6.0 BACK-UP LAUNCH OPPORTUNITIES

The baseline mission concept utilizes a launch opportunity in June 2015 and a VEEGA trajectory. As noted in Appendix E, there are many alternative launch opportunities and associated trajectory types for transfer from Earth to Jupiter. An alternate VEEGA opportunity in January of 2017 was selected as the backup to the 2015 opportunity due to its higher delivered mass performance and similar flight times and propulsive needs. The other alternatives were not pursued for analysis herein.

The January 2017 launch opportunity provides better mass performance, allows easier ramping of the funding profile, and allows more time to solicit and select the payload than does the baseline. There is almost no impact on the spacecraft design except that the propellant tanks would be sized slightly (~2%) larger to provide the larger ΔV. Since the time-of-flight from Earth to Jupiter is roughly half a year shorter for the 2017 case, even though the launch is 18 months later, arrival at Jupiter is only 14 months later. **Table 6.0-1** compares these key parameters describing the June 2015 and January 2017 launch opportunities. Postponement of the launch until the March 2020 VEEGA launch opportunity would allow for the development of the ARTG.and launch on an Atlas V 521 as shown in **Table 6.0-1**.

Additional data is presented in §3, **Table 3.4-2**.

Table 6.0-1. *2017 Backup Trajectory Provides Better Delivered Mass Performance and More Development Time than the 2015 Baseline. The 2020 Backup Offers the Potential for a Smaller Launch Vehicle at the Risk of ARTG Technology Development Delays.*

	June 2015	January 2017	March 2020
Trajectory Type	VEEGA	VEEGA	VEEGA
Launch Period (days)	21	21	21
C_3 (km^2/s^2)	14.1	10	9.8
Launch Vehicle	Delta IV-H	Delta IV-H	Atlas V 531
Minimum Heliocentric Range (AU)	0.67	0.72	0.70
Flight Time to Jupiter (years)	6.1	5.7	5.9
Jupiter Arrival	July 2021	Sept 2022	February 2026
Jupiter Arrival V_∞	6.2	6.1	5.6
Mission ΔV required	2755 m/s	2798 m/s	2400 m/s
Power Source	6 MMRTGs	6 MMRTGs*	3 ARTGs
Injected Mass (kg)	7230	>7780	>3695
Dry Mass Delivered to Europa Orbit (kg)	2837	>3013	>1500
2008 Funding Required ($MFY07)	8	5	n/a
2009 Funding Required ($MFY07)	162	32	n/a

* Further refinement could make this mission feasible with ASRGs on an Atlas V 551

7.0 SUMMARY

The 2007 Europa Explorer mission study demonstrates that a mission to Europa is scientifically compelling, technologically ready, and consistent with the budgetary expectations of a flagship mission. The 2007 study refines and validates the cost, schedule and risk results of the Europa Explorer (EE) study performed by JPL in 2006, resulting in a mission concept which is ready to proceed into Phase A. There were three major focus areas of the 2007 study effort. First, cost estimates with supporting detail were generated. The second area of focus was the independent validation and documentation of the radiation design approach. Thirdly, the team focused on understanding and documenting the operational scenario trade space including several scenarios which emphasize different priorities. The costing and operational scenarios work was done for both the floor and baseline mission concepts. The floor mission was intended to provide the lowest cost option which still met the science objectives. Lowering the mass and power adequately to launch on an Atlas V 551 was crucial to this cost savings. **Table 7.0-1** describes the key parameters which define the floor and the baseline mission concepts.

7.1 Cost Estimate

The total cost estimate by fiscal year was assessed using a WBS line item specific approach to focus on areas with the largest uncertainty. The instrument cost estimates are understandably rough as the final payload is anticipated to be selected by NASA HQ via AO; estimates for the payload were made by augmenting instrument cost models for the additional complexity required to operate in a high radiation environment. Workforce estimates were obtained for areas in which grass-roots estimating approaches were used. Schedules were generated to understand the basic lead times for the Project and for the estimated budget profile which would be required. A risk assessment was performed which resulted in a significant risk list which includes severity of potential impacts and potential mitigation approaches.

7.2 Radiation Design Assessment

The main purpose of this task was to characterize the residual radiation risk. A series of five independent reviews were performed focusing on the identified approach to the radiation design for the EE mission concept including assumed radiation dosage, shielding approach, part technologies and mission lifetime. This assessment culminated with the final review board stating that the current approach was sound and conservative. The board reports are included as part of Appendix C, Radiation Assessment Report. The recommendations from each independent review will be addressed as the planning for the subsequent project phases continues.

7.3 Operational Scenarios

The complex nature of this mission results in constraints on the allowable operational scenarios. The high radiation fluence in Europa orbit both limits the ultimate lifetime

Table 7.0-1. *Key Characteristics for both Mission Architectures*

	Baseline	Floor
Launch Vehicle	Delta IV-H	Atlas V 531
Launch Date	June 2015	June 2015
Trajectory	VEEGA	VEEGA
Flight Time to Jupiter	6.1 yr	6.1 yr
Tour Duration	2 yrs	2 yrs
Radiation Design Point	2.6 Mrad	2.3 Mrad
Europa Orbital Lifetime	1 year (75% confidence)	6 months at >75% confidence, 6 months costed
Europa Science Phase Daily Data Volume	20 Gbits/day	7 Gbits/day
Payload mass (CBE)	~158 kg	~77 kg
# of Instruments/investigation	11 + radio science - gravity	8 + radio science - gravity
Power source	6 MMRTG	5 ASRG
Payload orbital average power (CBE)	~106 W	~58 W
Unallocated Dry Mass	~185 kg	~127 kg
Estimated Mission Cost	$3.3 BFY07	$2.4 BFY07

of the flight system and also creates a complex interaction between flight system design, mission operations system design and operational approaches. This EE study team focused on the in-depth understanding of how the flight and mission operations systems interact to ensure that the science objectives are met. The engineering team worked hand-in-hand with the SDT to reach agreement on data gathering and return strategies for both the floor and baseline missions to ensure that the science goals and objectives could be met with flexible operational scenarios that are within small extensions of the experience base of current missions.

7.4 Mission Concept Readiness

This study has resulted in a mission concept which comprehensively addresses the over-arching science goal: Explore Europa and investigate its habitability. The mission offers two years of Jupiter system science, culminating with a year of low-altitude Europa science. The last decade (**FO-5**) has brought significant advancements in launch vehicle capability, rad-hard electronics and memory, mission design and radiation modeling tools, and scientific knowledge of Europa, allowing the current concept to achieve a Phase A readiness level of maturity. The optimization of many parameters is still outstanding until the final project and science teams are assembled. Draft Level 1 science requirements are proposed herein (§4.1.1) but will need to be negotiated between NASA HQ, the SDT and Project Management. Specific project implementation decisions will modulate the exact cost, schedule, technical details and operational approach, but the results of this study should provide a fairly accurate basic framework within which decisions can be made and the general mission concept can be executed.

7.5 Science Value

The science value of the baseline and floor missions was discussed in §2.4.5 and summarized at the investigation level in **Table 2.4-4**. **FO-8** includes the full science value matrix evaluated at the measurement level.

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE

Goal	Science Objective	Science Investigation	Measurement	Instrument	FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS				
					1 Global Framewrk		2 Regional Proc.		3 Targ. Proc.	1 Global Framewrk		2 Regional Proc.		3. Targ. Proc.
					1A	1B	2A	2B		1A	1B	2A	2B	
Explore Europa and investigate its habitability.	**A Characterize the ocean and deeper interior.**	A1. Determine the amplitude and phase of the gravitational tides.	A1a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient.	A1a. Telecom system.	3	3	4	4	5	3	4	4	5	5
			A1b. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1-m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A1b. Laser altimeter.	3	4	5	5	5	4	5	5	5	5
		A2. Determine the induction response from the ocean over multiple frequencies.	A2a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for at least one month.	A2a. Magnetometer.	2	4	4	4	4	2	4	4	4	5
		A3. Characterize surface motion over the tidal cycle.	A3a. Topographic differences at cross-over points from globally distributed topographic profiles, with better than or equal to 1 m vertical accuracy, to recover h_2 to 0.01 (at the orbital frequency).	A3a. Laser altimeter	4	5	5	5	5	4	5	5	5	5
			A3b. Doppler shift from spacecraft tracking via two-way Doppler, to resolve 2nd degree gravity field time dependence. Doppler velocity of 0.1 mm/s over 60 s accuracy to recover k_2 to 0.0005 (at the orbital frequency). Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient.	A3b. Telecom system.	3	3	4	4	5	3	4	4	5	5
		A4. Determine the satellite's dynamical rotation state.	A4a. Doppler shift from spacecraft tracking via two-way Doppler, to determine mean spin pole direction. Doppler velocity of 0.1 mm/s over 60 s accuracy. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient.	A4a. Telecom system.	2	2	3	4	4	2	3	4	5	5
			A4b. Topographic differences at cross-over points from globally distributed topographic profiles to determine spin pole direction and libration amplitudes, with better than or equal to 1 m vertical accuracy.	A4b. Laser altimeter.	2	2	3	4	5	2	3	5	5	5
		A5. Investigate the core and rocky mantle.	A5a. Doppler shift from spacecraft tracking via two-way Doppler, to resolve high degree gravity field. Doppler velocity of 0.1 mm/s over 60s accuracy. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient.	A5a. Telecom system.	2	2	3	3	4	2	2	3	3	4
			A5b. Topographic profiles to resolve coherence with gravity, with better than or equal to 1 m vertical accuracy.	A5b. Laser altimeter.	2	2	3	3	4	2	2	3	3	4
			A5c. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously for several months.	A5c. Magnetometer.	1	2	3	4	4	1	2	3	4	5
	B Characterize the ice shell and any subsurface water, and the nature of surface-ice-ocean exchange.	B1. Characterize the distribution of any shallow subsurface water.	B1a. Identify and locally characterize physical subsurface horizons related to the current or recent presence or water or brine, by obtaining sounding profiles of subsurface thermal, compositional, or structural horizons, with ≤50 km profile spacing over >80% of the surface, at depths of 100 m to 3 km at 10 m vertical resolution, and perform targeted detailed characterization of selected sites.	B1a. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth).	2	2	3	3	4	3	3	4	4	5
			B1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over >80% of the surface, co-located with sounding profiles.	B1b. Wide-angle camera (stereo) and laser altimeter.	1	2	3	4	4	1	2	3	4	4
		B2. Search for an ice-ocean interface.	B2a. Identify deep dielectric subsurface horizons, by obtaining sounding profiles of subsurface thermal, compositional, or structural horizons, with ≤50 km profile spacing over >80% of the surface, at depths of 1 to 30 km at 100 m vertical resolution.	B2a. Radar sounder (nominally ~5 or 50 MHz, with ~1 MHz bandwidth).	1	2	2	3	4	1	3	3	4	5
			B2b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over >80% of the surface, co-located with sounding data.	B2b. Wide-angle camera (stereo) and laser altimeter.	1	2	3	4	4	1	2	3	4	4
		B3. Correlate surface features and subsurface structure to investigate processes governing communication among the surface, ice shell, and ocean.	B3a. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with ≤50 km spacing over >80% of the surface, plus targeted characterization of selected sites.	B3a. Radar sounder (dual-frequency, nominally ~5 & ~50 MHz, with ~1 and ~10&1 MHz bandwidth)	2	2	3	3	4	3	3	4	4	5
			B3b. Map thermal emission from the surface by measuring the albedo over >80% of the surface at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, and make targetted thermal observations at better than 250 m/pixel spatial resolution and temperature accuracy	B3b. Thermal instrument	2	2	3	3	4	2	3	3	4	5
			B3c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 μm (0.4-2.5 μm desireable), and better than 12 nm through a spectral range of at least 2.5-5 μm.	B3c. IR imaging spectrometer.	1	1	2	3	4	1	2	3	4	5
			B3d. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution and accuracy, over >80% of the surface, co-located with sounding data.	B3d. Wide-angle camera (stereo) and laser altimeter.	1	2	3	4	4	1	2	3	4	4
			B3e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel, and topographic sampling of targeted sites with better than 1 m vertical accuracy.	B3e. Narrow-angle camera and laser altimeter.	1	1	1	1	1	1	2	3	3	4
			B3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface.	B3f. Wide-angle camera, color.	4	4	5	5	5	4	4	5	5	5
			B3g. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 μm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterizatoin of selected sites.	B3g. UV imaging spectrometer.	0	0	0	0	0	2	3	4	4	5
			B3h. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	B3h. Medium-angle camera.	2	2	3	3	4	2	2	3	4	5
			B3i. Doppler velocity of 0.1 mm/s over 60 s accuracy, to identify regions of density contrast within the ice crust. Multi-frequency communication (e.g. Ka & X) is best, but X is sufficient.	B3i. Telecom system.	1	1	2	2	3	1	2	3	3	4

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

5	Definitely addresses full science investigation.
4	May address full science investigation.
3	Definitely addresses partial science investigation.
2	May address partial investigation.
1	Touches on science investigation.
0	Does not address science investigation.

continued

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE

Goal	Science Objective	Science Investigation	Measurement	Instrument	FLOOR SCIENCE CAMPAIGNS					BASELINE SCIENCE CAMPAIGNS				
					1 Global Framewrl		2 Regional Proc.		3 Targ. Proc.	1 Global Framewrl		2 Regional Proc.		3. Targ. Proc.
					1A	1B	2A	2B		1A	1B	2A	2B	
Explore Europa and investigate its habitability.	**C Determine global surface compositions and chemistry, especially as related to habitability.**	C1. Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability.	C1a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm, along profiles with ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites.	C1a. IR imaging spectrometer.	2	2	3	4	5	2	2	3	4	5
			C1b. Characterize the composition of sputtered products from energetic particle bombardment of the surface, using ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C1b. INMS.	0	0	0	0	0	2	2	3	3	3
			C1c. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites.	C1c. UV imaging spectrometer.	0	0	0	0	0	2	3	4	4	5
		C2. Relate compositions to geological processes, especially communication with the interior.	C2a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm.	C2a. IR imaging spectrometer.	2	2	3	3	3	2	3	3	4	5
			C2b. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with better than 50 km spacing, plus targeted characterization of selected sites.	C2b. Radar sounder.	2	2	3	3	4	3	3	4	4	5
			C2c. Surface reflectance measurements by ultraviolet spectroscopy of targeted features at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm.	C2c. UV imaging spectrometer.	0	0	0	0	0	2	3	4	4	5
			C2d. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	C2d. Medium-angle camera (stereo).	2	2	2	3	4	2	2	3	4	5
			C2e. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at better than or equal to 250 m/pixel spatial resolution, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy <2 K, over >80% of the surface.	C2e. Thermal instrument	2	2	3	3	4	2	3	3	4	5
			C2f. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	C2f. Narrow-angle camera.	0	0	0	0	0	1	2	3	3	4
			C2g. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution over >80% of the surface, and topographic characterization at better than 10 m/pixel spatial scale and better than or equal 1 m vertical resolution and accuracy for targeted features, co-located with sounding data.	C2g. Wide-angle camera (stereo), medium-angle camera (stereo), and laser altimeter.	2	2	2	3	3	2	3	3	4	5
		C3. Assess the effects of radiation on surface materials, albedo, sputtering, and redox chemistry.	C3a. Surface reflectance measurements by visible to short wavelength infrared spectroscopy of targeted features at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm.	C3a. IR imaging spectrometer.	1	1	2	3	4	1	2	3	4	5
			C3b. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites.	C3b. UV imaging spectrometer.	0	0	0	0	0	2	3	4	5	5
			C3c. Characterize the composition of sputtered products from energetic particle bombardment of the surface, through ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C3c. INMS.	0	0	0	0	0	2	2	3	3	3
			C3d. Characterize the structure of the sputter-produced atmosphere using ultraviolet stellar occultations, and ultraviolet imaging of atmospheric emissions, at equal to or better than 3 nm spectral resolution and 100 m/pixel scale through a spectral range of at least 0.1-0.35 µm.	C3d. UV spectrometer.	0	0	0	0	0	2	3	4	5	5
			C3e. Determine global distribution of bombarding energetic electron flux, and detect upstream impacting energetic ions, by measuring magnetospheric electrons in the energy range 100 keV to 10 MeV, with pitch angle distribution and ΔE/E ~0.1 over Europa's surface, and ion from 15 keV to 750 keV from the ram direction.	C3e. Particle and plasma instrument.	1	2	3	4	5	1	3	4	5	5
			C3f. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface.	C3f. Wide-angle camera, color.	4	4	5	5	5	4	4	5	5	5
			C3g. Measure the surface albedo at spatial resolution of better than or equal to 250 m/pixel to 10% radiometric accuracy, over >80% of the surface.	C3g. Thermal instrument.	5	5	5	5	5	5	5	5	5	5
			C3h. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	C3h. Narrow-angle camera.	0	0	0	0	0	1	2	3	3	4
		C4. Characterize the nature of exogenic materials.	C4a. Determine the energy spectrum of energetic jovian electrons in the energy range 100 keV to 10 MeV to ΔE/E=0.1.	C4a. Particle and plasma instrument.	1	2	3	4	5	1	3	4	5	5
			C4b. Determine the flux and composition of plasma ions impacting Europa by measuring ions from 10 eV to 10 keV with 15 degree angular resolution to ΔE/E=0.15, and ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	C4b. Particle and plasma instrument and INMS.	1	1	2	2	2	1	2	3	3	4
			C4c. Surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm, along profiles with ≤25 km spacing over >80% of the surface, plus targeted characterizatoin of selected sites.	C4c. IR imaging spectrometer.	1	1	2	3	4	1	2	3	4	5
			C4d. Surface reflectance measurements by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeted characterization of selected sites.	C4d. UV imaging spectrometer.	0	0	0	0	0	2	3	4	4	5
			C4e. Determine surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface.	C4e. Wide-angle camera, color.	1	3	4	5	5	1	3	4	5	5

