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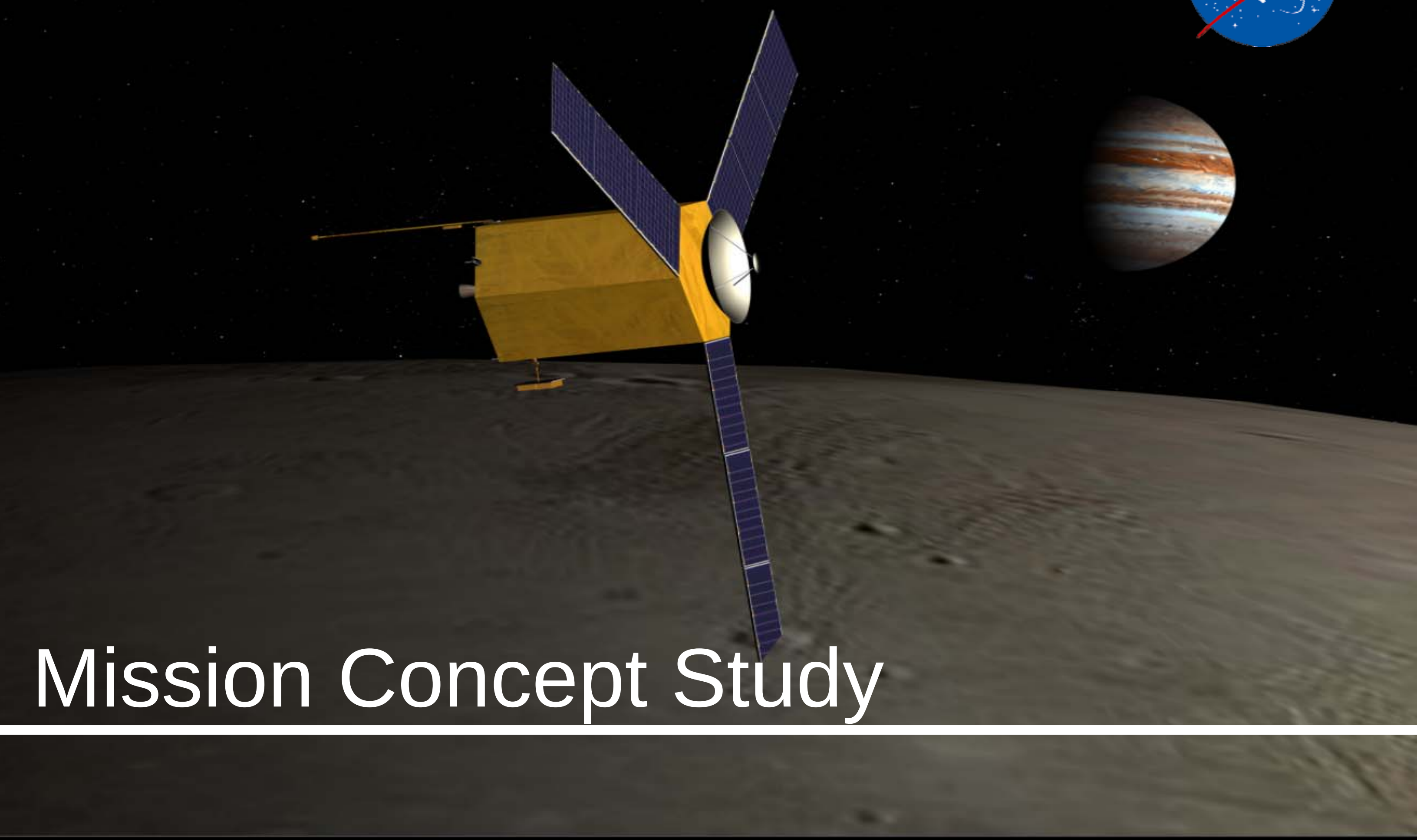

Mission Concept Study

Planetary Science Decadal Survey
Ganymede Orbiter

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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.

Cover Art: Ganymede Orbiter in Circular Polar Orbit (July 25, 2030). Illustration created with JPL's Team X trajectory visualization tool, with artist enhancement courtesy Mr. Corby Waste.

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Mission Concept Study Final Report

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Executive Summary

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 mission and flight system architecture suitable to perform a scientifically viable Ganymede Orbiter (GO) mission responsive to science traceability matrix (STM) requirements formulated by NASA's science panel. This report documents the results of that study.

The results support the following conclusions:

1. The Ganymede Orbiter mission would offer a scientifically interesting, scientifically viable outer-planets mission option.
2. The technology is ready, with no new development required.
3. The estimated project cost of the "Floor" option (the least ambitious, though still scientifically viable, of the three mission options studied) would be close enough to the cost caps currently under consideration by NASA for outer planet missions to enable Ganymede mission cost viability.

The Floor option is composed of the following key elements:

- Atlas V 541 launch vehicle
- E-VEE-J gravity assist trajectory with three mission phases: Heliocentric, Jupiter (JOI to GOI), and Ganymede Orbital Operations
- Three science data observation/acquisition phases: Ganymede Flyby Phase, Ganymede Pump-down Phase, and Ganymede Nominal Science (Orbital Tour) Phase.
- Three-month Ganymede orbital tour: circular, polar, 90-deg inclination, 200-km altitude, 63-deg phase angle Ganymede orbit
- Six-instrument science payload consisting of medium resolution camera (MRC), flux gate magnetometer (FGM), V/NIR imaging spectrometer (VNIRIS), laser altimeter (LA), and low- and high-energy plasma packages
- A three-axis-stabilized, solar-powered spacecraft, with conventional bi-propellant propulsion; a continuously Earth-pointed, body-fixed HGA; a nadir-tracking scan platform; Ka-band science data downlink; and a "Juno-like" radiation vault to house sensitive electronics
- One 34-m DSN Ka-band ground station

1. Science

Science Rationale

Ganymede is the largest satellite in the solar system (radius = 2634.1 km) and has many unique properties such as being the most centrally condensed satellite in the solar system, generating a strong internal magnetic field, and possessing a magnetosphere. Its mean density of 1.936 gm/cm^3 is consistent with an internal composition consisting of equal parts of water (mostly in the form of ice) and rocks. Its extremely low normalized moment of Inertia (0.3105) suggests that the rocks have further differentiated to form a central metallic core. The presence of a magnetic field in the current epoch suggests that the core is molten and convecting. Its varied surface displays ages from a few hundred millions years to billions of years, recording its history as it evolved from internal processes such as differentiation and tectonism and external processes such as asteroid impacts over the age of the solar system. Understanding Ganymede's formation and evolution is therefore central to understanding the Jupiter system as a whole and other large satellites of the solar system.

Ganymede is in a 1:2:4 resonance with the Galilean moons Io and Europa. Though tidal forces may have played a strong role in the heating of its interior in the past, there is no evidence of appreciable heat outflow from the moon at the current time. Galileo's magnetometer presented the evidence of an ocean in Ganymede from the electromagnetic induction signature that it generates in response to the rotating field of Jupiter and its magnetosphere. There is no evidence of recent cryovolcanic activity on Ganymede, but the subsurface may have warm regions where liquid water may exist in pockets.

Most of the information about Ganymede is derived from the eight flybys made by Galileo during 1995–2002. The best resolution global map has a resolution of 1 km and covers roughly two-thirds of the surface. Only a minor fraction of Ganymede was covered at a resolution of tens to hundreds of meters. However, these images paint a picture of a onetime active moon where lineaments crisscross the surface and activity occurs in an episodic fashion such that new lineaments create bright patches of grooved terrain rich in fresh ice and destroy the old dark terrain. It has been suggested that capture of Ganymede into the 1:2:4 resonance with Io and Europa may have been one of the episodes of intense activity in Ganymede. Only the much older surface of Ganymede would have preserved the clues of this capture, whereas Io's and Europa's much younger surfaces have since been resurfaced. Extremely low resolution infrared spectroscopic images show that spectral differences are related both to tectonics and the interaction of Ganymede with Jupiter's magnetosphere. The few high resolution infrared spectral images clearly show the presence of hydrated minerals similar in composition to those found on Europa, suggesting that brines may have had access to the surface. Infrared spectra also show absorption bands between 3.4 and 4.6 microns, providing evidence for trapped volatiles such as SO_2, CO_2, H_2S, and C-H bonds in tholins. Therefore, obtaining higher resolution global maps of Ganymede in visible wavelength at a scale of 100 meters or better and obtaining infrared spectral images with a resolution of tens to hundreds of meters over a few percent of the surface are high priorities.

Evidence of an internal ocean was provided mainly by the induction signal measured by the magnetometer. Because of the strong internal field of Ganymede (which is 15 times stronger than the induction field), the induction field needs to be reconfirmed from an orbiting spacecraft to take advantage of enhanced signal-to-noise ratio from averaging over harmonic signals present in induction, such as the synodic rotation period of Jupiter and the orbital period of Ganymede. In addition, other techniques can be used to further confirm the presence of an ocean. Theoretical studies suggest that tides caused by the eccentricity of Ganymede's orbit would vary by 3 meters if an ocean is present inside and would have an amplitude of much less than a meter if no ocean is present. The variable tides could be observed either by monitoring the gravity field of Ganymede from radio tracking (requires both range and Doppler measurements) or by monitoring time variations in the elevation of the surface from laser altimetry.

One of the conundrums of the Jovian system is that Ganymede is fully differentiated, whereas similarly sized Callisto is only partially differentiated (ice has separated from the rocks in the top layer). Callisto also shows no hint of past activity. Thus, a comparison of Ganymede with Callisto and Ganymede with the very active moons Europa and Io, which the Jupiter Europa Orbiter (JEO) mission would study, is a high priority for this mission.

The trailing hemisphere of Ganymede, which is more exposed to the magnetospheric-charged particles, shows the presence of molecular oxygen and ozone trapped in ice. The bright polar regions of Ganymede, which house the open field lines connected to Jupiter’s magnetosphere, show the evidence of frost formation from plasma bombardment (see Figure 1-1 for a diagram of Ganymede’s magnetosphere). In addition, micrometeorite gardening is suspected of reducing the ice grain size in the leading hemisphere. UV observations from Hubble of an airglow, which is excited when atomic oxygen is formed by the dissociation of molecular oxygen, provides the evidence of a thin atmosphere with a surface density in the range of 1-7 X 10^8 cm^3. The rather moderate atmosphere also supports a robust ionosphere, which further excites aurorae in the polar region. UV and neutral and ion mass spectrometry observations are thus required to fully understand the generation and retention of a molecular oxygen atmosphere on Ganymede.

Figure 1-1 shows a diagram of Ganymede’s magnetosphere based on magneto-hydrodynamic simulations. Three types of field lines are visible: fully open, which connect to Jupiter’s ionosphere on both ends; partially open, which connect at one end to Jupiter and the other end to Ganymede; and, finally, fully closed field lines in the equatorial region of Ganymede, which have both ends connected to Ganymede. Plasma cannot easily penetrate onto the region that contains fully closed field lines. The image is courtesy of Xianzhe Jia of the University of Michigan.

Ganymede’s field is three times stronger than that of Mercury, resulting in a permanent magnetosphere. Reconnection of fully closed field lines on the upstream side of Ganymede with the field lines of Jupiter’s magnetosphere results in a plasma convection process in Ganymede’s magnetosphere that convects flux and plasma in Ganymede’s magnetosphere over the polar caps. When these open flux tubes reach the far downstream regions, they merge together and become closed field lines, which then convect back to the upstream side at low latitudes. It appears that even in the highly steady state upstream conditions, the reconnection process is highly sporadic in Ganymede’s magnetosphere, providing us a natural plasma laboratory to understand plasma processes in astrophysical plasma. A good complement of field and plasma instruments (magnetometer, plasma package and, if possible, plasma wave spectrometer) would be required to fully explore the boundaries and the interior of Ganymede’s magnetosphere.

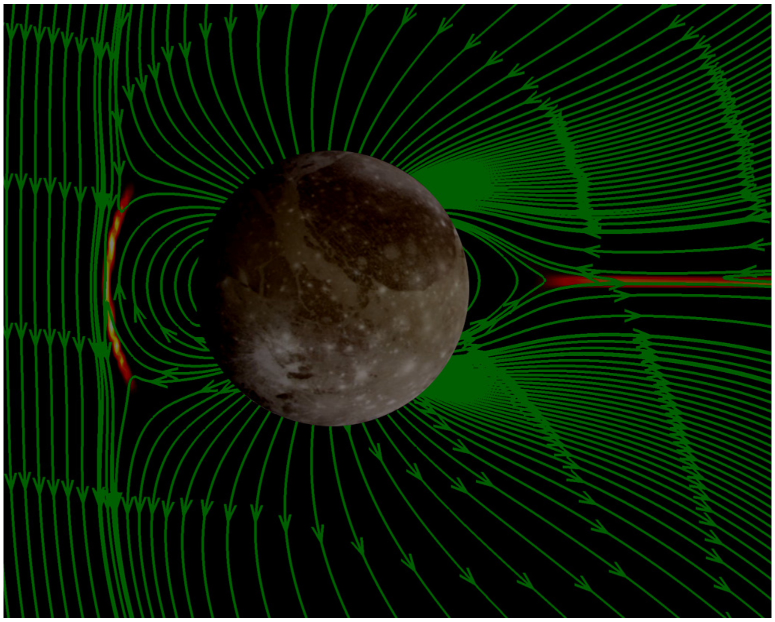


Figure 1-1. Ganymede's Magnetosphere

Science Questions and Objectives

The key science objectives are listed in priority order, from highest to lowest. Details pertaining to the required measurements are shown in Table 1-1, the science traceability matrix.

The overarching goal of the Ganymede mission concept is to gain new insight into the origin and evolution of the Jupiter system by comparing and contrasting the Europa–Io pair to be studied by the future JEO mission with the Ganymede–Callisto pair to be studied by the future Ganymede mission.

The prioritized science objectives, from highest to lowest, are as follows:

1. Ganymede’s ocean: Further characterize Ganymede’s subsurface ocean. What are its physical properties such as location, thickness, and composition?
2. Ganymede’s geology: Is Ganymede’s surface in contact with the ocean? What is the nature of its geological history, including tectonism, icy volcanism, viscous modification of the surface, and other resurfacing mechanisms such as asteroid/comet and micrometeoroid impacts?
3. Ganymede’s magnetic field and magnetosphere: How is the magnetic field of Ganymede generated? Characterize its unique magnetosphere.
4. Ganymede’s origins: What does the current physical and chemical state of Ganymede tell us about its origin and evolution?
5. Ganymede’s deep interior structure: Characterize Ganymede’s gravity anomalies and place constraints on the size and composition of its core and rocky and icy mantles.
6. Ganymede’s interaction with the rest of the Jovian system:
    a. Laplace resonance and its role in maintaining tidal heating in Io, Europa, and Ganymede.
    b. How much plasma is picked up near Ganymede and how is the surface of Ganymede modified by the impacting plasma?
    c. What is the structure and dynamics of Jupiter’s atmosphere and magnetosphere?
7. Ganymede’s atmospheric composition and structure: Characterize its variability in space and time.
8. Callisto’s ocean and interior: Further characterize Callisto’s subsurface ocean. Is most of Callisto undifferentiated?

Science Traceability

The science traceability matrix shows the desired science objectives and measurement requirements. The matrix describes the linkages between science objectives and how they are achieved. It also permits selection of payload instrumentation responsive to the mission science priorities. Note that functional requirements are requirements placed by science on the mission concept (e.g., requirements on the flight system, trajectory, mission architecture, etc.). In some cases, the mission design does not meet the measurement requirements. In these cases, a pragmatic compromise has been made between meeting the measurement requirements and mission cost/risk.

