# Return to Europa: Overview of the Jupiter Europa Orbiter Mission

K. Clark* (Karla.B.Clark@jpl.nasa.gov), G. Tan-Wang* (Grace.H.Tan-Wang@jpl.nasa.gov), J. Boldt+ (John.Boldt@jhuapl.edu), R. Greeley^ (greeley@asu.edu), I. Jun* (Insoo.Jun@jpl.nasa.gov), R. Lock* (Robert.E.Lock@jpl.nasa.gov), J. Ludwinski* (Jan.M.Ludwinski@jpl.nasa.gov), R. Pappalardo* (Robert.Pappalardo@jpl.nasa.gov), T. Van Houten* (Tracy.J.VanHouten@jpl.nasa.gov), T. Yan* (Tsun-Yee.Yan@jpl.nasa.gov)
* Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109
\+ Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Rd., Laurel, MD 20723
^ Arizona State University School of Earth and Space Exploration, Tempe, AZ 85287

*Abstract*—Missions to explore Europa have been imagined ever since the Voyager mission first suggested that Europa was geologically very young.[1][2] Subsequently, Galileo supplied fascinating new insights into that satellite's secrets. The Jupiter Europa Orbiter (JEO) would be the NASA-led portion of the Europa Jupiter System Mission (EJSM), an international mission with orbiters developed by NASA, ESA and possibly JAXA. JEO would address a very important subset of the complete EJSM science objectives and is designed to function alone or in conjunction with ESA's Jupiter Ganymede Orbiter (JGO).

The JEO mission concept uses a single orbiter flight system which would travel to Jupiter by means of a multiple-gravity-assist trajectory reaching Jupiter and perform a multi-year study of Europa and the Jupiter system, including 30 months of Jupiter system science and a comprehensive Europa orbit phase of 9 months.

The JEO mission science objectives, as defined by the international EJSM Science Definition Team, include:

A. **Europa's Ocean:** Characterize the extent of the ocean and its relation to the deeper interior

B. **Europa's Ice Shell:** Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange

C. **Europa's Chemistry:** Determine global surface compositions and chemistry, especially as related to habitability

D. **Europa's Geology:** Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration

E. **Jupiter System:** Understand Europa in the context of the Jupiter system

In concert with achieving these science objectives, NASA has provided study guidelines, including:

- Launch no earlier than 2020, with preferred flight times to Jupiter of < 7 years
- Use the 34m DSN station network for primary science downlink
- Carry robust margins in all areas (technical and financial)

The primary challenge of a Europa orbital mission is to perform in Jupiter's radiation environment, radiation damage being the life limiting parameter for the flight system. Designing for reliability and long life requires key knowledge of the environment, understanding of available hardware, conservative hardware and software design approaches, and a management structure that elevates the importance of radiation issues to the project office level. Instilling a system-level radiation-hardened-by-design approach very early in the mission concept would mitigate the pervasive mission and system level impacts (including trajectory, configuration, fault protection, operational scenarios, and circuit design) that can otherwise result in run-away cost and mass growth.

This paper will address the mission concept developed by a joint JPL and APL team to address the science objectives as defined by an international Science Definition Team formed in 2008 while designing for the Jupiter environment and meeting NASA guidelines.

**TABLE OF CONTENTS**



1———————————



[2] IEEEAC paper #1065, Version 9, Updated January 9, 2009

## 1. INTRODUCTION

Starting in late 1995, the Galileo mission delivered orbit after orbit of new insights into the Jupiter system and the worlds of Io, Europa, Ganymede and Callisto. Extensive architectural studies building on and expanding on Europa, Ganymede, and Jupiter System science have been performed over the past decade. The Galilean satellites are quite diverse with respect to their geology, internal structure, evolution and degree of past and present activity. In order to place Europa and its potential habitability in the right context, as well as to fully understand the Galilean satellites as a system, the two internally active ocean-bearing bodies—Europa and Ganymede—are of significant interest.

Since 1996, NASA has studied concepts to reach Europa and unveil its secrets. Most recently, in 2006 and 2007, NASA performed two extensive and detailed Europa mission studies, where current technologies were evaluated to achieve the science defined by Science Definition Teams.

In 2007, ESA put forth a call for mission concepts of its Cosmic Vision Programme. The selected *Laplace* concept was for three separate spacecraft to explore the Jupiter system: a Europa orbiter, a Jupiter orbiter, and a small drop-off spacecraft in Jupiter orbit to study the magnetosphere.

In 2008, the NASA Europa Explorer Study and the ESA *Laplace* Study teams began working together to merge their respective concepts and align the goals through an integrated Joint Jupiter Science Definition Team (JJSDT). The resulting Europa Jupiter System Mission (EJSM) concept complements the Juno mission and allows combined organizational strengths, budgets, and timelines to be realized, in order to carry out a systematic and in-depth study of the Jupiter system which aims at a common and overarching theme:

***The emergence of habitable worlds around gas giants.***

The baseline architecture for EJSM consists of two primary elements operating in the Jovian system at or near the same time: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). This paper describes the NASA element of the proposed Europa Jupiter System Mission – Jupiter Europa Orbiter [1].

## 2. SCIENCE GOALS AND OBJECTIVES

*Relevance and Motivation*

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

By understanding the Jupiter system and unraveling its history from origin to the possible emergence of habitats, we would know better how gas giant planets and their satellites form and evolve. Perhaps more importantly, we would shed new light on the potential for the emergence of life in our galactic neighborhood and beyond.

*Science Goal and Objectives*

To address the overarching EJSM theme of "The emergence of habitable worlds around gas giants", JEO would explore the Jupiter system and study the processes leading to the diversity of its associated components and their interactions. The focus would be to characterize the conditions that may have led to the emergence of habitable environments among its satellites, with special emphasis on the internally active ocean-bearing world, Europa.

Derived from the EJSM theme, JEO's goal would be:

***Explore Europa and investigate its habitability.***

Based on previous magnetometer data, Europa is believed to have a saltwater ocean beneath a relatively thin (several to tens of kilometers thick) and geodynamically active icy crust (**Figure 1**). Europa is unique among the large icy satellites because its ocean is in direct contact with its rocky mantle beneath, where the conditions could be similar to those on Earth's sea floor. The discovery of biologically-rich hydrothermal fields on Earth's sea floor suggests that such areas are rich habitats, powered by geothermal energy and fed by nutrients that result from reactions between the sea water and silicates. Analogously then, Europa is a prime candidate in the search for habitable zones in the solar system.

NASA's JEO spacecraft would establish Europa's characteristics with respect to geophysical activity and habitability. JEO would investigate Europa in detail and has objectives to:

A. **Europa's Ocean:** Characterize the extent of the ocean and its relation to the deeper interior. This includes investigations related to: Europa's gravitational tides; the magnetic environment (including plasma); tidal surface motion; the satellite's dynamical rotation state; and its core, mantle and rock-ocean interface.

B. **Europa's Ice Shell:** Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange. Relevant investigations are: detection of shallow water within the ice shell; detection of the ice-ocean interface; material exchange between the surface and ocean; and heat flow variations.

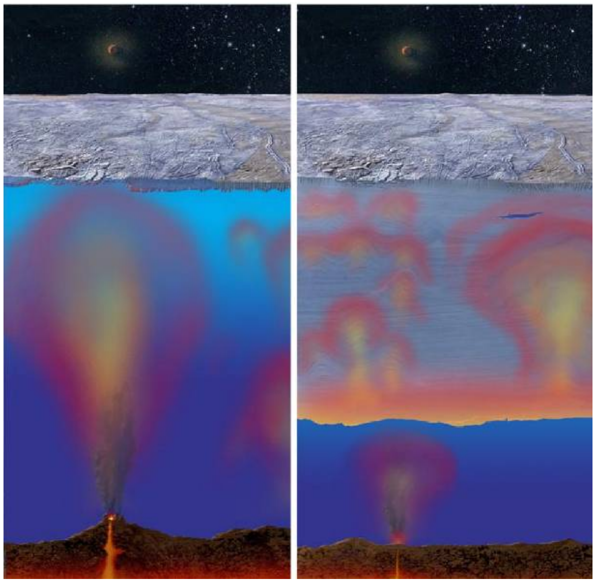


***Figure 1:*** *The NASA Jupiter Europa Orbiter (JEO) would address the fundamental issue of whether Europa's ice shell is ~few km (left) or >30 km (right), with different implications for processes and habitability. In the thin ice case, the ice shell can melt, allowing for direct contact with the surface. In the thick ice case, convection within the ice shell can move warm ice from the base of the shell (orange colors) toward the surface. In either case, the ocean is in direct contact with the rocky mantle below, which can infuse the chemical nutrients necessary for life.*

***Figure 2****: JEO would greatly improve upon simple models of the interior structures of the Galilean satellites based on Galileo data. The smaller rockier pair are Io and Europa (top), and the larger icier pair are Ganymede and Callisto (bottom). All three ice-covered moons are believed to harbor oceans (blue); Europa's is the only ocean beneath a thin ice shell and in direct contact with its rocky mantle. Within Callisto, the degree of ice-rock differentiation is highly uncertain. The satellites are shown to scale, along with the western edge of Jupiter's Great Red Spot (background).*

C. **Europa's Chemistry:** Determine global surface compositions and chemistry, especially as related to its habitability. Relevant investigations include: understanding the satellite's organic and inorganic chemistry; relationships of composition to geological processes; radiation effects on chemistry; and the nature of exogenic materials.

D. **Europa's Geology:** Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration. Investigations relevant to this objective include: formation history and three-dimensional characteristics of surface features; the existence of current or recent activity and the characterization of future landing sites; and processes of erosion and deposition.

E. **Jupiter System:** Understand Europa in the context of the Jupiter system. This includes several sub-objectives, specifically: satellite surfaces and interiors; satellite atmospheres; plasma and magnetospheres; Jupiter's atmosphere; and rings.

The Jupiter system includes a broad diversity of objects, including Jupiter itself, 55 currently known outer irregular satellites, the Jovian ring system, four small inner satellites, and the four large Galilean Satellites: Io, Europa, Ganymede, and Callisto.

The Galilean satellites comprise a fascinating and diverse array of planetary bodies (**Figure 2**). Io is the solar system's most volcanically active world. The "ocean world" Europa has a relatively thin ice shell above an ocean in direct contact with its rocky interior. The ice-rich moons Ganymede and Callisto have similar bulk properties and both are believed to have internal oceans, but these moons have divergent evolutionary histories: Ganymede is strongly differentiated with a hot convecting core and a history of active tectonics and icy volcanism; but Callisto is weakly differentiated with no signs of internal geological activity. To understand the Galilean satellites as a system, our strategy would be to conduct a comparative study of the Galilean satellites with in-depth focus on the internally active moon Europa and its ocean. The results would be placed in the broader context of the whole Jupiter system.

Io, Europa, and Ganymede are coupled in a stable resonance which maintains their orbital periods in a ratio of 1:2:4 and forces their orbital eccentricities. Tidal interaction heats the interior of Io and is responsible for its unparalleled volcanic activity; in turn, Io is the primary mass supplier to Jupiter's magnetodisk. JEO results would enable detailed comparative studies of how the different initial conditions with respect to tidal heating and the Laplace resonance have led to different histories and internal structures, surfaces, and dynamic activities among the four Galilean satellites.