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

5	Definitely addresses full science investigation.
4	May address full science investigation.
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continued

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE

Goal	Science Objective	Science Investigation	Measurement	Instrument	FLOOR SCIENCE CAMPAIGNS: 1 Global Framewrl 1A	1B	2 Regional Proc. 2A	2B	3 Targ. Proc.	BASELINE SCIENCE CAMPAIGNS: 1 Global Framewrl 1A	1B	2 Regional Proc. 2A	2B	3. Targ. Proc.
Explore Europa and investigate its habitability.	**D Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	D1. Characterize magmatic, tectonic, and impact features.	D1a. Determine the distributions and morphologies of surface landforms at regional and local scales, by determining surface color characteristics at ~100 m/pixel scale in at least 3 colors, over >80% of the surface, and characterize surface morpphology at ~10 m/pixel over targeted sites.	D1a. Wide-angle camera (color) and Medium-angle camera.	3	3	4	4	5	3	3	4	4	5
			D1b. Topography at better than or equal to 100 m/pixel spatial scale and better than or equal to 10 m vertical resolution, over >80% of the surface, co-located with sounding profiles.	D1b. Wide-angle camera (stereo).	1	3	3	5	5	2	3	3	5	5
			D1c. Topographic characterization at better than 10 m/pixel scale and better than or equal to 1 m vertical resolution and accuracy for targeted features, co-located with sounding profiles.	D1c. Medium-angle camera (stereo) and laser altimeter.	2	2	2	2	3	2	2	3	4	5
			D1d. Global identification and local characterizaton of physical and dielectric subsurface horizons, at depths 1 to 30 km at 100 m vertical resolution and depths of 100 m to 3 km at 10 m vertical resolution, by obtaining sounding profiles with ≤50 km spacing over >80% of the surface, plus targeted characterization of selected sites.	D1d. Radar sounder (nominally ~50 MHz, with ~10 MHz bandwidth).	2	2	3	3	4	3	3	4	4	5
			D1e. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D1e. Narrow-angle camera.	0	0	0	0	0	1	2	3	3	4
		D2. Search for areas of recent or current geological activity.	D2a. Thermal mapping better than or equal to 250 m/pixel spatial resolution and temperature accuracy < 2 K, over >80% of the surface, with the same regions observed in both the day and night.	D2a. Thermal instrument.	2	2	3	3	4	2	2	4	4	5
			D2b. Search for and identify any regions of outgassing using ultraviolet stellar occultations, and ultraviolet imaging of the surface and atmosphere, at better than or equal to 3 nm spectral resolution and 100 m/pixel scale through a range of at least 0.1-0.35 µm, using limb views, along with surface profiles of ≤25 km spacing over >80% of the surface.	D2b. UV spectrometer.	0	0	0	0	0	2	3	4	5	5
			D2c. High-resolution visible stereo imaging of targeted features, at better than or equal 10 m/pixel.	D2c. Medium-angle camera (stereo).	1	1	2	2	3	2	3	4	4	5
			D2d. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D2d. Narrow-angle camera.	0	0	0	0	0	1	1	2	3	3
			D2e. Identify and map any age-sensitive chemical and physical indicators (e.g. H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeting of selected sites.	D2e. IR spectrometer and UV spectrometer.	1	2	2	3	3	2	3	4	4	5
		D3. Investigate global and local heat flow.	D3a. Map thermal emission from the surface by measuring albedo to 10% radiometric accuracy at spatial resolution better than or equal to 250 m/pixel, and by making thermal observations at spatial resolution better than or equal to 250 m/pixel spatial resolution and temperature accuracy < 2 K, over >80% of the surface.	D3a. Thermal instrument.	2	2	3	3	4	2	3	3	4	5
		D4. Assess relative surface ages.	D4a. Determine regional and global stratigraphic relationships with imaging at ~100 m/pixel scale in at least 3 colors, with near-uniform lighting conditions and solar phase angle ≤ 45 degrees, over >80% of the surface.	D4a. Wide-angle camera (color).	3	3	5	5	5	3	3	5	5	5
			D4b. Identify any regional or local areas of anomalously high heat flow, by mapping nighttime temperatures at better than or equal to 250 m/pixel spatial resolution and and temperature accuracy < 2 K.	D4b. Thermal instrument.	2	2	3	3	4	3	3	4	4	5
			D4c. Determine small-scale surface morphology, with stereo imaging at ~1 to 10 m/pixel over targeted high-priority sites, with vertical rsolution of better than or equal 1 m.	D4c. Medium-angle camera and/or Narrow-angle camera.	2	2	2	2	3	2	3	4	4	5
			D4d. Identify and map any age-sensitive chemical and physical indicators (e.g. H_2O frost, ice crystallinity, SO_2, H_2O_2) using surface reflectance measurements by visible to short wavelength infrared spectroscopy at better than or equal to 25 m/pixel spatial resolution, with better than 6 nm spectral resolution through a spectral range of at least 0.9-2.5 µm (0.4-2.5 µm desireable), and better than 12 nm through a spectral range of at least 2.5-5 µm, and by ultraviolet spectroscopy at better than or equal to 100 m/pixel spatial resolution, and better than or equal 3 nm spectral resolution, through a spectral range of at least 0.1-0.35 µm, using profiles at ≤25 km spacing over >80% of the surface, plus targeting of selected sites.	D4d. IR spectrometer and UV spectrometer.	1	2	2	3	3	2	3	4	4	5
		D5. Characterize the physical properties of the regolith, and assess processes of erosion and deposition.	D5a. Determine thermal inertia of surface materials, by thermal mapping; to better than or equal to 250 m/pixel spatial resolution and better than 2 K absolute temperature over >80% of the surface, with the same regions observed in both the day and night.	D5a. Thermal instrument.	2	2	3	3	4	2	2	3	4	5
			D5b. Detailed morphological characterization of targeted features through imaging at better than or equal 1 m/pixel.	D5b. Narrow-angle camera.	0	0	0	0	0	1	2	3	3	4
			D5c. Measure ion-cyclotron waves and relate to plasma-pickup and erosion by magnetic field sampling at 32 vectors/s and a sensitivity of 0.1 nT.	D5c. Magnetometer.	2	3	4	4	5	2	3	4	4	5

5	Definitely addresses full science investigation.
4	May address full science investigation.
3	Definitely addresses partial science investigation.
2	May address partial investigation.
1	Touches on science investigation.
0	Does not address science investigation.

Europa Explorer Themes: Origins | Evolution | Processes | Habitability | Life

continued

EUROPA EXPLORER: TRACEABILITY MATRIX AND SCIENCE VALUE

Goal	Science Objective	Science Investigation	Measurement	Instrument	FLOOR SCIENCE CAMPAIGNS 1 Global Framewrl 1A	FLOOR 1 Global Framewrl 1B	FLOOR 2 Regional Proc. 2A	FLOOR 2 Regional Proc. 2B	FLOOR 3 Targ. Proc.	BASELINE SCIENCE CAMPAIGNS 1 Global Framewrl 1A	BASELINE 1 Global Framewrl 1B	BASELINE 2 Regional Proc. 2A	BASELINE 2 Regional Proc. 2B	BASELINE 3. Targ. Proc.
Explore Europa and investigate its habitability.	E Characterize the magnetic environment and moon-particle interactions.	E1. Characterize the magnetic environment.	E1a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E1a. Magnetometer.	2	4	4	4	4	2	4	4	4	5
		E2. Characterize the ionosphere and neutral atmosphere and their dynamics, with implications for surface interactions.	E2a. Understand how sputtering generates an exosphere, by measuring the ion flux from energies of 10 keV to 1 MeV to ΔE/E=0.1, and measuring ions from 10 eV to 10 keV with 15 degree angular resolution to ΔE/E=0.15.	E2a. Particle and plasma instrument.	1	2	3	4	5	2	3	4	4	5
			E2b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E2b. Magnetometer.	2	3	4	4	5	2	3	4	4	5
			E2c. Determine the fluxes of positive ions and neutral particles, by ion mass spectrometry over a mass range of 300 Daltons, mass resolution of ≥500, and pressure range of 10^{-6} to 10^{-17} mbar, and energy resolution of 10%.	E2c. INMS.	0	0	0	0	0	2	2	3	3	4
			E2d. Identify atmospheric emissions, and characterize spatial heterogeneity and temporal variation including through the synodic cycle, by ultraviolet imaging of the atmosphere at better than or equal 3 nm spectral resolution, and sampling on time scales of hours, through a spectral range of at least 0.1-0.35 µm.	E2d. UV imaging spectrometer.	0	0	0	0	0	2	3	4	5	5
		E3. Characterize relationships between the magnetic field and plasma.	E3a. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E3a. Magnetometer.	2	3	4	4	5	2	3	4	4	5
			E3b. Understand how plasma interaction currents affect the induction field signature, by measuring 50 eV to 10 keV ions with 15 degree angular resolution and ΔE/E=0.15.	E3b. Particle and plasma instrument.	1	3	4	5	5	1	3	4	5	5
		E4. Characterize the global radiation environment.	E4a. Global detection of energetic ion and electron fluxes, by measuring Jovian electrons at energies from 100 keV to 10 MeV, and Jovian ions from energy of 10 keV to 10 MeV to ΔE/E=0.1.	E4a. Particle and plasma instrument.	1	3	4	5	5	1	3	4	5	5
			E4b. Magnetic field measurements at 8 vectors/s and a sensitivity of 0.1 nT, near-continuously.	E4b. Magnetometer.	2	3	4	4	5	2	3	4	4	5
			E4c. Determine plasma distribution function to characterize the particle environment at all pitch angles, by measuring ions from 10 eV to 10 keV with 15 degree angular resolution to ΔE/E=0.15.	E4c. Particle and plasma instrument.	1	3	4	5	5	1	3	4	5	5
	F Determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons.	F1. Determine the nature and history of the geological activity and interior evolution of the Galilean satellites.	F1a. Understand the mechanisms responsible for formation of surface features and implications for geological history, evolution, and levels of current activity, by means of: visible imaging, IR spectroscopy, and UV spectroscopy to resolve surface features; UV stellar occultations; subsurface sounding; and thermal imaging of Io.	F1a. Cameras (including color & stereo), IR spectrometer, UV spectrometer, Radar Sounder, and Thermal Instrument.										
			F1b. Determine the surface compositions and implications for the origin, evolution and transport of surface materials, by means of: visible color imaging, IR spectroscopy, and UV spectroscopy to determine composition; subsurface sounding; and ion and neutral compositions near satellites.	F1b. Cameras (especially color), IR spectrometer, UV spectrometer, Radar Sounder, and INMS.										
			F1c. Determine the compositions, origins, and evolution of the atmospheres, including transport of material throughout the Jovian system, by means of: UV stellar occultations; ion and neutral compositions near satellites; magnetic field, particle, and plasma measurements near satellites; and radio occultations.	F1c. UV spectrometer, INMS, Magnetometer, Particle and plasma instrument, and Telecom system.										
			F1d. Determine the interior structures and processes operating in the Galilean satellites in relation to the formation and history of the Jupiter system and potential habitability of the moons, by means of: magnetic field measurements; Doppler gravity measurements.	F1d. Magnetometer and Telecom system.										
			F1e. Investigate the small bodies and rings in the Jovian system, by means of: visible imaging, IR spectroscopy, and UV spectroscopy.	F1e. Cameras, IR spectrometer, and UV spectrometer.										
		F2. Understand the processes that determine the composition, structure and dynamics of the Jovian atmosphere as a type example of a gas giant planet.	F2a. Map the distribution of condensable and trace species in the Jovian atmosphere, by means of: UV, visible, IR, and thermal imaging at high spatial, spectral, and temporal resolution; UV stellar occultations; and radio occultations.	F2a. UV spectrometer, Cameras, IR spectrometer, and Thermal instrument.										
			F2b. Investigate the energy transport in the Jovian atmosphere, by means of: UV, visible, IR, and thermal imaging at high spatial, spectral, and temporal resolution; UV stellar occultations; and radio occultations.	F2b. UV spectrometer, Cameras, IR spectrometer, and Thermal instrument.										
		F3. Study the interactions between Jupiter's magnetosphere and its satellites.	F3a. Understand the magnetospheric and ionospheric environments of Jupiter and its moons, and their interactions, by means of: magnetic field, particle, and plasma measurements throughout the magnetosphere, especially at boundaries and near satellites; UV and visible observations of the Io torus, UV and visible observations of Jovian aurorae and satellite footprints; radio occultations.	F3a. Magnetometer, Particle and plasma instrument, UV spectrometer, and Cameras.										
				Total score (of	108	138	184	208	242	146	207	270	304	351
				% s	30%	38%	50%	57%	66%	40%	57%	74%	83%	96%
				Eurosols into orbital mis	4	8	14	20	26	4	8	14	20	26
				Davs into orbital mis	14	28	64	71	92	14	28	64	71	92

Europa Explorer Themes: | Origins | Evolution | Processes | Habitability | Life |

5	Definitely addresses full science investigation.
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8.0 TEAM MEMBERS AND ROLES

8.1 Team Overview

The study was conducted by two closely interacting teams. The NASA-chartered SDT focused on the science aspects while the JPL/APL Engineering Team focused on the technical and programmatic aspects of the mission concept. There was extensive interaction between the two teams throughout the study ensuring that the science goal and objectives were feasible given the technical and programmatic constraints and approaches. A listing of the team members, their affiliations and their areas of expertise are given in **Tables 8.1-1** and **8.1-2**.

The SDT held four face-to-face meetings and weekly telecons. The SDT invited specific individuals to present at the SDT meetings to ensure a broad input on the science and potential investigational methods. Two sub-groups, one for defining science value and the second to directly work operational scenarios and science observational strategies were formed which focused the efforts.

Additionally, the EE SDT worked very closely with the JSO SDT to understand and evaluate the ability of each mission concept to achieve the science objectives of the alternate concept. A joint White Paper is being prepared to document this evaluation and will be released later this year.

The invited talks were from: Chris Chyba and Kevin Hand (Princeton and Stanford—Astrobiology), Tom Gardner (Raytheon—Lander), Jim Shirley and Eric Slimko (JPL—Landers), Mike Watkins (JPL—Gravity Measurements from Sub-satellites), Karl Strauss (JPL—Mass Memory Technology), Mark Allen (JPL—Radar Spectrometry), Amanda Hendricks (JPL—UV Spectroscopy), Wendy Edelstein (JPL—Radar Inteferometry),

***Table 8.1-1.** Science Definition Team*

Member	Affiliation	Expertise
Ron Greeley—Co-Chair	Arizona State University	Europa
Bob Pappalardo—Co-Chair	Jet Propulsion Laboratory	Europa and Jupiter System
Krishan Khurana	University of California – Los Angeles	Magnetic Fields
Bill Moore	University of California – Los Angeles	Interiors
Don Blankenship	University of Texas	Subsurface and Radar
Louise Prockter	Applied Physics Laboratory	Geology and JSO SDT Co-Chair
Diana Blaney	Jet Propulsion Laboratory	Multi-wavelength imaging
Tom McCord	Bear Fight Institute	Surface Composition
Bruce Bills	Goddard Space Flight Center	Geophysics/Interior
Chris Paranicas	Applied Physics Laboratory	Particles and plasma
Mitch Sogin	Marine Biological Laboratory	Astrobiology

***Table 8.1-2.** Engineering Team*

Member	Affiliation	Expertise
Karla Clark—Lead	Jet Propulsion Laboratory	Project Management and Systems Engineering
Rob Abelson	Jet Propulsion Laboratory	Systems Engineering
Ed Jorgenson	Jet Propulsion Laboratory	Cost
Peter Kahn	Jet Propulsion Laboratory	Systems Engineering
Karen Kirby	Applied Physics Laboratory	Systems Engineering
Rob Lock	Jet Propulsion Laboratory	Mission Planning and Operational Scenarios
Guy Man	Jet Propulsion Laboratory	Systems Engineering
Bob Rasmussen	Jet Propulsion Laboratory	Systems Engineering
Bill Russell	Jet Propulsion Laboratory	Schedules
Rusty Woodall	Jet Propulsion Laboratory	Mission Assurance
James Kinnison	Applied Physics Laboratory	Systems Engineering - Risk Assessment
Andy Spry	Jet Propulsion Laboratory	Planetary Protection
Ken Klaasen	Jet Propulsion Laboratory	Instruments
Nick Pinkine	Applied Physics Laboratory	Operations
Greg Welz	Jet Propulsion Laboratory	Operations

Bob Johnson (UVa—Particle Sputtering), Lonne Lane (JPL—UV Spectroscopy), Soren Madsen (JPL—Radar Interferometry), Paul Rosen (JPL—Radar Instrumentation), Ali Stefanini (JPL—Radar Sounding), Peter Seigel (Caltech—Radar Spectroscopy), John Spencer (SWRI—Thermal Imaging), Jeff van Cleve (Ball Aerospace—Thermal Imaging), Hunter Waite (SWRI—INMS), Mau Wang (JPL—INMS), and Maria Zuber (MIT—Laser Altimetry).