Table 1-1. Science Traceability Matrix

	Science Objectives	Measurement	Instrument	Functional Requirement
1	Ganymede's Ocean: Does Ganymede have a subsurface ocean? What are its physical properties such as location, thickness and composition?	Obtain topographic profiles at 1-m vertical resolution as a function of orbital phase to map static and time-variable topography	Laser Altimeter	15 tie points with different phase based on satellite harmonics for calibration in additional to global mapping
		Time variations of the degree-2 gravity field to an accuracy of 1E-8 m/s^2 to yield tidally induced distortion of satellite interior	Doppler tracking	Tracking at X & Ka-bands Requires USO on the spacecraft
		Measure time-varying vector magnetic field at the Jovian spin and Ganymede orbital period with a resolution 0.1 nT and cadence of 1 sec	Magnetometer	Dual magnetometers preferred to remove spacecraft interference Minimum 3 months time in orbit
2	Ganymede's Geology: Is Ganymede's surface in contact with the ocean? What is the nature of its geological history, including tectonism, viscous modification of the surface, and other resurfacing mechanisms such as asteroid/comet and micrometeoroid impacts?	Imaging (One filter / panchromatic filter) with a resolution of 200 m/pxl for at least 50 % of the surface area	Medium Resolution Camera	Color filters Coherent image mosaics (camera data) at given spatial resolution and viewing angle (not too oblique plus suitable sun elevation - e.g. mid-morning/mid-afternoon)
		Mid-res global surface coverage (~ 500 m/pxl)		
		Global surface coverage (~1–2 km/pxl) using four spectral filters from about 350 nm to 1000 nm		
		Characterize the spectral properties of surface with a resolution of 500 m/pixel over 1280 bands in visible and infrared	VIRHIS	Small phase angles (< 70 degrees)
		High-res coverage (~10s of m/pixel) of targeted areas	Narrow Angle Camera	Extended phases beyond 3 months required to get enough targets
		--	Subsurface Radar	High bandwidth requires 1 year time in orbit.
3	Ganymede's magnetic field and magnetosphere: How is the magnetic field of Ganymede generated? Characterize its unique magnetosphere	Characterize the internal magnetic field to order and degree 10. Look for secular variations in the dipolar component by comparing with Galileo measurements	Magnetometer	A magnetometer boom of > 5 meter required to reduce interference from spacecraft. Synergistic science with future JEO possible.
		Explore the boundaries, structures and dynamics of Ganymede's magnetosphere by making continuous field and plasma measurements in the magnetosphere	Plasma Package	Continuously measure fluxes of ions and electrons from 10 eV to 1 MeV over 4π steradians with a E/dE = 20 and cadence of 10 s

	Science Objectives	Measurement	Instrument	Functional Requirement
4 & 5	Origins: What does the current physical and chemical state of Ganymede tell us about its origin and evolution? Ganymede's interior structure: Characterize Ganymede's gravity anomalies and place constraints on the size and composition of its core and mantle	Identify Ganymede's stratigraphic and structural units and their relationships at high resolution (10 m/pixel) to understand how tectonism works on Ganymede	MRC, NAC	--
		Characterize the gravity field to order and degree 10	Doppler	Requires USO
		Characterize the internal magnetic field to order and degree 10	Magnetometer	Magnetometer boom > 5 meters in length.
6 & 7	Ganymede's interaction with the rest of the Jovian system: Laplace resonance and its role in maintaining tidal heating in Io, Europa and Ganymede. How much plasma is picked up near Ganymede and how is the surface of Ganymede modified by the impacting plasma, what is the structure and dynamics of Jupiter's magnetosphere?	Constrain the tidally varying potential and shape - Time dependent altimetry and gravity to determine Love numbers h2 (tidal amplitudes) and k2 (tidal potential) at an accuracy of 0.01	Laser Altimeter, Doppler	Return to the same location on Ganymede (> 5 times) at different phases of its orbit. Tracking at X & Ka-bands Requires USO on the spacecraft
		Measure the pole position with an accuracy of 10 m to determine the obliquity and libration of the spin axis over a temporal baseline of > 3 years	MRC	May require extended mission.
		Measure the sputtered neutral and charged particles in the atmosphere and exosphere of Ganymede	INMS	Low altitude orbits desired (20-50 km). Feasible at 100 km but long integration times.
		Characterize the auroral emissions from Ganymede	UVIS	Off nadir pointing required to image the auroral curtain.
		Color ratio global maps of Ganymede's surface in visible and infrared with a resolution of 500 m/pixel	VIRHIS	Phase angle < 70 degree.
		Measure magnetic field (resolution of 0.1 nT and cadence of 1 s) Some orbits in Jupiter's magnetotail with apojove of > 100 Rj	Magnetometer	Dual magnetometer to remove interference from s/c.
		Measure plasma fluxes (10 eV to 1 MV, ions and electrons with a 4π coverage in Ganymede's and Jupiter's magnetosphere	Plasma Package	--
		Measure plasma and radio waves in Ganymede and Jupiter's magnetosphere to understand field and plasma interactions in these magnetospheres	Plasma Wave Spectrometer	Extremely high bandwidth requires minimum 1 year residence in orbit.
8	Callisto's ocean and interior: Does Callisto have an ocean? Is most of Callisto undifferentiated?	Characterize Callisto's gravity field to order 2	Doppler	Requires USO.
		Characterize the induction field at the Jovian spin and Callisto orbital periods	Magnetometer	Multiple flybys (5 or more) at different phases of Callisto's orbit.
		Look for signs of former endogenic activity on Callisto in images with a resolution of at least 10 m/pixel over at least 10% of its surface	MRC, WAC, NAC	Multiple flybys whose tracks on Callisto cover a range of longitudes and latitudes.

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 mission and flight system architecture suitable to perform a scientifically viable Ganymede Orbiter (GO) mission responsive to science traceability matrix (STM) requirements formulated by the Science Champion designated by the Decadal Survey Satellites panel. Increased mission duration and modest enhancements to the flight system were used to accommodate enhanced payloads for a "Baseline" and an "Augmented" mission.

The Science Champion was specifically interested in a mission that would fit within NASA's New Frontiers proposal constraints. Architecture trade space analyses as well as detailed point designs were to be performed by JPL. To meet the study's needs, the work was divided into two phases: (1) an initial examination of the architecture trade space by a standalone study team staffed by generalists and specialists chosen for their knowledge relevant to the problem; and (2) detailed point design and cost estimating of the mission architectures emerging from the standalone team's analyses by JPL's concurrent engineering team—Team X. This arrangement allowed for a free-ranging exploration of possible mission architectures by the standalone team, followed by a detailed point design phase leveraging the efficiency and experience of Team X designing spacecraft and costing total mission architectures, areas routinely handled by Team X. The work was done in close coordination with the Decadal Survey's Satellite Subpanel, with panel members actively engaged throughout the process in the design decisions leading to the Ganymede Orbiter mission described in this study report.

Table 2-1 shows the key requirements and constraints identified by the study team to guide the Ganymede Orbiter mission design. The requirements and constraints in Table 2-1 were selected on the basis that they were: 1) required by the NASA Decadal Survey ground rules, 2) identified by the Science Champion as critical to achieving the mission science objectives, or 3) identified by the Ganymede study team as essential to the achievement of an affordable, low-risk flight system design.

Table 2-1. Key Project Requirements and Constraints

Requirements/Constraints	Origin/Comments
Project/Systems Engineering	
Arrival in the Jupiter system in 2026–2029 (during future EJSM). Accommodate JPL design principles. Accommodate NASA Planetary Protection requirements. Class B mission.	Science Champion Ganymede Study Team Ganymede Study Team Ganymede Study Team
Mission Design	
Accommodate minimum 3-month Ganymede orbital tour, 6-month and 12-month options.	Science Champion/ Ganymede Study Team Minimize flight system exposure to Ganymede radiation
Payload	
Accommodate Science-Panel-defined payload options: Floor, Baseline, and Augmented	Affects flight system pointing, instrument duty cycles, coverage strategy, and mission design
Payload data compression is not to exceed a factor of 3 to 5 (i.e., "lossless").	Science Champion Affects instrument internal design and/or flight system Command and Data Handling subsystem

Requirements/Constraints	Origin/Comments
Operations	
Accommodate payload data acquisition requirements	Need accurate flight system position knowledge during altimetry measurements Need eight “turns to limb” for the UV imaging spectrometer measurements
Flight System	
No new technology	Goal. Minimize project cost/risk
Conventional bi-prop propulsion, solar power, 3-axis stabilization	Minimize flight system cost/risk. Accommodate payload pointing
Accommodate instruments and instrument duty cycles	--
Accommodate radiation environment with an RDM = 2	Total mission dose is 325 krad behind 100 mils AL with RDM = 1 for the 3-month Ganymede orbital tour (Floor mission). One-year Ganymede orbital tour dose is 250 krads behind 100 mils AL with RDM = 1.
Use Ka-band for data downlink	Decadal Survey ground rule
Downlink data rate at Ganymede in the range 40 to 70 Kbps	Goal for the study intended to help minimize flight system mass/cost
0.01 deg (3 sigma) pointing for a fixed high-gain antenna	Up to 0.05 deg pointing acceptable. Fixed HGA to minimize flight system mass/complexity/cost
2-DOF solar array if needed	0 or 1 DOF acceptable if good trade
Ground System	
34-meter DSN antenna	Decadal Survey ground rule
One antenna at each DSN site (i.e., no arraying)	Study team interpretation of Decadal Survey ground rule

The core principle driving the Ganymede mission design was to design a mission and flight system architecture suitable to perform a scientifically viable, “Floor” Ganymede mission responsive to the Ganymede science traceability matrix requirements and to use increased mission duration with modest (if any) enhancements in flight system capabilities to accommodate enhanced payload options. This core principle was chosen because the Ganymede study team considered it offered the lowest cost and lowest risk pathway to achieving the “Floor” mission objectives and accommodating the more ambitious “Baseline” and “Augmented” mission objectives.

In response to the core principle, three mission options, each with increasing mission duration, science return, and cost, were identified for study:

- **“Floor” mission:** three months in Ganymede orbit.
  Wide angle and medium resolution cameras, magnetometer, radio science and micro laser altimeter, visual/near IR imaging spectrometer, and plasma packages.
- **“Baseline” mission:** six months in Ganymede orbit.
  Floor mission plus ion and neutral mass spectrometer and UV imaging spectrometer.
- **“Augmented” mission:** one year in Ganymede orbit.
  Baseline mission plus radio and plasma wave instrument, narrow angle camera, and sub-surface radar.

Given the core principle, and the success the study team had in implementing it, the mission, flight system, operations, and ground system elements that emerged from the study were nearly generic for the three mission options, with the principal differences between the options limited to the instrument payloads and increased shielding mass due to the increased mission duration. Therefore, throughout the report, unless specifically stated otherwise, the mission design parameters for all three options are the same.

In summary, as described in detail in later sections of this report, a mission system architecture consisting of the following elements was selected for the Ganymede mission:

- Atlas V launch vehicle: Atlas V 541 (Floor option), Atlas V 551 (Baseline option), and Atlas V 551 (Augmented option)
- EVEEJ gravity assist trajectory, with three mission phases: Heliocentric, Jupiter (JOI to GOI), and Ganymede Orbital Operations
- Three science data acquisition/observation phases: Ganymede Flyby Phase, Pump-down Phase, and Nominal Science (Orbital Tour) Phase
- Three- , six-, and twelve-month Ganymede orbital tour options: circular, polar, 90-deg inclination, 200-km altitude, 63-deg phase angle Ganymede orbit
- A three-axis-stablized, solar powered spacecraft, with conventional bi-propellant propulsion; a continuously Earth-pointed, body-fixed HGA; a nadir-tracking scan platform; Ka-band science data downlink; and a "Juno-like" radiation vault to house sensitive electronics
- One 34-m DSN Ka-band ground station
- Instrument payload options consistent with the "Floor," "Baseline," and "Augmented" mission definitions

Concept Maturity Level

Table 2-2 summarizes the NASA definitions for concept maturity levels (CMLs). Upon completion of the Ganymede study, with point designs in place, all three identified mission options are considered to be at CML 4. The architectures studied were defined at the assembly level with estimates developed for mass, power, data volume, link rate, and cost using JPL's institutionally endorsed design and cost tools. Risks were also identified and assessed as to their likelihood and mission impact, as discussed later in the report.

Table 2-2. 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

All flight system elements—spacecraft and instruments—are currently at or above TRL 6, with no new technology development required.

For the spacecraft, the key required Ganymede flight system elements are being developed and demonstrated for Jupiter applications on the Juno mission. These would include the solar array and radiation vault. The Ganymede Orbiter solar array panels would be similar in size or just slightly larger than the Juno mission arrays and would be exposed to a lower total radiation dose. The Ganymede Orbiter-required vault thickness would be less than required for Juno. Therefore, the subsystem and overall spacecraft design would be high heritage based on technology that would already have flown. However, the telecommunications subsystem does make use of a universal space transponder (UST) that, while not currently flight qualified, is planned for flight demonstration on the 2016 ExoMars mission.

The instruments are all based on technology that is either highly developed or has already flown, as shown in Table 3-1. For the instruments, only engineering development necessary to accommodate the mission life and accommodate the Ganymede radiation environment would be required.

Key Trades

Propulsion (Conventional versus Solar Electric Propulsion)

A trade study looked at the potential benefit of using solar electric propulsion (SEP) to increase delivered mass to Ganymede and potentially enable use of a smaller launch vehicle with its attendant cost savings. A SEP system would save 0.4-year in flight time. Due to lower C3 requirement [0.5 $(km/s)^2$ versus 13.75 $(km/s)^2$], the SEP option would allow for a smaller launch vehicle (LV), with a cost saving of ~$14M. This cost saving would be offset by extra cost associated with development of the SEP system: an additional $46.4M. This would include $13M for NExT engine/PPU development and qualification and added project cost. Besides the cost, there would be schedule risks associated with engine/PPU qualification and SEP operations. Whether chemical or SEP, the large delta-V required at Jupiter would be the same (2606 m/s), with SEP helping only in reducing the LV required performance by one step, saving the ~$14M. Therefore, the net SEP option cost is estimated to be ~$30M more than the all-chemical option plus an unquantified additional cost for SEP during Phase E operations. In addition, the SEP option would be expected to increase risk. Therefore, the conventional chemical option was selected.

Power (Solar versus Nuclear)

The NASA Decadal Survey study guidelines require the use of solar power unless nuclear power is enabling. The solar power design developed for the Ganymede mission would require similar power levels to the Juno mission, experience lower radiation than the Juno mission, and operate at similar range, with the required array sizes for all three mission options readily achievable with conventional array materials and design techniques. The solar-powered Juno mission will fly this decade, therefore demonstrating the required Ganymede performance. Nuclear power is therefore not enabling, resulting in the selection of solar power.

Attitude Control (Three-axis Stabilization versus Spin Stabilization)

Three-axis stabilization would be selected because the Ganymede mission science objectives emphasize measurements favoring three-axis stabilization. This would include imaging, spectroscopy, altimetry, and radar measurements. The estimated mass savings of several tens of kilograms attendant to the use of spin stabilization would not be enough to enable significant mission/system architecture advantages: launch vehicle downsize or payload enhancement, for instance. Instrument accommodation advantages are significantly more valuable than modest mass savings, so three-axis stabilization would be selected for this study.

3. Technical Overview

Instrument Payload Description

The candidate science instrumentation consists of cameras, spectrometers, an altimeter, a radar, and field and particle instruments. Some instruments require nadir pointing and are accommodated on an instrument scan platform. Instruments not requiring nadir pointing are either spacecraft body-fixed or boom mounted. The selection of the notional mission instrumentation was based on three main criteria:

1. Ability to meet science objectives
2. Resource requirements
3. Maturity

The goal of the notional instrumentation selected in this study is to access rough-order flight system resource requirements including, in particular, mass and power, and instrument drivers for the mission and flight system architectures. Table 3-1 shows the instruments selected for the three mission options, and Tables 3-2 through 3-12 provide details for each of the instruments.

Table 3-1. Instrument Summary

Payload Suite			Instrument Name	No. of Units	TRL	Heritage Instruments	Total + Cont. (kg)	Op. Power CBE (W)	Stand by Power (W)
Opt. 3—Augmented Payload	Opt. 2—Baseline Payload	Opt. 1—Floor Payload	Medium Resolution Camera	1	9	Mars PanCam	4.60	13	2
			ST5 Flux Gate Magnetometer	2	9	Galileo	1.27	1	1
			V/NIR Imaging Spectrometer	1	7	Ralph, VIMS	19.55	20	2
			Laser Altimeter	1	6	LOLA, MOLA	23.00	31	2
			Plasma Package #1 (Low Energy)	2	6	PEPSSI, PEPE	6.81	2	1
			Plasma Package #2 (High Energy)	1	6	IMAGE Mission	1.64	1	1
			Ion and Neutral Mass Spectrometer	1	9	Cassini	11.85	32	2
			UV Imaging Spec.	1	8	Cassini, Galileo	5.95	5	1
			Radio and Plasma Wave Instrument	1	9	Cassini	43.33	16	2
			Narrow Angle Camera	1	9	LORRI, MRO	9.20	15	2
			Sub-Surface Radar	1	7	MARSIS, CHARAD	20.75	39	2

Opt. 1—Floor Payload Totals	**56.87**	**68**
Opt. 2—Baseline Payload Totals	**74.67**	**104**
Opt. 3—Augmented Payload Totals	**147.94**	**175**

Instrument 1—Medium Resolution Camera (MRC)

MRC would be primarily used to acquire Ganymede surface imagery, which is helpful in understanding Ganymede's geology, geodesy, and geophysics.

Observation requirement:

5 global coverage of Ganymede surface

- 1–50-m resolution panchromatic
- 4–200-m resolution in four colors

This instrument would operate in push-broom mode during satellite flybys as well as during the orbit phase. The camera is nadir pointed and would acquire imagery when target surface areas are in direct sunlight. Though it is understood that imaging may be possible on the dark side due to surface illumination by Jupiter, the baseline observation strategy is to only make observations during direct illumination from the sun.

Calibrations would include a camera-pointing alignment and radiometric calibration from star observations.

Table 3-2. Medium Resolution Camera (MRC)

Item	Value	Units
Type of instrument	Optical	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.25x0.05x0.05	m x m x m
Instrument mass **without** contingency (CBE*)	4	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	5.2	kg
Instrument average payload power **without** contingency	13	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	16.9	W
Instrument average science data rate^ **without** contingency	6400	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	6400	kbps
Instrument fields of view (if appropriate)	14.7	degrees
Pointing requirements (knowledge)	0.25	degrees
Pointing requirements (control)	0.50	degrees
Pointing requirements (stability)	26	arcsec/sec

*CBE = Current best estimate

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

Instrument 2—ST5 Flux Gate Magnetometer (FGM)

Two boom-mounted magnetometers would be used to measure the magnetic field. The instrument would be operated continuously with simple on/off and data rate commands. During magnetically steady regions of cruise, low-rate magnetometer data would be gathered. Magnetometers would be the first instrument to be switched on so that magnetic disturbances from other instrumentation could be understood.

Calibration would occur on the ground so that spacecraft-induced fields could be determined from in-flight calibrations.

Table 3-3. ST5 Flux Gate Magnetometer (FGM)

Item	Value	Units
Type of instrument	Fields	--
Number of channels	2	--
Size/dimensions (for each instrument)	0.1x0.2x0.05	m x m x m
Instrument mass **without** contingency (CBE*)	0.6	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	0.9	kg
Instrument average payload power **without** contingency	0.6	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	0.7	W
Instrument average science data rate^ **without** contingency	0.9	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	0.88	kbps
Instrument fields of view (if appropriate)	N/A	degrees
Pointing requirements (knowledge)	2	degrees
Pointing requirements (control)	2	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Instrument 3—V/NIR Imaging Spectrometer (VNIRIS)

VNIRIS is a visible and infrared hyperspectral imaging spectrometer that would allow inferring the surface/ atmosphere composition of a target by measuring the emitted spectral radiance (W m-2 µm-1 sr-1). Its spectral range is 0.4-5.2 um with 3.4-deg field of view (FOV). The instrument is composed of a deployable optical head with cover and a harness with less than 1-m length between the optical head and electronics. The detector would be passively cooled by an external radiator with view to space.

