23.6 kg**
Processor: RAD750	0.6 kg	2	1.1 kg
Custom_Special_Function_Board: CRC	0.7 kg	2	1.3 kg
Memory: NVMCAM	0.7 kg	2	1.4 kg
Telecom_I_F: MTIF	0.7 kg	2	1.5 kg
General_I_F: MSIA	0.7 kg	2	1.4 kg
Analog_I_F: MREU	0.8 kg	2	1.6 kg
Power: CEPCU	1.2 kg	4	4.6 kg
Backplane: CPCI backplane (8 slots)	0.8 kg	2	1.7 kg
Chassis: CDH chassis (8 slot)	3.8 kg	2	7.7 kg
General_I_F: MCIC	0.7 kg	2	1.3 kg
Power		**28**	**177.6 kg**
GaAs TJ Rigid Solar Array (38.02 m^2)	33.9 kg	2	67.9 kg
Li-CFx (Primary Battery)	0.0 kg	0	0.0 kg
Li-ION (Secondary Battery)	12.7 kg	7	88.6 kg
Thermal Battery (Thermal Battery)	0.0 kg	0	0.0 kg
Advanced Stirling (ASRG-850C)	0.0 kg	0	0.0 kg
Chassis	5.5 kg	1	5.5 kg
Array Segment Switches* Boards	0.8 kg	2	1.6 kg
Load Switches Boards	0.8 kg	2	1.6 kg
Thruster Drivers* Boards	0.8 kg	2	1.6 kg
Pyro Switches* Boards	0.8 kg	4	3.2 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.
Houskeeping DC-DC Converters* Boards	1.0 kg	2	2.0 kg
Power/Shunt Control* Boards	1.0 kg	1	1.0 kg
High Voltage Down Converter* Boards	20.0 kg	0	0.0 kg
Battery Control Boards	0.8 kg	4	3.2 kg
ARPS (Stirling) Controller* Boards	0.8 kg	0	0.0 kg
Diodes* Boards	0.0 kg	0	0.0 kg
Shielding	1.5 kg	1	1.5 kg
Propulsion		**97**	**111.7 kg**
System 1: Monoprop		97	111.7 kg
Hardware		97	87.9 kg
Gas Service Valve	0.3 kg	3	0.9 kg
HP Latch Valve	0.4 kg	6	2.1 kg
HP Transducer	0.3 kg	1	0.3 kg
Gas Filter	0.1 kg	1	0.1 kg
NC Pyro Valve	0.2 kg	2	0.4 kg
NO Pyro Valve	0.2 kg	1	0.2 kg
Press Regulator	0.7 kg	2	1.5 kg
Temp. Sensor	0.0 kg	8	0.1 kg
Liq. Service Valve	0.4 kg	1	0.4 kg
LP Transducer	0.3 kg	3	0.8 kg
Liq. Filter	0.5 kg	1	0.5 kg
LP Latch Valve	0.4 kg	4	1.4 kg
Temp. Sensor	0.0 kg	32	0.3 kg
Lines, Fittings, Misc.	4.5 kg	1	4.5 kg
Monoprop Main Engine	0.7 kg	8	5.9 kg
Monoprop Thrusters 1	0.2 kg	12	2.0 kg
Monoprop Thrusters 2	0.3 kg	8	2.6 kg
Pressurant Tanks	9.5 kg	2	18.9 kg
Fuel Tanks	45.0 kg	1	45.0 kg
Pressurant			4.4 kg
Residuals			19.4 kg
Mechanical		**40**	**365.7 kg**
Struc. & Mech.		38	300.5 kg
Primary Structure	102.8 kg	1	102.8 kg
Secondary Structure	16.4 kg	1	16.4 kg
Solar Array Structure	57.0 kg	2	114.1 kg
Solar Array Latch/Release, Hinges, and Booms	5.0 kg	2	10.0 kg
Scan Platform Structure	2.0 kg	1	2.0 kg
Scan Platform Actuator	6.0 kg	1	6.0 kg
Vault	40.0 kg	1	40.0 kg
Mag Boom	1.0 kg	1	1.0 kg
Mag Boom Launch Lock and Deploy Mechanism	1.0 kg	1	1.0 kg
Integration Hardware	7.2 kg	1	7.2 kg
Adapter, Spacecraft side	14.7 kg	1	14.7 kg
Cabling Harness	50.5 kg	1	50.5 kg
Telecom		**38**	**66.9 kg**
X/Ka-HGA 3.0m diam Parabolic High Gain Antenna	33.7 kg	1	33.7 kg
X-MGA (19dB) MER	0.6 kg	1	0.6 kg
X-LGA	0.5 kg	2	0.9 kg
SDST X-up/X&Ka-down	3.2 kg	2	6.4 kg
X-band TWTA, RF=25W	3.0 kg	2	6.0 kg
Ka-band TWTA, RF<100W	2.9 kg	2	5.8 kg
Coax Transfer Switch (CXS)	0.1 kg	1	0.1 kg

	CBE Mass Per Unit	# of Units	Current Basic Est.