Because of the challenge and complexity of the radiation issue, a task was undertaken to provide an independent assessment of the EE approach to radiation design and mitigation and to characterize the residual radiation risk. A series of peer reviews and workshops was organized to allow discipline experts to evaluate specific focus areas. Six such peer evaluations were conducted. The final integrated system review summarized the findings from the discipline reviews and integrated the approaches into a broad system approach. Members of these peer reviews and their affiliation are listed in **Table 8.1-3**.

8.2 APL Role

Louise Proctor and Chris Paranicus from APL are members of the SDT. APL also supplied people for the independent radiation assessment as identified above. APL took the lead role in the Project Risk Assessment and a supporting role in the Instrument activity.

8.3 GSFC Role

In addition to Bruce Bills' support to the SDT, GSFC also supplied people for the independent radiation assessment as identified above.

8.4 GRC Role

GRC supported the evaluation of the materials radiation assessment as identified above. GRC Advanced Radioisotope Power System personnel (Jeff Schrieber and Dick Shaltens) also supported one SDT meeting to discuss the potential impacts of using ASRGs for this mission.

8.5 APL-JPL Outer Planets Steering Group

The Study Team interacted with and was advised by a steering group consisting of the following people:

- Walt Faulconer—APL: Civilian Space Business Area Executive
- Rob Strain—APL: Space Department Head
- Rob Gold—APL: Space Department Chief Technologist
- Chris Jones—JPL: Director for Solar System Exploration
- Doug Stetson—JPL: Manager of the Solar System Mission Formulation Office
- Jim Cutts—JPL: Chief Technologist for Solar System Exploration and Manager of the Strategic Mission and Advanced Concepts Office

8.6 Study Results Review

Different parts of this concept study report have been reviewed by independent sets of discipline specialists and by APL/JPL management as follows:

1. The team has already sought and gained the support of the NASA PPO for the PP approach concept. [email from Cassie Conley to James A. Spry, Wed, 22 Nov 2006 13:53:22]
2. The Science Goal and Objectives were subjected to a review by an independent panel of planetary scientists.
3. The Science Goal and Objectives and the mission concept were presented at the Outer Planets Assessment Group (OPAG) meeting in June 2007 and at the Committee on Planetary Exploration (COMPLEX) meeting in July 2007.
4. The implementation has been reviewed by a technical, management, and cost review board internal to JPL and APL.
5. Finally, the overall concept study report was reviewed by both JPL and APL management prior to submission.

Table 8.1-3. *Radiation Assessment Team*

Team Member	Affiliation
Environments Review	
Chris Paranicus—Chair	Applied Physics Laboratory
Barry Mauk	Applied Physics Laboratory
Richard Thorne	University of California – Los Angeles
Tom Armstrong	Fundamental Technology
Steve Levine	Jet Propulsion Laboratory—Juno Deputy Principal Investigator
John Cooper	Goddard Space Flight Center
Shielding and Transport Analysis	
Jeff Johnson—Chair	Oak Ridge National Laboratory
Laurie Waters	Sandia National Laboratory
Ken Adams	Science Applications International Corporation
Richard Kemski	Jet Propulsion Laboratory
Mark Looper	The Aerospace Corporation
Parts	
Ron Lacoe—Chair	The Aerospace Corporation
Ken LaBel	Goddard Space Flight Center
Ethan Blansett	Sandia National Laboratory
Steve McClure	Jet Propulsion Laboratory—Juno Parts Engineer
Materials	
Jim Sutter	Glenn Research Center
Chuck Barnes	Jet Propulsion Laboratory
Bill McAlpine	Jet Propulsion Laboratory—Juno Radiation Engineer
Systems	
Richard Kingsland—Chair	Implementation Technology Inc
Steve Leete	Goddard Space Flight Center
John Bolt	Applied Physics Laboratory
Greg Levanas	Jet Propulsion Laboratory
Glenn Reeves	Jet Propulsion Laboratory
Integrated Systems	
Joe Srour—Chair	The Aerospace Corporation
John Henley	Science Applications International Corporation
Ralph McNutt	Applied Physics Laboratory
Dave Kusnierkiewicz	Applied Physics Laboratory—Chief Engineer
Sammy Kayali	Jet Propulsion Laboratory—Juno Mission Assurance Manager
Duncan MacPherson	Jet Propulsion Laboratory—Engineer Fellow
Gentry Lee	Jet Propulsion Laboratory—Engineer Fellow

A. ACRONYMS AND ABBREVIATIONS

AACS	Attitude and Articulation Control Subsystem
ACS	Attitude Control System
A/D	Analog to Digital
ADC	Analog to Digital Converter
AMTEC	Alkali Metal Thermoelectric Converter
amu	atomic mass unit
AO	Announcement of Opportunity
APD	Avalanche Photodiode
APL	Applied Physics Laboratory
APL	Approved Parts List
APS	Active Pixel Sensor
ARPS	Advanced Radioisotope Thermoelectric Generator
ARR	ATLO Readiness Review
ARTG	Advanced Radioisotope Thermoelectric Generator
ASD	Acquisition Sun Detector
ASIC	Application Specific Integrated Circuit
ASRG	Advanced Sterling Radioisotope Generator
ASU	Arizona State University
ATLO	Assembly, Test and Launch Operations
AU	Astronomical Unit
B	Magnetic Field Strength
BOE	Basis of Estimate
BOL	Beginning of Life
BOM	Beginning of Mission
C	Centigrade
C_3	Launch energy per unit mass; also the square of the hyperbolic excess velocity
C22	Callisto encounter number 22 (Galileo)
C&DH	Command and Data Handling subsystem
CADRe	Cost Analysis Data Requirements
CBE	Current Best Estimate
CCAFS	Cape Canaveral Air Force Station
CCD	Charge-Coupled Device
CDR	Critical Design Review
CEASE	Compact Environmental Anomaly Sensor
cg	Center of Gravity
CID	Charge Injection Device
CMMI	Capability Maturity Model Integration
CMOS	Complementary Metal–Oxide–Semiconductor
COMPLEX	Committee on Planetary and Lunar Exploration
CODACON	Coded Anode Array Converter
COSPAR	Committee on Space Research
C_{OV}	Coefficient of Variation

CPU	Computer Processing Unit
CRAM	Chalcogenide Random Access Memory
DAC	Digital to Analog Converter
Db	deadband
DC	Direct Current
DD	Displacement Damage
Deg	degree
DG	Divine-Garrett
DHMR	Dry Heat Microbial Reduction
DoD	Department of Defense
DoE	Department of Energy
DOR	Differential One-way Range
DPA	Destructive Physical Analysis
DPM	Deputy Project Manager
DPMR	Deputy Project Manager for Radiation
DPP	Design Practices and Principles
DPSER	Deputy Project System Engineer for Radiation
DRAM	Dynamic Random Access Memory
DRO	Distant Retrograde Orbit
DSM	Deep Space Maneuver
DSN	Deep Space Network
DTM	Development Test Model
ΔDOR	Delta-Differential One-way Range
ΔV-EGA	Delta Velocity – Earth Gravity Assist
EAC	Estimate at Completion
EDAC	Error Detection and Correlation
EDL	Entry, Descent and Landing
EE	Europa Explorer
EEE	Electrical, Electronic and Electromechanical
EGA	Earth Gravity Assist
EGE	Europa Geophysical Explorer
EHF	Extremely High Frequency
EIS	Environmental Impact Statement
ELDRS	Extreme Low Dose Rate Sensitivity
EM	Engineering Model
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
EO	Europa Orbiter
EOI	Europa Orbit Insertion
EOM	End of Mission
EPA	Environmental Protection Agency
EPD	Energetic Particle Detector
EPF	Europa Pathfinder
ESA	European Space Agency

ESD	Electrostatic Discharge
ESG	Europa Sub-group
ESSP	Europa Surface Science Package
EUV	Extreme Ultraviolet
eV	electron Volt
EVM	Earned Value Management
Fe-RAM	Ferroelectric-random access memory
FER	Frame Error Rate
FET	Field-Effect Transistor
FIPS	Fast Imaging Plasma Spectrometer
FMECA	Failure Modes Effect and Criticality Analysis
FO	Foldout
FOV	Field of View
FPGA	Field Programmable Gate Array
FPP	Flight Project Practices
FSS	Fine Sun Sensor
FSW	Flight Software
FUV	Far Ultraviolet
G	Giga
Gb	Gigabit
G/L	Guidelines
G&C	Guidance and Control
GDS	Ground Data System
G-G	Gravity Gradient
GIRE	Galileo Interim Radiation Electron
GNC	Guidance, Navigation and Control
GPHS	General Purpose Heat Source
GRACE	Gravity Recovery And Climate Experiment
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
Gyr	Billion years
h_2	tidal Love number
HEPA	High Efficiency Particulate Air
HGA	High Gain Antenna
HQ	Headquarters
hr	hour
HRSC	High Resolution Stereo Camera
Hz	Hertz
IC	Internal Charging
IESD	Internal Electrostatic Discharge
IFOV	Instantaneous Field of View
IML	Icy Moons Lander
IMS	Infrared Mapping Spectrometer

IMU	Inertial Measurement Unit
InD	Instrument Development
INMS	Ion and Neutral Mass Spectrometer
INSRP	Interagency Nuclear Safety Review Panel
IPR	Ice-Penetrating Radar
IR	Infrared
IRS	Infrared Spectrometer
I&T	Integration and Test
ITAR	International Tariff And Trace Regulation
ITI	Implementation Technology, Inc.
ITL	Integrated Test Laboratory
J	Joule
JEDI	Juno Energetic-particle Detector Instrument
JIMO	Jupiter Icy Moons Orbiter
JMI	Jovian Moon Impactor
JOI	Jupiter Orbit Insertion
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
k	kilo
K	Kelvin
k_2	potential Love number
keV	kilo- Electron Volt
km	kilometer
KSC	Kennedy Space Center
L	Magnetic Shell Parameter
LA	Laser Altimeter
LA	Launch Approval
LAE	Launch Approval Engineering
LANL	Los Alamos National Laboratory
LED	Light Emitting Diode
LEMMS	Low Energy Magnetospheric Measurement System
LGA	Low Gain Antenna
LILT	Low Intensity Low Temperature
LOLA	Lunar Orbiter Laser Altimeter
LOS	Line of Sight
LROC	Lunar Reconnaissance Orbiter Camera
LV	Launch Vehicle
LVA	Launch Vehicle Adapter
LVDO	Low Voltage Dropout (Regulator)
LVDS	Low-Voltage Differential Signaling
LVPS	Low voltage power supply
m	meter
m	milli

µ	micro
M	Million (Mega)
M^3	Moon Mineralogy Mapper
Ma	Million years
MAC	Medium-Angle Camera (Descoped payload)
MAC	Medium-Angle Stereo Camera (Baseline payload)
MAG	Magnetometer
MAGIC	MSAP Analog GNC Interface Card
MAM	Mission Assurance Manager
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding
MDAS	Mission Data Analysis System
MEL	Mass (Master) Equipment List
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
Mb	Megabit
mbar	millibar
MCR	Mission Concept Review
MDR	Mission Definition Review
MER	Mars Exploration Rover
MeV	Mega- Electron Volt
MEV	Maximum Expected Value
MGA	Medium Gain Antenna
MHD	Magnetohydrodynamics
MHz	Megahertz
MLI	Multi-layer Insulation
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MREU	MSAP Remote Engineering Unit
MRI	Medium Resolution Instrument
MRO	Mars Reconnaissance Orbiter
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MON	Monitor
MOS	Mission Operation System
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
M&P	Materials and Processes
MPV	Maximum Possible Value
MRO	Mars Reconnaissance Orbiter
MSAP	Multi-Mission Spacecraft Architectural Platform
MSIA	MSAP System Interface Assembly
MSL	Mars Science Laboratory
MSO	Mars Science Orbiter
MSTB	Mission System Testbed
MTIF	MSAP Telecom Interface

MVPS	Medium voltage power supply
n	nano
N	Newton
N	number
NAC	Narrow-Angle Camera
NASA	National Aeronautics and Space Administration
Nav	Navigation
NAVCAM	NAVigational Camera
NEAR	Near Earth Asteroid Rendezvous
NEPA	National Environmental Protection Agency
NICM	NASA Instrument Cost Model
NLR	NEAR Laser Rangefinder
NMO	NASA Management Office
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPR	NASA Program Requirement
NRC	National Research Council
nT	nanoTesla
NTO	Nitrogen Tetroxide
NUV	Near Ultraviolet
NVM	Non-volatile Memory
OPAG	Outer Planets Assessment Group
OpSc	Science Operations
ORNL	Oak Ridge National Laboratory
ORT	Operational Readiness Test
OSTP	Office of Science and Technology Policy
OTM	Orbital Trim Maneuver
Pa	Pascal
PA	Plutonium Availability
PAF	Payload Attach Fitting
PCA	Power Converter Assembly
PDR	Preliminary Design Review
PEL	Power Equipment List
PEPSSI	Pluto Particle Spectrometer Science Investigation
PET	Proton/Electron Telescope
PI	Principal Investigator
PIA	Power Interface Assembly
PIA	Propulsion Interface Assembly
PIDDP	Planetary Instrument Definition and Development Program
PIND	Particle Impact Noise Detection
PL	Payload
PM	Project Manager
PMCM	Parametric Mission Cost Model
POC	Proof of Concept

PP	Planetary Protection
PPI	Particle and Plasma Instrument
PPO	Planetary Protection Office(r)
PRA	Probabilistic Risk Assessment
PS	Project Scientist
PSE	Project System Engineer
PSG	Project Science Group
QPSK	Quadrature-Phase-Shift Keying
Qual	Qualification
RadE	Radiation Environment
RADFET	Radiation Sensing Field Effect Transistor
RadPSM	Radiation Effects in Parts, Sensors, and Materials
RAM	Random Access Memory
RDF	Radiation Design Factor
RFA	Request for Action
RFP	Request for Proposal
RGA	Residual Gas Analysis
RHU	Radioisotope Heater Unit
RLAT	Radiation Lot Acceptance Test(ing)
RMS	Radiation Monitoring Subsystem
ROD	Record of Decision
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPS	Radioisotope Power Source
RSE	Radiation System Engineer
RTG	Radioisotope Thermoelectric Generator
RTI	Real Time Interrupt
RTOF	Reflection Time of Flight
RW	Reaction Wheels
s	second
S	Siemens
SAIC	Science Applications International Corporation
SAR	Safety Analysis Report
S&M	Structures and Mechanisms
SAMPEX	Solar, Anomalous, Magnetospheric Particle Explorer
S/C	Spacecraft
SDST	Small Deep Space Transponder
SDT	Science Definition Team
sec	second
SEE	Single Event Effects
SEL	Single Event Latch-up
SER	Safety Evaluation Report
SEU	Single Event Upset
SHARAD	Shallow (Subsurface) Radar

SMD	Science Mission Directorate
SNL	Sandia National Laboratory
SNR	Signal to Noise Ratio
SONOS	Silicon Oxide Nitride Oxide Semiconductor
SPF	Single Point Failure
SRAM	Static Random Access Memory
SRR	System Requirements Review
SS	Sub-system
SSES	Solar System Exploration Subcommittee
SSPA	Solid State Power Amplifier
SSR	Solid State Recorder
ST	Star Tracker
ST5	Space Technology 5
STOUR	Satellite Tour (trajectory software)
T	Tera-
T	Tesla
TAA	Technical Assistance Agreements
Tb	Terabit
TBD	To Be Determined
TCM	Trajectory Correction Maneuver
TCS	Thermal Control Subsystem
TDI	Time-Delay Integration
THEMIS	Thermal Emission Imaging System
TI	Thermal Instrument
TID	Total Ionizing Dose
TLM	Telemetry
TMC	Technical, Management, and Cost
TOF	Time of Flight
TTC&M	Tracking, Telemetry, Command and Monitoring
TVC	Thrust Vector Control
TWG	Technical Working Group
TWTA	Traveling Wave Tube Amplifier
UCLA	University of California Los Angeles
U of A	University of Arizona
U of Col	University of Colorado
U of H	University of Houston
UTJ	Ultra Triple Junction
UTMC	United Technologies Microelectronics Center, Inc
UVS	Ultraviolet Spectrometer
UVIS	(Cassini) Ultraviolet Imaging Spectrometer
VDE	Valve Drive Electronics
VEEGA	Venus-Earth-Earth Gravity Assist
VGA	Venus Gravity Assist

VRHU	Variable Radioisotope Heater Unit
V&V	Verification and Validation
WAC	Wide-Angle Camera
WBS	Work Breakdown Structure
WY	Work Year
YAG	Yttrium Aluminum Garnet
yr	year
§	Section

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C. RADIATION ASSESSMENT REPORT

C1. Introduction

Missions that spend a significant time in Jupiter's radiation belts face unique design challenges. Radiation damage to electronic parts is expected to be the main life-limiting factor for such missions. Significant investment has been made in the last ten years in studying and preparing for a mission that could return to Jupiter to further investigate recent discoveries, most notably, from Galileo. Programs such as X2000, Europa Orbiter, JIMO, and other radiation programs (NPOESS, DoD missions) provided much needed knowledge to go forward. Juno has discovered a very unique mission design which allows it to accumulate only a small amount of radiation dosage through the first 2/3 of the mission. The combination of a central vault, rad-soft parts (25–50 krad) and the unique mission design allows Juno to meet its science objectives while reaching only about 500 krad behind 100 mils of Al. These previous efforts and the Juno experience are in the basis of a Europa orbiter radiation design [*Boland 2006*] and then further refined in 2007. This Appendix augments the main Europa Explorer Mission Study: Final Report by documenting two key activities performed in 2007; external technical peer review of the radiation design for EE and the newly developed mission lifetime model.