Table 3-4. V/NIR Imaging Spectrometer (VNIRIS)

Item	Value	Units
Type of instrument	Optical	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.3x0.25x0.2 sensor 0.5x0.4x0.3 electronics	m x m x m
Instrument mass **without** contingency (CBE*)	17	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	22.1	kg
Instrument average payload power **without** contingency	20	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	26	W
Instrument average science data rate^ **without** contingency	5000	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	5000	kbps
Instrument fields of view (if appropriate)	3.4	degrees
Pointing requirements (knowledge)	0.03	degrees

Item	Value	Units
Pointing requirements (control)	0.06	degrees
Pointing requirements (stability)	13	arcsec/sec

*CBE = Current best estimate

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

Instrument 4—Laser Altimeter (LA)

The LA is a modified copy of the lunar orbiter laser altimeter (LOLA). It would be used to produce a high-resolution (1-meter vertical resolution, 50-meter horizontal resolution) global topographic map and geodetic framework.

Table 3-5. Laser Altimeter (LA)

Item	Value	Units
Type of instrument	Optical	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.45x0.51x0.36	m x m x m
Instrument mass **without** contingency (CBE*)	12.6	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	16.4	kg
Instrument average payload power **without** contingency	31.3	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	40.7	W
Instrument average science data rate^ **without** contingency	28	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	28	kbps
Instrument fields of view (if appropriate)	0.0057	degrees
Pointing requirements (knowledge)	0.015	degrees
Pointing requirements (control)	0.03	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

The LA could be operated during day and night; however, during the day, observations would have to overcome solar background noise.

Ranging measurements would support spacecraft tracking and gravity field modeling.

Instrument 5—Plasma Package #1 (Low Energy)

This package is composed of two electrostatic analyzers (ESAs) that would measure how many electrons and ions they detect with a specified energy from a certain direction at a given time (the particle distribution function) over the energy range from ~3 eV to 30 keV. These thermal electrons and ions are the particles responsible for creating the aurora. The ESA measurements would allow scientists to derive the density, velocity, and temperature of the ambient electrons and ions (plasma).

Table 3-6. Plasma Package #1 (Low Energy)

Item	Value	Units
Type of instrument	Particle	--
Number of channels	2	--
Size/dimensions (for each instrument)	TBP	m x m x m

Item	Value	Units
Instrument mass **without** contingency (CBE*)	3	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	4.7	kg
Instrument average payload power **without** contingency	1.7	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	2.2	W
Instrument average science data rate^ **without** contingency	40	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	40	kbps
Instrument fields of view (if appropriate)	4 Pi	steradians
Pointing requirements (knowledge)	N/A	degrees
Pointing requirements (control)	5	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Instrument 6—Plasma Package #2 (High Energy)

The second plasma package consists of a solid state telescope (SST) that would measure superthermal particle distribution functions, namely the number of ions and electrons coming towards the spacecraft from specified directions with specified energies within the energy range from 25 keV to 6 MeV. These particles are much more energetic (and therefore superthermal) than the main magnetospheric population, but they are quite important as tracers of acceleration and heating in the magnetosphere.

Table 3-7. Plasma Package #2 (High Energy)

Item	Value	Units
Type of instrument	Particle	--
Number of channels	1	--
Size/dimensions (for each instrument)	TBP	m x m x m
Instrument mass **without** contingency (CBE*)	1.4	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	1.9	kg
Instrument average payload power **without** contingency	1.2	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	1.6	W
Instrument average science data rate^ **without** contingency	40	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	40	kbps
Instrument fields of view (if appropriate)	4 Pi	steradians
Pointing requirements (knowledge)	N/A	degrees
Pointing requirements (control)	5	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Instrument 7—Ion and Neutral Mass Spectrometer (INMS)

This instrument would be a copy of the Cassini orbiter ion and neutral mass spectrometer (INMS) design. It would measure the positive ion and neutral species composition and structure in the upper atmosphere of Ganymede and magnetosphere of Jupiter as well as measure the positive ion and neutral environments of Ganymede. The major functional components of the INMS instrument are an open ion source, a closed ion source, a quadrupole deflector and lens system, a quadrupole mass analyzer, and a dual detector system.

Table 3-8. Ion and Neutral Mass Spectrometer (INMS)

Item	Value	Units
Type of instrument	Particle	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.42x0.37x0.20	m x m x m
Instrument mass **without** contingency (CBE*)	10.3	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	13.4	kg
Instrument average payload power **without** contingency	31.9	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	41.5	W
Instrument average science data rate^ **without** contingency	1.5	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	1.51	kbps
Instrument fields of view (if appropriate)	100	degrees
Pointing requirements (knowledge)	N/A	degrees
Pointing requirements (control)	5	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Instrument 8—UV Imaging Spectrometer (UVIS)

The Cassegrain telescope of the UVIS has a 250-millimeter aperture and collects light from the observation target. The UVIS instrument uses a ruled grating to disperse this light for spectral analysis. This light then passes through an exit slit into photomultiplier tubes that produce pulses or "sprays" of electrons. These electron pulses are counted, and these count numbers are the data that are sent to Earth. The UVIS would preferably be located at the corner of an articulated 2-degree of freedom scan platform.

Table 3-9. UV Imaging Spectrometer (UVIS)

Item	Value	Units
Type of instrument	Optical	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.48x0.2x0.33	m x m x m
Instrument mass **without** contingency (CBE*)	5.1	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	6.7	kg
Instrument average payload power **without** contingency	4.7	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	6.1	W

Item	Value	Units
Instrument average science data rate^ **without** contingency	403.2	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	403.2	kbps
Instrument fields of view (if appropriate)	0.1x2.0	degrees
Pointing requirements (knowledge)	0.1	degrees
Pointing requirements (control)	0.2	degrees
Pointing requirements (stability)	180	arcsec/sec

*CBE = Current best estimate

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

Instrument 9—Radio and Plasma Wave Instrument (RPWI)

The radio and plasma wave instrument (RPWI) instrument would receive and measure the radio signals coming from Ganymede, including the radio waves given off by the interaction of the solar wind with Jupiter and its moons. The instrument would study the configuration of Ganymede's magnetic field and its interaction with the Jovian system. It would also monitor and map Ganymede's ionosphere and plasma and lightning from Jupiter's atmosphere.

Table 3-10. Radio and Plasma Wave Instrument (RPWI)

Item	Value	Units
Type of instrument	Electromagnetic	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.15x0.15x0.08	m x m x m
Instrument mass **without** contingency (CBE*)	37.7	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	49	kg
Instrument average payload power **without** contingency	16.4	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	21.3	W
Instrument average science data rate^ **without** contingency	0.99	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	0.99	kbps
Instrument fields of view (if appropriate)	N/A	degrees
Pointing requirements (knowledge)	5	degrees
Pointing requirements (control)	5	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Instrument 10—Narrow Angle Camera (NAC)

The NAC would map Ganymede's surface with a 1.03 arcsec pixel size resolution.

Table 3-11. Narrow Angle Camera (NAC)

Item	Value	Units
Type of instrument	Optical	--
Number of channels	1	--
Size/dimensions (for each instrument)	0.5x0.2x0.2	m x m x m

Item	Value	Units
Instrument mass **without** contingency (CBE*)	8	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	10.4	kg
Instrument average payload power **without** contingency	15	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	19.5	W
Instrument average science data rate^ **without** contingency	25000	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	25000	kbps
Instrument fields of view (if appropriate)	0.29	degrees
Pointing requirements (knowledge)	0.015	degrees
Pointing requirements (control)	0.03	degrees
Pointing requirements (stability)	5	arcsec/sec

*CBE = Current best estimate

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

Instrument 11—Sub-Surface Radar (SSR)

The SSR would map the distribution of water, both liquid and solid, in the upper crust of the Ganymede’s surface. Its antenna would be more than 10-m long (Mars Express deployed a 40-m antenna).

Table 3-12. Sub-Surface Radar (SSR)

Item	Value	Units
Type of instrument	Active EM	--
Number of channels	1	--
Size/dimensions (for each instrument)	TBP	m x m x m
Instrument mass **without** contingency (CBE*)	18	kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE+Reserve)	23.5	kg
Instrument average payload power **without** contingency	39	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	50.7	W
Instrument average science data rate^ **without** contingency	45	kbps
Instrument average science data^ rate contingency	0	%
Instrument average science data^ rate **with** contingency	45	kbps
Instrument fields of view (if appropriate)	57	degrees
Pointing requirements (knowledge)	1	degrees
Pointing requirements (control)	5	degrees
Pointing requirements (stability)	N/A	arcsec/sec

*CBE = Current best estimate

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

Flight System

The flight system would consist of a single Ganymede orbiter that enters Ganymede orbit following approximately a two-year period during which the spacecraft would be performing Ganymede and Callisto flybys while lowering its apoapsis with respect to its initial Jupiter polar orbit following Jupiter orbit insertion.

The nearly identical flight systems for each of the three mission options would employ three-axis stabilization and have the following: a continuously Earth-pointed, body-fixed HGA and a continuous nadir-tracking scan platform; a Ka-band science data downlink; solar power with three non-gimbaled solar arrays symmetrically mounted perpendicular to the HGA boresight; conventional bi-propellant chemical propulsion; a hexagonal-shaped spacecraft bus; and a ”Juno-like” radiation vault to house sensitive electronics.

The key requirement driving the flight system concept and operations strategy is the requirement for precision spacecraft location knowledge during altimetry measurements, which dictates that the spacecraft maintain a telecommunications link with the Earth during the measurements. This led to exploration of the concept that was ultimately selected for the Ganymede mission concept, which is a spacecraft with a body-fixed HGA, fixed solar arrays with the HGA continuously Earth-pointed, and a scan platform for instrument pointing to nadir. This design has the advantage of a relatively large antenna and solar array that would not require large, costly gimbal mechanisms, while at the same time would be implementable with modest impact on solar array size and mass (and lower cost to increase array size than to add gimbals to the HGA and solar arrays). This would make up for the small (<2%) predicted cosine power loss penalty attendant to off-pointing the arrays from sun normal to maintain continuous HGA Earth pointing.

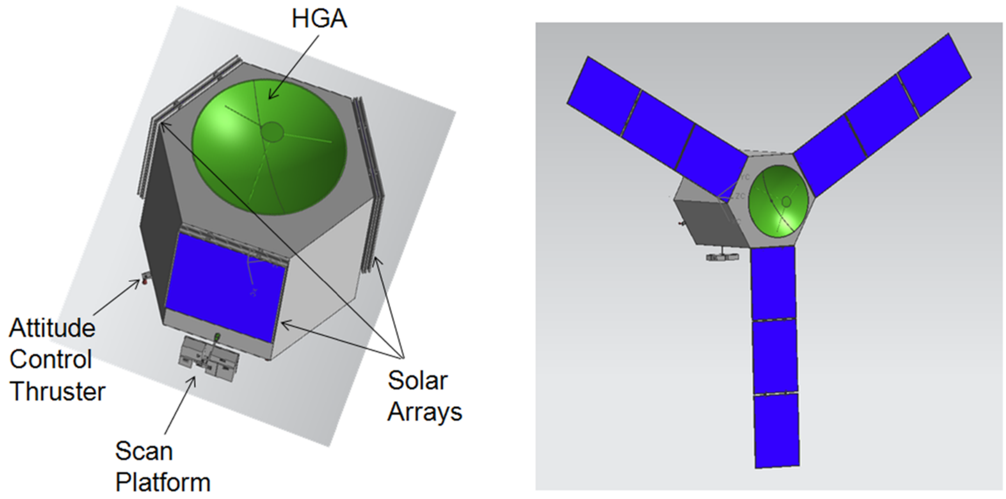
The flight system would be dual string with cold spares, with a 3-m-diameter HGA antenna and a total solar array area, dependant on mission option, of 64–70 m^2 divided among three array panels. The solar arrays would be approximately the same size or slightly larger than the Juno mission arrays. The power system design is driven by the long Jupiter eclipse and the gravity science requirement for spacecraft location knowledge during the altimetry measurements, requiring, as previously discussed, a concurrent downlink with the Earth. The scan platform would use redundant gimbal drive electronics and fault tolerant windings in the gimbal drive motors. Science data post-processing would be utilized to remove the effects of instrument rotation about the spacecraft ground track, with the addition of a third degree of freedom to the scan platform (rotation about the platform boesight), an option to eliminate the rotation effects at the source. The internal spacecraft configuration was driven by the desire to minimize required heater power. To do so, the electronics vault would be placed at the center of the bus between the propellant tanks, thereby permitting the use of its waste heat for tank heating. Additionally, to minimize heater power requirements, radioisotope heater units would be used.

To protect sensitive electronics from the total ionizing dose (TID), a “Juno-like” central electronics radiation vault along with smaller dispersed instrument vaults would be utilized. The vault design is based directly on the Juno design. The radiation vault would include enough shielding to lower the total radiation dose to levels that existing avionics can survive, eliminating the need for technology development. Required shielding mass would be increased for the longer duration mission options to maintain the same total dose inside the vault for the three options.

Figure 3-1 shows the spacecraft in its stowed and deployed configurations, and Figure 3-2 shows the flight system functional block diagram.

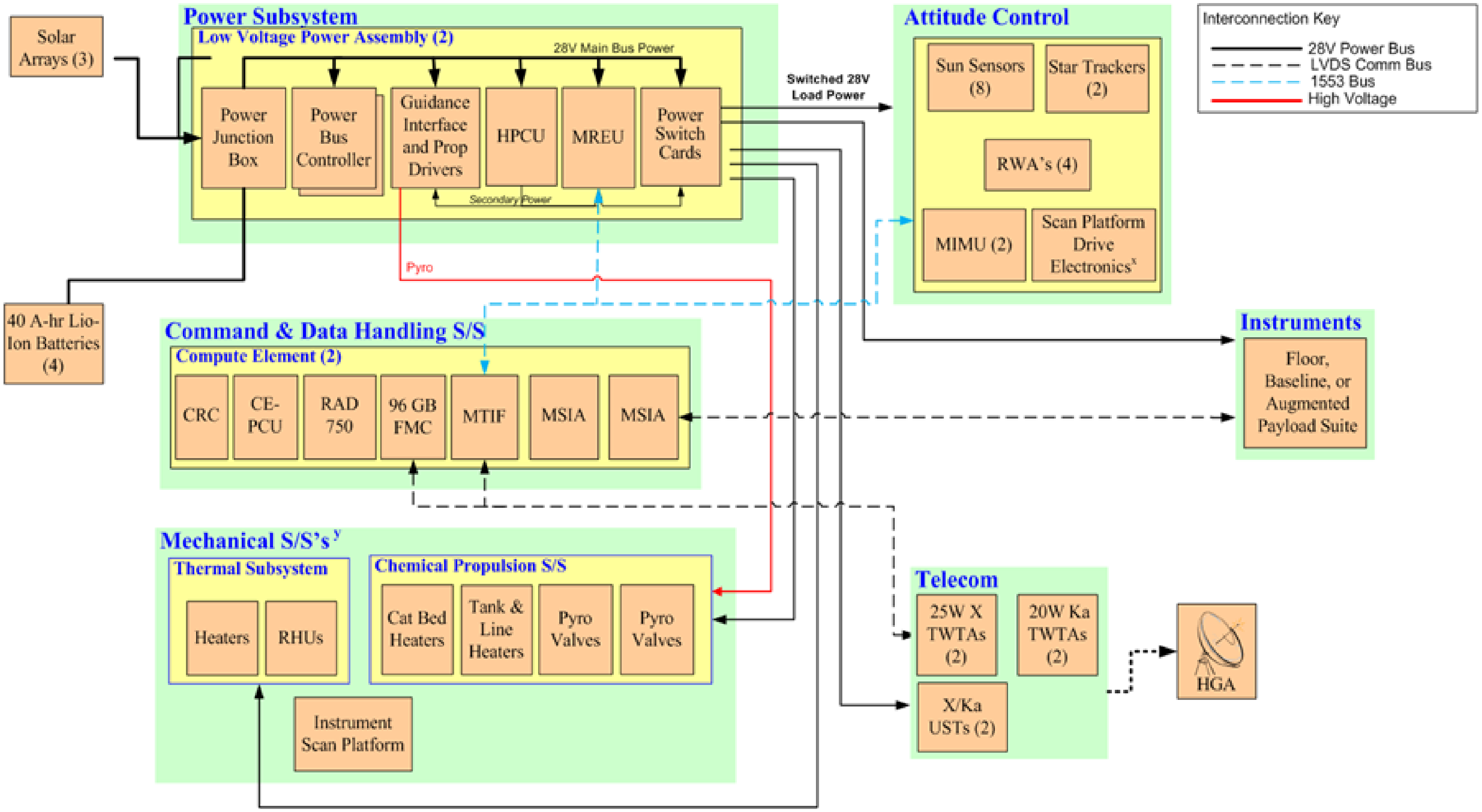
Tables 3-13 through 3-15 provide mass summaries for the three mission options. The mass differences between the options originate primarily from structures and instruments. This reflects the additional vault mass required to accommodate the higher radiation doses during the longer duration mission options 2 and 3 and the additional instruments in options 2 and 3. The additional science instruments add mass but are assumed to operate during the period of the additional science duration only, thus minimizing demands for additional power. For example, the ion and neutral mass spectrometer and the UV imaging spectrometer added in option 2 are assumed to operate only during months three to six of the science orbit, thereby minimizing the impact of payload growth on the flight system design. All subsystems apply a 30% mass contingency to the current best estimate (CBE). Additionally, in accord with JPL design principles, an additional 13% contingency is added to spacecraft dry mass. This ensures that the spacecraft dry mass has 43% contingency.

