Europa Jupiter System Mission

A mission concept to explore the Jupiter System and its Galilean satellites

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1.0 OVERVIEW

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. 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 resonance-locked, 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. 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) would carry out a systematic and in-depth study of the Jupiter system addressing a common and overarching theme: ***The emergence of habitable worlds around gas giants.***

The baseline EJSM architecture consists of two primary elements operating in the Jovian system: a NASA-led Jupiter Europa Orbiter (JEO), and an ESA-led Jupiter Ganymede Orbiter (JGO). JEO and JGO would execute coordinated exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively.

JEO and JGO would carry complementary instruments to monitor dynamic phenomena, map the Jovian magnetosphere and its interactions with the Galilean satellites, and characterize water oceans beneath the ice shells of Europa and Ganymede. Each spacecraft would conduct "stand-alone" measurements, including the detailed study of Europa and Ganymede, providing significant programmatic flexibility.

Although engineering advances are needed for JEO (radiation designs) and JGO, no new technologies are required to execute either EJSM mission element. Risk mitigation activities have been underway for the past year to ensure that the radiation designs are implemented in the lowest-risk approach. The baseline mission concept includes robust mass and power margins. The development schedule for these missions is such that a technology developed by about 2013 could easily be incorporated if it enhances the mission capability.

The mission concept described here is a summary of the concept further described in *Europa Jupiter System Mission Joint Summary Report, dated January 16, 2009.*

2.0 SCIENCE GOALS AND OBJECTIVES

Together, JEO and JGO address the science goals and objectives of EJSM (**Figure 1**). Each intensely investigates one internally active icy satellite and provides significant science for another, and each addresses significant aspects of Jupiter system science. The overlap provides important synergistic and complementary observations. Nonetheless, each has the potential to be a "stand-alone" mission, providing compelling science.

JEO has as its sub-goal***: Explore Europa and investigate its habitability***. During its Europa orbital phase, JEO addresses this sub-goal by using a comprehensive set of instruments to systematically address the highest priority science while retaining the ability to quickly focus the operational scenarios to follow up on discoveries made days to weeks earlier. Modest modifications of the JEO instruments ensure that they are also excellent for remote sensing and *in situ* observations of the Jupiter system, both from afar and during close satellite flybys.

While the primary focus of JEO is to orbit Europa, the science return encompasses the entire Jovian system, especially as is relevant to Europa's potential habitability. JEO uniquely includes flybys of Io and Europa, and includes flybys of Ganymede and Callisto, along with ~ 2.5 years observing Jupiter's atmosphere, magnetosphere, and rings.

JGO has three sub-goals: ***Determine***

whether the Jupiter System harbors habitable worlds; Characterize the processes within the Jupiter System; Gain new insight into the origin of the Jupiter System. JGO addresses its sub-goal of determining whether the Jupiter System harbors habitable worlds by focusing on Ganymede. From Ganymede orbit, JGO characterizes Ganymede's ocean, deeper interior, magnetosphere, and surface using techniques analogous to those of JEO. To address the Jupiter system sub-goals, JGO investigates Callisto from a resonant orbit, and JGO makes extensive observations of the Jupiter system to complement those of JEO.

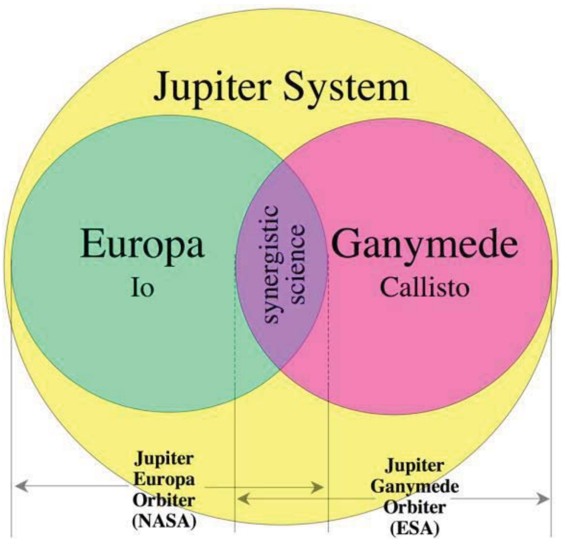

Figure 1: *The satellite-specific objectives of each are encompassed by Jupiter system science, as addressed in significant part by both spacecraft.*

JGO results would enable detailed comparisons with the results for Europa. These results would be coupled with the data to be returned from Io, Callisto, and the Jupiter system as a whole, to provide unparalleled insight into the archetypical gas giant planetary system. In this way, JEO and JGO combine to address the overall EJSM theme of the emergence of habitable worlds around gas giants.