C2. External Peer Review Process and Findings

EE has a comprehensive approach to handle radiation. An independent peer review process, involving external experts, favorably validated the project approach. A series of five external, independent peer reviews were commissioned from 4/18/07–5/10/07 to provide independent validation of the approach. Four reviews/ workshops covered disciplines of: radiation environment and modeling; transport analysis and shielding design; parts and materials; and systems engineering and operations. The results of these reviews were reported to a larger panel of systems experts consisting of chief engineers and managers with radiation design and mission experience. The results of the reviews are included in §C8. Detailed radiation design material was presented to the board and is not repeated here.

The chair of the reviews and the organizations involved are shown in **Figure C2-1**. The charge to the board, board membership, affiliations, finding, recommendations and RFAs are provided in §C8. In additional to the review objectives listed, the board was also asked to identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

The project found the boards' findings and recommendations both comprehensive and useful. The Integrated Systems Peer review board finding was:

> *"In general, the JPL team is performing high-quality work in preparing for the Europa Explorer mission. At the present review, the Europa team did a very good job of presenting an overview of their progress, recommendations, and plans in radiation-related areas. The visibility of radiation issues and the integration of radiation expertise on the Europa program are commendable and essential for success. Very good teamwork and healthy communications are evident. The inclusion of an excellent peer review process on the program is notable."*

Summaries of the findings for each of the review are listed on **Foldout 9 (FO-9)**.

The "Materials" technical peer review was handled differently due to the existence of an extensive design document "Materials Survivability and Selection for Nuclear Powered Mission," JPL D-34098 June 2006, developed by the Prometheus Project [*Willis 2006*]. This document has been restricted for NASA distribution only. It provides a brief description of Radioisotope Power Systems (RPS) powered missions (all in high radiation environments), and a brief discussion of radioisotope power sources. Separate sections give an overview of major radiation effects on materials. Next, the document describes the effects of radiation on materials that have been "binned" into major classes. The document ends with an engineer's "roadmap" as to how to qualify and test additional materials for

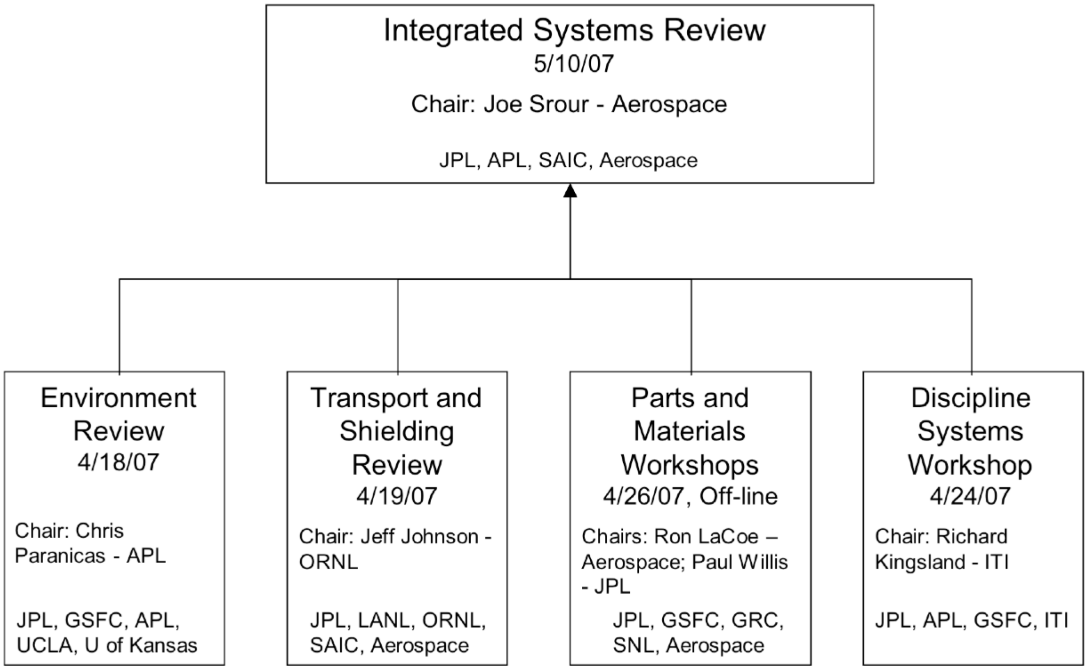

Figure C2-1. *Five External Technical Peer Reviews for Radiation Assessment*

acceptability in high radiation environments. This document should serve as a “mini-handbook” and perhaps first source of radiation physics for the flight system engineer.

Prior to publication, the document was thoroughly reviewed by Chuck Barnes and Bill McAlpine, both having strong backgrounds in nuclear physics and materials effects at JPL. Jim Sutter of NASA GRC also reviewed this document in May 2007 and submitted the following comment:

> *“This document provides a significant basis for many of our future science missions. Particular attention to the capabilities of Advanced Stirling were helpful and will be shared with the GRC team. Aside from the interests of GRC, groups working several Constellation programs throughout NASA and DOE should have this document at their ready.*

> *“Specific projects underway between ORNL and GRC on the Materials survivability will utilize this document. The use of several organic-related materials in Stirling devices for larger RPS devices are actively pursued. This points to the timeliness of your document. I’ve marked several comments throughout the document . . .”*

The RFAs from each review were assessed and dispositioned; see §C8.7. The Integrated Systems Board Chair has reviewed and concurred with the responses to the recommendations from the Integrated Systems Review; see §C8.7. Whether RFAs are closed in Phase A or Phase B is identified in that section.

C3. Mission Duration And Margin

To predict and design for mission lifetime in a high radiation environment requires system engineering previously unavailable. Past missions used conservative design practices and subsequently lasted well past their design points. There was no method available to understand the probability of achieving a given mission lifetime. A tool is now available to systematically understand how the flight system design approach impacts its lifetime. The tool takes as input the desired mission duration and a confidence level. Given those two inputs, the new mission life prediction model will provide a radiation design point for the mission. This model incorporates statistical information and uncertainties including those due to the radiation environment, electronic parts hardness and flight system reliability.

Summary of Radiation Peer Reviews

	Review Objectives	Key Board Findings	Key Board Recommendations
Environment Model	Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission? 1. Is the GIRE model an appropriate representation of the environment? 2. Have we incorporated past experience appropriately? 3. Is the way we use the statistical data appropriate? a. Usage of mean vs. 1 σ vs. 2 σ values. b. Usage of average level in a 90-day window from multiple year data. 4. Is the treatment of the C22-type events or "storms" appropriate? 5. Is our conclusion on the probability of actual radiation level below design level appropriate? 6. Have we captured assumptions and considered design margins appropriately? 7. Is the plan for Phase A appropriate?	1. The radiation dose approach results in an estimate for TID that is reasonable and conservative. 2. The current version of the original Divine and Garrett model is the GIRE model. This model and its predecessors are the standard model for calculating radiation dose for Jupiter mission planning. These models are based primarily on *in situ* data from the Pioneers, Voyagers, and Galileo. GIRE matches the mean data well but it is not yet designed to include variability with parameters such as time and Jovian longitude. 3. Limitations of the model include the following. The greater than 10 MeV electron estimate is too conservative. This estimate was based on very limited data coverage above 10 MeV in the original calculation. No publications revisiting these data have appeared since the original modeling. One panel member suggested that while GIRE has been updated to include new data it has never been fully rebuilt, with a proper weighting of all previous data and in light of new calibrations and analyses.	1. Model the near-environment of Europa including the induced magnetic field of the satellite. Further analyze the Galileo energetic charged particle data near Europa. Also, run test particles (high energy electrons for dose and heavy ions for SEUs) through a hybrid or MHD model of the Europa environment to study the altitude at which primarily MeV charged particles are excluded from the environment. 2. The high-energy electron data and GIRE modeling of it is potentially critical to the TID. We have two recommendations for improving our understanding of these electrons. First, re-examine the 21 and 35 MeV electron data from 2 experiment sources on Pioneer 10 and 11; also look at angular response to improve pitch angle distributions in model. Second, run a radial transport model that includes losses (e.g. Salammbo) to follow 10-100 MeV electrons from the radial distance of Europa to the inner magnetosphere and compare these fluxes with synchrotron observations.
Transport Analysis and Shielding	Is the approach to transport analysis and to shielding mass calculation appropriate? 8. Is the modeling assumption and approach appropriate? a. Ray-trace-in vs. ray-trace-out methods. b. Treatment of secondary and bremsstrahlung effects 9. Given the phase of the project, is the model fidelity acceptable? 10. Is our spot shielding approach appropriate? 11. What are the alternative shielding approaches and which additional ones should we consider in Phase A/B? 12. Is our radiation design point selected appropriately? 13. Have we captured assumptions and considered design margins appropriately? 14. Is the plan for Phase A appropriate?	1. Given the information presented in the review material and presentations, the committee feels the shielding mass estimates are conservative at this phase of the design process. If the follow-on analyses address the issues raised by the committee, the uncertainty on the mass estimate can be reduced. 2. The committee did not find any major flaws in the approach or assumptions used in the analyses presented to them. From the information presented, it appears the Jovian/Europa environment will be the main design driver in regards to the shielding design strategy. Consequently, focusing the preliminary shield design on TID for this environment was determined to be acceptable. The committee did, however, note that an investigation into the other environments and addressing DD and SEE should be performed as early as possible to validate the assumptions for this analysis … . The major areas for improvement and additional focus come naturally in the design process. For this mission, these would be in improvement in the radiation transport model fidelity and reducing and/or quantifying the uncertainties in the radiation environment sources. These two areas will yield the highest payoff in yielding an optimized design with adequate design margin for mission success and reducing mission risk.	In addition to the recommendations on the Request for Action Forms (RFAs), the committee makes the following recommendations: 1. The results of the calculations and experimental measurements should include error bars to distinguish statistical fluctuations from physical trends. This will aid in quantifying the uncertainty associated with the analysis or experiment. 2. Initiate Rad Hard APL early. Identify all known rad hard parts. Identify all rad soft parts (memories, ADC's, DC/DC converters, etc.) and perform industry survey radiation testing to find the hardest, most SEL-immune part(s) in these families. Include this information in the RFPs as guidance for contracted items. 3. Parts should be tested to higher doses to determine out of spec performance. This could yield potential mass savings in the shield design. 4. The pressure transducers had the lowest TID capability and accounted for a significant fraction of the Pre Phase A shield mass. Pressure transducers are routinely used in the civilian reactor industry in high radiation fields. We recommend investigating these devices to see if they are applicable for this mission.

continued

FOLDOUT 9 (2 OF 3)
SUMMARY OF RADIATION PEER REVIEWS

	Review Objectives	Key Board Findings	Key Board Recommendations
Systems and Operations	Do we have a technical approach that handles radiation for the Europa environment for systems, autonomy and operations? Do we have a technical approach that handles uncertainties? 1. Do we understand the implication of radiation during operation? (e.g. instantaneous faults, faults over time, SEU) 2. Do we have a sound system and mission approach to radiation? 3. c. Do we have a failed-operational approach for the operation of the mission? (How do we deal with unanticipated faults? How about testing?) 4. Have we captured assumptions and considered design margins appropriately? 5. Is our plan for phase A appropriate?	1. Radiation is the biggest hurdle to this mission and thus far seems to be understood well enough to validate the credibility of the mission. 2. The failed operations approach and autonomous recovery seems reasonable given the limited lifetime of Europa system in the radiation environment. But this approach must be coupled to a program to gain the best possible understanding of the system and its possible response modes and the best possible design practices to minimize complex feedback mechanisms and unwanted coupling between system elements. 3. The mass memory limitation is a significant design driver affecting the telecommunications system design and operation with follow through consequences to the use and demands on the DSN. 4. The AOs prepared for the Instrument Systems must be comprehensive and deal with the spacecraft interface in the areas of shielding and the radiation support that will be provided to the instrument builders. Other non radiation areas, e.g., thermal are also identified as areas requiring careful definition.	The Board as a group generated a total of 25 RFAs, these include the Board's recommendations. Many of the RFAs are aligned with ongoing activities or activities planned by the Europa team and the document will demonstrate the importance the Board places on the activity and identify areas for emphasis and focus. Some RFAs are similar in nature but generated by different authors. Each is included in the compilation below to assure the authors concerns and focus is communicated to the Europa team. The RFAs are organized by author. They fall into 5 broad categories: 1. Uncertainties in the radiation environment 2. Coordination, quality and ITAR restrictions on radiation protection 3. Internal spacecraft charging 4. Optimized fault recovery definition and operations 5. Interface coordination between spacecraft developer and instrument developers
Parts	Are the parts and design assumptions for implementation sound? 1. In the current stage of study, pre-phase A, we choose to address parts and materials by examining classes of parts. Do we have the appropriate assumptions and approaches for parts and material? 2. Are there any classes of parts that we do not have solution? 3. What Phase A/B tasks are critical to start early? 4. Have we captured assumptions and considered design margins appropriately? 5. Is the plan for Phase A appropriate?	1. In the current stage of study, pre-phase A, the project chose to address parts by examining class of parts. This approach is appropriate but the presentations did not cover instruments/sensors and supporting electronics that reside near the exterior to the spacecraft and may prove the most problematic from a total-dose perspective. 2. All classes of parts have a path toward a solution. However, there are certain classes of parts that have significant risks: ASICs, volatile memory, non-volatile memory, processors, ADC/DAC, linear voltage regulators, op amps and comparators. 3. Optoelectronics need to be evaluated early for TID and displacement damage as well as transient effects. 4. As to assumptions and design margins, the flow down of total dose requirements due to the environment and the application of shielding to levels as low as 100 Krad appears to be reasonable.	1. Reexamine the potential application of FPGAs for this program. The program should become familiar with the RH products and roadmaps for Xilinx, Actel and Aeroflex FPGAs. 2. Develop a strategy for ASIC procurement. Examine commercial foundry and structured-ASIC approaches. 3. Building LVDOs using discretes should be considered. 4. Examine approaches where key electronics is left unpowered during the cruise phase of the mission to increase TID margins. 5. Study issues related to the proper evaluation of the reliability of parts from low volume foundries. 6. To get a better handle on "realistic" TID requirements for specific parts, a 3D ray trace of the Cassini spacecraft using the Europa Explorer orbit should be performed.

continued

	Review Objectives	Key Board Findings	Key Board Recommendations
Integrated Systems	Do we have a sound systems and mission approach to radiation? 1. Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission? 2. Is the approach to transport analysis and to shielding mass calculation appropriate? 3. Are the parts, material and design assumptions for implementation sound? 4. Do we have a technical approach that handles radiation for the mission/systems? 5. Do we have a technical approach that handles uncertainties? 6. Is our plan for Phase A appropriate?	1. More analyses and trades are needed regarding the currently baselined mission design, which involves a Jovian tour prior to injection into Europa orbit. The present design minimizes post-launch ΔV by including that tour, and thereby delays Europa orbit insertion. That delay increases mission risk. Further analyses and trades should examine the impact of an earlier exit from the planned Jovian tour on the total radiation dose. Inclusion of radiation dose timelines for different mission scenarios would be beneficial. The cost of the additional ΔV needed for alternative mission profiles should also be considered. 2. Dosimetric adaptability is important for Europa. If the onboard dosimeters reveal that the radiation environment is significantly more severe than expected, then plans must be in place to handle that situation. 3. NASA AOs for Europa Explorer instruments must contain a sufficient amount of detail regarding radiation requirements for the mission. Key areas for inclusion are the radiation environment, shielding guidelines, parts information (e.g., what classes of parts are allowed or excluded, such as FPGAs), and the types of radiation support that will be provided by JPL to instrument suppliers. 4. The Europa Explorer team has made good initial progress toward identifying those technical achievements that will constitute mission success. Additional work is needed in that area to quantify, and obtain concurrence on, the minimum science achievements for a successful Europa mission. 5. Detailed planning is needed for the materials and parts radiation testing program. That planning should include identification of appropriate radiation facilities and their cost, estimation of the number and types of materials and parts to be tested, consideration of irradiation and measurement conditions and approaches, deciding on the types of radiation effects to be examined in parts (i.e., the numerous singleevent effects (upset, latchup, burn-out, gate rupture, transients), total ionizing dose effects (including ELDRS), displacement damage effects), and manpower estimates for testing. 6. The panel concurs with the statement made at the review that the radiation environment and parts capabilities in that environment must be known well to avoid significant issues for the Europa Explorer mission. 7. The area of radiation effects on materials and selection of appropriate materials for the Europa mission needs more work. The presentation made to the review panel provided general information of value, but seemed generic and less focused on the mission at this point than the other areas presented.	1. Perform additional analyses and trades to examine alternative mission profiles. 2. Develop plans to handle radiation environments that are more severe than expected. 3. Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments. 4. Quantify and obtain concurrence on minimum science criteria for a successful mission. 5. Perform detailed planning for the parts and materials radiation testing program. 6. Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring. 7. Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.