Tables 3-16 through 3-18 show the power requirements and modes. Table 3-19 provides an overall summary of the flight system characteristics for the three options.



Stowed **Deployed**

Figure 3-1. Flight System Configuration—All Options



Notes: 1) Fully redundant S/C design.

2) Internally redundant scan platform.

3) Fully redundant Thermal Subsystem. String redundant Propulsion Subsystem.

Figure 3-2. Flight System Functional Block Diagram—All Options

Table 3-13. Flight System Element and Total Spacecraft Mass—Option 1

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms (including S/C adapter & harness)	599.6	30	779.5	See details in Flight System Element Power Modes tables.		
Thermal control	65.1	30	84.6			
Propulsion (dry mass)	145.7	30	189.4			
Attitude control	31.2	30	40.6			
Command & data handling	23	30	29.9			
Telecommunications	71.4	30	92.8			
Power	239.9	30	311.9			
Total Flight Element Dry Bus Mass	**1175.9**	**30**	**1528.7**			
Instruments	49.5	30	64.35			
System Contingency	-	13	159.3			
Total Spacecraft Dry Mass	**1225.4**	**43**	**1752.3**			

Table 3-14. Flight System Element and Total Spacecraft Mass—Option 2

	Mass			**Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms (including S/C adapter & harness)	647.1	30	841.2	See details in Flight System Element Power Modes tables.		
Thermal control	66.7	30	86.7			
Propulsion (dry mass)	153.6	30	199.7			
Attitude control	31.2	30	40.6			
Command & data handling	24.4	30	31.7			
Telecommunications	71.4	30	92.8			
Power	240.4	30	312.5			
Total Flight Element Dry Bus Mass	**1234.8**	**30**	**1605.2**			
Instruments	64.9	30	84.4			
Systems Contingency	-	13	169			
Total Spacecraft Dry Mass	**1299.7**	**43**	**1858.6**			

Table 3-15. Flight System Element and Total Spacecraft Mass—Option 3

	Mass			**Driving Average Power**		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms (including S/C adapter & harness)	726.7	30	944.7	See details in Flight System Element Power Modes tables.		
Thermal control	67.5	30	87.8			
Propulsion (dry mass)	154.6	30	201			
Attitude control	31.2	30	40.6			
Command & data handling	24.4	30	31.7			
Telecommunications	71.4	30	92.8			
Power	249.4	30	324.2			
Total Flight Element Dry Bus Mass	**1325.2**	**30**	**1722.8**			
Instruments	128.6	30	167.2			
Systems Contingency	-	13	189			
Total Spacecraft Dry Mass	**1453.8**	**43**	**2078.9**			

Table 3-16. Flight System Element Power and Modes—Option 1

Subsystem/Instrument	Power [W]								
	Launch	Cruise	Fly-by	Ganymede Pump	Science + Telecom	Science	Telecom	SAFE	Jupiter Eclipse
Instruments	8.6	9.5	39.0	27.5	47.9	19.1	9.5	9.0	9.5
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Control	11.8	17.7	17.7	17.7	18.1	17.7	17.7	18.1	33.4
Propulsion	51.6	3.3	51.6	51.6	3.3	3.3	3.3	51.6	3.3
Attitude control	33.7	39.1	39.1	39.1	37.0	37.0	33.4	33.7	33.4
Command & data handling	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9	46.9
Telecommunications	76.0	76.0	15.0	15.0	80.0	15.0	70.0	76.0	15.0
Power	52.2	49.4	50.9	49.9	52.9	44.7	48.0	48.5	48.7
TOTALS	**280.7**	**241.9**	**260.2**	**247.6**	**286.0**	**183.6**	**228.7**	**283.8**	**190.2**
Systems Contingency %	43%	43%	43%	43%	43%	43%	43%	43%	43%
Subsystems with Contingency	**401.5**	**345.9**	**372.0**	**354.1**	**409.0**	**262.6**	**327.1**	**405.8**	**272.0**
Duration (hours)	3.0	24.0	6.0	2.0	24.0	24.0	8.0	3.0	9.0

Table 3-17. Flight System Element Power and Modes—Option 2

Subsystem/Instrument	Power [W]									
	Launch	Cruise	Fly-by	Ganymede Pump	Science + Telecom (1-3 months)	Science + Telecom (3-6 months)	Science	Telecom	SAFE	Jupiter Eclipse
Instruments	11.6	12.5	42.0	30.5	52.2	50.5	23.4	12.5	12.0	12.5
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Control	13.0	20.3	20.3	20.3	19.9	20.3	20.3	19.9	22.2	33.9
Propulsion	51.6	3.3	51.6	51.6	3.3	3.3	3.3	3.3	51.6	3.3
Attitude control	33.7	39.1	39.1	39.1	37.0	37.0	37.0	33.4	33.7	33.4
Command & data handling	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7
Telecommunications	76.0	76.0	15.0	15.0	80.0	70.0	15.0	70.0	76.0	15.0
Power	13.0	20.3	20.3	20.3	19.9	20.3	20.3	19.9	22.2	33.9
TOTALS	**292.1**	**254.7**	**273.0**	**260.5**	**299.4**	**287.1**	**197.8**	**241.1**	**302.6**	**196.5**
Systems Contingency %	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Subsystems with Contingency	**417.8**	**364.2**	**390.4**	**372.5**	**428.2**	**410.6**	**282.9**	**344.8**	**432.7**	**281.0**
Duration (hours)	3.0	24.0	6.0	2.0	24.0	24.0	24.0	8.0	3.0	9.0

Table 3-18. Flight System Element Power and Modes—Option 3

Subsystem/Instrument	Power [W]									
	Launch	Cruise	Fly-by	Ganymede Pump	Science + Telecom (1-3 months)	Science + Telecom (3-6 months)	Science + Telecom (6-12 months)	Telecom	SAFE	Jupiter Eclipse
Instruments	17.6	18.3	48.0	36.5	58.2	56.5	69.3	18.5	18.0	18.5
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Control	13.4	20.6	20.6	20.6	20.1	20.6	20.6	20.1	22.6	35.1
Propulsion	51.6	3.3	51.6	51.6	3.3	3.3	3.3	3.3	51.6	3.3
Attitude control	33.7	39.1	39.1	39.1	37.0	37.0	37.0	33.4	33.7	33.4
Command & data handling	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7	52.7
Telecommunications	76.0	76.0	15.0	15.0	80.0	70.0	70.0	70.0	76.0	15.0
Power	54.1	51.4	52.9	51.9	54.9	53.9	55.1	49.9	55.0	46.4
TOTALS	**299.1**	**261.3**	**279.8**	**267.3**	**306.2**	**293.9**	**308.0**	**247.9**	**309.6**	**204.4**
Systems Contingency %	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
Subsystems with Contingency	**427.6**	**373.7**	**400.1**	**382.2**	**437.9**	**420.3**	**440.4**	**354.5**	**442.7**	**292.3**
Duration (hours)	3.0	24.0	6.0	2.0	24.0	24.0	24.0	8.0	3.0	9.0

Table 3-19. Flight System Element Characteristics

Flight System Element Parameters	**Option 1**	**Option 2**	**Option 3**
General			
Design Life, months	~ 113	~ 116	~ 121
Structure			
Structures material	Aluminum, titanium, composites		
Number of articulated structures	1 scan platform		
Number of deployed structures	3 solar panels, 1 Magnetometer boom		
Thermal Control			
Type of thermal control used	Active and Passive		
Propulsion			
Estimated delta-V budget, m/s	2762	2762	2662

Flight System Element Parameters	Option 1	Option 2	Option 3
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Bi-propellant Hydrazine/NTO		
Number of thrusters and tanks	1 main engine, 4 main engine control engines, 16 attitude control engines; 2 propellant & 2 pressurant tanks		
Specific impulse of each propulsion mode, seconds	325 & 215		
Attitude Control			
Control method	3-axis		
Control reference	Solar		
Attitude control capability, degrees	0.028		
Attitude knowledge limit, degrees	0.014		
Agility requirements (maneuvers, scanning, etc.)	Body mounted HGA tracks Earth, with scan platform for nadir pointing		
Articulation (#, axes, solar arrays, antennas, gimbals, etc.)	Scan Platform/2 DOF		
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	8 coarse sun sensors; 2 star trackers with 6 arcsec accuracy; 2 IMUs each containing 3 gyros with 0.005 deg/hour bias; 4 reaction wheels with 5 Nms, 0.07 Nm capability		
Command & Data Handling			
Flight Element housekeeping data rate, kbps	2		
Data storage capacity, Gbits	768		
Maximum storage record rate, kbps	25,600		
Maximum storage playback rate, kbps	102,400		
Power			
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Rigid, Deployed		
Array size, meters x meters	64.4	64.7	69.4
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	GaAs TJ		
Expected power generation at beginning of life (BOL) and end of life (EOL), Watts	15.5 kW (BOL @1 AU); 530 W (EOL @ 5.6 AU)		
On-orbit average power consumption, Watts	409 (Science & Telecom)	430 (Science & Telecom)	440 (Science & Telecom)
Battery type (NiCd, NiH, Li-ion)	Li-Ion		
Battery storage capacity, amp-hours	40		

Subsystem Descriptions

Structure

All three options in this study would include a hexagonal bus structure containing two propellant tanks and two pressurant tanks placed around a 1-m×1-m×1-m central radiation vault used to house the spacecraft's sensitive electronics. The bus shape and layout were driven by the desire to place the electronics vault between the propellant tanks to utilize the vault's waste heat to keep the propellants warm and minimize the need for dedicated heater power for propellant heating. The radiation vault design is modeled after and scaled from the Juno vault design. Also included are external instrument vaults to provide protection for radiation-sensitive external pieces such as the medium resolution camera head. Table 3-20 shows the shielding masses required for the central radiation vault and external vaults for each of the three mission options. The indicated shielding masses would permit achievement of a 50-krad total radiation dose inside the vaults with RDM=2. The models used for the radiation estimates are the JPL–SPE1 [1] model for solar protons and GIRE2 [2] for trapped proton and electron fluences at Jupiter. When in Ganymede orbit, Ganymede shielding is assumed to account for a 50% reduction in the trapped fluences. Total ionizing dose (TID) is calculated from the combined fluences using a radiation model called Novice3 [3]. For all options, structure would be provided to accommodate 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.

Table 3-20. Radiation Vault Design

Opt.	Total Radiation (100 mil. Al, RDM=2)	Primary Electronics Vault Thickness	Primary Electronics Vault Mass (CBE)	External Instrument Vault Thickness	Number of External Instrument Vaults	Total External Instrument Vault Mass (CBE)	Total Star Tracker Shielding Mass (CBE)
1	680 krad	3.07 mm	49.4 kg	3.95 mm	5	3.1 kg	8 kg
2	820 krad	4.63 mm	74.3 kg	5.75 mm	7	6.1 kg	8 kg
3	1110 krad	6.93 mm	112 kg	8.32 mm	10	12 kg	8 kg

Thermal Control

The thermal design for the mission would be driven by the requirement to maintain the propulsion module within specified temperature limits while minimizing heater power so as to keep the spacecraft power to a minimum. As a result, the thermal design would use both active and passive thermal control. The dissipated power from the vault would be used to provide thermal energy to the propulsion module. Therefore, the vault would be placed between the large propellant tanks, and a capillary pumped heat pipe (CPHP) would transfer the thermal energy from the vault to the tanks. Additionally, a total of 35 radioisotope heater units (RHUs), regular and variable, would be used in the bus and at the thruster clusters to minimize heater power. Other heritage components used in the thermal design would include multi-layered insulation (MLI), thermostats, temperature sensors, and thermal surfaces. Due to the Venus gravity assist, a Venus shield would also be included in the design. This thermal design would be the same for all three options, with only slight variations resulting in small mass differences.

Propulsion

The propulsion system would be designed to provide three-axis control during cruise and Jovian tour, momentum wheel unloading, and main engine burn control authority. The deterministic ΔV requirement for the mission would be 1762 m/s, but the propulsion system would be designed with 1000 m/s allowances for various trajectory correction maneuvers (TCMs) and for orbit trims during Ganymede orbit phase. It would be a bi-propellant system and would be composed of the following elements: (1) one Aerojet R-42DM 890N main engine used for all deep space maneuvers (DSMs), orbit insertions, and orbit pump down; (2) four Aerojet MR-107P 90N engines used for main engine control authority; (3) sixteen Aerojet MR-103D attitude control engines in two redundant branches used for three-axis control and momentum wheel unloading.

There would be single Hydrazine fuel and NTO oxidizer tanks, which are composite overwrapped with Titanium liners and propellant management devices (PMDs) for propellant expulsion, and single fuel and oxidizer pressurant tanks, which are composite overwrapped with Titanium liners. The propulsion subsystem would be composed of all high TRL heritage hardware with no need for development.

Attitude Control

The attitude control subsystem (ACS) would be a dual-string, cold-spare design that would provide three-axis stabilization using reaction wheels for fine pointing control. The medium resolution camera would drive the ACS design: it would require pointing within 0.028 degrees and pointing stability within 0.003 degrees/second relative to a target on the surface. The fixed HGA would require boresight pointing within 0.05 degrees of Earth. ACS sensors used for attitude determination would include star trackers, gyros in inertial measurement units, and sun sensors. Sixteen 0.9 N-thrusters would be used for momentum unloading and small orbit correction maneuvers, and four 90 N-thrusters would be used for orbit maintenance maneuvers and thrust vector control during main engine burns. A 2-DOF scan platform would be used to maintain nadir pointing for the instruments that require nadir pointing. Instrument data post-processing would be used to remove the effects of instrument rotation about the spacecraft ground track. Optionally, at extra cost, a third degree of freedom (rotation about the scan platform boresight) could be added to the scan platform to eliminate the effects of instrument rotation. Star trackers can experience high rates of false star indications in environments where highly energetic particles are present. Additional shielding would therefore be added around each star tracker to provide mitigation. The ACS design would be identical for all three mission options.

Command and Data Handling

The command and data handling (C&DH) subsystem would be a dual-string system that utilizes cold sparing. Storage requirements are driven by the data volume of the Ganymede and Calisto flybys. In the flyby phase, approximately 20 GB would need to be stored. Additionally, the number of instruments in the payload would drive the interface design.

The C&DH design assumes build-to-print heritage components with no additional development requirements. The design would include a RAD750 processor, critical relay control card (CRCC), flash memory controller (96 GB non-volatile memory), telecommunication interface card, serial interface assembly, compute element power converter unit (CE-PCU), remote engineering unit, and a 6U-extended chassis. All of the avionics would be housed inside the vault in a 50-krad radiation environment. Since not all C&DH components would be hardened to 50 krad, some additional spot shielding would be placed around those components.

Option 1 would have the fewest number of instruments and consequently would require only two serial interface assembly cards. Options 2 and 3 would require three serial interface assembly cards due to the increased number of instruments (interface requirements).

Telecommunications

The telecommunications subsystem would be required to support a two-way X-band link with Earth during the mission for command uplinks and engineering telemetry downlinks. Additionally it would need to support a Ka-band downlink of 28 kbps (maximum achievable with one 34-m BWG DSN antenna) for science data return, as well as simultaneous X-band up and down and Ka-band up and down for gravity science. The telecommunications system for all options would be a fully redundant X-band and Ka-band system. The design would consist 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 20-W TWTAs, two X-band 25-W TWTAs, and two X/Ka up/down universal space transponders (USTs). The design would assume that high-rate downlinks and science acquisition occur simultaneously during the Ganymede orbit science and telecom mode. In all other cases, data flow to/from Earth would be its own event/mode.

The design for all three options would be the same with the exception of the data rate. After the first three months of Ganymede orbital operations, the downlink data rate would be reduced to 25 kbps due the further Earth range of 6.35 AU (as opposed to 6 AU).

Power

A solar-powered approach would be selected and, consequently, the power subsystem design would be similar to that of the Juno mission. Three solar array wings would supply approximately 530 W at end of life (EOL) and at a solar range of 5.6 AU. The non-articulating wings would be composed of rigid composite panels with GaAs triple junction cells with a total area of 64.4, 64.7, and 69.4 m^2 for options 1, 2, and 3, respectively. String switching of varied length strings would be utilized for power control at different solar ranges. Conventional power electronics would be housed within the spacecraft electronics radiation vault. Four 40 A-hr lithium ion batteries would support all primary operations, including launch and eclipses, with an additional 40 A-hr battery for redundancy. Due to the battery chemistry, the electronics package would include charge control boards to prevent overcharge on the high capacity cells. The design of the battery would be based on a one-time estimated depth of discharge (DoD) of 50–60% during the Jupiter Eclipse power mode (option 1 = 52% DoD, option 3 = 57% DoD). This one-time deep DoD on the battery should be beneficial for general battery state of charge and possible assessment of remaining capacity during mission operations.

Since the added instruments in options 2 and 3 would be assumed to operate in their own power mode—so as to not significantly impact the flight system design—the power subsystem for all three options would be very similar. In all options the solar array size would be driven by the “Telecom & Science” mode, and the battery size was driven by the nine-hour “Jupiter Eclipse” mode (~2400–2600 W-hr energy, including 43% margin on the 28-V bus).