3.0 MISSION CONCEPT

3.1 Mission Architecture Overview and Design

The expansive Jupiter system is scientifically rich and is best studied using multiple elements. To explore the system in detail, two flight systems, performing a choreographed dance to explore the system from every perspective, are envisioned. Although both would examine the whole system, one would focus on the inner two Galilean satellites and the other would focus on the outer two Galilean satellites. JGO focuses on Ganymede and Callisto, while JEO focuses on Io and Europa (but also studying Callisto and Ganymede up close). This architecture allows JGO to stay outside the most intense radiation belts and, thus, be designed for a lesser radiation environment. JEO and JGO carry 11 science instruments each. Complementary instrumentation allows for each flight system to study the whole system from different perspectives and provide data for synergistic science.

Independently launched in early 2020, each spacecraft would use Venus and Earth gravity assists to arrive at Jupiter ~6 years later **(Table 1)**. It is important to note that the JEO and JGO launches are NOT interdependent. The Jovian system trajectories are very flexible and can be easily altered to accommodate changes in programmatic or scientific priorities. Numerous design parameters provide flexibility to alter flight times, tour lengths, and orbital insertion timing to adjust the coincidence of the two flight systems in orbit at Jupiter. Each flight element is operated independently to meet its primary science goals.

Table 1: *By using Venus and Earth gravity assists, very capable flight systems can be delivered to Jupiter within 6 years.*

	JEO	JGO
Launch Vehicle	Atlas V 551	Ariane 5 ECA
Launch Date	2/29/20	3/11/20
Trajectory	VEEGA	VEEGA
Flight Time to Jupiter	5.8 years	5.9 years
Delta V	2260 m/s	2800 m/s
Propellant	2646 kg	2562 kg

After insertion into Jupiter orbit, both flight systems would perform tours of the Jupiter system using gravity assists of the Galilean moons to shape the trajectory and to perform science measurements. JGO uses a gravity assist maneuver at Ganymede to shape its initial highly elliptical Jupiter orbit, thereby avoiding the main radiation belts of Jupiter. After a nearly 10-month tour through the Jupiter system — performing measurements in the magnetosphere, observing Jupiter and performing a series of Ganymede flybys — JGO moves to a Callisto resonant orbit. There it performs remote sensing observations during multi-flyby opportunities. After more than a year in this resonant orbit with Callisto, JGO moves to an elliptical polar orbit around Ganymede for 80 days, acquiring, among other observations, measurements in the magnetosphere of Ganymede. Thereafter, JGO enters into a 200 km near-polar circular orbit for close observations of Ganymede. The mission ends when the flight system impacts Ganymede's surface.

JEO enters the Jupiter system by using Io for gravity assist. This lowers the required propellant load but increases the radiation exposure of the flight system. JEO performs a ~30-month Jupiter system tour that includes 4 Io flybys, 9 Callisto flybys, 6 Ganymede flybys, and 6 Europa flybys, all with data acquisition. When JEO enters orbit at Europa it spends the first month in a 200-km circular orbit and then descends to a 100 km-circular for another 8 months. The mission ends with the spacecraft impacting Europa's surface.

3.2 Flight Element

The two flight systems are similar to other large orbital spacecraft (e.g., Cassini, Mars Reconnaissance Orbiter) (**Figures 2** and **3**).

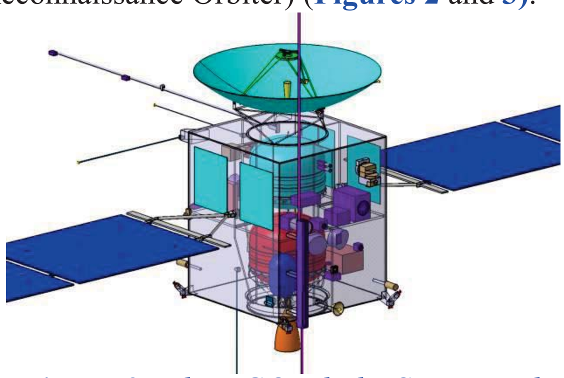

Figure 2: *The JGO Flight System utilizes solar power to operate 10 instruments.*

Propellant accounts for 50 - 60% of the total mass of both these systems. Dominated by the significant amount of propellant required to enter orbit at their respective destinations, the flight systems use the large propulsion tanks as the primary structure around which the system is built.