The specified mission lifetime of 1-year at Europa at 75% confidence led to a design point of 2.6 Mrad Si behind 100 mil of Al. Holding the design point constant, it is expected that as early conservative assumptions are replaced with more realistic estimates later in the design process, radiation dose margin will grow. This margin can be subsequently re-allocated to longer lifetime, or to mission design changes that could enhance science return. This model has been favorably peer reviewed by some of the most experienced engineers in JPL and APL.

Understanding the interactions between design and mission lifetime involves four steps:

a) model the radiation environment including the transport mechanism
b) model the reliability of individual parts exposed (with certain levels of intervening shielding) to the Jovian radiation environment
c) combine the environment model and part models into a flight system model representative of the Europa design, and
d) quantify the flight system model, using data for the individual parts.

C3.1 Radiation Environment and Transport Model

The TID environment for a representative Europa mission was obtained using the GIRE average model with the Divine-Garrett Model pitch angle variations. NOVICE, a 3-dimensional adjoint transport code, was used for the modeling the transport of the radiation through the flight system.

C3.2 Parts Reliability Model

The probability that a part will fail due to radiation exposure during the Europa science mission was calculated using the *stress-strength* formulation described in Section 14 of NASA's PRA Procedures Guide [*Stamatelatos et al. 2002*]. The *stress* is equated to the Total Ionizing Dose (TID) received by the part. Since this dose increases monotonically with time, a time-dependent model for part failure (or its complement, reliability) can be determined. Part *strength*, in this approach, is identified as the part hardness with respect to radiation.

The probability density function for part TID is predicated upon statistical models for the Jovian radiation environment developed by [*Jun et al. 2005*], and [*Boland et al. 2006*]. A lognormal probability density function was used to model uncertainty in the TID, predicated upon Jun et al. [*2005*].

A lognormal probability density function was also used to model uncertainty in part hardness. Parameters for these models, which are dependent upon part type, are summarized in **Table C3-1**. For a given part category, the mean rating is the rating assigned to the part by the manufacturer. Failure is defined as hard or catastrophic, meaning that the part either is unable to function, or its function is so severely degraded that it cannot support the other hardware in the circuit

The values in **Table C3-1** are critical in determining mission life. General observations are as follows:

- The mean failure level is the part rating multiplied by the scaling factor, which is define as $D_F(i)$, where i represents the ith part type.
- If the shielding is comparable for all components, then the weakest component is determined by D_F for that component along with the coefficient of variation (C_{OV}) for that component.

Table C3-1. *Radiation Hardness for Various Categories of Electronic Parts*

Part Category	Mean Rating Mrad	Scaling Factor	C_{OV}
Digital CMOS	1	3	0.15
CMOS Memory	1	2	0.15
Hardened Linear	1	2	0.15
High Performance Linear	0.15	2	0.15
I/O	1	3.5	0.15
ADC	1	2	0.15
Hybrid	1	1.5	0.20
Transistors	1	3	0.15
Power MOSFET	0.6	1.5	0.15
Other	1	1.5	0.15
Sensors	1	2	0.15
GaAs	8	3	0.15

- In most cases the mission life will be determined by the weakest component unless additional shielding is added to raise the effective value of D_F to a level that is comparable to that of other components used in the flight system.
- Although there is a general knowledge of the types of parts that will be used, along with their rated radiation levels, there is less certainty about either the scaling factor or C_{OV}.

The coefficient of variation was determined from earlier work on radiation data for Cassini, along with evaluations of data for newer radiation hardened and radiation tolerant parts. In most cases the distribution of radiation responses was relatively tight, which is reflected by the 0.15 value (15%) that was used for all devices except the hybrid. There are exceptions, where data showed that larger values of C_{OV} should be used. Nevertheless, the 15% C_{OV} value appears to be reasonable for most electronic parts.

Even though rather simple statistical methods are being applied to this problem, there are physical reasons that can be used to argue that the actual distribution should be truncated at both the low and high ends. The basic argument is that device properties are constrained within a relatively narrow range by the electrical specifications. Parts with extreme variations in physical properties will be screened out by the electrical parameters, along with the requirement to subject flight parts to burn in.

C3.3 Combined Environment, Transport and Parts Model

The flight system model assumes that there are "vulnerable" parts, which either work (possibly at a degraded but acceptable level) or fail (either totally or past some unacceptable level of degradation). This is consistent with the model for parts. The flight system model also assumes that only hazards associated with escalating radiation dose are important. Other hazards that would increase the background hazard rate are ignored. Comparison of this model with a flight system model which ignores the radiation hazard demonstrates the validity of this simplifying assumption (i.e., radiation is the dominant failure mechanism at Europa).

All parts will not have the same "vulnerability" to the Jovian radiation. For example, GaAs parts are so radiation resistant that their contribution to flight system failure can be neglected. Parts that are fairly radiation intolerant (e.g., Spec Linears and Power MOSFETs) will receive additional shielding which will also diminish their contribution to flight system failure (e.g., spot shielded to a RDF of 3 instead of the usual factor of 2). Consequently, the duration of the science mission at Europa will be dominated by the lifetimes of those parts with intermediate levels of vulnerability to radiation.

Parts in redundant circuits will be exposed to comparable radiation levels. Although two redundant parts will have somewhat different part-specific dose levels at which they will fail (as expressed by the C_{OV} in the **Table C3-1**), both parts will, nevertheless, tend to fail at similar times (i.e., the redundant parts cannot be modeled as totally independent). Therefore, the radiation environment lessens the typical advantages associated with redundancy.

Table C3-2 is a summary of the design issues considered in this stochastic model. Effects were quantified if possible. Otherwise conservative assumptions are imposed.

Table C3-2. *List of System Issues Modeled in the Stochastic Flight System Model*

Decreases Lifetime	Increases Lifetime
Incomplete part testing to identify weak parts	Radiation Design Factor of 2
Weakest part can bring down the whole system	Parts are not tested to failure
Uncertainties in parts and materials reliability model	Qualification failure does not lead to loss of functionality
Uncertainties in radiation environment model	Unlikely extreme value sometimes for radiation dose
Uncertainties in transport model	Neglect annealing
Hazards that would increase the background rate is not considered (e.g. transient, displacement damage)	Neglect redundancy and cross-strapping
Electron charging from high energy electrons not considered	Conservative circuit design
	Only statistic of hard failure is considered—robust operation in the presentation of degradation is not considered

Salient uncertainties in the estimate include the:

- actual number of parts whose *intermediate levels of vulnerability to radiation* will dominate the duration of the Europa science mission;[1]
- radiation impacts on powered-off parts;
- extent of the loss of reliability in redundant circuits;
- part properties (especially the scaling factors);[2] and
- probability distributions appropriate for the various part categories.[3]

C3.4 Quantified Model Results

The model produces a probability of failure assessment versus time. As shown in **Figure C3-1,** EE is highly likely to function one year post EOI (75% confidence).

A second analysis was performed by first developing a PRA model for the flight system using SAPHIRE [http://saphire.inel.gov], [*Smith et al. 2005*], quantifying the flight system reliability in the absence of radiation, and finally modifying the initial reliability estimate by considering the impact of radiation on the flight system based on the statistics shown in **Table C3-1**. This analysis is based on past Prometheus/JIMO and Mars Science Orbiter work but tailored to the EE flight system level model and using mean time to failure for like elements from MER database. The results from this second analysis are similar to **Figure C3-1** in that there is high confidence that the duration of the science mission at Europa will be between one and two years. This independent analysis correlates very well with the first estimate.

An appropriate perspective on the results is that they demonstrate confidence in a design process rather than representing a rigorous technical analysis of a specific flight system design. The deliberative process associated with development of **Figure C3-1** involved discussing various flight system configurations, understanding failure mechanisms and modeling approaches and integrating into a comprehensive tool which can be used by system engineers to understand trade offs in mission concepts and implementation. This model was favorably peer reviewed by some of the most experienced engineers in JPL and APL on July 10, 2007. Review involving a broader community is planned in the near future.

C4. Reduction of Uncertainty for Environmental Model

The environmental model. requires refining and updating to quantify and reduce uncertainties by incorporating known data and new understandings. This work will be ongoing throughout development but high priority tasks include improving the high-energy particles model used to predict the environment and better understand transient phenomenon in the environment such as seen by Galileo. For EE, the mission fluences of trapped high-energy electrons and protons are expected to be very high compared to those encountered in past interplanetary and planetary missions that NASA has flown. The high-energy electrons and protons are mostly responsible for total ionizing dose (TID)

[1] The flight system model, as stated previously, assumes that there are "vulnerable" parts, which either work or fail. All parts will not have the same "vulnerability" to the Jovian radiation. Radiation resistant parts are unlikely to fail, while radiation intolerant parts will receive additional shielding. Consequently, the duration of the science mission at Europa will be dominated by the lifetimes of those parts with *intermediate levels of vulnerability to radiation*. The number of such parts that will actually be flown is unknown.

[2] Scaling factors in **Table C3-1** relate the part rating to the best estimate of where the part will actually fail. Failure, of course, is defined as hard or catastrophic. For a given part, hard failure depends on the robustness of the circuit as well as the actual radiation tolerance of the specific part. Different circuits will have inherently different degrees of robustness, and for any particular part category in **Table C3-1**, some parts within that category will be less vulnerable to radiation than others. This introduces uncertainty into the **Table C3-1** scaling factors.

[3] Lognormal probability density functions were used for part hardness. These are considered the most appropriate, given the current state of knowledge. However, Weibull distributions may afford reasonable representations for certain types of parts. There is also concern that the actual distribution should be truncated at both the low and high ends for physical reasons. Both of these issues can impact the predicted mission life.

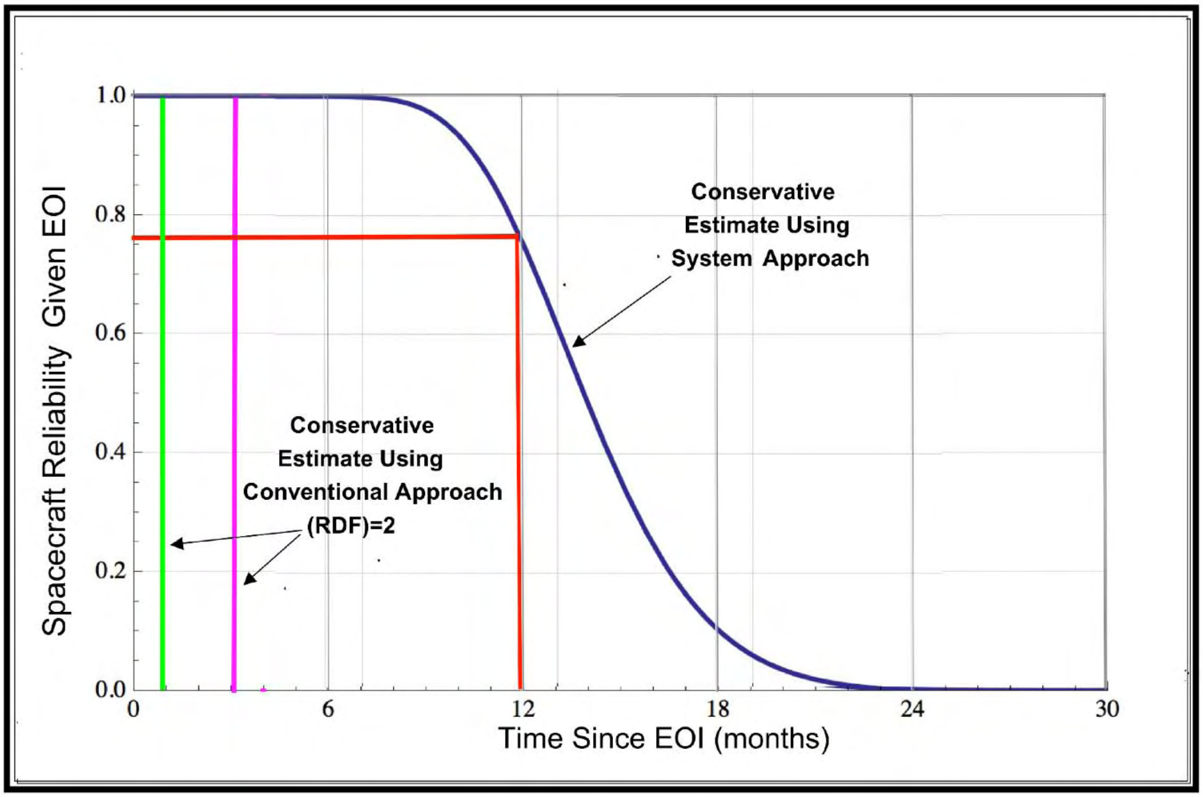

Figure C3-1. Probability of a given duration of the science mission at Europa. The blue curve is the conservative lifetime estimate of 1 year based on this new system approach. The new equivalent design point is 2.6 Mrad Si occurs at 120 days after EOI using the mean value of the GIRE radiation model. The green and the magenta lines are estimates based on using the conventional approach; the green line is for the Europa Orbiter estimate in 2001 of 30 day lifetime after EOI and the magenta line is the subsequently improved EE estimate in 2007 of 90 days after EOI based on an updated Europa environment model from Galileo data. Given the conservatism in the model, EE is highly likely to function one year post-EOI (75% confidence).

effects on flight systems and science instruments.

The TID environment for a representative Europa mission was obtained using the GIRE average model with the Divine-Garrett Model pitch angle variations. For the Jovian tour portion of the mission, the trajectory is assumed to be in the same family as the "99-35" low radiation moon tour trajectory developed for the Europa Orbiter project. **Figure C4-1** shows the electron and proton fluence accumulated during the tour prior to going into Europa orbit.

For the purposes of radiation design, the flight system was assumed to orbit Europa at an altitude of 200 km. The trapped electron and proton fluences for the first 120 days in orbit were calculated using the GIRE model and are shown in **Figure C4-2**. Note that the radiation environments in **Figure C4-2** do not include possible local shielding effects by Europa. When considering a particle's (especially for electrons) bounce and drift motion in a magnetic field together with any particle interactions with Europa itself, a large reduction of the charged particle environment near Europa is expected. These energy-dependent reduction factors have been calculated [*Paranicas et al. 2007*] and are presented in **Figure C4-3**. Finally, **Figure C4-4** shows the dose-depth curve using the environments described above, which is the selected design TID environment for the EE mission study.

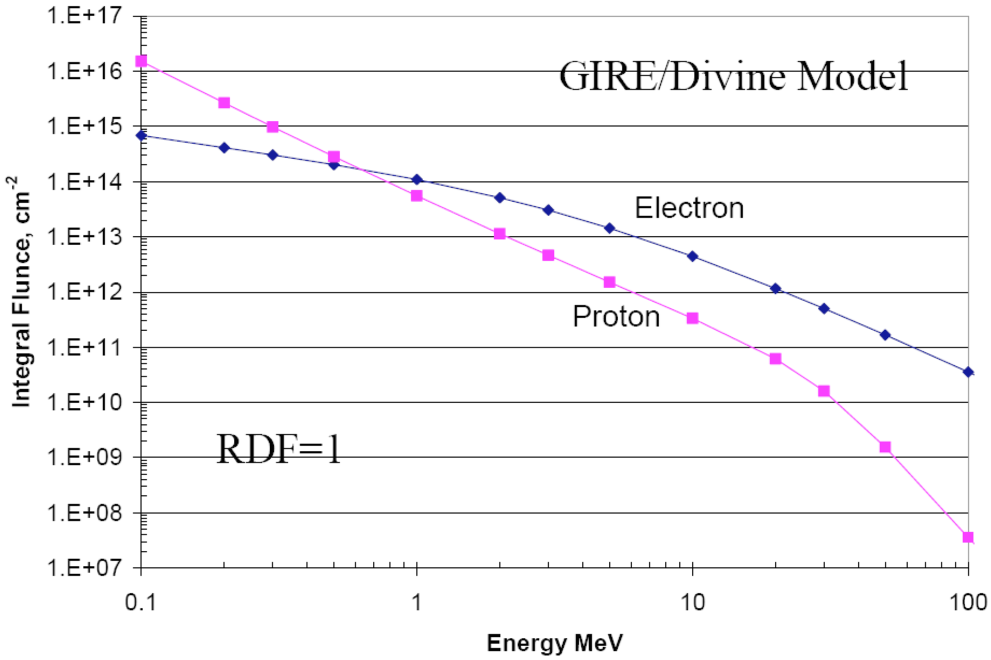

Figure C4-1. *Jovian Tour ("99-35" trajectory) electron and proton fluences.*

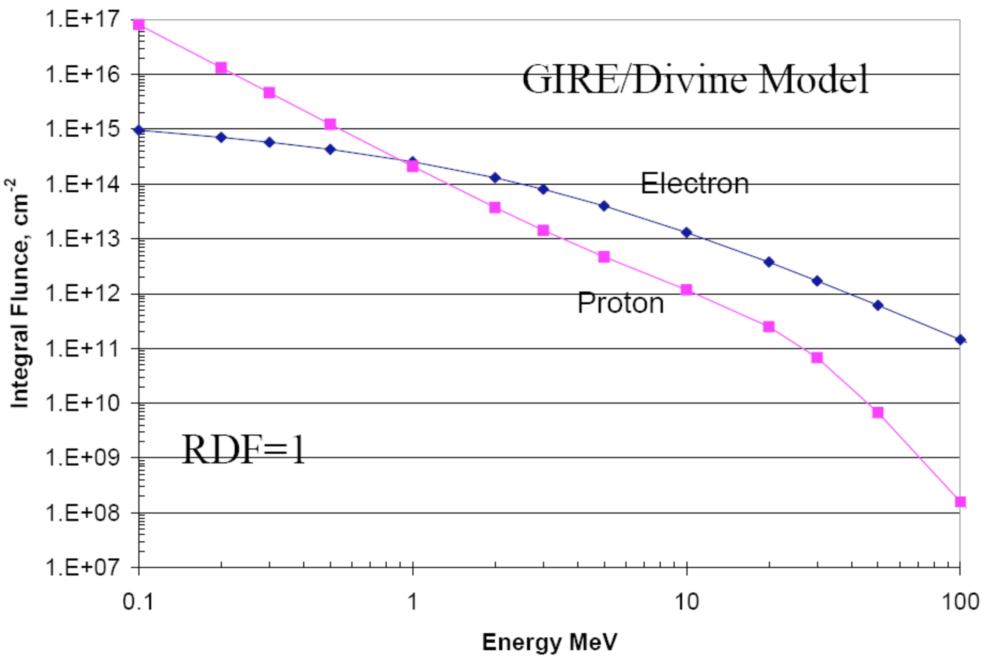

Figure C4-2. *Europa 120-day science orbit electron and proton fluences (not including local shielding effect)*