Mission Design and Concept of Operations

Mission Design

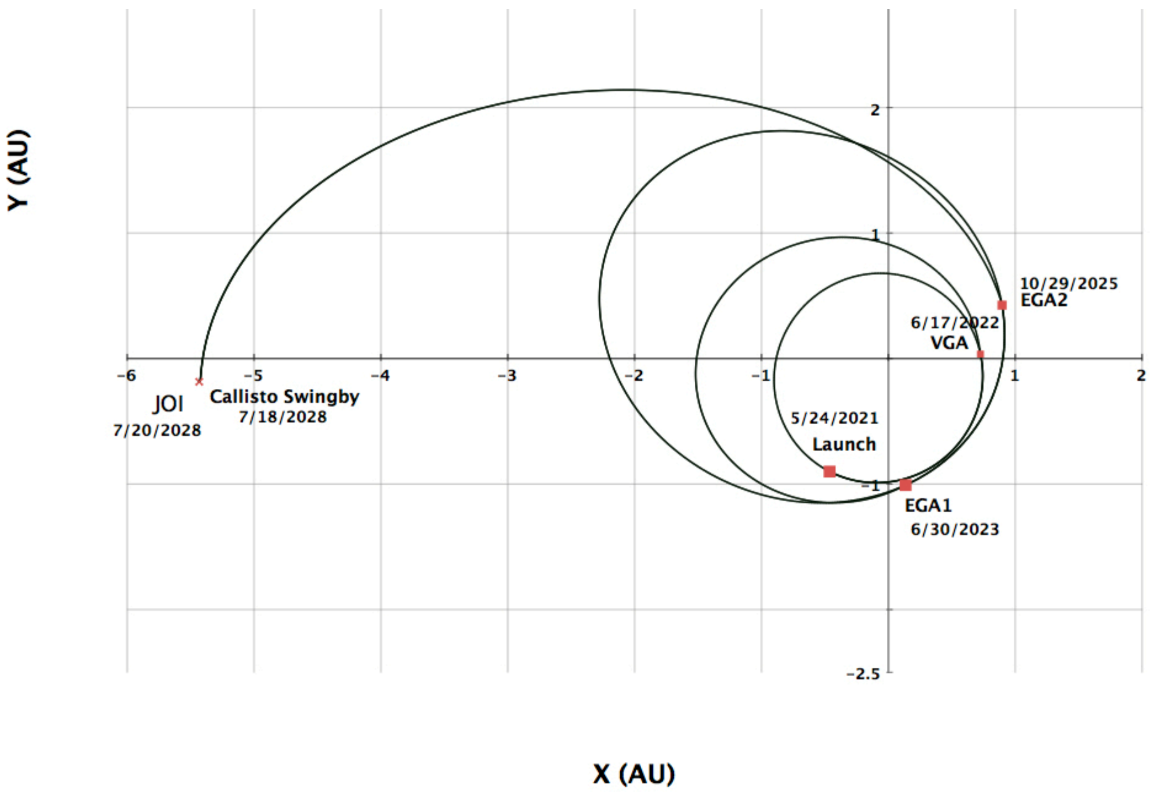
Launch Opportunities: A comprehensive search of launch opportunities during the 2016 to 2026 required launch window of interest was conducted. Various trajectory types using Earth and Venus assists were considered, and corresponding mass performances were measured in conjunction with the use of Atlas V launch vehicles. The proposed trajectory E-VEE-J to be launched in May 2021 was selected as the best for the following reasons: 1) it has superior mass delivery potential; 2) it satisfies the preferred Jupiter arrival dates of 2026–2029; and 3) there are two other launch opportunities in 2023 and 2024 with nearly identical performance and key system design parameters suitable as back-up launch opportunities.

Mission Phases: A candidate trajectory with three mission phases was developed for the mission: Heliocentric Phase, Jupiter (JOI to GOI) Phase, and Ganymede Orbital Operations Phase (Post-Ganymede Orbit Insertion Phase).

Heliocentric Phase: This phase would provide for transfer of the spacecraft from the Earth to Jupiter and Jupiter orbit insertion. The nominal trajectory is characterized by a VEE gravity-assisted path without post-launch ΔVs. It would utilize a flyby of Callisto prior to JOI to reduce the JOI ΔV requirement. To minimize spacecraft radiation, JOI would be performed at 15 Rj. Figure 3-3 summarizes the phase.

Jupiter (JOI to GOI) Phase: This phase would provide for spacecraft insertion into Ganymede orbit. Five Callisto flybys would be performed to satisfy the science team requirement for six Callisto flybys and to simultaneously pump down the size (orbit period) of the Jupiter-centered orbit. After the Callisto flybys are implemented, three more gravity assists of Ganymede would be used to achieve Ganymede orbit insertion (GOI). Figure 3-4 summarizes the phase.

Ganymede Orbital Operations Phase: This phase would provide for pump-down to the final required Ganymede polar circular orbit and orbital operations. The phase would include 10 Ganymede elliptical orbits prior to the start of pump-down. The objectives of the 10 elliptical orbits are: 1) minimize gravilty loss in GOI, and 2) provide an opportunity for magnetosphere study. Due to the presence of Europa and Io nearby, the envisioned scenario (two-body assumption) is not quite accurate, but the objectives could still be met with future N-body analysis. Table 3-21 describes the phase.



Events	Date	Parameters
Launch	5/24/2021	C3=12.688 $(km/s)^2$ DLA=-15.53° RA=140.43°
VGA1	6/17/2022	Vhp=6.071 (km/s) HCA=3199 Km
EGA1	6/30/2023	Vhp=10.92 (km/s) HCA=6544 km
EGA2	10/19/2025	Vhp=10.89 (km/s) HCA=2361 km
Callisto-1	7/18/2028 16:56:1	Vhp=8.50 (km/s) HCA=300 (km)
JOI	7/20/2028 07:17:34	Vhp=4.374 (km/s) RP=14.976 RJ DEC=-6.181° ΔV(JOI)=899 m/s

Figure 3-3. Heliocentric Phase

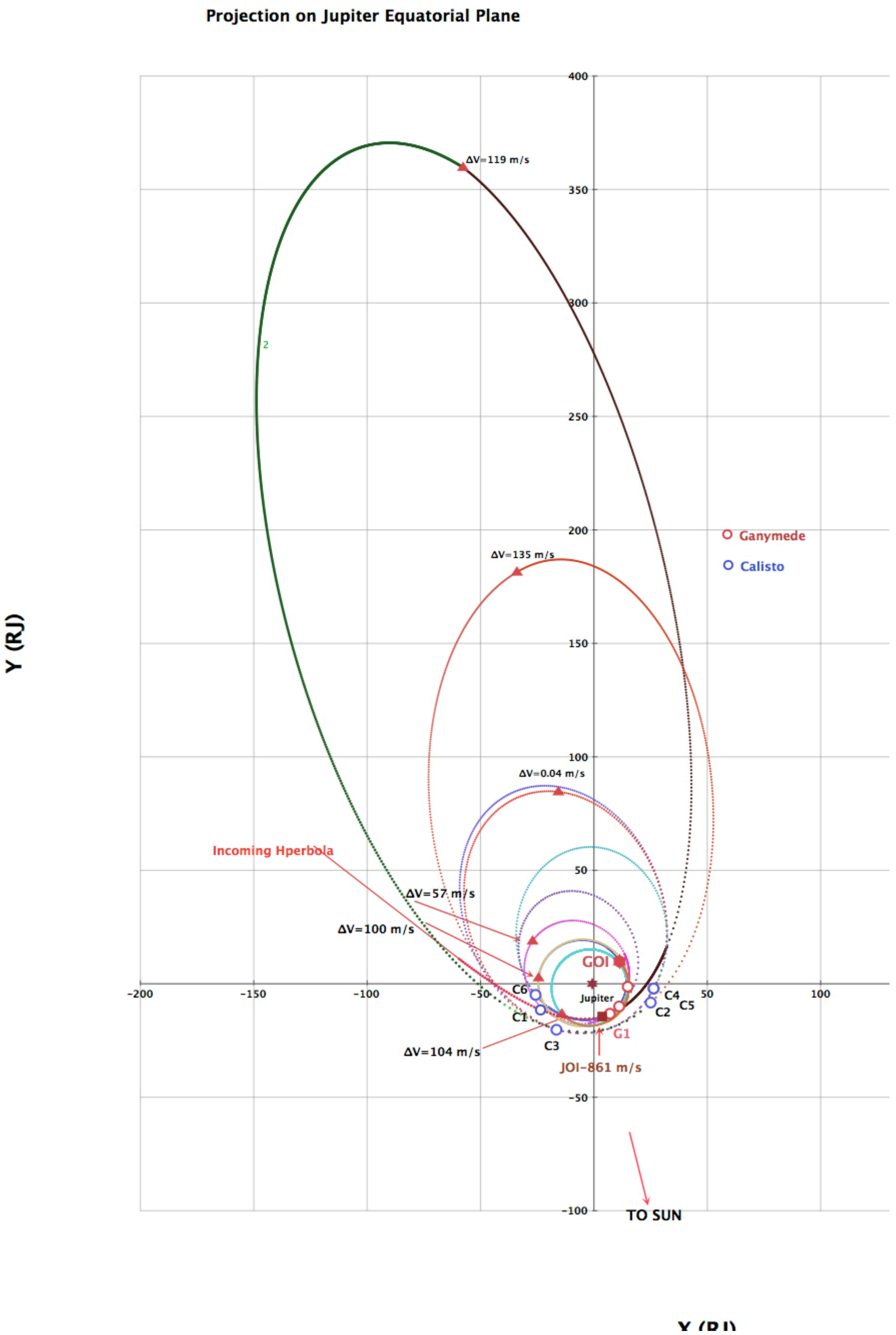
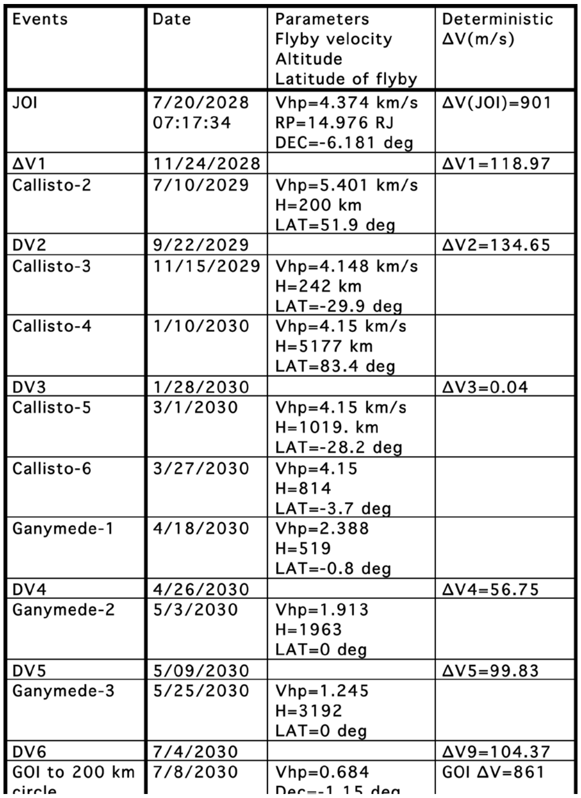


Figure 3-4a. Jupiter (JOI to GOI) Phase (Trajectory Plot)



Events	Date	Parameters Flyby velocity Altitude Latitude of flyby	Deterministic ΔV(m/s)
JOI	7/20/2028 07:17:34	Vhp=4.374 km/s RP=14.976 RJ DEC=-6.181 deg	ΔV(JOI)=901
ΔV1	11/24/2028		ΔV1=118.97
Callisto-2	7/10/2029	Vhp=5.401 km/s H=200 km LAT=51.9 deg	
DV2	9/22/2029		ΔV2=134.65
Callisto-3	11/15/2029	Vhp=4.148 km/s H=242 km LAT=-29.9 deg	
Callisto-4	1/10/2030	Vhp=4.15 km/s H=5177 km LAT=83.4 deg	
DV3	1/28/2030		ΔV3=0.04
Callisto-5	3/1/2030	Vhp=4.15 km/s H=1019. km LAT=-28.2 deg	
Callisto-6	3/27/2030	Vhp=4.15 H=814 LAT=-3.7 deg	
Ganymede-1	4/18/2030	Vhp=2.388 H=519 LAT=-0.8 deg	
DV4	4/26/2030		ΔV4=56.75
Ganymede-2	5/3/2030	Vhp=1.913 H=1963 LAT=0 deg	
DV5	5/09/2030		ΔV5=99.83
Ganymede-3	5/25/2030	Vhp=1.245 H=3192 LAT=0 deg	
DV6	7/4/2030		ΔV9=104.37
GOI to 200 km circle	7/8/2030	Vhp=0.684 Dec=-1.15 deg	GOI ΔV=861

Figure 3-4b. Jupiter (JOI to GOI) Phase (Key Characteristics)

Table 3-21. Ganymede Orbital Operations Phase

Events	Time (days from GOI)	ΔV (m/s)	Orbit Size (Peri-alt [km] x Apo-alt [RG or km])	Orbit Period (days)	Comments
GOI-1	0	220	200 x 10	1.288	• This elliptical orbit is intended for magnetospheric measurements. • It reduces the gravity loss in ΔV if inserted to the 200-km circular orbit in one step. • It is envisioned to stay in this orbit for 10 orbits, requiring about 13 days. • Due to non-trivial perturbations from other Galilean satellites, significant distortion in the orbit shape is expected.
GOI-2	12.88	128	200 x 4.67	0.482	• Next four gradual reductions in orbit size before entering the 200-km circular orbit is intended for minimizing the potential gravity losses.
GOI-3	13.37	128	200 x 2.87	0.274	
GOI-4	12.64	128	200 x 1.43	0.139	
GOI-5	13.78	128	200 x 1.08	0.111	
GOI-6 (Final)	13.89	128	200 x 200	0.105	• This is the final mapping orbit. • The orbit offers imaging with phase angles roughly 63 degrees.
Total		861			

Table 3-22 provides a summary of the key mission design parameters for the three mission options, and Table 3-23 summarizes key information pertinent to mission operations uplink and downlink. Note option 3 in Table 3-22 has a small negative launch vehicle mass margin of −1 kg. This margin is within the margin of error of the launch vehicle capability calculations and is therefore small enough to confirm option viability.

Table 3-22. Mission Design Parameters

Parameter	Option 1	Option 2	Option 3
Orbit	At Ganymede; circular, polar, 90-deg inclination, 200-km altitude, 63-deg phase angle		
Mission lifetime (months)	113	116	121
Maximum eclipse period (min)	540 (Jupiter Eclipse); 26 (Ganymede orbit eclipse)		
Launch site	KSC		
Total flight element dry mass with contingency (includes instruments, 43% contingency) (kg)	1752	1858.6	2079
Propellant mass without contingency (kg)	2457	2652.2	2664.8
Propellant contingency (%)	8.4	8.9	9.4
Propellant mass with contingency (kg)	2683.1	2910.8	2941
Launch adapter mass with contingency (kg)	38.2 (S/C side)	40.9 (S/C side)	42.6 (S/C side)
Total launch mass (kg)	4435	4769	5020
Launch vehicle	Option 5 per Decadal Survey Study guidelines		
Launch vehicle lift capability (kg)	4560	4953	4953
Launch vehicle mass margin (kg)	124.7	183.2	-67.6
Launch vehicle mass margin (%)	3	4	-1

Table 3-23. Mission Operations and Ground Data Systems

	Helocentric[2]		Jupiter (JOI to GOI)	Ganymede Orbital Operations
	Cruise	Quiet Cruise		
Downlink Information				
Number of contacts per week[1]	7	1	10	21
Number of weeks for mission phase, weeks[1]	14	205	16	12
Downlink frequency band, GHz	Ka-band, 31.8–32.3			
Telemetry data rate (Ka-band), kbps	> 28	> 28	28	28
Transmitting antenna type(s) and gain(s), DBi	3 m, X/Ka-band Parabolic HGA X-band = 45.8; Ka-band = 57.5			
Transmitter peak power, Watts	Dual-band, 80			
Downlink receiving antenna gain, DBi	34 m beam wave guide (BWG)			
Transmitting power amplifier output, Watts (RF)	25 for X-band; 20 for Ka-band			
Total daily data volume (with 7% overhead, 20% margin) (MB/day)	69[2]	13[2]	26	208
Uplink Information				
Number of uplinks per day	1	0.15	0.3	3
Uplink frequency band, GHz	X-band @ 7.145-7.190; Ka-band @ 34.2-34.7			
Telecommand data rate, kbps	2			
Receiving antenna type(s) and gain(s), DBi	3 m, X/Ka-band Parabolic HGA; X-band 44.4; Ka-band 58.1			

[1] See Appendix C for details

[2] Includes flybys

Science Data Observation/Acquisition Phases

The Ganymede mission's science observations are divided into three phases: 1) Ganymede Nominal Science (Orbital Tour) Phase, 2) Ganymede Pump-down Phase, and 3) Flyby Phase.

The core principle (or goal) underlying the science data acquisition strategy for all mission options is to satisfy the Ganymede STM science objectives in priority order, with the highest priority objectives first. This leads to a unique data acquisition strategy for the Nominal Science (or Orbital Tour) Phases for each of the three missions options and a common strategy for the Flyby and Pump-down Phases and the Earth–Jupiter Cruise Phase (including Venus and Earth flybys), which is available in all options for instrument check-out and calibration.

Key flight and ground system features pertinent to the data acquisition strategy, which have been built into the architecture described in this study, include, for the flight system a 28-kbps downlink data rate (flight-system power limited), 96-GB memory (Flyby Phase sized), and x3 science data compression. For the ground system, the features include 24/7 34-m Ka-band DSN coverage during the Orbital Tour and Pump-down Phases (requiring a DSN antenna dedicated to the mission at each ground station) and two 8-hour passes per week during the Earth–Jupiter Cruise and Flyby Phases. Should the assumption of a dedicated 34-m DSN antenna at each station for the duration of the mission (three months for the Floor mission, six and twelve months, respectively, for the Baseline and Augmented missions) prove nonviable due to other demands on the tracking network, or for other reasons, the mission could alternatively provide its own ground station or stations.