Both JEO and JGO are designed conservatively with significant mass margins (**Table 2**). Typical mass and power margins held in Pre-Phase A are 30 - 50% (margin/CBE). There is flexibility on both spacecraft to operate with available power by strategically cycling the instruments. Even with current assumptions, the resources available for instrument operations far exceed those needed to meet the minimal science requirements as defined by the JJSDT.

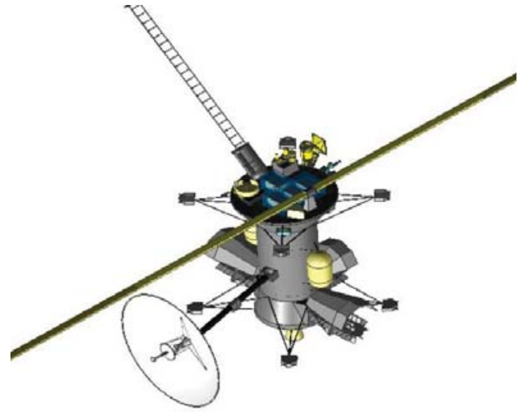

Figure 3: *The JEO Flight System uses radioisotope power to operate 11 instruments.*

Design characteristics that are similar for the two orbiters are:

- Full redundancy for engineering functions.
- Three-axis-stabilized structure using both thrusters and reaction wheels for control.
- Bi-propellant chemical propulsion systems with single main engine.
- Lithium ion battery energy storage.
- Multi-Layer Insulation and radiators for thermal control.
- X/X-band for telecommunications, commanding, tracking, and emergency communications.
- A Ka-band transponder for dual-band radio science (X and Ka).

Table 2: *Significant mass margin is available for the 2020 launch opportunity with both systems carrying enough propellant for the full dry mass capability.*

Dry Mass (excluding Adapter)	JEO	JGO
Current Best Estimate (CBE) without contingency or margin	1371 kg	957 kg
Subsystem Contingency	338 kg	106 kg
Required System Margin	224 kg	213 kg
Extra Margin	336 kg	333 kg
Total Dry Mass Available	2271 kg	1610 kg
Total Margin (Total Margin/CBE)	66%	68%
Total Margin (Total Margin/Total)	40%	41%%

Radiation design points established for both flight elements provide mission and component engineers margin for performing trades within the spacecraft without adjusting designs when the radiation estimates fluctuate based on trajectories. Estimated radiation exposures based on baseline trajectories are currently within the design points (**Table 3**).

***Table 3:** The radiation environment experienced by JEO contains more penetrating spectral components than JGO.*

	JEO	JGO
Design Point behind 100 mils (2.5 mm) of Al	2.9 Mrad	
Current estimated exposure behind 100 mils (2.5 mm) of Al	2.8 Mrad	900 krad
Design Point behind 8 mm of Al	820 krad	150 krad
Current estimated exposure behind 8 mm of Al	810 krad	82 krad
Current best estimate for shielding mass	190 kg	80 kg

Since JGO focuses on Callisto and Ganymede, it can stay outside Jupiter's main radiation belts. JGO uses shielding as the primary protection for standard electronics, resulting in approximately 80 kg of shielding which corresponds to the 150-krad environment.

The JEO radiation design levels are much higher than is practical for standard parts without excessive amounts of shielding. Therefore, JEO takes a more aggressive approach and assumes all electronics would be designed with radiation-hardened electronics to minimize shielding required. The current JEO approach allows flexibility for different part tolerance levels (100 krad to 1 Mrad) to avoid having to shield everything down to the lowest common denominator part tolerance level. Approximately 190 kg of shielding is estimated for the JEO mission. Other significant flight system differences between JEO and JGO are:

- JGO uses a 1-degree of freedom, 51-m^2 solar arrays with GaAs solar cells optimized for Low Intensity Low Temperature. JEO uses Radioisotope Power Sources.
- JGO uses a heritage 2.8-m fixed High Gain Antenna while JEO uses a heritage 3.0-m 2-degree-of-freedom High Gain Antenna.
- JEO augments the telecom system with Ka-Band downlink for telemetry.
- JEO augments its electrical heater thermal system with Radioisotope Heater Units.
- The computer system for JEO consists of RAD750 computer and has 20 Gbits of memory (4 Gbits are mega-rad hard). JGO uses a LEON2 Fault Tolerant processor and 256 Gbits of flash memory.