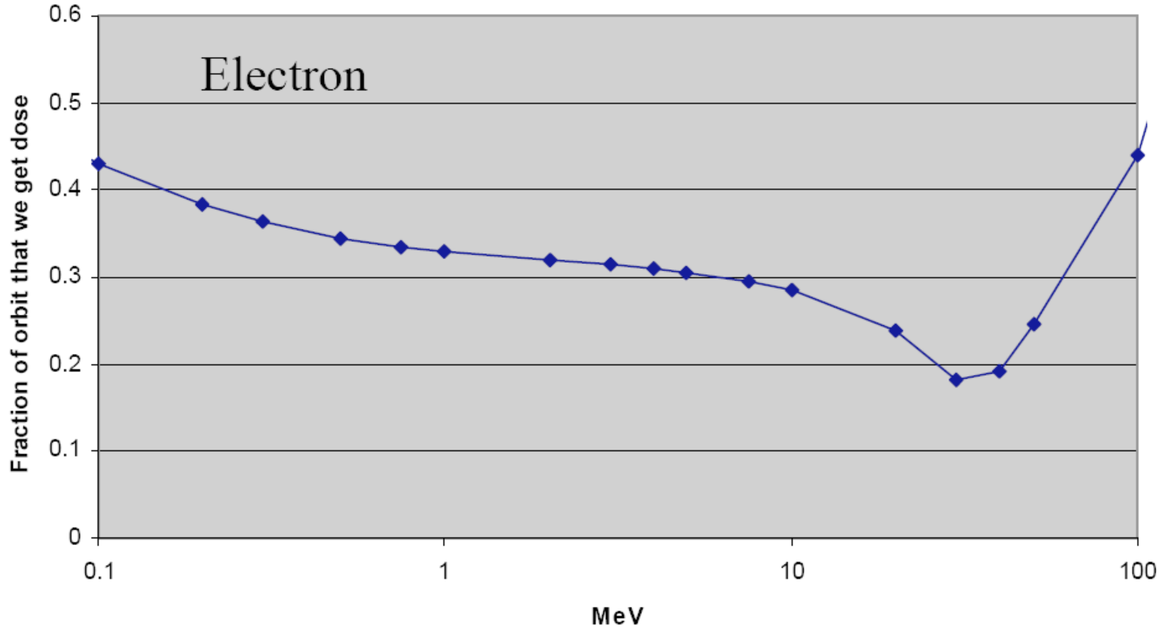

Figure C4-3. *Energy dependent reduction factor of the electron environment at Europa (200 km altitude).*

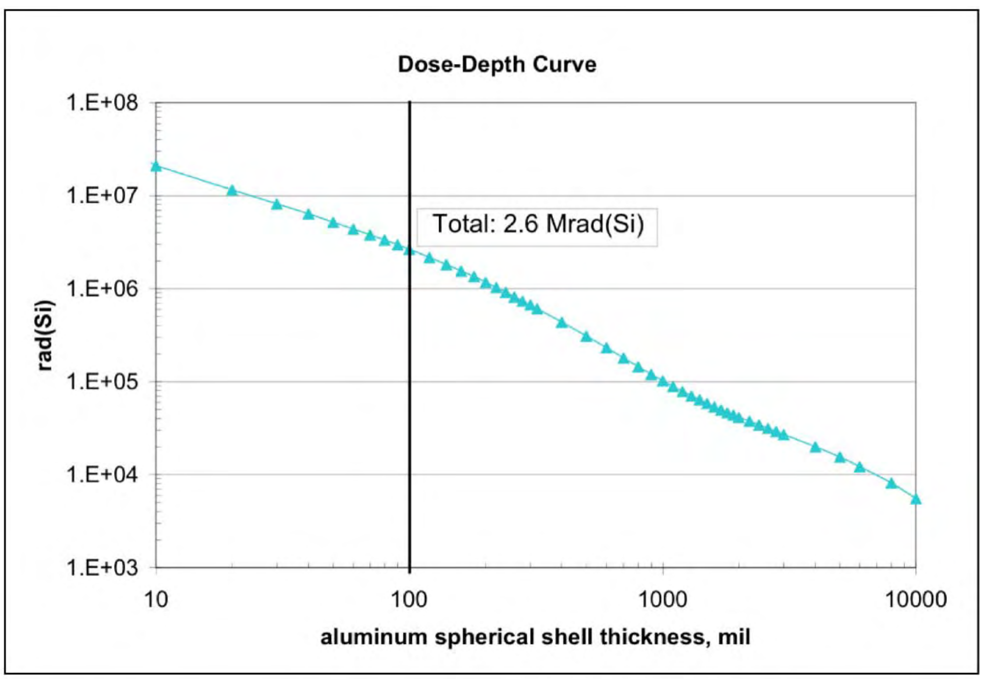

Figure C4-4. *Dose-depth curve, includes the local shielding effect, at Europa as a function of aluminum spherical shell thickness.*

Following a careful review by a team of experts, several concerns were raised about the conservatism of the GIRE/Divine family of radiation models. Some of the main ones are listed below:

1) Europa can block and scatter the charged particles interacting with it thereby reducing the radiation fluxes in its vicinity. Paranicas et al. [*2007*] attempts to estimate these effects. These variations need to be included in future models of the Europa radiation environment (current assessments were done by hand).
2) The GIRE (and Divine) model is based on Pioneer electron data at 30 MeV as the Galileo data only went up to 11 MeV. The uncertainty in the distribution of electrons above 11 MeV primarily impacts the dose calculations for highly shielded radiation sensitive components. It is planned to revisit the original Pioneer data and determine if the calibrations are still valid and to estimate the results of possible uncertainties in the Pioneer data. Other measurements from Galileo may also be useful in evaluating the energy range above 30 MeV and will be investigated.
3) GIRE currently is based on the VIP4 magnetic field model. Newer models [e.g., *Khurana and Schwarz 2005*] may provide a better representation in longitude/local time and should also be considered in modeling the Jovian radiation belts. Steps will be taken to secure an up to date version of the Khurana model for comparison with the VIP4 model predictions.
4) Instead of (B,L) coordinates for ordering the radiation environment around Jupiter, it has been suggested that the first adiabatic invariant and R_j be used. This ordering method will also be investigated.

C5. Reduction of Uncertainty for Transport and Shielding

The transport and shielding analysis model interfaces to use the best available flight system mechanical design Computer Aided Design (CAD) model need to be simplified and the uncertainty in the resulting shielding design needs to be quantified. In the EE radiation environment, optimized shielding design is very important to minimize shielding mass. Any added shielding mass is considered to be “dead” mass that does not have any active function for flight systems or science instruments and is deemed unnecessary.

A variety of radiation transport codes exist in the community. JPL mainly uses NOVICE, a 3-dimensional adjoint transport code, for the TID calculations. It is widely used in the space radiation shielding community, and compares well with other codes for TID calculations and shielding designs. (**Figure C5-1**).

One of the major uncertainties associated with the transport calculation originates from mass modeling. The mass modeling refers to a geometric representation of flight system structure in a radiation transport calculation. Ideally, as much of the flight system mass as possible should be captured in the calculations to maximize the shielding effect of existing mass. This will allow unnecessary shielding mass to be reduced. The geometry of the flight system is manually input into NOVICE and therefore it is very time-consuming to model all the small details of the flight system. Compromises between the modeling detail and the resources (budget and schedule) available for the transport calculation are often required. This results in a conservative estimate of the radiation effects and shielding mass. A CAD interface program that automatically generates a NOVICE geometric input file will be very beneficial for capturing as much existing mass as possible in the radiation transport calculations for faster mass modeling and for minimizing shielding mass. There is a plan to investigate a possibility of using an advanced CAD interface program in the early stages of the project. This effort will result in new ways the shielding design engineer, mechanical design engineer and the radiation system engineer can work together.

Another major uncertainty associated with NOVICE is the accuracy of its predictive capability. Although NOVICE has been used in past JPL flight projects, there has not been comprehensive study for validating and verifying the NOVICE results against experiments or against other well-validated codes. This is true not only for TID, but also for other radiation effects such as displacement

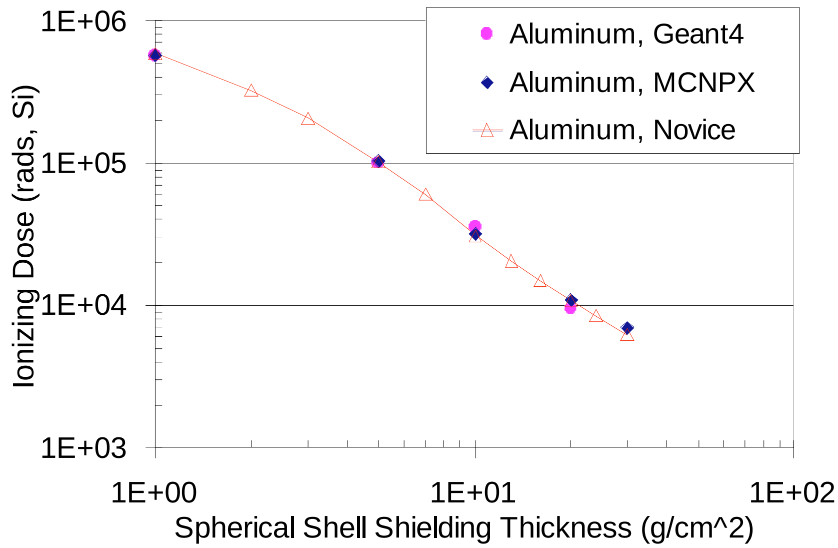

Figure C5-1. *A sample dose-depth curve comparison using representative radiation transport codes, NOVICE, MCNPX, and Geant4, shows that the use of NOVICE for transport modeling is consistent with other modeling techniques.*

damage dose and single event effects. A benchmark program will be established in the early stage of the project to better understand the predictive capability of NOVICE (and other codes) and thus to reduce the uncertainty associated the radiation transport calculations.

C6. Modeling Electronic Parts and Materials

The model associated with the behavior of electronic parts and materials requires updating to accurately reflect the parts included in the system design. The approach is to select and test parts and materials and quantify their radiation hardness for flight system design.

C6.1 Electronic Parts

The high radiation environment of the EE will have a large impact on the selection of electronic parts and the implementation of design practices that will ensure a successful mission. Although the effects of galactic cosmic rays on electronic parts are common to most space missions, few flight systems have had to deal with the high total dose and displacement damage requirement of the trapped radiation belts near Jupiter. The success of the Galileo and Cassini missions shows that JPL’s approach in designing flight system for this environment is highly effective. That same approach will be used for the EE, adapting it to new part technologies that have been developed since the Cassini mission.

Three basic ideas are essential to succeed in this challenging environment.

- Parts must be selected and evaluated early in the program, considering both radiation vulnerability and reliability.
- Sufficient conservatism must be used in the design, providing extra margin and eliminating single-point failures.
- Robust testing of hardware and software must be done during and after the design phase. The distinction between hardware and software is blurred by the extreme complexity of modern integrated circuits and the use of fault tolerant techniques to mitigate soft errors from galactic cosmic rays.

Despite the success of previous missions with high radiation environments there are several challenges that have to be dealt with for the EE. The most important is dealing with new part types and technologies. Parts used on the Cassini program are obsolete and (for the most part) unavailable, requiring new parts and some changes to qualification methods. Although hardened parts considered for the mission have been qualified for DoD missions, those qualification methods are based on tests with gamma rays that will underestimate damage in the specific radiation environment near Jupiter.

Specific challenges for radiation qualification include:

- Displacement damage from electrons and protons, which will require additional testing as well as the development of methods to combine displacement and ionization damage in devices.
- Enhanced low dose rate damage (ELDRS), which causes more damage to occur at the low dose rates in space for bipolar transistors and some types of linear integrated circuits. This can be accommodated by testing devices at low dose rate. The dose rate will be about two orders of magnitude higher than the actual mission dose rate in order to complete the testing in reasonable time intervals.
- New degradation modes, such as the decrease in breakdown voltage of power MOSFETs when they are exposed to high radiation levels.
- Synergistic effects between the different environments, such as increases in the single-event upset rate that are caused by total dose and displacement damage which reduce internal circuit margins.

JPL has developed an approach to deal with these issues for the previous JIMO mission and for the current Juno mission. The EE approach will be based on past experience from these projects.

Reliability is another challenge because of the long mission duration. It may be necessary to update reliability models for advanced part. However, the approach used in the past—which requires derating of maximum current and voltage specification, as well as restrictions on temperature—has been very successful. Recent experience on the MER, which continue to work far beyond their expected life, shows that the existing approach for reliability is effective for newer technologies.

Conservative design practices are imposed by the design principles at JPL, and are part of the reason for the success of earlier missions. An essential part of the design practice is using a radiation design factor (RDF) to ensure that there is extra margin between the anticipated radiation environment and the "design point" used for circuit design and part degradation. The starting point for design is establishing an internal data base that derates electrical parameters to account for the effects of radiation damage, temperature, and aging (reliability). Designers then use the derated parameters to implement their circuit and system designs. In order to be effective, radiation characterization data must apply to the specific device lots that are used in the actual mission.

The worst-case data base addresses permanent damage, but not single-event upset effects. SEU phenomena are more difficult because their effects are usually circuit specific. In order to deal with them a companion data base will be developed that includes upset rates for SEU and functional interrupts. Voltage derating will also be included for catastrophic effects, such as latchup (CMOS) and gate rupture (power MOSFETs).

After the circuits are designed, they are subjected to a separate analysis that verifies whether they meet the worst-case requirements, and to determine the effects of failures on the overall performance of the specific circuit or subsystem (failure mode effects analysis). A circuit that results in "single string failure" is not allowed.

Some decisions regarding key part technologies can have a large impact on the mission. One of the most important is whether to use FPGA technologies, and if they are used, which specific technologies and design verification methods to require. FPGAs have many advantages, including reduced cost and greater flexibility during design, but newer FPGAs are extremely complex. This makes it difficult to verify that the specific design will actually work in all of the modes required in the total flight system application. Reliability and radiation damage can potentially alter FPGAs, producing faults that are difficult to categorize and guard against in a mission that must have extremely high reliability. Until further qualification work can be successfully completed, FPGAs are not acceptable for this mission.Custom design options (e.g., ASICS and full custom circuits) provide an alternative to FPGAs. It is more straightforward to test and verify circuit functionality for custom designs, but the cost and development time is far longer than for FPGAs.

Unhardened commercial devices are used to a limited extent, testing and qualifying them to verify that they will meet radiation and reliability requirements. Examples include discrete transistors, and optoelectronic devices such as LEDs, laser diodes, and optocouplers. The main risk in using such devices is that once the commitment is made, there is no viable hardened option if the qualification approach shows that the commercial circuit will not work satisfactorily. The key to success is understanding the part technology and failure mechanisms, and performing qualification testing early in the program.

Knowledge of the physics of radiation failure and existing data for electronic parts was used to estimate radiation hardness levels and risk for various part categories, as shown in **Table C6.1-1**.

Hardened digital CMOS and memory devices are available that are expected to meet mission requirements, reducing risk for those important device categories. The most difficult categories are high-performance linear devices, hybrids (particularly power converters and power switch assemblies), power MOSFETs, and sensors. Despite the higher risk, it should still be possible to identify devices that will meet EE requirements. The key is to work on the high-risk areas first, and ensure that the components being considered are tested and evaluated in a way that ensures they will meet the radiation and long-term reliability goals of the program.

There are a number of ways to deal with high-risk parts. Some of the most important are discussed below.