Jupiter's internal and atmospheric structures are intimately coupled to the greater Jovian system environment. JEO would extend Juno's investigations to the lower latitudes of Jupiter's atmosphere while focusing on complementary scientific questions through measurements of the troposphere, stratosphere, thermosphere, and ionosphere for comparisons with Jupiter's interior and magnetosphere.

Jupiter's magnetosphere is closely coupled to the upper atmosphere and interior by electrodynamic interactions. This giant magnetized environment, driven by the fast rotation of its central spinning zone and populated by ions coming from its moons, is the most accessible and intense environment for direct investigations of general astrophysical processes. JEO would measure the dynamics of the Jovian magnetodisk (with angular momentum exchange and dissipation of rotational energy), determine the electro-dynamic coupling between the planet and the satellites, and assess the global and continuous acceleration of particles.

One of the most important aspects of solar system studies is the identification of the processes leading to the formation of gas giant planets. JEO would provide new insight into this issue through understanding of the interior structure and properties of the Galilean satellites (especially Europa), derivation of the bombardment history on the Galilean satellites for application to the Jupiter system, and comparative compositional study of the satellites. Along with better understanding of Jupiter's composition, this would improve knowledge of the thermodynamics of the Jovian circumplanetary disk.

*Responses to Decadal Survey*

The JEO mission concept is fully responsive to the US National Research Council's Planetary Decadal Survey. The Planetary Survey's Steering Group recommended a Europa orbiter as the single top-priority flagship mission for the decade 2003-2013, based chiefly on the satellite's unique astrobiological significance. The Decadal Survey listed six specific objectives for the Europa orbiter each of which would be fully addressed by the JEO element of EJSM. Moreover, the Large Satellites Panel developed a list of 20 specific and overarching high-priority questions for exploration of the outer solar system's large satellites, and the JEO concept directly addresses all but one of them.

## 3. SCIENCE INSTRUMENTS

The JEO model payload has been defined to quantify engineering aspects of the mission and spacecraft design, and to analyze operational scenarios required to obtain the data necessary to meet the science objectives. The instruments, while notional, were defined to demonstrate a viable approach to meeting the measurement objectives, to perform in the radiation environment at Europa, and to meet planetary protection requirements. The actual JEO instrument suite would ultimately be the result of a solicitation through a NASA Announcement of Opportunity.

The model payload consists of a notional set of remote sensing instruments, *in situ* instruments, and both X- and Ka-band telecoms systems which would provide Doppler and range data for accurate orbit reconstruction. All instruments would be co-aligned and nadir pointed for simplification of operations. Instrument articulation required for target motion compensation, limb viewing or other purposes is assumed to be implemented within the instrument. All instruments would be mounted on the nadir-facing deck of the spacecraft with the exception of the Magnetometer (MAG) which would be located on a 10-m boom. The high-gain antenna (HGA) would be deployed well clear of instrument fields of view and would be articulated in 2 axes to decouple instrument pointing from the telecom link to Earth.

The JEO instruments would require substantial radiation shielding. The most mass-efficient approach to providing this shielding is to centrally locate as much of the instrument electronics as possible, minimizing the electronics that must be co-located with the sensor portion of the instrument. This payload architecture would include a common Science Electronics Chassis supporting 22 electronics boards on the industry standard 6U cPCI format. This chassis would provide shielding sufficient to allow use of components hardened to 300 krad without additional spot shielding. Internal partitioning of the science electronics is baselined to provide electrical isolation between instruments and to mitigate electromagnetic interference (EMI). Louvers would provide thermal control of the science electronics chassis in the same manner used for the spacecraft avionics systems. Spacecraft telemetry and command interfaces would be Spacewire for high-bandwidth instruments and Mil-Std-1553 for low-bandwidth instruments. Instrument power would be provided by a 28 V bus.

The JEO model payload is comprised of 11 instruments including radio science. In most cases the notional instrument defined for the model payload meets or exceeds the JEO science objectives and desired measurements. In some cases, the desired measurement envelope is greater than the measurement capability provided by the model payload instrument and reflects decisions by the JSDT regarding the priority of science objectives in light of limited resources. This does not preclude future selection of instruments with broader capabilities.

An overview of the notional instruments comprising the JEO model payload follows. Additional details can be found in **Table 1**.

*Ice Penetrating Radar (IPR)*

The notional IPR is a dual-frequency sounder operating at 50 MHz with 10 MHz bandwidth and at 5 MHz with 1 MHz bandwidth. The higher frequency band is designed to provide high spatial resolution for studying the upper 3 km of the subsurface with high vertical resolution (~10 m). The lower frequency band is designed to search for the ice/ocean interface or the possible transition from brittle to ductile ice in the deep subsurface at a depth of up to 30 km with modest vertical resolution (~100 m). Either mode employs a dipole antenna array. Significant data processing within the instrument for range compression, presumming, Doppler filtering, data averaging and resampling, would be required to reduce the output data volume in the global survey mode.

*Camera Package (WAC+MAC)*

The Camera Package consists of a Wide-angle Camera (WAC) and a Medium-angle Camera (MAC). The notional WAC would obtain global color imagery (3-color plus panchromatic) with 100 m resolution from a 100 km orbit. Stereo imagery from overlapping tracks supports development of a digital elevation model. The notional MAC would obtain panchromatic context imagery of selected targets with 10 m resolution from 100 km.

*Narrow-angle Camera (NAC)*

The notional NAC has both framing and pushbroom modes and would obtain high resolution panchromatic (~1 m from 100 km) imagery of high priority targets at Europa and provides images used for optical navigation. Color filters would be tailored for Jupiter system science.

*Vis-IR Spectrometer (VIRIS)*

The notional VIRIS would provide surface composition measurements, covering a wavelength range from 0.4 to 5.2 µm with spectral resolution of 5 nm below 2.5 µm and 10 nm above 2.5 µm. A full-resolution targeted mode employs a single-axis scan mirror for target motion compensation, allowing sufficient integration time to achieve 25 to 50 m spatial resolution with acceptable signal to noise ratios. A global mapping mode employs data processing and data reduction within the instrument to produce lower-resolution, lower-bandwidth data products.

*Laser Altimeter (LA)*

The notional LA would provide ranging measurements in support of detection of a tidal bulge at Europa. The LA consists of a 1.064 µm laser transmitter, receiver optics and time-of-flight processing electronics providing better than 1 m range precision. A 50 m laser spot size with a 26 Hz pulse repetition rate would provide continuous coverage along-track from the 100 m orbit and ample opportunities for cross-over analysis.

*Magnetometer (MAG)*

The notional MAG is a dual fluxgate magnetometer with 3-axis sensors located at the tip and the halfway point of a spacecraft provided 10 m boom. A sensitivity of 0.1 nT would support detection of the magnetic induction signal from an ocean within Europa. A maximum sampling rate of 32 Hz is required for measurement of ion cyclotron waves near Europa. A maximum field range of 3000 nT supports measurements near Io.

*Plasma and Particle Instrument (PPI)*

The notional PPI consists of an energetic particle detector, a plasma detector and an array of omnidirectional high-energy electron detectors interfaced to a common set of processing electronics. Wide-angle coverage of ions and electrons would be obtained for viewing of plasma flow around Europa.

*Ultraviolet Spectrometer (UVS)*

The notional UVS would perform stellar occultation measurements over a range of 70 – 200 nm with 0.5 nm spectral resolution to characterize Europa's tenuous atmosphere. A single axis scan system would provide views in the spacecraft anti-ram direction with analysis showing multiple occultation opportunities per day in Europa orbit.

*Thermal Instrument*

The notional TI would provide imagery in two wavelength bands for surface temperature measurements with better than 2 K accuracy. Four additional wavelength bands are tailored for Jupiter atmospheric measurements. Spatial resolution of 250 m is obtained from 100 km.

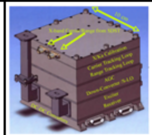
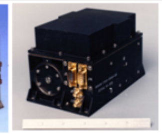
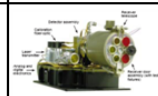
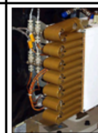
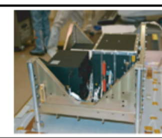
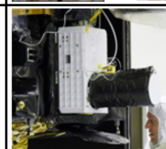
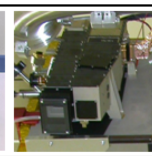
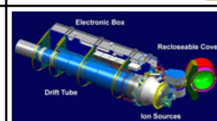
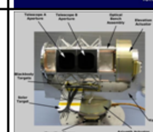
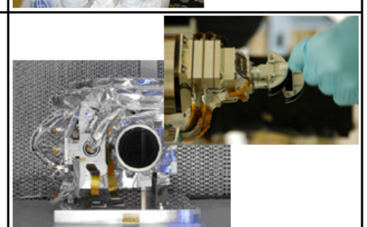
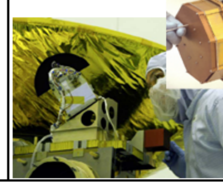
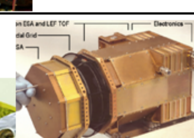
*Ion and Neutral Mass Spectrometer*

The notional INMS would sample a mass range of 1 – 300 Daltons in Europa's atmosphere and ionosphere with mass resolution greater than 500 and a pressure range of $10^{-6}$ to $10^{-17}$ mbar for neutrals and low-energy ions. Close fly-bys during the JEO tour would enable additional INMS composition measurements.

*Radio Science-Gravity*

A dual-frequency X and Ka band transponder in the spacecraft telecommunication system supports 2-way coherent X/Ka Doppler tracking and range measurements required for orbit reconstruction for gravity measurements. Radio occultations would be used to measure the ionosphere and neutral atmospheres of Europa and other Jovian moons during JEO flybys. An Ultra-Stable Oscillator would provide the capability for improved radio science during ingress and egress.