As a result of both the higher power and higher telecommunication antenna gain on JEO, its downlink data rate is roughly 10 times that for JGO (300 - 600 kbps vs. 40 - 66 kbps).

3.3 Model Payloads

The EJSM model payload instruments were identified by the JJSDT to respond directly to the science objectives, along with traceability back to the science measurement requirements **(Table 4)**. This model payload was used to bound the engineering aspects of the mission design, spacecraft, and operational scenarios. The notional instruments were used to show proof of concept only, and should not be taken to be final selections nor final implementations. Alternative instrument concepts and techniques may be selected via the NASA/ESA coordinated Announcement of Opportunity process to meet the mission objectives.

Model payload instruments were chosen on the basis of their ability to meet the measurement objectives, perform in the radiation environment, and meet planetary protection requirements. Synergistic and complementary instruments carried by the separate mission elements enhance the science while maintaining a strong science return value for each independent element.

3.4 Science Operational Scenarios

The mission operational scenarios are summarized in **Table 5**.

3.4.1 Jupiter System Science

The Jupiter System Science investigations fall into five categories: satellite surfaces and interiors, satellite atmospheres, plasma and magnetosphere, rings and small bodies, and Jupiter atmosphere. 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 trajectories are optimized for meeting the science requirements along with duration, delta-V and radiation dose. In addition to the encounter observations, periodic distant monitoring observations of Io, its plasma torus, Jupiter, and its ring system, dust and gas, and small bodies are planned. Monitoring and measurement of the system plasma environment and magnetosphere and the Jupiter atmosphere would be accomplished through routine periodic measurements. During the Jupiter System Science sub-phase the instruments focusing on Jupiter science would be operating with higher priority with respect to the other instruments.

***Table 4:** The complementary model payloads on the two flight systems provide unprecedented opportunities to obtain simultaneous observations of a single phenomenon.*

Instrument	Jupiter Europa Orbiter	Jupiter Ganymede Orbiter
Laser Altimeter	***LA***: Single-beam @ 1064 nm, 50 m spot 1 m resolution @ 100 km	***LA***: Single-beam @ 1064 nm, 10 m spot 1 m resolution @ 200 km
Radio Science	***RS***: 2-way Doppler and range Ka/Ka, X/X, X/Ka USO	***JRST***: 2-way Doppler and range Ka/Ka, X/X, X/Ka USO
Ice Penetrating Radar	***IPR***: Dual frequency: ~5 & ~50 MHz Vertical depths: 3 & 30 km Dipole antenna: 30 m	***SSR***: Single frequency: 20-50 MHz Vertical depth: 5 km Dipole antenna: 10 m
Visible-IR Spectrometer	***VIRIS***: Pushbroom with along-track scan system, two channels, 400-5200 nm	***VIRHIS***: Hyperspectral imager, 2 channels, 400-5200 nm, resolution 2.8 & 5 nm
UltraViolet Spectrometer	***UVS***: EUV + FUV: 70-200 nm, scan system for stellar occultations	***UVIS***: EUV: 50-110 nm FUV + MUV: 110-320 nm
Ion and Neutral Mass Spectrometer	***INMS***: Reflectron Time-of-Flight 1-300 Daltons	Combined with the Plasma and Particles Package, M/ΔM > 1000
Thermal Instrument	***TI***: Pushbroom imaging thermopile line arrays, 8-20 μm and 20-100 μm, 4 narrow filter bands	N/A
Narrow Angle Camera	***NAC***: Panchromatic pushbroom plus nine color framing mode	***HRC***: High resolution, panchromatic pushbroom and framing mode, 350 -1050 nm, IFOV 0.005 mrad
Wide and Medium Angle Camera	***WAC***: Wide-Angle: pushbroom, 3-color + panchromatic, IFOV 1 mrad ***MAC***: Medium-Angle: pushbroom, panchromatic, IFOV 0.1 mrad	***WAC***: Wide-Angle: framing camera, 12 filters, 350 – 1050 nm, IFOV 2 mrad ***MRC***: Medium-Angle: stereo, pushbroom, 4-color + panchromatic, 350 – 1050 nm, IFOV 0.25 mrad
Magnetometer	***MAG***: Dual tri-axial fluxgate sensors on 10 m boom	***MAG***: Dual tri-axial fluxgate sensors on external boom
Plasma and Particles	***PPI***: Plasma Analyzer: Electrons: 10 eV to 30 keV Ions: 10 eV to 30 keV Particle Analyzer: Electrons: 30 keV to 1 MeV Ions: 30 keV to 10s of MeV	***PLP***: Plasma Analyzer: Electrons: 1 eV to 20 keV Ions: 1 eV to 10 keV Particle Analyzer: Electrons: 15 keV to 1 MeV Ions: 3 keV to 5 MeV ENA: 10 eV -10 keV
Submillimeter Wave Instrument	N/A	***SWI***: 2 channels, 557 & 1200 GHz, 100 kHz resolution
Radio and Plasma Wave Instrument	N/A	***RPWI:*** Plasma Wave: electrons, ions Electric and magnetic fields vector, QTNS
Mass (without contingency)	**106 kg**	**104 kg**