- Electrical Screening: It is often possible to develop electrical screens that can be used to reduce the variability of the radiation response of electronic parts. This has done this for linear integrated circuits and for optoelectronic devices and can be a very effective way to extend the operating range of devices by eliminating the weaker devices through electrical screens.
- Annealing and Related Mitigation Methods: Various approaches can be used to anneal the effects of radiation damage. Some effects can be annealed by subjecting devices to a temperature of about 120°C for several hours, providing a potential mitigation approach for devices that are placed in modules where special heaters could be used to implement a controlled annealing cycle. In other cases increasing the forward current applied to a device can enhance annealing. That method was used to restore operation of the tape recorder on Galileo after it failed on the last orbit.
- Cold spares are another option, although not all radiation effects are reduced when devices are unbiased.
- Shielding: The last element in adapting parts with lower radiation tolerance is to

Table C6.1-1. *Basic Part Categories, Status and Risk.*

Part Category	Mean Rating (Mrad)	Status	Risk and Variability
Digital CMOS	1	Rad-hard lines available (2 vendors)	Low
CMOS Memory	1	Rad-hard available, but limited density	Medium for higher density devices
Hardened Linear	1	Limited selection of rad-hard devices	Medium for hardened linear; high for rad-tolerant
High Performance Linear	0.15	Few high-performance devices are available.	High
I/O	1	Rad-hard devices available	Low
ADC	1	Rad-hard devices are available (12-bit); 14-bit in development	Low for 12-bit, medium for 14-bit; very high for > 14 bit
Hybrid	1	Uncertain	High
Transistors	1	Hardened devices are available	Medium because of plethora of applications
Power MOSFET	0.6	Hardened devices available, but require more evaluation before they can be used.	High unless extra shielding is used
Sensors	1	Highly variable	High; sensors will require extensive effort
GaAs	8	GaAs devices are available	Low; reliability probably more important than radiation damage

add shielding. This is more difficult for Europa, because of the volume and mass required, but it is still a viable option in most cases.

These methods are all potentially effective. In most cases there is sufficient information available to determine how to proceed, but specific work will be needed.

The approach used for testing and qualification is an essential part of risk reduction. The first step is to make sure that parts are qualified and applied in a way that is consistent with mission requirements, and also recognizes all of the failure modes and mechanisms that can cause parts to fail from radiation and reliability.

Catastrophic part failure is the main overall concern because most circuits will work even with parts that have degraded significantly. Conservative design practices add additional margin for parametric degradation, but do not necessary affect catastrophic degradation. Radiation testing needs to consider the actual environment—electrons and protons—and it will probably be necessary to do radiation tests with those particles instead of cobalt-60 gamma rays for linear circuits, optoelectronics, and other technologies where displacement damage is important.

Low dose rate effects are an important area for risk. ELDRS testing is essential for many bipolar technologies. However, the best approach is to select devices that are insensitive to ELDRS in order to avoid the extreme complication of combining displacement and ELDRS effects in bipolar devices for this mission.

Older missions have assumed that part derating for aging is independent from radiation damage, which can penalize design parameters because the two factors are combined independently. Less allowance can be used for aging when we apply extreme derating for radiation damage (except in special cases where aging and radiation damage are directly linked), allowing parts to work effectively for much longer time periods and at higher radiation levels.

The success of previous JPL missions with severe radiation requirements provides the foundation for part qualification and design practices that are necessary for these classes of missions. The most important challenge for the EE is to extend the older approaches to the newer part technologies that will be used on the mission. Key issues include reliability mechanisms and modeling, which will have to be updated for newer technologies; displacement damage effects that add to total dose damage, reducing the effective radiation hardness level of parts when the actual environment is considered; dealing with the low dose rate damage problem; and establishing an approach for single-event testing and design that is effective in a wide range of circuit applications.

The most important factor is to select parts and perform testing and qualification early in the program, allowing sufficient time to substitute alternative parts or to modify designs. Equally important is recognition of the underlying mechanisms that affect radiation response and reliability of the various part technologies, as well as synergisms between them that could reduce the effective radiation survival level.

Risk can be further mitigated by using redundancy and cold spares, or by providing an overall architecture that allows some of the radiation damage to recover through thermal or current-enhanced annealing.

C6.2 Materials

Many materials may have to be qualified by testing because much of the data is forty years old, inaccurate, and uses gamma ray in air instead of electrons in vacuum. The most damaging radiation effects on materials are from ionizing dose and displacement damage. The deposition of ionizing doses may cause: darkening of optics; bond breakage/ crosslinking in polymers; discoloration of polymers; degradation of adhesives, films, wire insulation and coatings; deposition of internal charge; and secondary effects due to x-ray production. Displacement damage occurs mainly in crystalline materials or where atoms are held in fixed positions. It can occur from exposure to neutrons, electrons, protons or heavy ions. Materials commonly affected include metals, glasses, ceramics and especially semiconductor devices. Metals may show signs of displacement only at high doses. Glasses (amorphous) will usually show signs of compaction (4–5 %) change in density. Ceramics and crystalline components usually show signs of expansion (3–6 %) decrease in density.

The test program must include all 15 classes of materials defined in JPL D-34098 [*Willis 2006*] and they are: polymers, elastomers, cables & wiring, polymer adhesives, composites, multi-layer insulation, "teflon" fluoropolymers, lubricants, metals, permanent magnets, ceramics, optical glasses, optical coatings, optical fibers, and thermal control coatings. A test plan is proposed. To simulate the Europa spectrum, a "group fluence" concept (bins), is proposed as shown in **Figure C6.2-1**.

The standard approach to materials testing subjects the specimens to a broad spectrum of radiation energies and flux intensities. Such an approach is both costly and time consuming. With the "group fluence" scheme, material specimens would only be tested to the environment they are expected to encounter during the mission. By restricting these tests to a more limited range of energies and flux intensities, needed data can be obtained with an abbreviated schedule and lower budget

An additional benefit is this scheme permit degraded materials to be identified early in the project with only survivors passing into the latter tests. Facilities have already been identified that can implement this approach. In general the JPL's flood gun facility will be used for the surface damage testing, JPL's Dynamitron linear accelerator will be used for intermediate range testing, and the Gaertner Radiation Laboratory at Rensselaer Polytechnic Institute will be used for the high end (i.e. > 25 Mev) energy levels. Special test requirements can be accommodated by other test facilities listed in Appendix 11, pp. 56–57 of the [*Willis 2006*] document. A set of draft flight system charging requirements have been developed to address surface charge build up and internal charging and they are provided in §8.

EE mission components are most likely to include: power cables, communications cables, connectors and materials such as Teflon, Tefzel, Phenolic, MLI, thermal control paints, optical coatings, composites, and others. Apart from mechanical degradation, the build up of internal static charges and consequent arcing is also of concern, and requires assessment.

In summary, materials degradation and possible charge accumulation is definitely an issue for Europa missions. The benefits of the proposed approach include simplified and cost-efficient testing, with results directly applicable to mission environments. These experiments should provide proof of the survivability of materials used in this mission. They will also provide a manageable model for the mission life estimation critical for

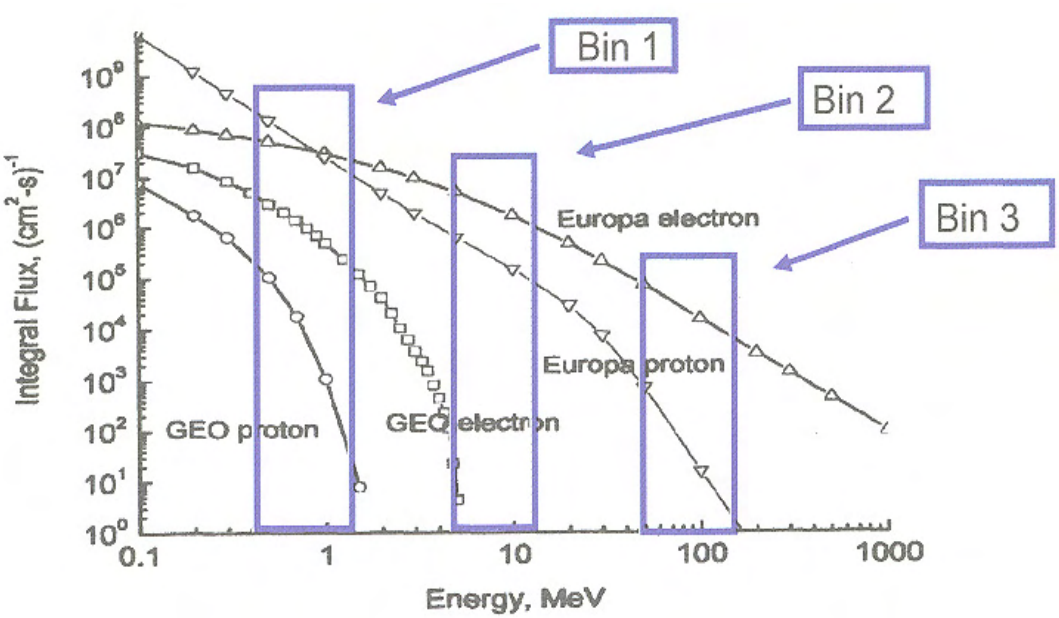

Figure C6.2-1. *Test Approach By "Group Fluence"* system engineering trades. Based on our understanding of radiation damage, the experience gained with previous missions, the learning experience gained from Prometheus, Juno, and a defensible plan for testing and qualification, the EE is in a good position to assess materials usage for a successful Europa mission.

C7. Radiation Dosimeter

The TID radiation environment is intrinsically variable at Europa. Aside from uncertainties in our knowledge of the average environment as determined by available models, the variations in Europa's longitude/latitude, magnetic field, and its plasma environment all contribute additional unknowns. Moreover, the uncertainties associated with radiation transport analysis and mass modeling mean that there will be concerns associated with the actual device performance in the Europa environment even if it was known exactly. Thus, as the mission environment evolves, the operations of the EE could be affected if the departures of the environment and systems performance from that predicted are larger and more systematic then expected. It may be possible, however, to manage if not control this type of risk by continually monitoring the actual environment at critical locations in the flight system. In particular, the measurement of the radiation characteristics (e.g., dose, electrostatic charging, SEU) at key locations around the flight system would allow an ongoing assessment of the actual status of the mission and its likelihood of success. This would permit real time risk assessment for the Europa mission at a relatively low cost in mass, power, data rate, and money. A Radiation Monitoring Subsystem has been added to the flight design. For more information, see §4.4.3.9.

C8. Supporting Material

1. Environment Modeling Peer Review Board Report, April 18, 2007
2. Transport Analysis and Shielding Peer Review Board Report, April 24, 2007
3. Discipline Systems and Operations Workshop Board Report, April 26, 2007
4. Parts Workshop Board Report, April 26, 2007
5. Integrated Systems Peer Review Board Report, May 21, 2007
6. RFA Disposition Status, June 4, 2007
7. Disposition of Recommendation for the Integrated Systems Peer Review, July 5, 2007
8. Draft Flight System Charging Requirements

1. Environment Modeling Peer Review Board Report, April 18, 2007

4/18/07

Technical Peer Review Board Report

Subject: Radiation Environment for Europa Explorer

To: Guy Man

From: Chris Paranicas

Review Objectives:

Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?

a. Is the GIRE model an appropriate representation of the environment?
b. Have we incorporated past experience appropriately?
c. Is the way we use the statistical data appropriate?
    i. Usage of mean vs. 1 σ vs. 2 σ values.
    ii. Usage of average level in a 90-day window from multiple year data.
d. Is the treatment of the C22-type events or "storms" appropriate?
e. Is our conclusion on the probability of actual radiation level below design level appropriate?
f. Have we captured assumptions and considered design margins appropriately?
g. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Dr. Chris Paranicas (Johns Hopkins University-Applied Physics Laboratory) - Chair
Dr. Richard Thorne (University of California at Los Angeles)
Dr. Steve Levin (Caltech – Jet Propulsion Laboratory)
Dr. Tom Armstrong (Fundamental Technology)
Dr. Barry Mauk (Johns Hopkins University - Applied Physics Laboratory)
Dr. John Cooper (Goddard Space Flight Center)

4/18/07

Scope of the Peer Review Material
(a summary of the information presented in bullets)

- Jupiter radiation model components, sources of data, and limitations
- Extrapolation of electron spectrum to high energy
- Comparison of model predictions with data, including with synchrotron radiation close to planet
- Assumptions and limitations of Jovian magnetic field model used
- Heavy ion detection and relevance to spacecraft
- Galileo orbit C22 flux enhancement event and how this is incorporated into radiation modeling
- Energetic electron direct and implicit (Galileo star-scanner data) detection
- How statistics are calculated in global radiation model
- Galileo radiation lessons learned including required capability of parts, hardware performance and unexpected events
- Radiation environment close to Europa
- Mission dose calculations and updates
- Summary of assumptions and design margins
- Outstanding issues for Phase A

4/18/07

Key Findings

The radiation dose approach results in an estimate for TID that is reasonable and conservative.

The current version of the original Divine and Garrett model is the GIRE model. This model and its predecessors are the standard model for calculating radiation dose for Jupiter mission planning. These models are based primarily on *in situ* data from the Pioneers, Voyagers, and Galileo. GIRE matches the mean data well but it is not yet designed to include variability with parameters such as time and Jovian longitude.

Limitations of the model include the following. The greater than 10 MeV electron estimate is too conservative. This estimate was based on very limited data coverage above 10 MeV in the original calculation. No publications revisiting these data have appeared since the original modeling. One panel member suggested that while GIRE has been updated to include new data it has never been fully rebuilt, with a proper weighting of all previous data and in light of new calibrations and analyses.

There is a great deal of scatter in the data among the many Galileo orbits and the panel discussed whether this scatter was truly time-, longitude-, etc. dependence or whether it could be reduced with a more up-do-date magnetic field model and/or re-plotting the data in invariant coordinates.

The Galileo orbit C22-like flux enhancements are low probability events and are not included in modeling the average fluxes. The panel finds that ideally the physics of such events be understood to properly incorporate these increases with weighting into the statistical averages.

The panel found that for a planned low altitude Europa orbit (100-200 km), the dose from 1-50 MeV electrons will be at least 50% lower than the dose at a radial distance of 9.4 R_J but at longitudes far from the satellite's longitude. This shielding effect by the moon could be enhanced further because of the induced magnetic field of the satellite and this requires further modeling.

Another radiation issue regards the radiation hardness of spacecraft parts and annealing. While Galileo's orbit took it deep into the radiation environment, the apoapsis of that spacecraft's orbit was in very low radiation so that some annealing took place during each orbit. A Europa orbiter might be continuously operating in an environment with a much higher dose floor.

4/18/07

Recommendations

Model the near-environment of Europa including the induced magnetic field of the satellite. Further analyze the Galileo energetic charged particle data near Europa. Also, run test particles (high energy electrons for dose and heavy ions for SEUs) through a hybrid or MHD model of the Europa environment to study the altitude at which primarily MeV charged particles are excluded from the environment.

The high-energy electron data and GIRE modeling of it is potentially critical to the TID. We have two recommendations for improving our understanding of these electrons. First, re-examine the 21 and 35 MeV electron data from 2 experiment sources on Pioneer 10 and 11; also look at angular response to improve pitch angle distributions in model. Second, run a radial transport model that includes losses (e.g. Salammbo) to follow 10-100 MeV electrons from the radial distance of Europa to the inner magnetosphere and compare these fluxes with synchrotron observations.

Evaluate the minimum dosimeter compliment that would be of value for diagnosing spacecraft, instrument, and science issues.

Gain a better understanding of the source and physics of the Galileo orbit C22 flux enhancement event so that the probability of such events can be folded into radiation modeling. Mechanisms to consider include: solar wind disturbances, Io volcanic activity, and Galileo wave activity during the event for local acceleration process.

In addition to accumulated dose, lessons from Galileo include that devices are "peak-flux" dependent. This means that radiation can disrupt functioning either because of large accumulated dose or because total flux of particles spikes suddenly. The effects of peak flux on parts should be studied: the modeling assumption should be examined in the light of peak-flux calculations.

To better manage the statistics the panel had 2 main suggestions. Organize the Galileo EPD data in μ-B space (i.e. re-plot the data by their first adiabatic invariant and observed scalar B, the magnetic field strength). Use K. Khurana's global magnetic field model instead of the VIP4 model to re-plot the data. These improvements could potentially reduce statistical scatter of the charged particle data at each L shell.

Prepare a mission timeline with dose as a function of distance to Jupiter to help make trades about dose and distance.

2. Transport Analysis and Shielding Peer Review Board Report, April 24, 2007

FINAL - 4/24/07

Technical Peer Review Board Report

Subject: Transport Analysis and Shielding for Europa Explorer

To: Guy Man

From: Jeffrey O. Johnson

Review Objectives:
The radiation environments associated with the Europa Explorer mission arguably present one of the most demanding technical challenges for ensuring mission success. The radiation transport analyses to design an effective shielding package/strategy with appropriate design margin and not overly conservative assumptions will be critical. Consequently, a technical peer review board was convened with the objective of evaluating the radiation transport and shielding design process and assessing the approach. In particular, the committee was asked to answer the following questions.

Is the approach to transport analysis and to shielding mass calculation appropriate?

a. Is the modeling assumption and approach appropriate?
    i. Ray-trace-in vs. ray-trace-out methods.
    ii. Treatment of secondary and bremsstrahlung effects
b. Given the phase of the project, is the model fidelity acceptable?
c. Is our spot shielding approach appropriate?
d. What are the alternative shielding approaches and which additional ones should we consider in Phase A/B?
e. Is our radiation design point selected appropriately?
f. Have we captured assumptions and considered design margins appropriately?
g. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Dr. Jeffrey Johnson (Oak Ridge National Laboratory) - Chair
Dr. Laurie Waters (Los Alamos National Laboratory)
Dr. Ken Adams (Science Applications International Corporation)
Mr. Richard Kemski (Caltech – Jet Propulsion Laboratory)
Dr. Mark Looper (The Aerospace Corporation)

FINAL - 4/24/07

Scope of the Peer Review Material

The committee was given a comprehensive presentation covering all the relevant aspects of the radiation transport analyses performed to date and the preliminary plans for support of Phase A of the project. In particular, the presentation included:

- An introduction to the various radiation environments (space and power source) of concern for the mission. The majority of this information was focused on the Jovian/Europa environments since they are considered the sources driving the shield design.
- An overview of radiation effects on electronics and materials indicating which radiation sources/environments are important to the TID, DD, and SEE damage mechanisms.
- A detailed description of the selected baseline radiation environment to be used in the preliminary shielding mass analyses for the Europa Explorer.
- A discussion of the various radiation transport tools used at JPL, along with their strengths, weaknesses, capabilities, and applicability. Some preliminary code comparison results were also presented in this section of the presentation.
- A detailed discussion of the shielding approaches used to arrive at the shielding mass estimates for the Europa Explorer
- A summary of the assumptions and design margins utilized in the preliminary analyses to date to aid in understanding the amount of conservatism that has been included.
- The radiation transport and shielding team's Phase A plan

FINAL - 4/24/07

Key Findings

- Given the information presented in the review material and presentations, the committee feels the shielding mass estimates are conservative at this phase of the design process. If the follow-on analyses address the issues raised by the committee, the uncertainty on the mass estimate can be reduced.