*Table 1: Science Model Payload Instruments*

| | Instrument | Characteristics | Similar Instruments | Similar Instrument Examples |
|---|---|---|---|---|
| Ocean Team | Radio Science (RS) | **Ka-band Transponder**<br>**Doppler Accuracy:** 0.01 mm/s<br>**Integration Time:** 60 seconds for stated accuracy<br><br>**Ultra Stable Oscillator**<br>**Stability:** 2 x $10^{-13}$<br>**Timescales:** 1 to 100 seconds for stated stability | Cassini<br>Juno<br><br>New Horizons<br>GRAIL |   |
| | Laser Altimeter (LA) | **Time-of-Flight Laser Rangefinder**<br>**Transmitter:** 1.064 µm laser<br>**Detector:** Avalanche Photodiode<br>**Resolution:** better than 1 m vertical<br>**Spatial:** 50 m laser spot size, 26 Hz pulse rate | NEAR NLR<br>MESSENGER MLA<br>LRO LOLA |  |
| Ice Team | Ice Penetrating Radar (IPR) | **Dual-Mode Radar Sounder**<br>**Shallow Mode:** 50 MHz with 10 MHz bandwidth<br>**Vertical Depth:** ~3 km<br>**Vertical Resolution:** 10 meters<br>**Deep Mode:** 5 or 50 MHz with 1 MHz bandwidth<br>**Vertical Depth:** ~30 km<br>**Vertical Resolution:** 100 meters | Mar Express MARSIS<br>MRO SHARAD |   |
| Chemistry Team | Vis-IR Spectrometer (VIRIS) | **Pushbroom Imaging Spectrometer**<br>**Detector:** two HgCdTe arrays<br>**Spectral Range:** 400 to > 5200 nm<br>**Spectral Resolution:** 5 nm from 400 to 2600 nm<br>**Spectral Resolution:** 10 nm from 2600 to 5200 nm<br>**Spatial Resolution:** 25 m from 100 km orbit<br>**FOV:** 9.2 deg cross-track **IFOV:** 0.25 mrad<br>**Articulation:** Along-track scan mirror | MRO CRISM<br>Chandrayaan MMM |   |
| | UV Spectrograph (UVS) | **Grating Spectrometer + High-Speed Photometer**<br>**Detector:** MCP + position sensitive anode<br>**Format:** 1024 spectral x 64 spatial pixels<br>**Spectral range:** 70 – 200 nm<br>**Spectral Resolution:** 0.5 nm<br>**Spatial Resolution:** 100 m from 100 km orbit<br>**FOV:** 3.7 deg cross-track **IFOV:** 1 mrad<br>**Articulation:** 1-D scan system for stellar occultations | Cassini UVIS<br>New Horizons Alice |   |
| | Ion Neutral Mass Spectrometer (INMS) | **Reflectron Time-of-Flight Mass Spectrometer**<br>**Mass Range:** 1 to > 300 Daltons<br>**Mass Resolution:** > 500<br>**Pressure Range:** $10^{-6}$ to $10^{-7}$ mbar<br>**Sensitivity:** $10^{-4}$ A/torr<br>**FOV:** 10 x 40 deg | Rosetta ROSINA RTOF |   |
| Geology Team | Thermal Instrument (TI) | **Temperature Sensing Thermopile Array**<br>**Detector:** Thermopile array with filters<br>**Detector Configuration:** 21 pixels cross-track, 6 bands<br>**Spectral Bands:** 8-20µ, 20-100µ, 21µ, 28µ, 40µ, 17µ<br>**Temperature Range:** >160K to 80K<br>**Spatial Resolution:** 250 m<br>**Resolution:** 2K<br>**IFOV:** 2.5 mrad | MRO MCS<br>LRO Diviner |  |
| | Narrow-angle Camera (NAC) | **Pushbroom and Framing Imager**<br>Panchromatic Pushbroom Imager + Color Framing Imager<br>**Detector:** CMOS array or CCD array + line array<br>**Detector Size:** 2048 pixels wide<br>**Color Bands:** 9 plus panchromatic<br>**Spatial Resolution:** 1 m from 100 km orbit<br>FOV: **1.2° IFOV: 0.01 mrad IFOV**<br>**Mechanism:** Filter wheel | New Horizons LORRI |  |
| | Camera Package (WAC+MAC) | **WAC - Pushbroom Imager with fixed color filters**<br>**Detector:** CMOS or CCD line arrays (4)<br>**Detector Size:** 1024 pixel line arrays (4)<br>**Color Bands:** <450 nm, 630-670 nm, >930 nm<br>**Spatial Resolution:** 100 m from 100 km orbit<br>**FOV:** 58° line scan, **IFOV:** 1 mrad<br><br>**MAC - Panchromatic Pushbroom Imager**<br>**Detector:** CMOS or CCD line array<br>**Detector Size:** 2048 pixels<br>**Spatial Resolution:** 10 m from 100 km orbit<br>**FOV:** 11.7 deg line scan **IFOV:** 0.1 mrad | MRO MARCI<br>MESSENGER MDIS<br>New Horizons MVIC |  |
| Fields & Particles Team | Magnetometer (MAG) | **Dual 3-axis Fluxgate Magnetometer**<br>**Boom:** 10 m<br>**Sensor Location:** 5-m and 10-m from s/c<br>**Dynamic Range:** 3000 nT<br>**Sensitivity:** 0.1 nT<br>**Sampling Resolution:** 0.01 nT<br>**Maximum sampling rate:** 32 Hz | MESSENGER MAG<br>Galileo MAG |  |
| | Particle and Plasma Instrument (PPI) | **Plasma: Top Hat Analyzer**<br>**Energy Range:** 10 eV to 30 KeV electrons<br>**Energy Range:** 10 eV to 30 KeV ions with composition<br>**FOV:** 360° x 90°<br><br>**Particles: Puck Analyzer**<br>**Energy Range:** 30 KeV to 1 MeV electrons<br>**Energy Range:** 30 KeV to 10's of MeV ions<br>**FOV:** 120° x 20°<br><br>**High Energy Electrons: Omnidirectional SSDs**<br>**Energy Ranges:** >2 MeV, >4 MeV, >8 MeV, >16 MeV | DS1 PEPE<br>MESSENGER FIPS<br>New Horizons PEPSSI<br>JEDI |   |

## 4. Mission Design

A summary of the proposed JEO trajectory, tour, and Europa orbit parameters is in **Table 2**.

***Table 2**: Baseline Mission Design Characteristics*

| Parameter | Value |
|---|---|
| Launch Vehicle | Atlas V 551 |
| Earth to Jupiter Trajectory | VEEGA |
| Earth Launch Period | 2/29/2020 to 3/20/2020 |
| $C_3$ ($km^2/s^2$) | Up to 12.8 |
| Interplanetary Deep Space $\Delta V$ (m/s) | Up to 93 |
| Jupiter Arrival Date | 12/21/2025 |
| Declination of Launch Asymptote (deg) | <2 |
| Jupiter Arrival $V_\infty$ (km/s) | 5.5 |
| JOI Earth Range (AU) | 4.3 |
| JOI Periapsis Altitude ($R_J$) | 5.2 |
| Jupiter Capture Orbit Period (days) | ~200 |
| Tour | 12/21/2025 to 7/3/2028 |
| EOI | 7/3/2028 |
| Primary Europa Science | 7/3/2028 to 3/30/2029 |
| Orbit Altitude, Average (km) | 200, then 100 |
| Orbit Period (min) | 138, then 126 |
| Ground Speed (km/s) | 1.2, then 1.3 |
| Orbits/day | 10.4, then 11.4 |
| Europa Initial Orbit Inclination (deg) | 95 |

*Launch and Interplanetary Cruise*

JEO would be launched from Cape Canaveral Air Force Station on an Atlas V 551 with a maximum $C_3$ of 12.8 $km^2/s^2$ during a 21 day launch period opening on 29 February 2020. JEO would use a Venus-Earth-Earth Gravity Assist (VEEGA) interplanetary trajectory, shown in **Figure 3**. The flight system is designed to launch on any given day in the launch period without modification. There is no deep-space $\Delta V$ required on the opening day of the launch period, but it grows steadily until reaching about 93 m/s on the last day of the launch period. That $\Delta V$ would occur near aphelion on the Earth-Earth leg of the trajectory.

*Jupiter Arrival*

After a cruise of just under six years, JEO would fly by Io roughly two hours prior to performing the Jupiter orbit insertion (JOI); see **Figure 4**. The current design conservatively plans for an Io flyby altitude of 1000 km, although the planned optical navigation would allow future consideration of much lower altitudes, thereby allowing a further reduction in JOI magnitude (~50 m/s if the flyby altitude is dropped to 500 km). This flyby is designed primarily to give JEO a gravity assist, reducing the magnitude of the JOI maneuver by about 200 m/s. JOI straddles the 5.2 Jovian radii (Rj) perijove and would put JEO into an orbit with a period of about 200 days.

Near apojove of the first orbit, a maneuver would target JEO to the second Io encounter of the mission, which would be the first Io encounter of the tour. In the process, it would correct for the solar perturbations induced as a result of the rather large initial orbit and remove any remaining errors from the initial Io flyby and JOI.

*Jovian Tour*

JEO would then perform a 30-month gravity-assist tour to lower its orbital energy with respect to Europa (saving at least 3 km/s over an earlier direct orbit insertion). Such a tour provides the further benefit of extensive opportunities for Jovian system science. In particular, the tour would begin with an Io Science Campaign involving three Io flybys after JOI, and continues with a System Science Campaign which would involve flybys of each of the other Galilean satellites. The baseline tour is only one possible design, to illustrate feasibility. It includes three close Io encounters (after JOI), six with Europa, six with Ganymede, and nine with Callisto. The tour also features non-targeted (less than 100,000 km range) flybys of Io and Europa. The tour, despite the requirement simply to demonstrate feasibility, achieves many of the science desires, including a low-altitude flyby (<300 km) over the active volcanic region of Io called Amirani, an early Europa flyby at $V_\infty$<7 km/s, and one high-latitude flyby of Callisto.

In addition to the observations acquired during satellite flybys, science observations of the Jovian magnetosphere and atmosphere, and monitoring of Io, would be possible between encounters during the Jovian Tour phase.

*Europa Orbit*

The tour would end on 3 July 2028 with Europa Orbit Insertion (EOI), a main engine burn that would result in capture into low circular orbit at Europa.

The science orbit at Europa must be low altitude (100–200 km), near circular, high inclination, with solar incidence angle near 45° (specifically, a 2:30 p.m. orbit). To meet the lighting requirement over the duration of the first three Europa Science Campaigns, a retrograde orbit was chosen, and the intersection of all the other science constraints puts the required inclination between 95 and 100°. If left uncontrolled, arbitrary orbits with these characteristics would become more eccentric, due primarily to Jupiter's gravitational perturbations, and generally impact Europa within about a month. These orbits need to be maintained on a regular basis.

A roughly five day engineering assessment and orbit adjustment period would follow EOI. The next 8 eurosols (~28 days) of the Europa orbital mission would be known as the Global Framework Campaign, which is performed at an altitude of approximately 200 km. After concluding the first

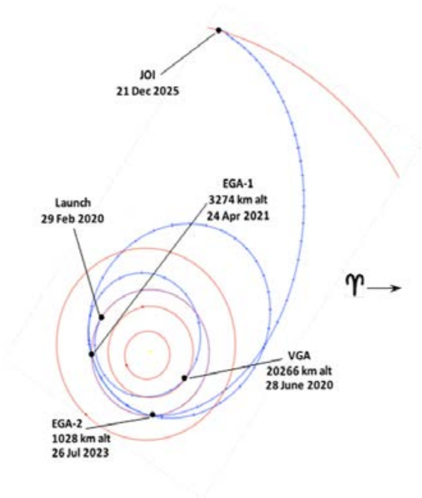



*Figure 3: Baseline 2020 VEEGA Trajectory (Conceptual Design)*

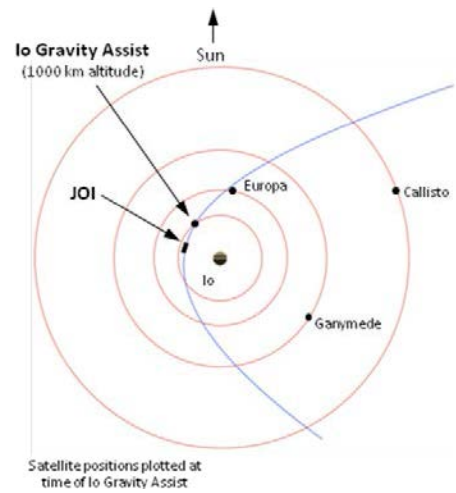



*Figure 4: View of +/-2 days around Io closest approach on Jupiter arrival day, 21 Dec 2025 (Conceptual Design)*

Europa Science Campaign, the flight system would maneuver to a circular orbit of approximately 100 km to begin the Regional Processes Campaign, which lasts 12 eurosols (~43 days). The third campaign, the Targeted Processes Campaign, would take 8 eurosols (~28 days) and ends about 105 days after Europa Orbit Insertion (EOI). The Focused Science Campaign comprises the rest of the prime mission and ends at EOI + 9 months.