The three science observation phases are described below.

Ganymede Nominal Science (Orbital Tour) Phase: This phase provides focused Ganymede science and satisfies the majority of the Ganymede science traceability matrix science objectives.

Figure 3-5 shows the spacecraft in its circular polar orbit about Ganymede on July 25, 2030, just after entering the Orbital Tour (Nominal Science) Phase. The illustration is technically accurate and was developed with JPL's Team X trajectory visualization tools. Table 3-24 shows the observation requirement fulfillment fractions (the fractions of the STM science objectives met) for the three mission options assuming 24/7 continuous DSN coverage. Note all STM science objectives are met by the Floor option (option 1) except spectroscopy.

Ganymede Pump-Down Phase: This phase provides an opportunity to supplement the Ganymede spectroscopy observations taken during the Nominal Science Phase, which fall short of meeting the STM spectroscopy measurement requirements, as well as perform studies of the Ganymede magnetosphere from various altitudes during pump-down to the final Ganymede orbit. In addition to providing for the instruments studying the magnetosphere to be on continuously, this phase provides for spectrometer or other instrument measurements during the 10 available two-hour windows circa Ganymede closest approach during the 13-day pump-down period. Table 3-25 shows a notional plan for using the data volume available after downlink of the magnetospheric data for spectrometer data downlink. The fractions in the box on the right of the table for the V/NIR instrument show the fraction of the data volume that can be downlinked to the Earth for spectrometer data. This phase assumes 24/7 coverage.

Flyby Phase: This phase provides an opportunity for focused Callisto science. Figure 3-6 shows the spacecraft one hour out from Callisto closest approach on its sixth and final pre-Ganymede-orbit-insertion Callisto flyby on March 27, 2030. The illustration is technically accurate and was developed with JPL's Team X trajectory visualization tools. Ganymede can be seen to the far left of the image. The instrument scan platform is in its nadir pointing orientation. The closest approach is at 814 km. The plan would provide for two-hour windows circa closest approach for science observations at each flyby during the phase. The phase assumes two 8-hour DSN passes per week. The phase also would provide three Ganymede flyby science observation opportunities. Table 3-26 shows a notional plan for data acquisition during the phase. It is key to note the total data that could be returned during each flyby.

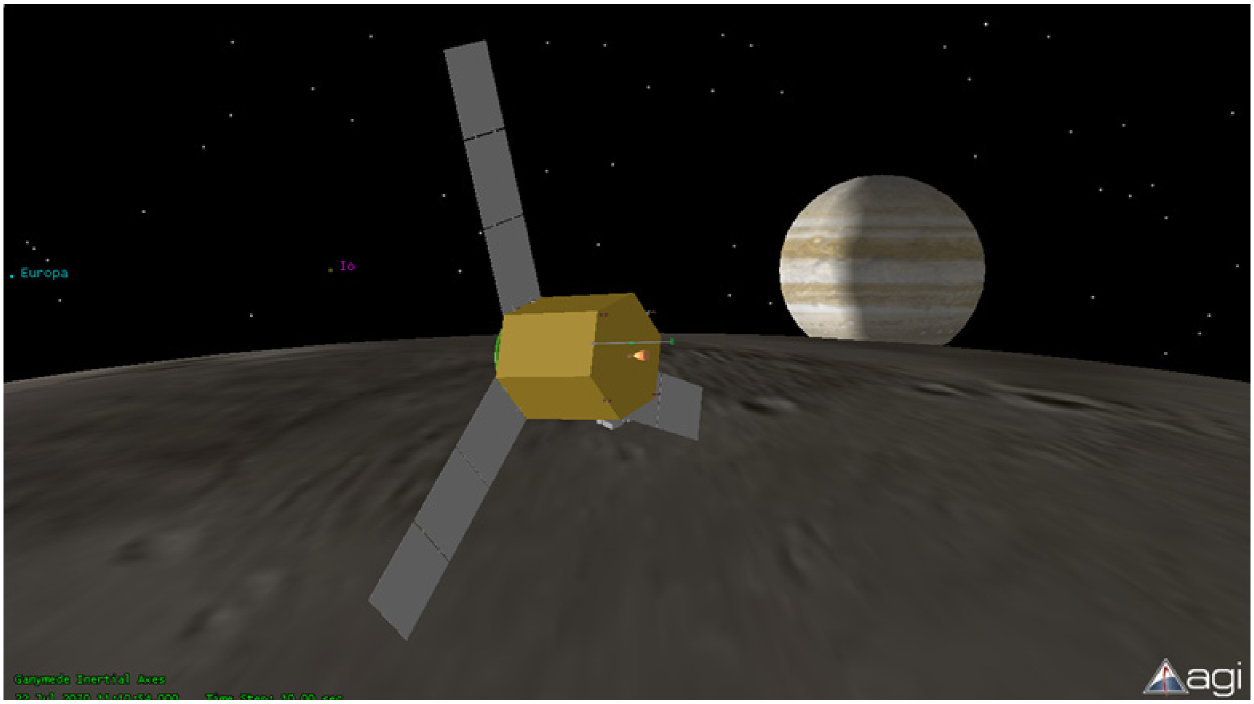


Figure 3-5. Ganymede Orbiter in Circular Polar Orbit (July 25, 2030)

Table 3-24. Observation Requirement Fulfillment Fractions

Instrument	Observation requirement summary	Option 1 Fraction Observation Fulfillment	Option 2 Fraction Observation Fulfillment	Option 3 Fraction Observation Fulfillment
Medium Angle Camera				
	Imaging 50% surface @ 200 meter/pixel over 1 band	1.00	1.00	1.00
	Imaging 100% surface @ 500 meter/pixel over 2 bands	1.00	1.00	1.00
	Imaging 100% surface @ 1000 meter/pixel over 4 bands	1.00	1.00	1.00
Vector Magnetometer				
	Measure time variable magnetic field @ 1 sec cadence	1.00	1.00	1.00
Radio Science (dual transponder)				
	Measure time variations in degree-2 gravity field	1.00	1.00	1.00
	Characterize gravity field to degree 10 (using doppler at X & Ka bands with USO)	1.00	1.00	1.00
VNIR Imaging spectrometer				
	Characterize spectra properties of 1% surface @ 500 meter/pixel over 1280 bands	0.10	1.00	1.00
Laser Altimeter				
	Measure topographic profiles @ 1 meter vertical resolution	1.00	1.00	1.00
Low/High Energy Plasma Packages				
	Measure fluxes of ions and electrons from 10 eV to 1 MeV over 4π steradians	1.00	1.00	1.00
Ion and Neutral Mass Spectrometer				
	Measure the sputtered neutral and charged particles		1.00	1.00
UV imaging spectrometer				
	Characterize the auroral emissions (no quantitative)		1.00	1.00
Radio and Plasma Wave				
	Measure plasma and radio waves (no quantitative)			1.00
Narrow Angle Camera				
	Imaging 10% surface @ 10 meter/pixel			0.10
Subsurface Radar				
	Subsurface (no requirement, but fully mapped, twice in 3 months)			1.00

Fulfillment fractions are calculated with consideration of D/L data rate limitations.

Due to D/L data rate limitations, spectroscopy cannot be fulfilled solely during the Nominal Science Phase. It is envisioned that Fly-by and Pump-down Phases will supplement spectroscopy requirements.

Due to D/L data rate limitations, high-resolution imagery cannot be fulfilled. Extended mission operations and/or trading other science objectives will require further exploration.

Table 3-25. Ganymede Pump-Down Phase Notional Instrument Data Acquisition Plan

Ganymede Pump-Down Science Phase							**Remaining [Gb]**	**Continuous**	MRC	RS	VNIRIS	LA	INMS	UVIS	RPWI	NAC	SSR
Altitude @ periapsis	**Altitude @ apoapses**	**Period [hours]**	**Date**	**# of Days**	**Downlink Option**	**Data Vol [Gb]**											
200	11752	30.9226	7/8/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/9/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/11/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/12/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/13/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/14/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/16/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/17/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/18/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	11752	30.9226	7/20/2030	1.28844	21 pass/wk	2.783	**0.000**	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00
200	4735	11.5621	7/21/2030	0.481754	21 pass/wk	1.041	**0.000**	1.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
200	2365	6.5828	7/21/2030	0.274285	21 pass/wk	0.592	**0.000**	1.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
200	1178	4.4632	7/22/2030	0.185968	21 pass/wk	0.402	**0.000**	1.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
200	468	3.3333	7/22/2030	0.138887	21 pass/wk	0.300	**0.000**	1.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
200	200	2.6481	7/22/2030														

Maintaining continuous Magnetometer & Plasma Packages operation.

Focus on Spectroscopy.

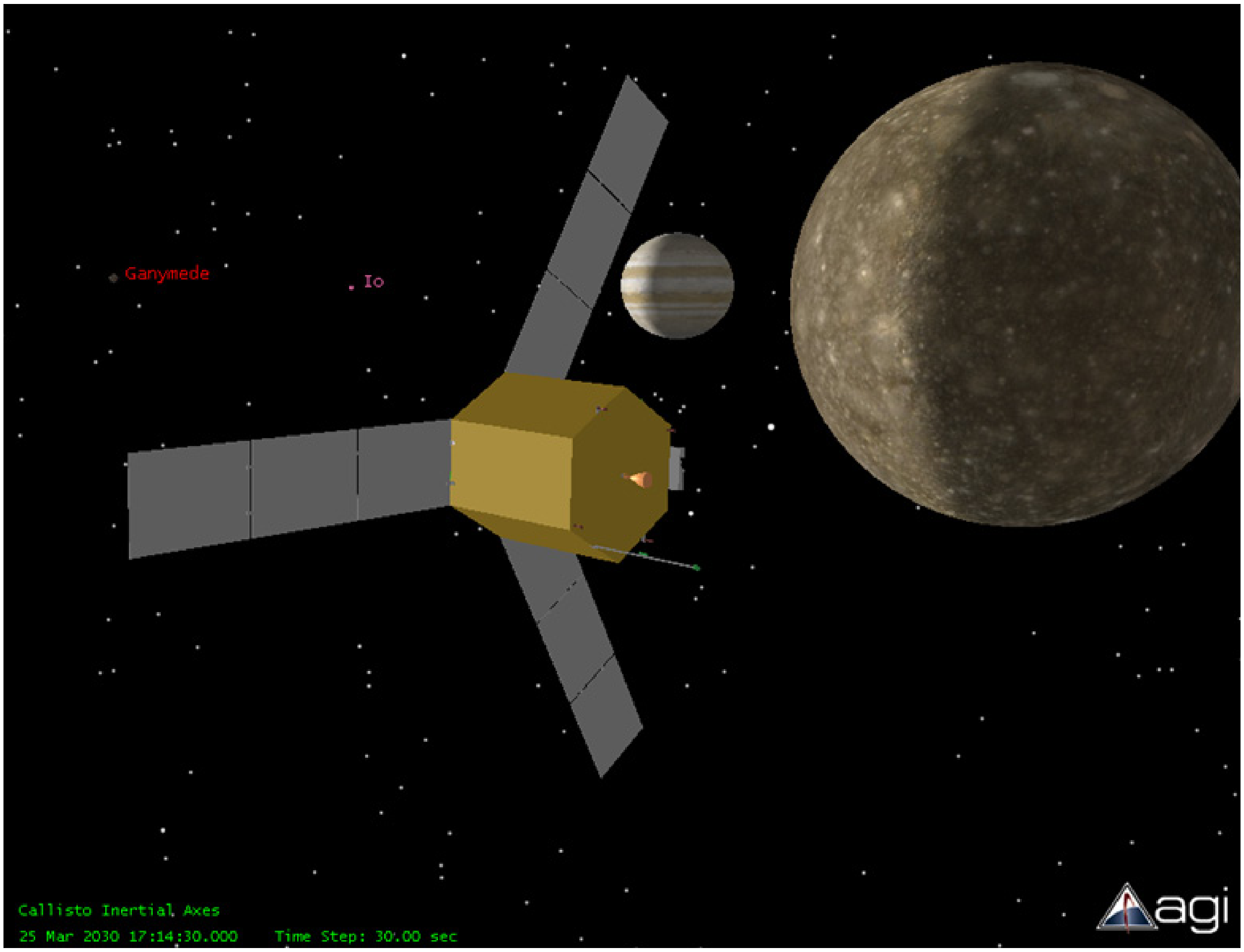


Figure 3-6. Ganymede Orbiter during Callisto Flyby (March 27, 2030)

Table 3-26. Ganymede Flyby Phase Notional Instrument Data Acquisition Plan

First Callisto Fly-by offers large science return.

# of days is the time between events.

Total data that can be returned.

Unallocated initial fly-bys may be used for instrument checkout and calibration.

Ganymede Fly-By Science Phase							**Remaining [Gb]**	**Continuous**	MRC	RS	VNIRIS	LA	INMS	UVIS	RPWI	NAC	SSR
Event	**Altitude [km]**	**Latitude [deg]**	**Date**	**# of Days**	**Downlink Option**	**Data Vol [Gb]**											
VGA 1	3199	?	6/16/2022	379	2 pass/wk	77.966	**77.966**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EGA 1	6544	?	6/30/2023	842	2 pass/wk	173.211	**173.211**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EGA 2	2361	?	10/19/2025	1003	2 pass/wk	206.331	**206.331**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Callisto-1	300	?	7/18/2028	357	2 pass/wk	73.440	**0.000**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.32	1.00
Callisto-2	200	51.9	7/10/2029	128	2 pass/wk	26.331	**0.000**	1.00	1.00	1.00	0.15	1.00	0.00	0.00	0.00	0.00	0.00
Callisto-3	242	29.9	11/15/2029	56	2 pass/wk	11.520	**0.000**	1.00	0.40	1.00	0.11	1.00	0.00	0.00	0.00	0.00	0.00
Callisto-4	5177	83.4	1/10/2030	50	2 pass/wk	10.286	**0.000**	1.00	0.30	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00
Callisto-5	1019	-28.2	3/1/2030	26	2 pass/wk	5.349	**0.000**	1.00	0.20	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Callisto-6	814	-3.7	3/27/2030	22	2 pass/wk	4.526	**0.000**	1.00	0.10	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
Ganymede-1	519	-0.8	4/18/2030	15	2 pass/wk	3.086	**0.000**	1.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00
Ganymede-2	1963	0	5/3/2030	22	2 pass/wk	4.526	**0.000**	1.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00
Ganymede-3	3192	0	5/25/2030	44	2 pass/wk	9.051	**0.000**	1.00	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00
GOI to 200 km			7/8/2030														

Magnetometer + Plasma packages continuously on after JOI.

Initial Ganymede encounters focuses on spectroscopy.

Planetary Protection

In accordance with NPR 8020.12C, the Ganymede mission is expected to be a planetary protection (PP) Category II mission. Accordingly, the Ganymede project would demonstrate that the 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 PPO in response to a written request from the Ganymede Project Manager, submitted by the end of Phase A.

The Ganymede project would prepare all PP documents and hold all reviews as required by the NASA PPO. The Ganymede project plans to demonstrate compliance, during the prime mission, with the non-impact requirement for Mars and non-contamination requirement for Europa by a combination of trajectory biasing and analyses performed by the navigation team. After the prime mission, the orbit would be allowed to decay, causing the spacecraft to be disposed into Ganymede. Compliance with the probability of biological contamination of Ganymede requirement would be demonstrated by analysis. The Ganymede 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 and Ganymede over the time period required to sterilize the spacecraft by radiation; a spacecraft impact analysis; and a thermal/heat flow analysis to determine extent of ice melting due to RHUs. If the probability of contamination exceeds the requirement(s), then the spacecraft would be cleaned/microbially reduced as needed to meet the requirement(s) (note: this is not included in the cost estimate). The results of all of these analyses would be documented in the PP pre-launch report.

Risk List

The study identified four medium (yellow) risks and five low (green) risks, as defined by the JPL Team X risk classification methodology. The top four risks (medium) and their mitigation strategies are described. Table 3-27 provides the risk level definitions used in the risk classification process. Figure 3-7 shows the Ganymede mission’s risks on a 5x5 risk matrix. Table 3-28 provides details for the four risks and mitigation strategies.