During the Callisto Science sub-phase, JGO would collect and downlink 12-20Gb for each Callisto flyby. JEO would make several close flybys of Callisto while JGO is in the resonant orbit, allowing synergistic science observations.

Specifically during the Io Science sub-phase, JEO would make close flybys of Io (as close as 75 km) and image 20% of Io's surface at 200 m/pixel resolution. At the same time, JGO would monitor Io from a distance to add context to JEO observations.

Each orbiter would be able to collect 10-20Gb of science data during closest approach for each flyby. JEO and JGO can store and return all of the collected data from flybys and observing opportunities within scheduled downlink times.

3.4.2 Icy Moon Orbital Science

Due to power and data downlink restrictions not all instruments can operate simultaneously during orbital operations. Prioritized observations and observational time-sharing are used to lower the average power required during any orbit. To ensure that all scientific goals can be achieved a combination of on-board data processing, data compression, and sequential operation of instruments would be used to reduce the data volume required for downlink.

The highest data return for JGO (~300 Gb) would occur during the Ganymede circular orbit campaign. Instruments would be operated in a sequence such that the data would fit into the ~1.7 Gb average daily downlink data volume. In the circular orbit campaign, JGO would collect observations for 16 hours per day and downlink data for 8 hours.

***Table 5.**Pre-planned mission phases and campaign allow for early decisions on the highest priority science and more efficient operations.*

Mission Phase	Jupiter Europa Orbiter	Jupiter Ganymede Orbiter
Jupiter System Science	Jupiter System Science Campaign: 18 months • 8 Callisto flybys, including North Pole observing • 6 Europa Flybys, IPR ocean search, 60% global imaging • 6 Ganymede flybys, 50% global imaging • Transfer to Europa circular orbit Io Campaign: 12 months • 1st Io flyby (pre-JOI) is primarily for engineering purposes • 3 Io flybys, 30% global imaging • 1 Callisto flyby	Jupiter System Science Campaign: 10 months • 4 Ganymede flybys • Move to resonant Callisto orbit Callisto Science Campaign: 13 months • Resonant Callisto orbits, 19 flybys • Global imaging • Move to Ganymede elliptical orbit
Icy Moon Orbital Science	Europa Orbital Science • Engineering Assessment: prepare for orbital ops (5 days) • Europa Campaign 1: Global Framework 200 km (28 days) • Europa Campaign 2: Regional Processes 100 km (43 days) • Europa Campaign 3: Targeted Processes 100 km (28 days) • Europa Campaign 4: Focused Science 100 km (165 days)	Ganymede Orbital Science • Ganymede Campaign 1: 200x6000 km orbit (80 days) • Ganymede Campaign 2: 200 km circular orbit (180 days)

For the JEO Europa Science phase, the data acquisition strategy is designed to obtain the highest-priority observations first and quickly. Data taking proceeds through 4 campaigns, beginning with the Global Framework campaign, then focusing on Regional Processes, then concentrating on Targeted Processes to address local-scale science questions and then performing Focused Science for follow-up on discoveries made during the earlier campaigns. During the Europa Science phase, some instruments collect data continuously. For the other remote sensing instruments, a 2-orbit repeating scenario is planned to permit power and data rate balancing. Even-numbered orbits emphasize optical remote sensing while odd-numbered orbits emphasize radar data collection.

JEO targeted observations are of two types; coordinated imaging targets and full rate Radar targets. The coordinated imaging targets collect nested observations among the optical remote sensing instruments, along with the profiling IPR mode, and the continuously operating instruments (**Figure 3**). Over 1900 targeted observations, of both types, are obtained during the Europa Science Phase.