## 5. Flight System Design

The JEO flight system concept is based on the wealth of work performed in last several years: the *Europa Explorer FY07 Final Report,* which in turn was based on the *Europa Explorer Design Team Report 2006* as well as from Europa Geophysical Explorer (2005), Europa Orbiter (2001), and numerous trade studies conducted over the past decade. The technology to fly such a mission has advanced in the past decade, especially in areas of launch vehicles, avionics, radioisotope power sources, and detectors. While showing incremental improvements, the overall design has become remarkably stable, suggesting that the requirements are well-understood.

*Flight System Overview*

Key design drivers on the spacecraft are Jupiter's radiation environment, planetary protection, high propulsive needs to get into Europa orbit, the large distance from the Sun and Earth and the accommodation of the instrument payload. The high-level constraints and assumptions on the JEO flight system design are:

- The flight system design shall employ technology that either exists already or is under development and is planned for qualification early in the JEO project lifecycle.
- The mission reference radiation design dose (referenced to 100 mil aluminum shell) is 2.9 Mrad.
- The required total $\Delta V$ is 2260 m/s.
- Approximately 7.3 Gbits of science data is returned per Earth-day during the Europa orbit phase and ~3.6 Gbits per Earth-day during the Jupiter tour phase.
- 34 m DSN antenna used during normal operations, with limited 70 m antenna use (or equivalent) for critical or emergency events.
- Heliocentric operating range of 0.7 AU to 5.5 AU, with a maximum Earth range of 6.5 AU.

Radiation is the key defining challenge and life limiting parameter for the flight system. Due to the high radiation environment at Jupiter, the flight system must be designed from the outset to address radiation tolerance. The JEO conceptual radiation approach has to go well-beyond conventional approaches to address a mission in such a harsh environment. The radiation protection for the JEO flight system would involve an approach that starts with a mission design that considers radiation dose while meeting JEO science objectives, a significant program to judiciously select radiation hardened parts and material capability, detailed shield mass composition design, deliberate component placement within assemblies, and systematic refinement of reliability assessment modeling of the electronics and subassemblies from the ground up. System lifetime analyses have been performed and provide the basis for projected mission duration of the JEO mission concept.

All electronics would need to be redesigned to incorporate rad-hard parts. Analyses and packaging would need to be re-done. Thus, no off-the-shelf electronics are assumed.

The radiation shielding approach is to communally shield assemblies of similar rad-hardness. Grouping similarly-rad-hard assemblies together in separate enclosures (as opposed to using a single vault for all assemblies, regardless of their need) would optimize shield mass (by avoiding a heavier shield mass penalty from having to shield everything down to the "lowest common denominator" part tolerance level) and allow for placement of electronics in strategic locations, such as the traveling wave tube amplifiers (TWTAs) on the back of the high gain antenna (HGA). More detailed description of the radiation treatment for this mission is discussed in the following section.

The JEO spacecraft is designed to meet the planetary protection requirements from the outset. The mission would be classified as Category III under COSPAR and NASA policy, which specifies that JEO show that the probability of inadvertent contamination of an Europan ocean be less than $1 \times 10^{-4}$. Given the limits of this paper, this topic will not be addressed here, but planning is underway to implement a process and strategy that would allow JEO to meet this requirement with cleanliness strategies embedded into the design, build and integration process.

The flight system would be a mostly redundant, 3-axis stabilized flight system powered by Multi-Mission Radio-isotope Thermoelectric Generators (MMRTGs). The baseline flight system has 11 instruments, as described previously, including the radio system for gravity science investigations. The flight system launch mass, including 43% margin, is 4704 kg with respect to the currently quoted Atlas V 551 capability of 5040 kg, as detailed in **Table 3**.

The high propulsive requirements to get into Jupiter orbit and subsequently into Europa orbit drive the large propellant load required and the dry mass of the propulsion subsystem to hold the propellant. The dual-mode, bi-propellant propulsion system holds approximately 2646 kg of propellant, comprised of hydrazine ($N_2H_4$) fuel and nitrogen tetroxide ($N_2O_4$ or NTO) oxidizer. The 890 N (200 lbf) bipropellant main engine would be 2-axis gimbaled. Radiation primarily affects two propulsion components; pressure transducer electronics and soft goods within electrical valves. Further research into pressure transducers used in the nuclear power industry is still required. The primary soft goods in valves are the sealing materials, such as Teflon, AF-E-411 (rubber), Vespel, etc. Better characterization of the properties and performance of these materials in high radiation environments is required.

Small thrusters, 4.5 N (1 lbf) each, would be used to reduce post-launch separation rates, to provide attitude control during cruise, small ΔV maneuvers, and to desaturate the reaction wheels during the Jupiter tour and Europa orbit

***Table 3:*** *Baseline Mass Equipment List shows conceptual JEO design fits with 43% margin on Atlas V 551 launch vehicle*

| JEO Baseline Mass Equipment List | | | | Comments |
|---|---|---|---|---|
| | Flight System Mass, kg | | | |
| | CBE | Cont. | CBE+Cont. | |
| Payload | 163 | 30% | 211 | |
| Model Payload | 106 | 30% | 137 | CAM, NAC, VIRIS, UVS, LA, IPR, TI, MAG, PPI, INMS |
| Payload Radiation Shielding | 57 | 30% | 74 | Shielding for instrument detectors and electronics chassis |
| Spacecraft | 1208 | 24% | 1498 | |
| Power (w/o RPSs) | 55 | 30% | 72 | Power distribution, converters, switches, & 12 Ahr batteries |
| C&DH | 34 | 17% | 40 | Redundant Rad750 SFC and 3GB CRAM SSR |
| Telecom | 56 | 27% | 70 | X/Ka 3 m HGA, X MGA & LGAs, 25 W Ka and 25 W X TWTAs |
| Structures & Mechanisms | 320 | 31% | 420 | S/C structure, HGA gimbal, mag boom, and S/C side LVA |
| Thermal | 68 | 30% | 88 | MLI, Venus/perihelion protection, heaters, (V)RHUs, etc. |
| Propulsion | 157 | 28% | 201 | 890N main engine, RCS thrusters, and COPV tanks |
| ACS | 69 | 33% | 91 | Reaction wheels, SIRU, star trackers, and sun sensors |
| Cabling | 83 | 30% | 108 | 7% of CBE S/C bus dry mass excluding shielding |
| Radiation Monitoring System | 8 | 30% | 10 | 8kg allocation from Europa Explorer has not been refined. |
| RPS System | 226 | 0% | 226 | 5 MMRTGs |
| Spacecraft Radiation Shielding | 132 | 30% | 172 | Shielding accounts for 2.9 Mrad reference mission |
| Flight System Total Dry | 1371 | 25% | 1709 | Includes P/L, S/C, shielding, and subsystem contingency |
| Additional System Margin to achieve study req. | | | 226 | Additional cont. on S/C and P/L to obtain 33% margin |
| Flight System Total Dry with Required Margin | | | 1935 | Includes P/L, S/C, shielding, and system contingency |
| Propellant | | | 2646 | Fuel, oxidizer, pressurant, residuals/holdup, and RCS prop |
| Flight System Total Wet | | | 4581 | Includes P/L, bus, shielding, system contingency, and prop |
| LV Adapter with required margin | | | 123 | LV-side adapter, LSA, cabling, blankets, and margin |
| Flight System Launch Mass Wet | | | 4704 | Entire wet s/c with LV adapter and required margin |
| Atlas V 551 Capability for 2020 VEEGA | | | 5040 | |
| Additional Margin | | | 336 | Mass margin beyond the required 33% margin |
| System Margin (33% required per study guidelines) | | | 43% | JEO easily fits on the Atlas V 551* |

*Note: Mass margin excludes MMRTGs from calculation because the MMRTG mass is considered a Not-To-Exceed value, and is therefore fully margined.

phases. Because the detection of the tidal signature would require an orbit reconstruction with a radial error of about 1 m, residual ΔV must be minimized during the Europa orbit phase and so the 4.5 N thrusters are coupled and redundant. The flight system attitude would be controlled primarily with reaction wheels during science operations.

Attitude sensors include redundant stellar reference unit (SRU), an internally redundant gyro, and multiple sun sensors, all of which would be selected based on their radiation tolerance. During peak radiation environments, such as near Io, the pointing knowledge performance would be degraded as the SRU may experience false star identification and pointing would rely on the gyros only. JPL has extensive experience with radiation mitigation strategies for SRUs in the Jovian environment as a result of work performed with SRU vendors for NASA's Juno New Frontiers Mission and the Europa Orbiter SRU Concept Design Study of 1999–2000. In both cases, shielding was key for detector total-dose survival as well as reduction of the transient noise and false stars, due to external electron and proton flux. Algorithms would be developed based on the understanding of transient thresholds of the various radiation environments, such as those during an Io flyby versus in Europa orbit.

Five Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) would power the flight system, providing about 540 watts of electrical power at End of Mission (EOM) with an unregulated, nominal 28 Vdc main power bus (22–36 VDC). The conceptual JEO design could also accommodate five Advanced Stirling Radioisotope Generators (ASRGs) in place of the MMRTGs if the ASRGs become available for use. Redundant 12-Ah lithium-ion batteries would provide for energy storage to handle transient demands for power throughout the mission, such as during Europa Science orbit when simultaneously operating science instruments and communicating back to Earth. Grounding would be established for a balanced bus, with both high side and return floating from spacecraft chassis for additional fault tolerance. Pyros would be fired directly off the main bus power through the Arm and Enable switches. All power electronics are designed to be radiation hard to 1.0 Mrad.

Waste heat from the MMRTGs would be used for thermal control to the maximum extent practical, in order to reduce electrical power that would otherwise be allocated for heaters. Radioisotope Heater Units (RHUs) and Variable RHUs would also be used for the same reason. In addition, the thermal design uses multilayer insulation (MLI), thermal surfaces, thermal conduction control, thermal louvers (both external and internal), electric heaters and thermostats/engineering sensors to thermally control the spacecraft. The Venus gravity assist flyby would impose the Venus IR thermal load as well as the direct solar incident energy on the flight system. The conceptual design would protect the flight system from both the Venus IR thermal load as well as the direct solar incident thermal energy using additional MLI layers with appropriate stand-off distances.

The 4.2 to 6.5 AU variation in distance from Earth during the Jupiter orbital mission requires a very capable telecommunications system to return the significant data required to meet the science objectives. The flight system would use Ka-band for the highest rate science data return and X-band for high and low rate communications system during cruise, safing, critical events, and for all uplink commanding, as well as a Ka-up/Ka-down carrier-only system for science. Key features of the design would include redundant cross-strapped X/Ka-band Small Deep Space Transponders (SDSTs), redundant cross-strapped 25 W Ka-band traveling wave-tube amplifiers (TWTAs), redundant cross-strapped 25 W X-band TWTAs, a 3-m X/Ka high gain antenna (HGA), a X-band medium gain antenna (MGA), two X-band low-gain antennas (LGAs), and an Ultra Stable Oscillator (USO) and Ka-band Transponder (KaT) for radio science.