Table 3-27. Risk Level Definitions

Level	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 will 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%

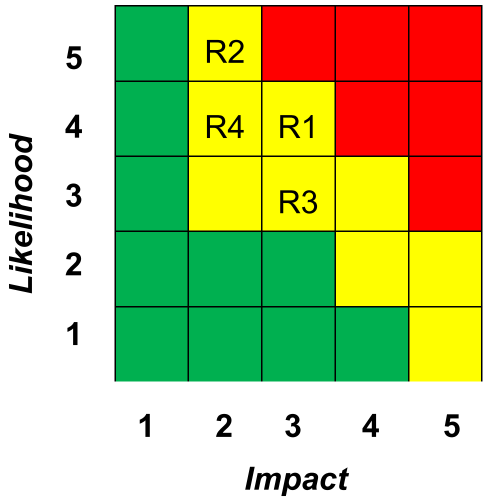


Figure 3-7. 5 x 5 Risk Matrix

Table 3-28. Detailed Risk Description and Mitigation Strategy

#	Risk	Level	Description	Impact	Likelihood	Mitigation
1	Effects of high radiation environment on instruments and components	M	The total radiation and single effect upsets in the high radiation environment could have severe effects on the mission success. While there is a certain level of radiation shielding included in the design, there is still a risk that radiation effects will degrade the mission, especially for the longer duration missions (Options 2 and 3). For example, the star trackers which are essential for the attitude control for the mission are sensitive to energetic particles. The total radiation dose, rate of exposure and/or single event radiation effects experienced in the Jovian environment could significantly impact instrument performance. The high radiation environment may lead to increased costs in the implementation phase due to additional design and testing that may be required. There is a risk that the current assumptions about the radiation environment may not be accurate, leading to increased cost and potential for schedule slip.	3	4	Additional shielding, increased design margin to account for uncertainty
2	Continuous Ka-Band DSN coverage not available	M	The design assumes continuous Ka-band DSN coverage for science data downlink during the science mission (3 months). Continuous coverage for extended periods will be very difficult to obtain from the DSN. If it is not available, the mission will have fewer science data downlink opportunities which will result in a reduction in science return.	2	5	Purchase a dedicated DSN antenna at each station (cost of an antenna ~$35M); Increase Phase E duration to achieve science goals with fewer downlinks
3	Reduction in science return from extended operations in Option 2 and 3	M	Option 2 (baseline) and 3 (augmented) include 3 and 9 months more of operations respectively compared to 3-month Option 1 (floor). The assumption for this study was that certain instruments for the baseline and augmented missions will not be used until after the first 3 months. There is the possibility that in the event of a failure on the spacecraft or radiation effects on the instruments which do not operate until late in the mission, a large proportion of the science associated with those instruments will be lost. However, the floor mission represents approximately 70% of the science return (if the augmented mission is considered 100%), so the loss of science for the baseline and augmented mission is approximately 15% to 30% respectively.	3	3	Schedule high priority science for all instruments in the first few months
4	Operational complexity due to power constraints	M	There will be a 76 min eclipse every 7 days coupled with 26 min eclipse over 2 hrs. The 76 minutes eclipse will cause an overall energy deficit for battery energy storage which must be regained numerous eclipse cycles prior to next 76 min eclipse. Otherwise, battery SOC will not be optimally maintained over mission life. This may lead to operational complexity during mission operations that is not accounted for in this study, and is beyond the assumptions of the Ground Systems model. In particular, scheduling which instruments can be on simultaneously may be complicated in order to stay within the power constraints. There may be an increase in the mission operations costs to account for this complexity.	2	4	No immediately identified mitigations

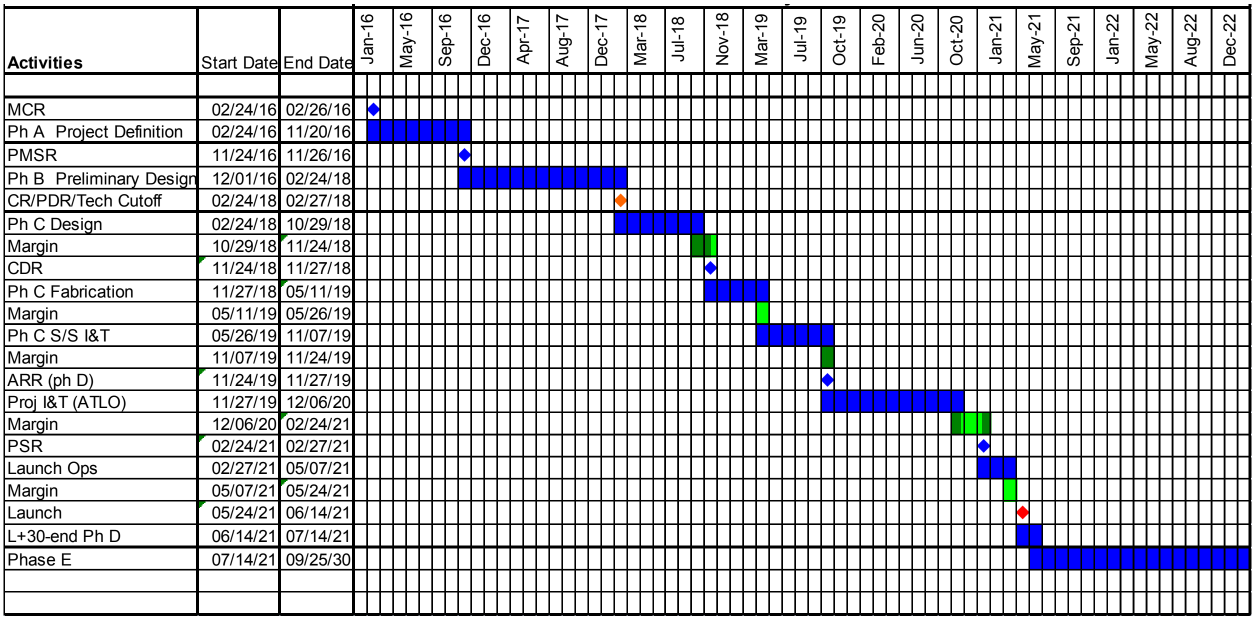
4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

The Ganymede mission would consist of a single instrument orbiter. The proposed schedule for all three options of the Ganymede mission is displayed on the following pages. The only difference between the schedules for the three options is in Phase E, as science operations for the options are 3, 6, and 12 months, respectively. The mission complexity falls between a basic mission similar to a Discovery mission and a complex or large directed mission. The reference schedules used are derived from the JPL mission, schedule database which goes back to Voyager.

The schedule is based on the assumption there will be no new technology development for the mission, only new engineering, consistent with the study team findings with regard to technology maturity. There are few analogous New Frontiers missions available for comparison to the Ganymede mission, although the Juno mission and Moonrise New Frontiers proposal, both of which are familiar to JPL Team X, offer useful references for comparison. Both have a 40-month Phase C/D and a long A/B phase. Using these schedules as a guide, considering that the Juno mission required significant additional time in Phase B to resolve design issues not required by the Ganymede mission, but that the Ganymede mission nevertheless could face significant design and testing challenges related to the radiation environment, a Phase B of 15 months was selected, 3 months longer than Moonrise. The selected Phase A schedule is nine months, consistent with the previous New Frontiers AO.

Figure 4-1 shows the Ganymede notional schedule, and Table 4-1 shows the key phase durations.



Activities	Start Date	End Date
MCR	02/24/16	02/26/16
Ph A Project Definition	02/24/16	11/20/16
PMSR	11/24/16	11/26/16
Ph B Preliminary Design	12/01/16	02/24/18
CR/PDR/Tech Cutoff	02/24/18	02/27/18
Ph C Design	02/24/18	10/29/18
Margin	10/29/18	11/24/18
CDR	11/24/18	11/27/18
Ph C Fabrication	11/27/18	05/11/19
Margin	05/11/19	05/26/19
Ph C S/S I&T	05/26/19	11/07/19
Margin	11/07/19	11/24/19
ARR (ph D)	11/24/19	11/27/19
Proj I&T (ATLO)	11/27/19	12/06/20
Margin	12/06/20	02/24/21
PSR	02/24/21	02/27/21
Launch Ops	02/27/21	05/07/21
Margin	05/07/21	05/24/21
Launch	05/24/21	06/14/21
L+30-end Ph D	06/14/21	07/14/21
Phase E	07/14/21	09/25/30

Figure 4-1. Notional Ganymede Schedule

Table 4-1. Key Phase Durations

Project Phase	Duration (Months)
Phase A – Conceptual Design	9
Phase B – Preliminary Design	15
Phase C – Detailed Design	21
Phase D – Integration & Test	15
Phase E – Primary Mission Operations	112 (Option 1), 115 (Option 2), 121 (Option 3)
Phase F – Extended Mission Operations	6
Start of Phase B to PDR	15
Start of Phase B to CDR	24
Start of Phase B to Delivery of All Instruments #1–11	36*
Start of Phase B to Delivery of Flight Element #1	36
System Level Integration & Test	15
Project Total Funded Schedule Reserve	5.5
Total Development Time Phase B–D	54

*Note: Indicated instrument develop duration is notional.

Technology Development Plan

No new technology would be required for the mission. However, due to the complexity of the instruments, additional time would be allocated for instrument design and test.

While not considered a development risk, the telecommunications subsystem design would utilize a universal space transponder (UST) being developed by the 2016 ExoMars mission.

Development Schedule and Constraints

No long-lead time procurements would be required.

Back-up launch options (5/15/2023 and 8/22/2024) with near-identical delivered-mass capability to Ganymede orbit permit easy accommodation of programmatic adjustments or changes (e.g., AO slip) or project technical delays.

5. Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

Table 5-1 summarizes the mission cost guidelines and assumptions.

Table 5-1. Cost Guidelines and Assumptions

Decadal Survey Ground Rules	Value	Comments
Fixed Year Dollars	2015, total	
Real Year Dollars	By year, total	
Reserves for Phases A–D	50%	
Reserves for Phase E	25%	
Schedule		
Project/Phase A Start	2016	
Phase A–D Duration	64 months	
Phase E Duration for Floor Mission	9.4 years	3 months Ganymede orbital operations
Phase E Duration for Baseline Mission	9.6 years	6 months Ganymede orbital operations
Phase E Duration for Augmented Mission	10.1 years	12 months Ganymede orbital operations
End of Mission	2031	
General		
Total mission cost funding profile assumes the mission is totally funded by NASA and all significant work is performed in the US		
Mission costed using JPL's institutional cost models within the Team X environment		
All options costed by WBS		JPL WBS
Instrument costs generated using NASA's Institutional Cost Model (NICM)		
Launch vehicle costed using the fifth L/V in the NASA Planetary Decadal Survey	5-meter fairing; performance of 4345−5300 kg; cost of $257M FY2015	

Cost Estimate

Option 1 (Floor): Tables 5-2 and 5-3 show the science costs and workforce (by phase), respectively, for the Option 1 (Floor) mission, and Table 5-4 shows the total mission cost funding profile for the mission.

Option 2 (Baseline): Tables 5-5 and 5-6 show the science costs and workforce (by phase), respectively, for the Option 2 (Baseline) mission, and Table 5-7 shows the total mission cost funding profile for the mission.

Option 3 (Augmented): Tables 5-8 and 5-9 show the science costs and workforce (by phase), respectively, for the Option 3 (Augmented) mission, and Table 5-10 shows the total mission cost funding profile for the mission.

The funding allocated to the Phase A concept studies would support preparation for the Preliminary Mission System Review (PMSR), with the key goal of the phase to ensure that a sound concept and a solid Phase B work plan (including trade studies and risk reduction activities) would be in place, leading to a successful Preliminary Design Review (PDR). For the Ganymede mission, this would mean focusing on the science instrument acquisition plans and requirements and detailed plans pertaining to accommodation of the Ganymede radiation environment.

Table 5-2. Science Costs by Phase—Option 1 (Floor)

	A $k	**B $k**	**C $k**	**D $k**	**E $k**	**F $k**	**Total FY'15 $k**
Science	**492.2**	**3,278.5**	**13,564.9**	**5,803.1**	**35,087.4**	**2,884.8**	**61,110.9**
Science Management	159.0	1,294.5	1,951.6	1,765.8	6,122.2	577.0	11,870.2
Science Office	159.0	1,294.5	1,951.6	1,765.8	6,122.2	577.0	11,870.2
Science Implementation	333.2	1,984.0	11,613.3	4,037.3	28,965.2	2,307.8	49,240.7
Participating Scientists	96.8	161.4	867.2	816.0	5,821.4	789.3	8,552.2
Teams Summary	236.4	1,822.6	10,746.0	3,221.3	23,143.8	1,518.5	40,688.5

Table 5-3. Science Workforce by Phase—Option 1 (Floor)

	A W-M	**B W-M**	**C W-M**	**D W-M**	**E W-M**	**F W-M**	**Total W-M**	**Total W-Y**
Science	**11.3**	**90.3**	**456.8**	**175.5**	**1,131.1**	**95.4**	**1,960.4**	**163.4**
Science Management	3.2	26.5	41.8	37.8	101.6	14.3	225.3	18.8
Science Office	3.2	26.5	41.8	37.8	101.6	14.3	225.3	18.8
Science Implementation	8.1	63.9	415.0	137.6	1,029.6	81.1	1,735.2	144.6
Participating Scientists	3.2	5.3	28.9	27.2	201.1	27.4	292.9	24.4
Teams Summary	4.9	58.6	386.1	110.5	828.5	53.7	1,442.2	120.2

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

Item	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	Total (Real Yr.)	Total (FY2015)
Cost																		
Phase A concept study **(included in Total A–D development cost below)**	7.2	2.05															9.24	8.95
Technology development																	0.0	0.0
	Phase A - D																	
Mission PM/SE/MA	0.7	5.6	17.4	25.2	25.8	19.3											94.0	83.8
Pre-launch science	0.2	1.6	4.8	7.0	7.1	5.3											26.0	23.1
Instrument PM/SE	0.1	0.9	2.8	4.0	4.1	3.1											15.1	13.4
Instrument #1	0.0	0.1	0.4	0.6	0.6	0.5											2.3	2.0
Instrument #2	0.0	0.3	0.9	1.3	1.3	1.0											4.7	4.2
Instrument #3	0.2	1.2	3.7	5.4	5.6	4.1											20.2	18.0
Instrument #4	0.2	1.5	4.5	6.5	6.7	5.0											24.4	21.8
Instrument #5	0.1	0.7	2.0	2.9	3.0	2.3											11.0	9.8
Instrument #6	0.0	0.3	1.1	1.5	1.6	1.2											5.7	5.1
Flight element #1 (Orbiter)	2.6	21.2	64.5	92.7	99.5	74.7											355.3	311.6
MSI&T [2]	0.4	3.0	9.2	13.3	13.7	10.2											49.8	44.3
Ground data system dev	0.2	1.4	4.4	6.4	6.6	4.9											24.0	21.4
Navigation & mission design	0.1	0.7	2.2	3.2	3.3	2.5											12.0	10.7
Total dev. w/o reserves	4.8	38.5	118.0	170.1	179.0	133.9											644.2	573.9
Development reserves	2.4	19.3	59.7	86.2	88.5	66.0											322.0	287.0
Total A–D development cost	7.2	57.8	177.7	256.3	267.5	199.8											966.2	860.9
Launch services			53.6	90.8	93.2	69.5											307.1	272.0
						Phase E												
Phase E science						1.3	4.9	5.0	5.2	5.3	5.5	5.6	5.8	5.9	6.1	0.4	50.9	38.0
Other Phase E cost						4.5	16.7	17.1	17.6	18.1	18.6	19.1	19.6	20.1	20.7	1.3	173.2	129.3
Phase E reserves						1.4	5.1	5.3	5.4	5.5	5.7	5.8	6.0	6.2	6.3	0.4	53.0	39.6
Total Phase E						7.1	26.7	27.4	28.2	28.9	29.7	30.5	31.3	32.2	33.0	2.1	277.1	206.8
Education/outreach	0.02	0.1	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.1	9.9	7.4
Other (specify)																	0.0	0.0
Total Cost	**$ 7.2**	**$ 57.9**	**$ 231.9**	**$ 347.6**	**$ 361.3**	**$ 277.1**	**$ 27.4**	**$ 28.2**	**$ 28.9**	**$ 29.7**	**$ 30.5**	**$ 31.3**	**$ 32.2**	**$ 33.0**	**$ 33.9**	**$ 2.1**	**$ 1,560**	**1347.1**
															Total Mission Cost			**$ 1,347**

(FY costs[1] 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. Science Costs by Phase—Option 2 (Baseline)

	A **$k**	**B** **$k**	**C** **$k**	**D** **$k**	**E** **$k**	**F** **$k**	**Total** **FY'15 $k**
Science	**623.4**	**4,091.2**	**17,698.6**	**7,375.9**	**47,962.3**	**3,703.1**	**81,454.5**
Science Management	183.7	1,453.6	2,225.8	2,013.8	7,253.7	635.1	13,765.8
Science Office	183.7	1,453.6	2,225.8	2,013.8	7,253.7	635.1	13,765.8
Science Implementation	439.7	2,637.6	15,472.8	5,362.1	40,708.6	3,067.9	67,688.8
Participating Scientists	124.5	207.5	1,144.8	1,067.1	8,352.2	1,043.3	11,939.4
Teams Summary	315.2	2,430.1	14,328.0	4,295.0	32,356.4	2,024.7	55,749.4

Table 5-6. Science Workforce by Phase—Option 2 (Baseline)

	A **W-M**	**B** **W-M**	**C** **W-M**	**D** **W-M**	**E** **W-M**	**F** **W-M**	**Total** **W-M**	**Total** **W-Y**
Science	**14.5**	**116.0**	**602.8**	**228.0**	**1,570.8**	**123.8**	**2,655.9**	**221.3**
Science Management	3.9	31.2	49.9	45.2	124.9	16.0	271.1	22.6
Science Office	3.9	31.2	49.9	45.2	124.9	16.0	271.1	22.6
Science Implementation	10.6	84.9	552.9	182.8	1,445.9	107.8	2,384.8	198.7
Participating Scientists	4.1	6.8	38.1	35.5	288.3	36.1	408.9	34.1
Teams Summary	6.5	78.1	514.8	147.3	1,157.5	71.6	1,975.9	164.7

Table 5-7. Total Mission Cost Funding Profile—Option 2 (Baseline)