3.4.3 Data Return

Detailed operational scenarios, based on achieving the highest priority data first, ensure that the instruments perform the required measurements for the science goals to be fulfilled. A total of ~ 1.5 Tbits of data is returned from JGO and ~ 4.5 Tbits from JEO through their prime missions. The potential cumulative data return is double that of the Cassini prime mission (2.8 Tbit) and is 3 orders of magnitude more than Galileo was able to return. Although Galileo was able to contribute invaluable scientific value, EJSM's increased data volume would able answers the questions raised by Galileo.

3.5 Challenges

Both radiation and planetary protection risks could directly impact the cost and schedule for both the spacecraft and instrument development. Robust implementation approaches with significant margins and early risk mitigation is crucial to decreasing the cost risk associated with fixing issues found late in the design cycle.

Current **Planetary Protection** policy [*NPR8020.12C 2005*] specifies requirements for Europa missions as follows: "Methods…including microbial reduction, shall be applied in order to reduce the probability of inadvertent contamination of an Europan ocean to less than 1×10^{-4} per mission." It has been determined that it is infeasible to leave Europan orbit at the end of the mission. This led to the conclusion that surface impact at the end of the mission is the appropriate technical and scientific approach. Accordingly, the JEO mission element would use a combination of heat and radiation sterilization as well as extensive mission design and analysis to ensure that requirements are met at any time during the mission. It is anticipated that each phase of the mission (Interplanetary cruise, Jovian tour and Europa orbital) would require separate analyses and that the emphasis within those analyses may be different. A Planetary Protection Review was inserted into the project schedule in mid-Phase B to ensure that the approach for the analyses and implementation was thoroughly vetted and agreed to early in the project life-cycle.

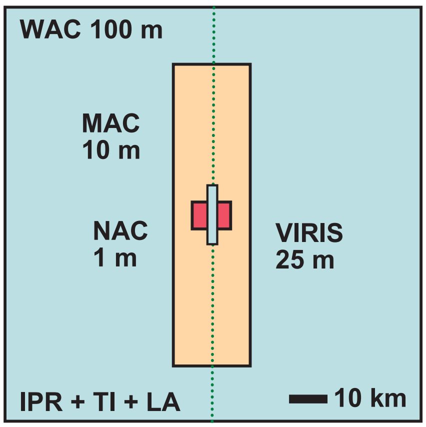

Figure 3: *Nested JEO FOVs provide for coordinated targeted observations (resolution/pixel indicated).*

Radiation poses a unique technical challenge for EJSM due to the flight system spending a significant time in the Jovian radiation belts. The implementation plan presented in the final report for JEO included specific activities and margins to deal with the radiation risk; the development schedule was extended, additional costs were built into the individual estimates, additional reserves were applied, additional personnel were added to the team both as advisors and as engineers to support the development of the hardware and software (spacecraft and instrument), the organizational structure was modified for management and system engineering to ensure adequate attention was being applied.

In 2008, NASA started executing an effort focused specifically on mitigating the risk imposed by radiation and planetary protection requirements. Implementing this plan (excluding other Pre-phase A activities) is estimated at >$10M over 4 years. The ongoing work provides further confidence that parts, materials and sensors/detectors are available to perform a JEO mission that meets the science objectives. Products are available via the http://opfm.jpl.nasa.gov website. The primary audience for this information is potential instrument providers to help mitigate design and operational risk associated with instruments proposed to the Announcement of Opportunity. Most of the information produced by NASA is relevant to JGO designs as well.

4.0 SUMMARY AND CONCLUSIONS

The EJSM concept represents the culmination of recent NASA and ESA studies to define a Jupiter system mission that would conduct a comprehensive exploration of the Jupiter system while also performing focused science related to formulated hypotheses.

The baseline architecture for EJSM consists of two primary elements operating in the Jovian system at or close to the same time: a NASA-led JEO and an ESA-led JGO. JEO and JGO are two free-flying flight elements that would conduct coordinated exploration of the Jupiter System with numerous flybys of Io, Europa, Ganymede and Callisto before they are inserted into orbit of Europa and Ganymede. The scientific return is resilient to changes in the launch date of either JEO or JGO.

Both JEO and JGO flight system designs are based on proven functionality of deep space orbiters. No new technologies are needed for JEO or JGO although significant engineering developments are required for JEO (radiation designs) and JGO. Due to inherent risk with the radiation levels encountered during the mission, specific risk reducing implementation plans have been developed. These risk mitigation activities are already under way to ensure that the lowest risk approaches are identified, developed and communicated to all interested parties.

EJSM is a robust mission concept which would revolutionize scientific knowledge of Europa, Ganymede and the Jupiter system. Both scientifically and technically mature, it is ready to be initiated now.