Most of the telecom hardware would be mounted on the back of the HGA thereby reducing the circuit loss between the output of the high-power amplifiers and the antennas. The medium gain antenna and 2 low gain antennas would be used for near earth and safe mode communications. Two sun sensors would be mounted on the HGA for safemode attitude on the MGA. During the Jupiter tour phase, the telecom subsystem would provide Ka band link performance of 64–144 kb/s over the 4.2 to 6.5 AU range to a DSN 34 m antenna. The link carries 3 dB of margin, and assumes 90% weather, 20 deg station elevation, Turbo coding (8920, 1/6) with frame error rates of $10^{-4}$, and residual carrier BPSK modulation. Traditional link designs typically assume worst case station elevation angles and other system noise sources (yearly weather effects, Jupiter hot body noise, etc.) when determining supportable data rate. By taking advantage of actual elevation angles and Jupiter noise conditions for each orbit lockup at occultation exit, planned data rates could be increased by roughly a factor of 2. For the Europa orbit phase, this strategy is assumed and the Ka-band link performance to a 34 m DSN antenna increases to 134–280 kbps over the 4.2–6.5 AU range.

The data processing and handling architecture includes a dual-string RAD750 computer running at 200 Mhz that would be capable of performing all science and engineering functions including identified science data compression. It would utilize Spacewire ports for high data rate connections and 1553B data bus for lower data rate interfaces and connections between the redundant strings. Data storage would be implemented using a hybrid Solid State Recorder (SSR) that would contain:

- 3.1 Gb of non-volatile chalcogenide random access memory (CRAM) with 1 Gb currently allocated for science use, and the remaining 2.1 Gb allocated for engineering and science flight software (FSW), engineering telemetry, processing space, and margin,

• 16 Gb of volatile synchronous dynamic RAM (SDRAM) dedicated to science use, particularly around the Galilean satellite flybys. The SDRAM would not be required to survive through Europa orbit insertion.

FSW would be a key component of the system architecture with features that would allow for ease of operations during flight and for a fault response approach that would balance continued degraded mission progress with transient fault recovery. A Europa mission would necessarily compress a series of essential activities into the confined space of months. This aggressive timeline is driven by high radiation levels in the vicinity of Europa. Addressing the needs for the JEO concept is within capabilities that have been demonstrated in past missions.

*Configuration*

The conceptual configuration of the baseline flight system is shown in **Figure 5** (Stowed in LV) and **Figure 6** (Operational). Major configuration drivers were as follows:

• Nadir pointing fields-of-view for remote sensing instruments

• Simultaneous pointing of instruments and pointing of HGA at Earth

• Large boom and radar antenna accommodation

• Usage of propellant tanks with existing diameter sizes

• Atlas V fairing envelope and access door size and number (3 doors, each at 1.2 × 1.8 m or 4 × 6 feet), accommodating 5 MMRTGs and the HGA

• MMRTGs view of each other and to space with maximum distance to instruments

• Eight RCS thruster clusters with placement driven by the coupling requirement and plume impingement avoidance of instruments, HGA, and MMRTG.

Long life, highly reliable deep space missions are founded in NASA's institutional design practices and processes. These systems are required to operate over long periods of time and over great distances with limited human interaction. Lessons learned from Voyager, Galileo, Cassini, and others, are incorporated into practices and designs including Extreme Value Worst Case Analysis, Parts Stress Analysis, block redundancy, autonomous fault recovery, cross-strapping, internal redundancy and functional redundancy in appropriate combinations to eliminate all non-exempt single point failures (SPFs). All redundancy, fault-protection logic, and cross-strapping circuitry are validated in the system testbeds or in integration and tested prior to launch.

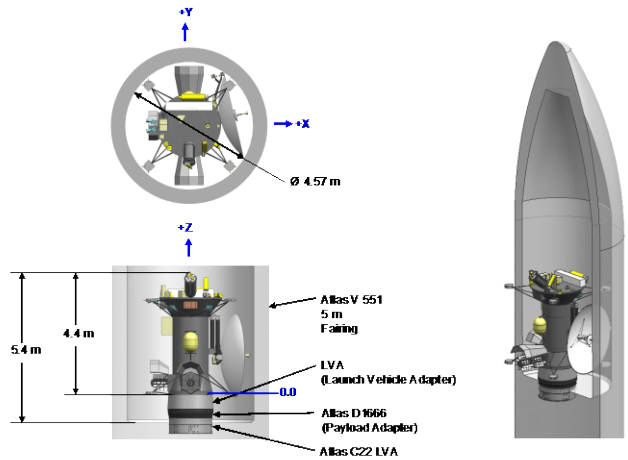



***Figure 5:*** *Stowed Configuration of JEO Flight System in Atlas V LV Fairing (Conceptual Design)*

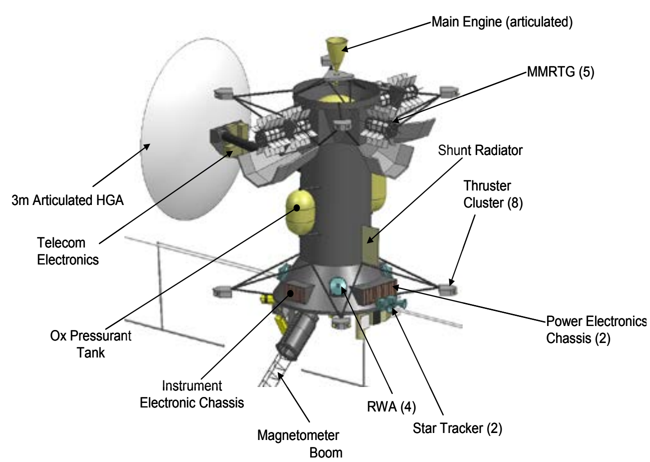



***Figure 6:*** *Operational Configuration of JEO Flight System (Conceptual Design)*

## 6. Radiation

The sheer magnitude of JEO's expected radiation dose poses a unique technical challenge for the JEO mission. To date there have been seven flybys of Jupiter by spacecraft (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini, and New Horizons) as well as the Galileo orbiter. Except for Galileo, all were single flybys. While Galileo spent the equivalent of several weeks in the Jovian magnetosphere, JEO will spend more than five times as long in those harsh radiation belts. JEO mission design would capitalize on Galileo's discoveries and leverage its technical know-how.

The Galileo mission design followed the conventional engineering practice by which the mission designers predicted the radiation environment and then multiplied the estimated value by a radiation design factor (RDF) of 2. The resultant 100% margin is used for the selection of parts, materials, detectors and sensors for radiation susceptibility, and shielding designs. This conventional approach has resulted in spacecraft designs that function well beyond their intended design environment. For example, Galileo's mission was extended three times with the spacecraft accumulating an estimated radiation dose of at least 8 times its design level, estimated by science data collected during the Galileo mission [2, 3]; there was no dosimeter on board to measure the actual environment. At the end of its mission, after almost 8 years at Jupiter, the basic spacecraft functionality was still available.

*Systems Engineering Approach for Radiation Environment*

The planned JEO radiation design recognizes the advantages of identifying and utilizing excessive margins in the development chain from parts selection, design of electronic subsystems and final system integration. This approach improves the traditional process and simultaneously provides a more accurate picture of estimating mission lifetime. Application of this system approach for radiation mitigation offers a new paradigm in the underlying process for reliability over long lifetimes.

In the conventional approach a basic trade in the design for radiation environment is one of shield mass versus lifetime. Many elements influence the trade space including: parts and material capability, shield mass composition, natural shielding by moons or other spacecraft elements (e.g., propulsion tanks), and even component placement within assemblies. Even taking advantage of the best options among these previous elements, if the designer applies the conventional approach to the planned JEO mission, the resulting shield masses required would be large for long missions in the Jovian radiation belts. On the other hand, reducing this added "dead mass" to a more acceptable level would significantly reduce the mission lifetime and increase the risk of premature mission failure. A more systems-oriented approach could go further to identify and utilize hidden margins to allow a larger trade space to be evaluated and resources to be better allocated.

Recent advances in electronics for military and nuclear applications have made many parts available up to several hundred krad (Si). Taking advantage of these newly available components and fabrication processes, coupled with more thorough testing and characterization as well as careful circuit configuration and layout, would significantly enhance the robustness of the electronic subsystems and thus extend the lifetime of the planned JEO mission. Refined methodologies developed for incorporating reliability results from lower levels into systems engineering analysis to quantify the overall design lifetime and manage margins provide tremendous insight into prioritizing science collection, designing fault protection and developing contingency plans to ensure graceful system degradation. These system-level implications can then be optimized in trade studies and risk analysis.

Based on conventional design approach, JEO's mission lifetime would end at the conclusion of Europa Campaign 3 (105-days in Europa orbit; see Section 7 on Operational Scenarios). However, the designer would not be able to provide any information about the likelihood of surviving beyond the 105 days. The JEO systems engineering approach captures the state of the JEO design in a system lifetime model that shows graceful degradation beyond Europa Science Campaign 3. The initial model was developed for the 2007 EE Mission Study. Per the lifetime model, there are ample design margins indicating the JEO mission would survive up to one year in Europa orbit.

*Jovian Radiation Model and Environment*

The planned JEO mission would be subjected to four major radiation sources: (1) solar energetic particles (protons, electrons, and heavy ions) during the interplanetary cruise, (2) galactic cosmic rays (protons and heavy iosn) during the interplanetary cruise, (3) trapped particles (electrons, protons, and heavy ions) in the Jovian magnetosphere during the Jupiter tour and the orbits at Europa, and (4) particles (neutrons and gammas) from the onboard nuclear power source, MMRTG.

Among the four radiation sources, the high-energy trapped electrons and protons at Jupiter would be the dominating contributors to the "life-limiting" total ionizing dose (TID) and displacement damage dose (DDD) effects. The Jovian trapped particles are not static, but vary in intensity and population spatially and temporally. Correctly defining and characterizing the radiation environments would allow the mission designer to optimize JEO tour and orbital trajectories; thus constraining the radiation exposure to an affordable design level. The 2008 JEO design includes a radiation dosimeter to monitor the field radiation exposure in real-time. Data accumulated would allow validation of the environment and shielding modeling effort.

The Jovian radiation environment model used for JEO would be a semi-empirical model based on data collected from Pioneers 10 and 11, Voyagers 1 and 2, and Galileo. Specifically, it is the Divine model augmented by the Galileo high energy electron data [4]. The Galileo data are also used to predict a statistical radiation environment [3]. More recently, Galileo data analysis, together with a theoretical calculation, was carried out specifically to characterize the environment in the near vicinity of Europa [5]. Further development effort would focus on refinement of the model to include temporal variation of the environment and directionality around Europa.

A reference mission scenario has been selected for the 2008 JEO mission, illustrated in **Figure 7's** total ionizing dose (TID) depth curve. The reference radiation design point is 2.9 Mrad (Si) behind a 100-mil (2.5 mm) aluminum shielding with RDF=1.