Item	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	Total (Real Yr.)	Total (FY2015)
Cost																		
Phase A concept study **(included in Total A–D development cost below)**	7.8	2.2															10.1	9.75
Technology development																	0.0	0.0
	Phase A - D																	
Mission PM/SE/MA	0.7	5.8	17.9	25.9	26.6	19.8											96.8	86.2
Pre-launch science	0.3	2.0	6.2	9.0	9.2	6.9											33.4	29.8
Instrument PM/SE	0.1	1.1	3.5	5.0	5.1	3.8											18.7	16.7
Instrument #1	0.0	0.1	0.4	0.6	0.6	0.5											2.3	2.0
Instrument #2	0.0	0.3	0.9	1.3	1.3	1.0											4.7	4.2
Instrument #3	0.2	1.2	3.7	5.4	5.6	4.1											20.2	18.0
Instrument #4	0.2	1.5	4.5	6.5	6.7	5.0											24.4	21.8
Instrument #5	0.1	0.7	2.1	3.0	3.1	2.3											11.1	9.9
Instrument #6	0.0	0.3	1.1	1.5	1.6	1.2											5.7	5.1
Instrument #6	0.2	1.7	5.2	7.5	7.7	5.7											27.9	24.9
Instrument #7	0.1	0.5	1.7	2.4	2.5	1.9											9.1	8.1
Flight element #1 (Orbiter)	2.7	21.5	65.4	94.0	100.9	75.8											360.3	320.8
MSI&T [2]	0.4	3.1	9.6	13.8	14.2	10.6											51.6	46.0
Ground data system dev	0.2	1.4	4.4	6.4	6.6	4.9											24.0	21.4
Navigation & mission design	0.1	0.7	2.2	3.2	3.3	2.5											12.0	10.7
Total dev. w/o reserves	5.2	42.0	128.7	185.5	194.9	145.8											702.2	625.4
Development reserves	2.6	21.0	65.1	94.0	96.5	71.9											351.1	312.9
Total A–D development cost	7.8	63.0	193.8	279.5	291.4	217.7											1053.2	938.3
Launch services			53.6	90.8	93.2	69.5											307.1	272.0
						Phase E												
Phase E science						1.7	6.5	6.7	6.9	7.0	7.2	7.4	7.6	7.8	8.0	2.6	69.5	51.7
Other Phase E cost						4.9	18.4	18.9	19.4	19.9	20.5	21.0	21.6	22.2	22.8	7.3	196.9	146.4
Phase E reserves						1.5	5.7	5.9	6.0	6.2	6.3	6.5	6.7	6.9	7.1	2.3	61.0	45.3
Total Phase E						8.2	30.6	31.4	32.3	33.2	34.1	35.0	35.9	36.9	37.9	12.1	327.4	243.4
Education/outreach	0.02	0.1	0.4	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.0	0.3	10.6	6.2
Other (specify)																	0.0	0.0
Total Cost	**$ 7.8**	**$ 63.1**	**$ 247.8**	**$ 370.9**	**$ 385.3**	**$ 296.0**	**$ 31.4**	**$ 32.2**	**$ 33.1**	**$ 34.0**	**$ 34.9**	**$ 35.9**	**$ 36.8**	**$ 37.8**	**$ 38.8**	**12**	**1698**	**$ 1,460**
															Total Mission Cost			**$ 1,460**

(FY costs[1] 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 5-8. Science Costs by Phase—Option 3 (Augmented)

	A $k	B $k	C $k	D $k	E $k	F $k	Total FY'15 $k
Science	**754.7**	**4,903.9**	**21,832.2**	**8,948.8**	**68,741.7**	**4,521.3**	**109,702.6**
Science Management	208.5	1,612.7	2,499.9	2,261.8	10,157.3	693.3	17,433.5
Science Office	208.5	1,612.7	2,499.9	2,261.8	10,157.3	693.3	17,433.5
Science Implementation	546.2	3,291.2	19,332.3	6,687.0	58,584.4	3,828.1	92,269.2
Participating Scientists	152.2	253.6	1,422.3	1,318.2	14,392.7	1,297.2	18,836.2
Teams Summary	394.0	3,037.6	17,910.0	5,368.8	44,191.7	2,530.8	73,432.9

Table 5-9. Science Workforce by Phase—Option 3 (Augmented)

	A W-M	B W-M	C W-M	D W-M	E W-M	F W-M	Total W-M	Total W-Y
Science	**17.6**	**141.7**	**748.8**	**280.5**	**2,270.2**	**152.2**	**3,611.1**	**300.9**
Science Management	4.5	35.8	58.0	52.5	194.0	17.8	362.6	30.2
Science Office	4.5	35.8	58.0	52.5	194.0	17.8	362.6	30.2
Science Implementation	13.1	105.9	690.8	228.0	2,076.2	134.4	3,248.5	270.7
Participating Scientists	5.0	8.3	47.4	43.9	497.0	44.9	646.4	53.9
Teams Summary	8.2	97.7	643.5	184.1	1,579.2	89.5	2,602.2	216.8

Table 5-10. Total Mission Cost Funding Profile—Option 3 (Augmented)

Item	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030	FY2031	Total (Real Yr.)	Total (FY2015)
Cost																		
Phase A concept study **(included in Total A–D development cost below)**	9.3	2.7															11.9	11.55
Technology development																	0.0	0.0
	Phase A - D																	
Mission PM/SE/MA	0.8	6.2	19.1	27.6	28.3	21.1											103.1	91.9
Pre-launch science	0.3	2.4	7.6	11.0	11.2	8.4											40.9	36.4
Instrument PM/SE	0.2	1.5	4.5	6.5	6.7	5.0											24.3	21.7
Instrument #1	0.0	0.1	0.4	0.6	0.6	0.5											2.3	2.0
Instrument #2	0.0	0.3	0.9	1.2	1.3	1.0											4.6	4.1
Instrument #3	0.1	1.2	3.6	5.2	5.4	4.0											19.5	17.4
Instrument #4	0.2	1.4	4.4	6.3	6.5	4.8											23.6	21.0
Instrument #5	0.1	0.7	2.1	3.0	3.1	2.3											11.1	9.9
Instrument #6	0.0	0.3	1.1	1.5	1.6	1.2											5.7	5.1
Instrument #7	0.2	1.7	5.2	7.5	7.7	5.7											27.9	24.9
Instrument #8	0.1	0.5	1.6	2.4	2.4	1.8											8.8	7.8
Instrument #9	0.3	2.4	7.6	10.9	11.2	8.4											40.8	36.4
Instrument #10	0.1	0.9	2.7	3.8	4.0	2.9											14.4	12.8
Instrument #11	0.4	3.1	9.5	13.7	14.1	10.5											51.3	45.7
Flight element #1 (Orbiter)	2.7	21.9	66.6	95.8	102.8	77.2											367.0	326.8
MSI&T [2]	0.4	3.2	9.9	14.3	14.7	10.9											53.3	47.5
Ground data system dev	0.2	1.4	4.4	6.4	6.6	4.9											24.0	21.4
Navigation & mission design	0.1	0.7	2.2	3.2	3.3	2.5											12.0	10.7
Total dev. w/o reserves	6.2	49.7	152.7	220.2	230.6	172.1											831.5	743.4
Development reserves	3.1	25.0	77.4	111.8	114.8	85.5											417.5	372.1
Total A–D development cost	9.3	74.7	230.1	331.9	345.4	257.7											1249.0	1115.5
Launch services			53.6	90.8	93.2	69.5											307.1	272.0
						Phase E												
Phase E science						2.3	8.6	8.9	9.1	9.3	9.6	9.8	10.1	10.4	10.7	10.7	99.4	73.3
Other Phase E cost						5.4	20.3	20.8	21.4	22.0	22.6	23.2	23.8	24.5	25.1	25.2	234.2	172.6
Phase E reserves						1.7	6.3	6.5	6.7	6.8	7.0	7.2	7.4	7.6	7.8	7.8	72.9	53.7
Total Phase E						9.4	35.2	36.2	37.1	38.2	39.2	40.2	41.3	42.4	43.6	43.7	406.5	299.6
Education/outreach	0.0	0.2	0.5	0.7	0.8	0.8	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.1	12.8	9.9
Other (specify)																	0.0	0
Total Cost	**$ 9.3**	**$ 74.8**	**$ 284.2**	**$ 423.5**	**$ 439.4**	**$ 337.3**	**$ 36.1**	**$ 37.1**	**$ 38.1**	**$ 39.1**	**$ 40.1**	**$ 41.2**	**$ 42.4**	**$ 43.5**	**$ 44.7**	**$ 44.8**	**$ 1,975**	**$ 1,697**
															Total Mission Cost			**$ 1,697**

(FY costs[1] 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

ACS	attitude control subsystem
AO	Announcement of Opportunity
BOL	beginning of life
BWG	beam wave guide
C&DH	command and data handling
CBE	current best estimate
CE-PCU	compute element power converter unit
CML	Concept Maturity Level
CPHP	capillary pumped heat pipe
CRCC	critical relay control card
DSM	deep space maneuver
DSN	deep space network
EOL	end of life
EOL	end of life
ESA	electrostatic analyzer
E-VEE-J	Earth Venus Earth Earth Jupiter
FGM	flux gate magnetometer
FOV	field of view
FY	fiscal year
GIRE2	Galileo interim radiation electron (radiation model)
GO	Ganymede Orbiter
GOI	Ganymede orbit insertion
HGA	high-gain antenna
INMS	ion and neutral mass spectrometer
JEO	Jupiter Europa Orbiter
JOI	Jupiter Orbit Insertion
JPL	Jet Propulsion Laboratory
LA	laser altimeter
LGA	low-gain antenna
LOLA	lunar orbiter laser altimeter
LV	launch vehicle
MEL	Master Equipment List
MEV	maximum expected value
MGA	medium-gain antenna
MLI	multi-layered insulation
MRC	medium resolution camera
NAC	narrow angle camera
NExT	New Exploration of Tempel
NRC	National Research Council
NTO	nitrogen tetroxide
PDR	Preliminary Design Review
PMD	propellant management device
PMSR	Preliminary Mission System Review
PP	planetary protection
PPO	Planetary Protection Officer
PPU	power processing unit
PRA	probability risk assessment
PSDS	Planetary Science Decadal Survey
RHU	radioisotope heater unit
RPS	radioisotope power system
RPWI	radio and plasma wave instrument
SEP	solar electric propulsion
SPE	solar proton events
SPE1	solar proton events 1 (radiation model)
SSR	sub-surface radar
SST	solid state telescope
STM	science traceability matrix
TCM	trajectory correction maneuver
TID	total ionizing dose
TRL	technical readiness level
TWTA	travelling wave tube amplifier
UST	universal space transponder
UV	ultraviolet
UVIS	UV imaging spectrometer
VNIRIS	V/NIR imaging spectrometer

Appendix B. References

[1] Feynman, J., G. Spitale, J. Wang, and S. Gabriel, "Interplanetary Proton Fluence Model: JPL 1991," *J. Geo. Res.* 98 (A8), 13281, August 1, 1993.

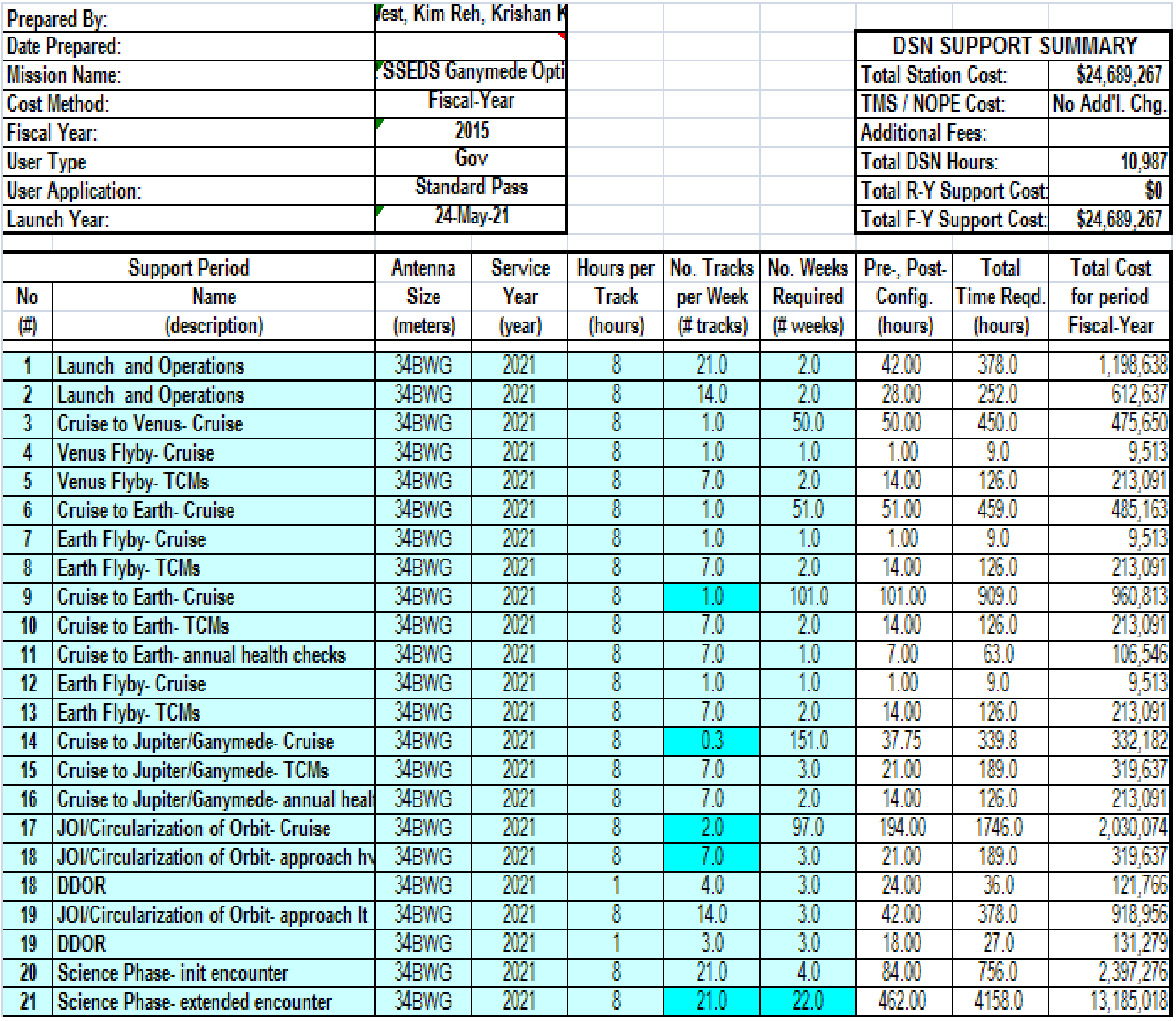
[2] Garrett, H.B., I. Jun, J.M. Ratliff, R.W. Evans, G.A. Clough, and R.W. McEntire, *Galileo Interim Radiation Model*, JPL D-24811, September 2002, and JPL Publication 03-006, February 2003.

[3] Jordan, T. “NOVICE, A Radiation Transport Shielding Code,” Experimental and Mathematical Physics Consultants, January 2006.

Appendix C. Special Technical Analyses

DSN usage was calculated using Table C-1. The breakout found in Table 3-23 of the main report is derived from this information.

Table C-1. DSN Support Summary



Prepared By:	est, Kim Reh, Krishan K
Date Prepared:	
Mission Name:	SSEDS Ganymede Opti
Cost Method:	Fiscal-Year
Fiscal Year:	2015
User Type	Gov
User Application:	Standard Pass
Launch Year:	24-May-21

DSN SUPPORT SUMMARY	
Total Station Cost:	$24,689,267
TMS / NOPE Cost:	No Add'l. Chg.
Additional Fees:	
Total DSN Hours:	10,987
Total R-Y Support Cost:	$0
Total F-Y Support Cost:	$24,689,267

	Support Period	Antenna	Service	Hours per	No. Tracks	No. Weeks	Pre-, Post-	Total	Total Cost
No	Name	Size	Year	Track	per Week	Required	Config.	Time Reqd.	for period
(#)	(description)	(meters)	(year)	(hours)	(# tracks)	(# weeks)	(hours)	(hours)	Fiscal-Year
1	Launch and Operations	34BWG	2021	8	21.0	2.0	42.00	378.0	1,198,638
2	Launch and Operations	34BWG	2021	8	14.0	2.0	28.00	252.0	612,637
3	Cruise to Venus- Cruise	34BWG	2021	8	1.0	50.0	50.00	450.0	475,650
4	Venus Flyby- Cruise	34BWG	2021	8	1.0	1.0	1.00	9.0	9,513
5	Venus Flyby- TCMs	34BWG	2021	8	7.0	2.0	14.00	126.0	213,091
6	Cruise to Earth- Cruise	34BWG	2021	8	1.0	51.0	51.00	459.0	485,163
7	Earth Flyby- Cruise	34BWG	2021	8	1.0	1.0	1.00	9.0	9,513
8	Earth Flyby- TCMs	34BWG	2021	8	7.0	2.0	14.00	126.0	213,091
9	Cruise to Earth- Cruise	34BWG	2021	8	1.0	101.0	101.00	909.0	960,813
10	Cruise to Earth- TCMs	34BWG	2021	8	7.0	2.0	14.00	126.0	213,091
11	Cruise to Earth- annual health checks	34BWG	2021	8	7.0	1.0	7.00	63.0	106,546
12	Earth Flyby- Cruise	34BWG	2021	8	1.0	1.0	1.00	9.0	9,513
13	Earth Flyby- TCMs	34BWG	2021	8	7.0	2.0	14.00	126.0	213,091
14	Cruise to Jupiter/Ganymede- Cruise	34BWG	2021	8	0.3	151.0	37.75	339.8	332,182
15	Cruise to Jupiter/Ganymede- TCMs	34BWG	2021	8	7.0	3.0	21.00	189.0	319,637
16	Cruise to Jupiter/Ganymede- annual healt	34BWG	2021	8	7.0	2.0	14.00	126.0	213,091
17	JOI/Circularization of Orbit- Cruise	34BWG	2021	8	2.0	97.0	194.00	1746.0	2,030,074
18	JOI/Circularization of Orbit- approach hv	34BWG	2021	8	7.0	3.0	21.00	189.0	319,637
18	DDOR	34BWG	2021	1	4.0	3.0	24.00	36.0	121,766
19	JOI/Circularization of Orbit- approach lt	34BWG	2021	8	14.0	3.0	42.00	378.0	918,956
19	DDOR	34BWG	2021	1	3.0	3.0	18.00	27.0	131,279
20	Science Phase- init encounter	34BWG	2021	8	21.0	4.0	84.00	756.0	2,397,276
21	Science Phase- extended encounter	34BWG	2021	8	21.0	22.0	462.00	4158.0	13,185,018