Waveguide Transfer Switch (WGTS)	0.4 kg	5	1.9 kg
X-band Diplexer, high isolation	0.8 kg	1	0.8 kg
Hybrid Coupler	0.0 kg	2	0.0 kg
Filter, high power	0.4 kg	1	0.4 kg
Coax Cable, flex (190)	0.2 kg	8	1.3 kg
WR-112 WG, rigid (Al)	1.3 kg	7	8.9 kg
WR-28 WG, rigid (Al)	0.0 kg	3	0.1 kg
Shielding		0	0.0 kg
Thermal		**276**	**36.4 kg**
Multilayer Insulation (MLI)	0.4 kg	53	19.8 kg
Thermal Surfaces		29	0.7 kg
General	0.0 kg	29	0.7 kg
Paints/Films	0.0 kg	0	0.0 kg
Chemical Processes	0.0 kg	0	0.0 kg
Thermal Conduction Control		1	0.5 kg
General	0.0 kg	0	0.0 kg
Isolation (G-10)	0.5 kg	1	0.5 kg
High Conductance	0.0 kg	0	0.0 kg
Heaters		65	4.5 kg
Catalogue	0.0 kg	0	0.0 kg
Custom	0.1 kg	40	2.0 kg
Propulsion Tank Heaters	0.1 kg	3	0.3 kg
Propulsion Line Heaters	0.1 kg	22	2.2 kg
Temperature Sensors		60	1.2 kg
Thermistors	0.0 kg	60	1.2 kg
PRT's	0.0 kg	0	0.0 kg
Thermostats		60	1.2 kg
Mechanical	0.0 kg	60	1.2 kg
Electronic	0.0 kg	0	0.0 kg
Relay Switches (Heater Control)	0.0 kg	0	0.0 kg
Thermal Louvers	1.0 kg	4	3.9 kg
Thermal Radiator (Area=m2)	10.5 kg	0	2.1 kg
Heat Pipes		1	2.0 kg
CCHP (Straight)	0.0 kg	0	0.0 kg
CCHP (2-D Bends)	0.0 kg	0	0.0 kg
VCHP	0.0 kg	0	0.0 kg
Loop HP	2.0 kg	1	2.0 kg
Cryogenic HP	0.0 kg	0	0.0 kg
Phase Change Material		0	0.0 kg
Wax	0.0 kg	0	0.0 kg
Water	0.0 kg	0	0.0 kg
Cryogenic Coolers		0	0.0 kg
Passive (1 Stage)	0.0 kg	0	0.0 kg
Passive (2 Stage)	0.0 kg	0	0.0 kg
Passive (3 Stage)	0.0 kg	0	0.0 kg
Passive (Contrator)	0.0 kg	0	0.0 kg
Mechanical (Stirling)	0.0 kg	0	0.0 kg
Mechanical (Sorption)	0.0 kg	0	0.0 kg
Mech. (Gas-Standing Wave)	0.0 kg	0	0.0 kg
Thermal Switch	0.0 kg	0	0.0 kg
Mechanical Pump Loop System	0.0 kg	0	0.0 kg
RHU's	0.0 kg	0	0.0 kg
Instrument Thermal Control	0.0 kg	0	0.0 kg
Other Components		3	0.5 kg
Thermal Radiator (Area=m2)	0.0 kg	2	0.0 kg
0	0.0 kg	0	0.0 kg
Venus Shield	0.5 kg	1	0.5 kg