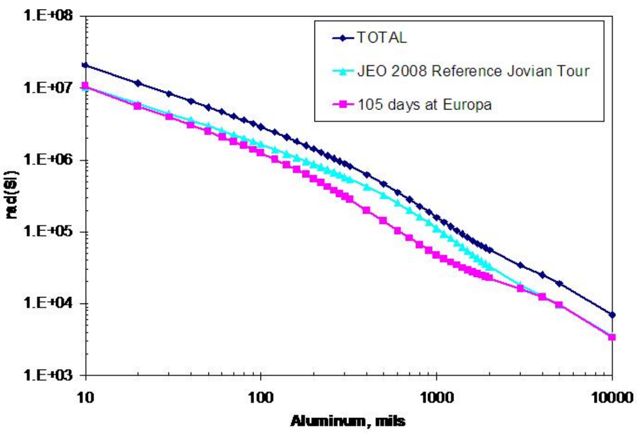



***Figure 7:*** *JEO Reference Total Ionizing Dose (TID) Depth Curve shows the reference radiation design point for the planed JEO Mission (RDF = 1).*

*Radiation Tolerant Design Approach*

Electronic assemblies are vulnerable to failure when exposed to a high radiation environment for long durations. Though many parts are functional after exposure, the parameter degradation may be different from typical parameters shown on specification sheets from vendors. The availability of radiation tolerant parts from 100 krad to 1 Mrad tolerance make a Europa mission much more viable than even 10 years ago. Early identification, documentation and dissemination of available parts, materials and design techniques would enable engineering and payload providers to adequately design for the harsh radiation environment. Furthermore, non-electronic components are generally preferable to electronic counterparts for radiation tolerant considerations. For example, mechanical thermostats and regulators may be preferred over electronic controllers.

*Shielding*

The baseline JEO electronic subsystems design incorporates a combination of shielded 6U chassis and enclosures to protect the electronics and detectors. Spot shielding would be used when necessary. This distributed/strategic approach significantly reduces shielding mass when compared to a centralized design where a single vault (e.g., Juno approach) would be used to shield all electronics. As the design matures and part radiation tolerances becomes better known, this trade would be periodically re-evaluated to take advantage of the most mass efficient approach.

For the current JEO design, all electronics packaged on standard 6U cards would be assumed to use a shielded chassis to reduce the radiation dose to one half the part-level tolerance value; thus satisfying the conventional radiation design point of RDF = 2. For pre-packaged electronics or sensors/detectors, shielded enclosures are used instead. The minimum part tolerance level of subsystem components (before factoring in the RDF) is typically 300 krads, with some exceptions (e.g. propulsion system pressure transducers rated for 75 krads).

The total estimated spacecraft shield mass using Tungsten-Copper is 189 kg (CBE), comprised of 57 kg for payload instrument detector and electronics shielding, and 132 kg for engineering electronics shielding. At the current design, Tungsten-Copper would provide more than 20% mass savings over Aluminum and over 5 times saving in terms of shield volume. Spot shielding estimates for sensitive components such as the star tracker detector are included. The thermal, structural and mechanical subsystems would not include any radiation sensitive components, and thus would not require any additional shielding.

*Parts and Materials*

The selection of electronic parts for radiation susceptibility and reliability presents the first hurdle to be overcome. The majority of NASA's radiation test and life test data on electronic parts has been taken in support of missions with low radiation requirements (<50 Krad) and short lifetimes (<5 years). Commercially available parts advertised to be compatible with 100 krad up to 1 Mrad environment are not generally used or tested for long duration missions. Therefore, parameter degradations due to high radiation exposure levels have not been fully characterized and documented. Consequently, there is limited data to support parts selection, Worst Case Analysis (WCA), and determination of risk areas for aggressive radiation environments such as those experienced by the JEO mission.

In particular, the following device technologies have been identified as critical areas where early evaluation, testing, and characterization would be pivotal for prudent radiation tolerant designs. Assessments are needed for the following device technologies:

- Non-Volatile Memory—radiation susceptibility/reliability
- FPGA—availability and reliability
- Power converter—radiation susceptibility and reliability
- MicroProcessor/Microcontroller—radiation susceptibility/reliability
- Data Bus Device—availability
- Linear Device—radiation susceptibility

The baseline approach for all electronics on the flight system is to use ASICs instead of FPGAs. This is a more conservative approach until FPGAs can be adequately evaluated for both TID tolerance and SEE (Single Event Effects) mitigation.

*Effects on Sensors and Detectors*

Radiation-induced effects on instrument detectors and other key instrument components ultimately impact the quality and quantity of the mission science return and the reliability of engineering sensor data critical to flight operations. High-energy particles found within the harsh Europa environment would produce increased transient detector noise as well as long-term degradation of detector performance and even potential failure of the device. Transient radiation effects are produced when an ionizing particle traverses the active detector volume and creates charges that are clocked out during readout. Radiation-induced noise can potentially swamp the science signal, especially in the infrared wavebands where low solar flux and low surface reflectivity result in a relatively low signal. Both TID and DDD effects produce long-term permanent degradation in detector performance characteristics. This includes a decrease in the ability of the detector to generate signal charge or to transfer that charge from the photo active region to the readout circuitry; shifts in gate threshold voltages; increases in dark current and dark current non-uniformities; and the production of high-dark-current pixels (hot pixels or spikes). It is important to identify and understand both the transient and permanent performance degradation effects in order to plan early for appropriate hardware and operations risk mitigation to insure mission success and high-quality science returns.

The project has performed an initial assessment on the detector and laser components required by the model payload and stellar reference unit. For each technology required for the payload, the project (i) reviewed the available radiation literature and test results, (ii) estimated the radiation environment incident on the component behind its shield, and (iii) assessed the total dose survivability (both TID and DDD) and radiation-induced transient noise effects during peak flux periods. The assessment included the following technologies: visible detectors, mid-infrared and thermal detectors, micro-channel plates and photomultipliers, avalanche photodiodes, and laser-related components (pump diode laser, solid-state laser, fiber optics).

It was concluded that the radiation challenges facing the JEO notional payload and SRU detectors and laser components are well understood. With the recommended shielding allocations, the total dose survivability of these components is not considered to be a significant risk. In many cases, the shielding allocation was driven by the need to reduce radiation-induced transient noise effects in order to meet science and engineering performance requirements. For these technologies—notably mid-infrared detectors, avalanche photodiode detectors, and visible detectors for star tracking—the extensive shielding (up to 3-cm-thick Ta) for transient noise reduction effectively mitigates all concern over total dose degradation. For the remaining technologies, more modest shielding thicknesses (0.3–1.0 cm Ta, depending upon the specific technology) were judged to be sufficient to reduce the total dose exposure and transient noise impact to levels that could be further reduced with known mitigation techniques (detector design, detector operational parameters, algorithmic approaches and system-level mitigations).

However, a caution is needed when inferring detector performance in the Jovian environment based on existing radiation test results where the irradiation species is typically not representative of the JEO concept's expected flight spectra. A rigorous "test-as-you-fly" policy with respect to detector radiation testing, including irradiation with flight-representative species and energies for TID, DDD, and transient testing, would be adopted for JEO.

*Radiation Summary*

In summary, radiation risk is the single largest technical challenge for any Europa mission. Extreme conservatism in designing and verifying spacecraft electronics subsystems in the harsh radiation environment often leads to excessive design margins and severely underestimates the mission lifetime. This commonly results from a compounding effect of applying worst-case assumptions at every level: from parts selection to system design and engineering. JPL plans to address this deficiency by developing a system-level approach of quantifying the uncertainties through rigorous analysis and validation through laboratory testing. The resulting system lifetime model; Jovian radiation model; radiation design methodology and guidelines; parts selection and testing strategy; and assessment of radiation effects on sensors and detectors of science instruments would establish a defined pathway to quantitatively perform trades in the mission and science value space. Application of this system approach for radiation mitigation offers a new paradigm in the underlying process for long duration mission designs. The systems engineering approach captures the graceful degradation behavior of mission lifetime beyond Europa Science Campaign 3 (after 105 days). Efforts are already underway to retire the majority of risks related to the parts and materials, electronic designs and radiation-induced effects on sensors and detectors as well as to develop design guidelines. There are no major obstacles perceived ahead with respect to mitigating radiation risks.

## 7. OPERATIONAL SCENARIOS

Operations scenarios for JEO would be driven by prioritized science objectives and in turn drive design of model payload, and the flight and ground systems.

Science objectives, investigations, and priorities for JEO are provided by the NASA/ESA JJSDT. The highest priorities focus on the Europa orbit science objectives and investigations with additional high priority objectives and investigations for Jupiter System science, based on slightly enhanced capabilities over those needed to achieve the Europa science goals.

The operations scenarios are based on incorporating key operations issues from the earliest concept studies. Some of these issues include:

- Make the flight and ground systems operable and maintainable for a high intensity, rapid turn-around operations environment in Europa orbit in the possible presence of radiation based anomalies

- Use modern system engineering methods to model the system behavior as early as possible to balance mission scope with system capability, complexity, risk, and cost

- Use lessons learned from previous similar missions to guide design philosophy and trade studies.

The most stringent and driving operational requirements and constraints for the JEO concept are derived from Europa Science orbit phase needs. Analysis and design was undertaken to determine additional requirements and constraints for operating in the Jovian Tour phase of the mission as well.

*Mission Phases*

The JEO mission would be composed of three mission phases. The Interplanetary phase, almost 6 years long, would be the period in which the orbiter is launched, performs gravity assist flybys of Venus and Earth, and prepares for the Jupiter Orbit Insertion (JOI) event and Jupiter science operations. The Jovian Tour phase would be focused on science activities in the 30 months after JOI and before arrival at Europa. The Europa Orbit phase would be the 9 months after Europa orbit insertion which returns the highest priority science for the mission. The Jovian Tour phase and the Europa Orbit phase are summarized below.

*Jovian Tour*

In the Jovian Tour phase, the flight system would make routine and frequent observations of Jupiter, its satellites, and its environment. The Tour phase would be divided into two science campaigns: Io Campaign and System Campaign.

The Jupiter system presents a rich and varied set of observing opportunities. The JEO 30 month baseline tour trajectory enables substantial Jupiter system science in five major themes: satellite surfaces and interiors, satellite atmospheres, plasma and magnetospheres. **Table 4** shows the number, range and phase angles for flyby and distant viewing opportunities for Jupiter and the Galilean satellites.

Measurements supporting satellite specific objectives would be accomplished during the satellite flyby encounters. Flyby geometries are highly varied for latitude and lighting but are opportunistic as the trajectory is optimized for arriving at Europa within allocations for duration, delta-V and radiation dose while also meeting the tour science requirements. The orbiter would be able to collect about 14 Gigabits of science data during the closest approach 1–2 hours for each encounter. This would enable NAC, MAC, UVS, and VIRIS observations, TI profiles, and altitude permitting, laser altimeter profiles and IPR full and low rate profiles.

The flyby scenarios are exemplified by a low altitude Io flyby (I4) as shown on **Figure 8**. A sample observation profile is shown detailing the number and timing of observations for each of the instruments. This Io flyby

***Table 4**: Baseline System Science Observing Opportunities (Conceptual Design)*

| | Opportunities | Ranges (km) | Phase Angles (deg) | Ground Speeds (km/s) |
|---|---|---|---|---|
| Jupiter | 33 | 560,000 – 1,000,000 | 10 – 100 | |
| Flyby Encounters | | (min. @ CA) | (±1 hr) | (peak @ CA) |
| Io | 4 | 75 – 3125 | 15 – 168 | 3.8 – 9.4 |
| *Europa* | 6 | 100 – 1200 | 14 – 163 | 1.5 – 9.8 |
| *Ganymede* | 6 | 135 – 1566 | 10 – 161 | 1.9 – 6.5 |
| *Callisto* | 9 | 78 – 3219 | 10 – 168 | 1.1 – 8.4 |
| Distant Viewing Opportunities (<500,000 km) | | | | |
| Io | 16 | 56,000 – 480,000 | 3 – 38 | |
| *Europa* | 8 | 81,000 – 449,000 | 32 – 155 | |
| *Ganymede* | 10 | 148,000 – 398,000 | 10 – 175 | |
| *Callisto* | 2 | 205,000 – 311,000 | 139 – 168 | |

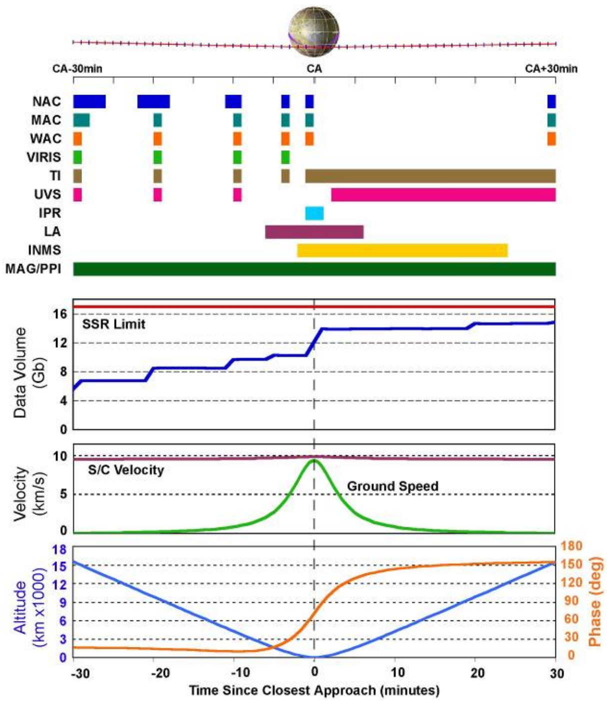



***Figure 8**: Conceptual Io flybys, (I4 shown here) have significant data volume available for intensive investigations by all instruments. Lighting, altitudes, and ground speeds are typical for all Io flybys and most early Tour flybys.*

represents a notional science sequence in which early observations collect global views at moderate to low resolution. Observations closer to closest approach have higher resolution but reduced extent. Because the period after the closest approach is at high phase angles (in the dark) imaging observations are limited to the lit limb and thermal profiles. Analyses for data volume accumulation, orbiter velocity and ground speed, orbiter altitude and sun phase angle, also shown in **Figure 8**, are used in developing each flyby scenario.

The groundtracks for all of the Io flybys are shown in **Figure 9**. The groundtrack for the first Io flyby (I0) is shown in dark grey. The start and end longitudes are similar for all groundtracks. This, together with the phase angles, means that global imaging would be collected mainly in one hemisphere (centered on 210 degrees west), allowing temporal changes from one encounter to the next to be emphasized. Imaging at resolutions of <1000 m/pixel would be possible over approximately 50% of Io's surface. Two Io flybys have closest approach altitudes less than 2000 km. This allows the collection of laser altimetry and IPR data (at altitudes <1000 km). Laser altimetry could be collected for 8000 km of total track length. Due to data volume allocation limits, IPR swaths would be collected for a total of 2 minutes for a total length of 1000 km.

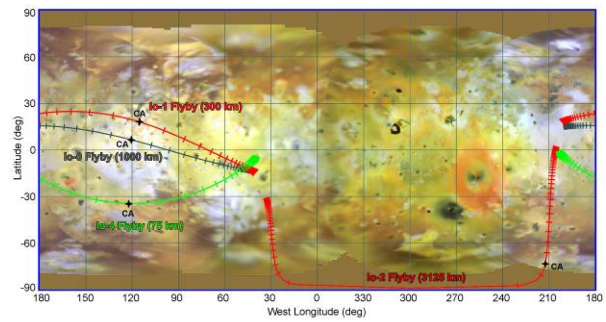
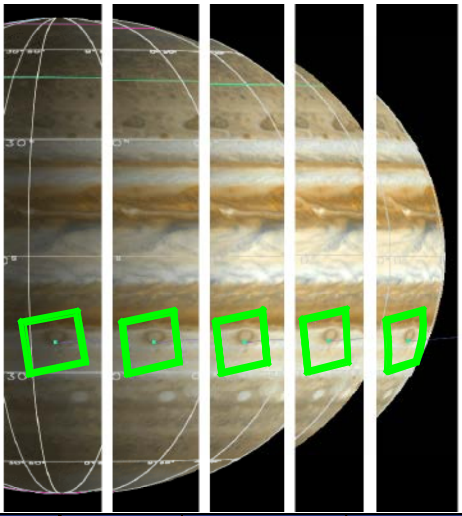



***Figure 9:** Conceptual Io flyby geometry would allow excellent viewing of one hemisphere, the South Polar region, and in situ measurements of volcanic plumes.*

Monitoring and measurement of the system plasma environment and magnetosphere would be accomplished through continuous data collection from the magnetometer and PPI instruments. Jupiter atmospheric and Io monitoring would make use of the 9-color NAC with detailed observations and dynamic studies every week or two.

High level scenario analysis shows that large numbers of monitoring images could be collected to support observations of Jupiter's atmosphere both globally with MAC, VIRIS, UVS, and TI and the periodic tracking of hundreds of features with the 9 color NAC. Because the large capacity SSR allows many observations to be collected over a short period of time, dynamic observations are possible (e.g., movies) even in conjunction with other observing activities such as Io monitoring. **Figure 10** shows an example analysis of Jupiter monitoring from 1.4 million km. This case occurs twice per Jupiter orbit and shows good sunlit viewing at a variety of close ranges and phase angles. For ranges greater than twice perijove, observing conditions are very good for tracking dynamic features in Jupiter's atmosphere. The table included in the figure shows that basic views of Jupiter including composition data, and multicolor images of hundreds of features are possible. Many of the images can be collected in the form of movies to examine dynamic structures at highest resolutions.

Early Jovian Tour sequences would last one to two months with special short term sequences developed for flybys. DSN tracking would be normally one 8 hour 34 m pass per day. Near flybys, additional 34 m passes would be scheduled for increased data return and 70 m passes, or equivalent, for key engineering telemetry and for contingency operations. Tracking would increase to nearly continuous levels in the month prior to EOI to support final navigation targeting and prepare for Europa science operations. The final month prior to EOI would have two close flybys of Europa, setting up the geometry for EOI.



| | Resolution (km) | Data Volume each (Mb) | Number of Images |
|---|---|---|---|
| NAC | 14 | 8 | Hundreds |
| MAC | 140 | 8 | 4 |
| VIRIS | 350 | 307 | 4 |
| UVS | 1400 | 25 | 24 |
| TI | 3500 | 0.1 | 4 |

***Figure 10:*** *Conceptual Jupiter monitoring example shows feature tracking. The green box represents the NAC FOV at 14 million km.*

*Europa Orbit*

The JEO Europa science scenarios are designed to obtain Europa Science objectives in priority order. Data collection spans 4 major campaigns:

• Europa Campaign 1, Global Framework at 200 km orbit for 8 eurosols (28 days), see **Figure 11**.

• Europa Campaign 2, Regional Processes at 100 km orbit for 12 eurosols (43 days),

• Europa Campaign 3, Targeted Processes at 100 km for 8 eurosols (28 days), and

• Europa Campaign 4 Focused Science at 100 km for 46 eurosols (165 days).

The earliest and highest priority goals would be accomplished during Europa Campaign 1, including 2 global maps, 1–2 degree global grids from the 4 profiling instruments, and several hundred coordinated targets with multiple instruments, in highest resolution modes, of high interest sites.

After the initial campaign, the orbit altitude would be lowered and higher resolution global maps, additional profile grids and hundreds more coordinated target observations would be collected to answer regional process questions.

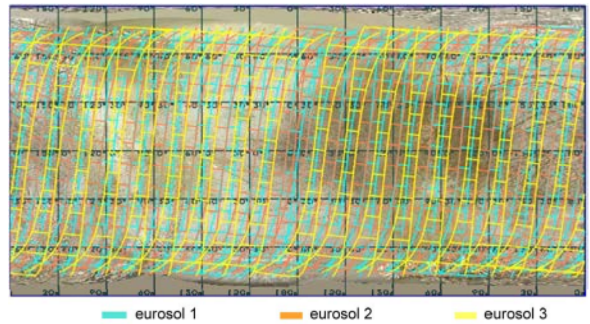



***Figure 11****: Conceptual Campaign 1 WAC coverage. Global color map complete in 10 days. Stereo map complete in 20 days.*

For Europa Campaign 1 and 2, science data collection is continuous and repetitive with continuous fields and particles, altimetry, and TI profile data collection, along with alternating orbit radar sounding and global imaging. On orbits when additional data volume is available, targeted data acquisitions comprising either coordinated targets (IPR profiles, NAC, MAC and VIRIS images) or full resolution IPR observations would be collected. Except for the low rate instruments, all observations would be taken when Earth is in view, enabling rapid downlink of high volume science data. Sequences for repetitive mapping activities would be uplinked once per week. Lists of targets to be acquired via on-board targeting software, would be developed and uplinked to the flight system every few days. Quick look data processing, mapping assessment, and target selection processes would all be rapid, needing about one day each. Data return would be via continuous 34 m tracking through the end of Europa Campaign 3. Data rates would be determined every orbit based on the DSN elevation angle and Jupiter radio (hot body) noise for that orbit. These variable data rates increase the average data volume returned by nearly 100% over traditional methods.

Europa Campaign 3 would have similar observing activities as the previous campaigns but the emphasis would shift from global mapping with limited targeted observations to primarily targeted observations with limited profiling and gap fill observations from the WAC.

Europa Campaign 4 would continue targeted observations but would include new observation activities not permitted in the first 3 campaigns. These might include off nadir imaging, Io and Jupiter monitoring, low altitude observing with imagers and INMS, and other observations designed in response to new questions arising from early observations.

Science data collection during Europa Campaign 4 would be planned for daily 8 hour passes to DSN 34 m stations. Sequence durations would be increased to 2–4 weeks. Target updates would be uplinked once per week.

*Science Data Return*

The 17 Gb hybrid SSR allows rapid and long term data collection at faster rates than the downlink rate. Days of downlink could be stored allowing the possibility of data retransmission in the event of a missed DSN pass, weather outage, link noise or orbiter safing.

Science observations and data downlink would largely be decoupled through the use of the gimbaled high gain antenna. Data volume would be allocated and factored into science sequences. Margins and flexible sequencing strategies would allow DSN track times to change without disrupting science observations. With time to process and space in the SSR to work with, data reduction techniques such as windowing or selective downlink become possible.

The SSR would function as a short term buffer for data acquired while the flight system communications are occulted by Jupiter or Europa or when data is collected at aggregate rates exceeding the downlink rate. The 16 Gb SDRAM partition of the SSR is assumed, for planning purposes, to have failed due to radiation effects, by start of the Europa Science phase. For most orbits, 10–15% of the 1 Gb CRAM SSR science partition would be needed for storing data from the continuously operating instruments while in occultation.

Up to once or twice per orbit, a coordinated target observation would be collected and stored in the SSR. The target observation sizes are constrained to fit, with margin, into the SSR. The data would be queued with all other data for subsequent downlink. Buffer architectures and queuing schemes have not yet been considered. The small SSR can be used for longer term storage of very small amounts of high priority data. For the most part, data collected would be downlinked in the order it was collected. No facility for re-transmission, data editing, or for accommodating long DSN gaps is possible. **Figure 12** shows the total data downlinked during the planned Jovian tour and Europa science orbit phase. The science objectives are systematic and repetitive. Observations needed to achieve the science goals can be rescheduled in the event of lost downlink time. It is assumed that all data transfers, compression, encoding, and other process steps would not cause significant latencies in the data flow and therefore congestion in the SSR.

Data rates vary with Earth range, from 64 to 144 kb/s for the tour phase (**Figure 13**) using standard link design methods (90% weather, 20° station elevation, max Jupiter hot body noise). For the Europa Science phase, rates would increase to 165 to 270 kbps assuming a variable data rate strategy.

## 8. CONCLUSIONS

The 2008 NASA JEO study focused on refining the NASA mission concept and reducing risk. The JEO mission concept was reviewed and updated to incorporate additional Jupiter System science and to take advantage of technology maturation. The resulting concept provides a mature evolution from previous concepts which could provide scientists with a vast amount of information to address both the specific JEO Goal and Objectives and the highest priority Decadal Survey science. The model payload described herein takes advantage of publically available information allowing innovative or proprietary concepts to enhance mission capabilities. The 2008 concept is mature and could only be summarized for this paper, with a focus on communicating the basic concepts and key results.

The 2008 study risk reduction activity resulted in a detailed plan for a multi-year risk mitigation approach and in the delivery of 27 design documents and tutorials which potential providers can use to mitigate the risk to their designs. An Instrument Workshop was held to engage potential instrument providers in the aspects of design which are most important. Many of these deliverables have been

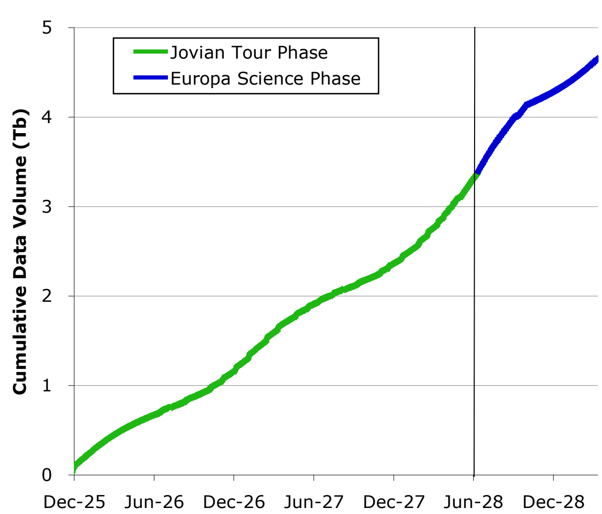



***Figure 12***: *Conceptual Cumulative Data Volume Returned*

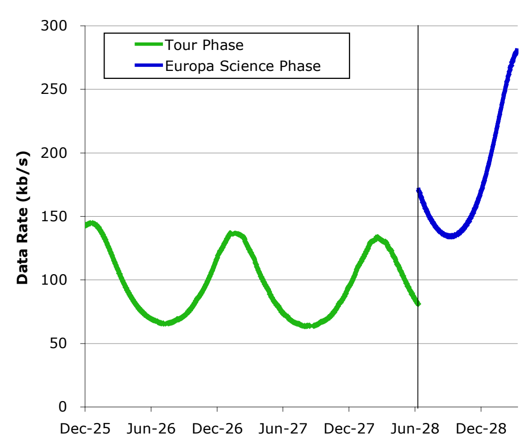



***Figure 13***: *Average Data Rates for 34 m DSN Stations. Post EOI data return rate is based upon dynamic rate simulations.*

made public via the Outer Planets Flagship Mission website http://opfm.jpl.nasa.gov. Several of the documents are ITAR sensitive and publically releasable versions are in the process of being made available. Additional design information is planned for public release during pre-phase A activities as part of a strategy to reduce cost risk. The exploration of the Jupiter system is invaluable for the insights it can provide into our own solar system and into planetary architecture and habitability throughout the universe. JEO would make the next giant leap in solar system understanding possible with a well-defined cost and risk posture for NASA. With better instruments, more focused tour objectives, extended time to study Europa and the Jupiter system up close, and over three orders of magnitude more data return, JEO would provide the opportunity to radically advance the knowledge of the Jupiter System and its relationship to the emergence of habitable worlds around gas giants.

## 9. ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the hard work completed by all of the members of the JJSDT, the NASA JEO study team, and the ESA JGO study team.

## 10. REFERENCES

[1] Clark, K. et al., "2008 Jupiter Europa Orbiter Study Final Report," JPL Internal Document D-48279. Publically released version forthcoming.

[2] Jun, I. et al., "Monte Carlo simulations of the Galileo energetic particle detector," Nuclear Instruments & Methods in Physics Research A 490:465–475, 2002.

[3] Jun, I. et al., "Statistics of the variations of the high-energy electron population between 7 and 28 jovian radii as measured by the Galileo spacecraft," Icarus 178:386–394, 2005.

[4] Garrett, H. B., I. Jun, J. M. Ratliff, R. W. Evans, G. A. Clough, and R. E. McEntire, "Galileo interim radiation electron model," JPL Publication 03-006, 2003.

[5] Paranicas, C., B. H. Mauk, K. Khurana, I. Jun, H. Garrett, N. Krupp, and E. Roussos, "Europa's near-surface radiation environment," Geophys. Res. Lett. 34, L15103, doi:10.1029/2007GL030834, 2007.

## 11. BIOGRAPHY

***Karla Clark*** *received her B.S. degree in chemical engineering from Rice University in Houston, Texas. After graduation, Ms. Clark worked at Hughes Aircraft Company developing flight batteries for communications satellites. Ms. Clark continued her education and received M.S. degrees in both mechanical engineering and engineering management from the University of Southern California. She joined JPL in 1987 where she has held numerous technical and managerial roles. Primary technical roles include system engineering efforts for the Cassini Power System & Outer Planets/Solar Probe Project. Management roles have ranged from Task Manager for Flight Battery Research; Power System Technical Manager for Cassini; Power Electronics Engineering Group Supervisor; Flight System Manager for Europa Orbiter; Spacecraft Manager and Contract Technical Manager for the Prometheus Project and her current position as study lead for JEO.*

***Grace Tan-Wang*** *is the lead flight systems engineer on JEO. She is currently also the lead spacecraft systems engineer on the Soil Moisture Active/Passive mission, an Earth orbiting mission launching in 2013. Previously, she was the flight system engineer for the Mars Exploration Rovers mission and for the Cassini mission to Saturn. Grace received her B.S. degree in Astronautics and Aeronautics Engineering from the Massachusetts Institute of Technology and a M.S. degree in Aerospace Engineering from the University of Southern California.*

***John Boldt*** *received his B.S. degree in Electrical Engineering from South Dakota State University in 1982. He has been with the Applied Physics Laboratory since that time and is currently the Assistant Group Supervisor of the Space Science Instrument Group. He performed a variety of roles including power systems lead engineer and mission operations lead engineer prior to focusing on science instrument development. He has designed flight hardware for a number of missions including Cassini, NEAR, MESSENGER, MRO and New Horizons and is the payload systems engineer for the current JEO mission study.*

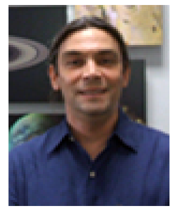
***Ron Greeley*** *is a Regents' Professor in the School of Earth and Space Exploration (SESE) at Arizona State University and Director of the NASA Regional Planetary Image Facility. He has been involved in lunar and planetary studies since 1967.*

*Current research is focused on understanding planetary surface processes and geological histories. After receiving his Ph.D. in Geology in 1966, Greeley worked for Standard Oil Company of California. Through military duty, he was assigned to NASA's Ames Research Center in 1967 where he worked in a civilian capacity in preparation for the Apollo missions to the Moon. Subsequently, he remained at NASA to conduct research in planetary geology. In 1977, Greeley joined Arizona State University. Current projects include study of wind processes on Earth, Mars, Venus, and Titan, field studies of basaltic volcanism, and planetary mapping. Current planetary mission membership includes the Mars Exploration Rovers and ESA's Mars Express mission. Greeley is currently Co-chair of the NASA Science Definition Team for the Europa Jupiter System Mission.*

***Insoo Jun** came to the United States from Korea in 1983. He received a B.S degree in nuclear engineering in 1986 from University of Massachusetts at Lowell and M.S. and PhD degrees in applied plasma physics and fusion technology from UCLA. He joined the Jet Propulsion Laboratory in 2000. He is currently a principal scientist and the supervisor of Mission Environments Group. Dr. Jun is a member of AGU and ANS. Areas of current interest are space radiation environments and effects, and shielding design. His experience includes the modeling of planetary and inter-planetary space environments (radiation, meteoroid, and plasma, etc.) and their impact analyses on spacecraft systems and components. His main interests are in computational physics of space radiation interactions with materials (spacecraft structure, planetary atmospheres, or surface materials, etc.) using Monte Carlo and deterministic radiation transport tools.*

***Rob Lock** received his B.S. degree in Aerospace Engineering from Cal Poly, San Luis Obispo in 1985. He came to the Jet Propulsion Laboratory in 1988 where he works as a systems engineer. He was a mission planner and later the mission planning team chief for the Magellan mission to Venus and was the lead mission planner for the Mars Sample Return mission during development. He has supported many advanced mission concept studies and has been a systems engineer for the JEO mission studies since 2006 where he provides operations scenarios, and key operability trade studies.*

***Jan Ludwinski** received his B.S. degree in Astrophysics from Michigan State University in 1980. He joined the Jet Propulsion Laboratory in 1985 as a mission planner on Galileo and later became the Mission Design Team Chief for Galileo. From 2001 to 2004, he was the Mars Exploration Rover Mission Planning Team Chief. In between, and since those assignments, has supported many advanced mission concept studies and has led the mission design for the 2001 Europa Orbiter project and for the JEO mission studies since 2007. He is currently the Assistant Division Manager for Formulation for the Systems and Software Division at JPL.*



***Robert Pappalardo** is a Senior Research Scientist in the Planetary Ices Group, at the Jet Propulsion Laboratory. His research focuses on processes that have shaped the icy satellites of the outer solar system, especially Europa and the role of its probable subsurface ocean. In 1986 he received his B.A. in Geological Sciences from Cornell University, and in 1994 he obtained his Ph.D. in Geology from Arizona State University. As an affiliate member of the Galileo Imaging Team while a researcher at Brown University, he worked to plan many of the Galileo observations of Jupiter's icy Galilean satellites. From 2001-2006, he was an Assistant Professor of Planetary Sciences in the Astrophysical and Planetary Sciences Department of the University of Colorado at Boulder, and he continues to mentor graduate student researchers.*

***Tracy Van Houten** received her B.S. degree in Aerospace Engineering from Cal Poly, San Luis Obispo in 2004 and her M.S. in Astronautical Engineering from the University of Southern California in 2008. She began working as a formulation-phase systems engineer for the Jet Propulsion Laboratory in 2004. The majority of her work has been as the Team X Lead Systems Engineer. She is currently a flight system engineer for the JEOmission.*

***Tsun-Yee Yan** is the JEO radiation team lead. He received a B.Sc. degree in Electronics from the Chinese University of Hong Kong with first honor, and his M.Sc. and Ph.D. degrees in System Science from the University of California, Los Angeles (UCLA). He is also a graduate of the Executive Program in Management from UCLA Anderson School of Management. Dr. Yan has published over 80 journal and conference papers, served on technical program committees and as program chair for many international conferences. He has managed many spacecraft technology development programs for NASA and has received numerous Awards and patents.*