- The committee finds that the modeling assumptions and approach are appropriate for this phase of the design. The team has used several different tools in an effective manner and attempted to optimize their tools for the various aspects of the problem.

- For the TID analysis, the treatment of secondary and bremsstrahlung effects have been properly accounted for. However, beyond TID, secondary particle effects were not discussed and should be appropriately considered when assessing the SEE and DD damage effects.

- For Pre-Phase A, the model fidelity is appropriate and acceptable for obtaining preliminary shield mass estimates that are conservative.

- The approach for spot shielding is also appropriate. Employing a RDF of 3 at 150krad is considered to be a valid conservative assumption at this stage.

- The alternative shielding approaches investigated (primarily relative to shield material selection) are appropriate for TID. However, SEE and DD effects should be evaluated early in Phase A before final selection of shield materials is made. Further improvements and/or adjustments in the shielding approach may also be obtained in the integrated shield optimization design.

- The radiation design point selected was appropriate given the early stage of the project and the incomplete analysis of alternatives. The 9935 trajectory chosen as the baseline for the analyses presented should be evaluated against an actual design point trajectory. If it is representative of the actual trajectory, then the 9935 will have been appropriate for this analysis.

- The assumptions and design margins employed by the radiation transport team were determined to be appropriate for this stage of shielding analysis.

- The preliminary plan for Phase A presented to the committee was appropriate. However, the committee added additional suggestions outlined in the recommendations and RFAs that need to be carefully considered.

In summary, the committee did not find any major flaws in the approach or assumptions used in the analyses presented to them. From the information presented, it appears the Jovian/Europa environment will be the main design driver in regards to the shielding design strategy. Consequently, focusing the preliminary shield design on TID for this environment was determined to be acceptable. The committee did, however, note that an investigation into the other environments and addressing DD and SEE should be performed as early as possible to validate the assumptions for this analysis. This was not deemed an omission, but rather an assumption that requires further validation and quantification in order to reduce the uncertainty. The major areas for improvement and additional focus come naturally in the design process. For this mission, these would be in improvement in the radiation transport model fidelity and reducing and/or quantifying the uncertainties in the radiation environment sources. These two areas will yield the highest payoff in yielding an optimized design with adequate design margin for mission success and reducing mission risk.

Recommendations

In addition to the recommendations on the Request for Action Forms (RFAs), the committee makes the following recommendations:

1. The results of the calculations and experimental measurements should include error bars to distinguish statistical fluctuations from physical trends. This will aid in quantifying the uncertainty associated with the analysis or experiment.

2. Initiate Rad Hard APL early. Identify all known rad hard parts. Identify all rad soft parts (memories, ADC's, DC/DC converters, etc.) and perform industry survey radiation testing to find the hardest, most SEL-immune part(s) in these families. Include this information in the RFPs as guidance for contracted items.

3. Parts should be tested to higher doses to determine out of spec performance. This could yield potential mass savings in the shield design.

4. The pressure transducers had the lowest TID capability and accounted for a significant fraction of the Pre Phase A shield mass. Pressure transducers are routinely used in the civilian reactor industry in high radiation fields. We recommend investigating these devices to see if they are applicable for this mission.

5. It is not readily apparent to the committee what the design margin is relative to the parts testing program using mono-energetic Co-60 sources to represent the real environment. In other words, the committee was not certain as to whether the RDF is intended to encompass whatever uncertainty is introduced by testing parts with high-dose-rate gammas instead of in the real environment. The committee recommends developing a strategy to quantify this uncertainty so that it can be effectively accounted for in the integrated design margin associated with the shield mass calculations.

3. Discipline Systems and Operations Workshop Board Report, April 26, 2007

Systems & Operations

4/26/2007

Subject: Europa Explorer Systems Engineering Workshop on Radiation

To: Dr. Guy Man

From: Richard Kingsland

A workshop was held 4/24/2007 to conduct a peer review of the work performed regarding the Systems Engineering and Operations of the Europa Explorer system with focus on the radiation implications for a successful mission. The board received presentations (Outline Below) from G. Man who discussed the Europa mission, the design of the spacecraft, programmatics, and plans for Phase A; R. Lock who discussed mission operations and margins; and R. Rasmussen who discussed system strategy. The presentations were professional, detailed, well structured, and organized. The first half of the review was generally formal with some interaction with the board and the second half highly interactive with questions and answers. It is not a technical measure but it certainly bodes well for a program when the people working the project are not only doing a good job but are enthusiastic about the effort. Such was certainly the case.

Charge to the Board - Review Objectives:

Do we have a technical approach that handles radiation for the Europa environment? Do we have a technical approach that handles uncertainties?

Systems, Autonomy and Operations

a. Do we understand the implication of radiation during operation? (e.g. instantaneous faults, faults over time, SEU)
b. Do we have a sound system and mission approach to radiation?
c. Do we have a failed-operational approach for the operation of the mission? (How do we deal with unanticipated faults? How about testing?)
d. Have we captured assumptions and considered design margins appropriately?
e. Is our plan for phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Membership:

Richard Kingsland – Chair, Implementation Technology Inc.
Steve Leete, GSFC
John Bolt, JHU-APL
Greg Levanas, JPL
Glenn Reeves, JPL

Systems & Operations

Outline:

• 8:30 Introduction	R. Kingsland
• 8:35 Mission Concept	G. Man
• 8:50 Mission Drivers from Radiation	G. Man
• 9:00 Layered Design Approach	
– Design of Spacecraft	G. Man
• Parts	
• Shielding	
• Fault Protection	
– Mission Operations	R. Lock
• Data Acquisition	
• Inherent Robustness - Margins	R. Lock
• 10:00 Programmatic	G. Man/K. Clark
• 10:10 Plan for Phase A	G. Man
• 10:15 Discussions - Systems Strategy	R. Rasmussen
• 11:00 Board Discussion	R. Kingsland
• 1:00 Adjourn	

2

Systems & Operations

Response to Review Objectives:

a. Do we understand the implications of radiation?
   - Yes, the implications are understood
   - Question how it gets communicated to the team
   - Question what level of uncertainty is used
   - Question on how dose rate effects the degradation of parts

b. Do we have a sound system approach?
   - Yes the board agrees the system approach is sound at its current level of development and expects that this will be a continuing effort.

c. Do we have a failed operational approach for operation?
   - Yes the concept of continuing science under fault conditions was accepted with priority of making sure the faulty source can be decoupled from the rest of the spacecraft. This board expects that this will be a continuing effort.

d. Have we captured the assumptions and considered design margins
   - Several assumptions have been captured and they look fairly comprehensive.
   - Continuing work needed on identifying and quantifying assumptions.
   - Design Margins are identified and are largely qualitative at this point
   - Continuing work needed to quantifying margins.

e. Is our plan for PHASE A appropriate?
   - Yes, but add to Phase A "plan to develop a road map for successful design". This roadmap should include a list of project priorities and a plan on how and when they will be addressed. Issues include parts obsolescence, ITAR implications on issues such as RADHARD parts availability, overseas, parts test program, early part family identification ...etc.

1. Any major flawed approaches or assumptions
   The Europa team has prepared a comprehensive set of assumptions that seem complete. Ongoing work must continue to validate these assumptions and reduce the large uncertainties that currently exist.

2. Any Major omissions
   None identified with the possible exception of internal charging

3. Areas for improvement or additional focus in the next design phase
   Areas for additional study and focus are identified in the RFAs

4. Statement of perceived residual risk
   Internal Charging
   Radiation dose and dose rate uncertainties
   Unknown spacecraft response to radiation and radiation induced faults
   Inability to retain a skilled, spacecraft knowledgeable team on the program during the life of the mission

Systems & Operations

Key Findings:

1. Radiation is the biggest hurdle to this mission and thus far seems to be understood well enough to validate the credibility of the mission.
2. There is a general concern regarding the meaning of the radiation dose predictions, the uncertainties. Are we using mean, 1, 2, 3 sigma numbers?
3. The failed operations approach and autonomous recovery seems reasonable given the limited lifetime of Europa system in the radiation environment. But this approach must be coupled to a program to gain the best possible understanding of the system and its possible response modes and the best possible design practices to minimize complex feedback mechanisms and unwanted coupling between system elements.
4. There is concern regarding the elimination of FPGAs as a design option and the effect this restriction will have, especially on the instrument packages.
5. The radiation parts philosophy of preferring to prioritize getting radiation pedigree parts and then parts via radiation tolerant processes is a good approach. However the radiation system engineers must completely understand the basis of the parts vendors' pedigree and process.
6. The mass memory limitation is a significant design driver affecting the telecommunications system design and operation with follow through consequences to the use and demands on the DSN.
7. The Europa team has done an outstanding job of dealing with the comprehensive considerations generated by the radiation environment and developing innovative operational modes to address the foreshortened lifetime of the Europa spacecraft when operating in the radiation environment.
8. The spacecraft, during the Jovian tour phase of the mission prior to Europa, will operate in both higher and lower radiation environments. This bounding experience will enable a better understanding of the spacecraft responses to the radiation environment and allow fine tuning of the automated recovery modes prepared and selected for the fault-operations approach.
9. The spacecraft sensors and radar will not operate through any significant atmosphere and there is no concern regarding door, attenuation or other radiation driven atmospheric effects.
10. The AOs prepared for the Instrument Systems must be comprehensive and deal with the spacecraft interface in the areas of shielding and the radiation support that will be provided to the instrument builders. Other non radiation areas, e.g., thermal are also identified as areas requiring careful definition.

4. Parts Workshop Board Report, April 26, 2007

4/26/07

Technical Workshop Board Report

Subject: Radiation Effects on Parts for the Europa Explorer

To: Guy Man

From: Ronald Lacoe

Review Objectives:

Radiation Effects on Parts
Are the parts, material and design assumptions for implementation sound?

1. In the current stage of study, pre-phase A, we choose to address parts and materials by examining classes of parts. Do we have the appropriate assumptions and approaches for parts and material?
2. Are there any classes of parts that we do not have solution?
3. What Phase A/B tasks are critical to start early?
4. Have we captured assumptions and considered design margins appropriately?
5. Is the plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Board Members:

Ronald Lacoe, Aerospace Corporation (Chair)
Ken Label, NASA - GSFC
Ethan Blansett, Sandia NL
Steve McClure, JPL

Participants:

Randy Blue, JPL
Karla Clark, JPL
Allan Johnston, JPL
Guy Man, JPL

4/26/07

Scope of the Peer Review Material

The following material was presented for discussion:

- An overview of the **proposed mission** including the concept overview and the mission duration, spacecraft features a description of the RTG power plant, and a comparison between Europa Explorer and Cassini.

- A description of the **radiation environment** including total ionizing dose, and displacement effects from intense Jovian radiation belts that is dominated by electrons and protons, galactic cosmic rays, radiation from the RTG and shielding assumptions.

- A description of **parts used on the Cassini baseline** for initial planning (needs updating) and short discussion on **issues that arose during Cassini** related to parts reliability, radiation effects and qualification.

- A discussion on **anticipated problem ar**eas for Europa Explorer and potential **new technology insertion opportunitie**s for Europa.

- A discussion on **potential radiation characterization issues** for the Europa Explorer, including total dose effects (including ELDRs, displacement damage effects, single event effects (including single event upset, latchup, single event gate rupture) and potential synergistic effects.

- A discussion on **potential reliability issues** for the Europa Explorer, including issues arising from multiple or non-constant activated processes, parts derating issues and particularly challenging qualification issues (hybrid devices, advanced memory devices, highly scaled digital devices, power semiconductors and optoelectronic devices).

- A discussion on potential **hardened digital technologie**s including flight computers (RAD750), mass memory (SRAM, CRAM), EEPROMs and flash memory, FPGA's (ruled out), multiplexers and ASICs.

- A discussion on **linear and mixed-signal hardened-part**s options such as ADCs, low dropout regulators, op-amps and comparators, voltage references

- A description on the part development effort for the X2000 program.

- Plan for Phase A.

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Key Findings

- In the current stage of study, pre-phase A, the project chose to address parts by examining class of parts. This approach is appropriate but the presentations did not cover instruments/sensors and supporting electronics that reside near the exterior to the spacecraft and may prove the most problematic from a total-dose perspective.

- All classes of parts have a path toward a solution. However, there are certain classes of parts that have significant risks:

  - ASICs: The rad hard foundries remain a viable alternative for the design and fabrication of Mrad hard ASICs. This approach, however, results in a lack of performance and increased power levels. The board discussed the potential for fabricating Mrad hard components in a commercial foundry using hardness by design approaches. This approach can be used for the fabrication of digital, analog and mixed-signal components. Total dose hardness has been demonstrated to 30 Mrad using this approach. This approach should be considered for this program from both a technical and cost point of view.

  - Volatile memory: SRAM + EDAC is viable for solid-state recorder memory and high-speed processor memory. 4 Mbit 1 Mrad SRAM has been demonstrated at BAE Systems. CRAM is a potential alternate for the solid-state recorder memory (see non-volatile memory). Risk-low to medium. SDRAM considered, but radiation effect risks for more advanced technologies likely to be problematic (TID, SEFI, latch-up).

  - Non-volatile memory: SONOS available at 256 Kbit at 300 Krad and demonstrated at 1 Mb at 300 Krad. Low risk solution for start-up memory. 4 Mb/1 Mrad CRAM has been demonstrated but is not yet in production. 16 Mbit CRAM is planned. If CRAM technology matures, it will be a viable option for solid-state recorder and start-up memory. CRAM is medium risk pending development. Flash memory and the Hitachi EEPROM are not likely options because of poor TID performance, although some newer flash components have shown TID hardness levels above 100 Krad.

  - Processors: The RAD 750 is a commercial CMOS processory/computer board available today. It is TID hard to above 100 Krad. The upgraded RAD 750 fabricated in a rad hard foundry has been demonstrated and it is likely to be available by 9/08. SEU performance on upgraded processor not yet known. Risk is low to moderate. Other rad hard processors (e.g. PPC 603 and MIPS processors) may be viable for certain processing tasks. The status of these processor options should be look at in the future.

  - ADC/DAC: There are viable 12 bit 300 Krad ADCs (20-50 MSPS). Higher resolution ADC such as 14 bit device is higher risk. For DACs, some of the newer components from TI, BICOM and BICOM3X series should be considered.

- Linear voltage regulators are problematic for total dose. There are a limited number of devices capable of performing to 100 Krad – 300 Krad. Need to consider both TID and displacement damage effects. Many will require significant qualifications. Risk is medium to high. Mitigation could be mixed signal ASICs.

- Op amps and comparators are problematic for total dose. There are a limited number of devices capable of performing to 100 Krad. Many will require significant qualifications. Risk is medium to high. Mitigation could be mixed signal ASICs.

- There are solutions for 5 volt rad hard logic. Lower voltage devices have limited availability. Mitigation would be mixed signal ASICs.

- Optoelectronics need to be evaluated early for TID and displacement damage as well as transient effects.

Critical tasks for Phase A/B:

- ASIC development
- Memory characterization
- ELDR testing on potential components
- The Phase A plan is appropriate if the above critical tasks are included.

Assumptions and Design Margins:

- The flow down of total dose requirements due to the environment and the application of shielding to levels as low as 100 Krad appears to be reasonable.

Recommendations

- Reexamine the potential application of FPGAs for this program. The program should become familiar with the RH products and roadmaps for Xilinx, Actel and Aeroflex FPGAs.

- Develop a strategy for ASIC procurement. Examine commercial foundry and structured-ASIC approaches.

- Building LVDOs using discretes should be considered.

- Examine approaches where key electronics is left unpowered during the cruise phase of the mission to increase TID margins.

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- Study issues related to the proper evaluation of the reliability of parts from low volume foundries.

- To get a better handle on "realistic" TID requirements for specific parts, a 3D ray trace of the Cassini spacecraft using the Europa Explorer orbit should be performed.

5. Integrated Systems Peer Review Board Report, May 21, 2007

5/21/07

Board Report

Subject: Technical Peer Review for Europa Explorer Radiation Integrated Systems

To: Guy Man

From: Joe Srour

Introduction

A meeting was held at JPL on May 10, 2007 to review the progress and plans in the general areas of radiation effects and radiation hardening for the Europa Explorer mission. Emphasis was placed on reviewing the envisioned strategies for system design and mission operations in the presence of a relatively severe radiation environment. This report includes the following items: objectives of the review; the review panel; the topics presented to the panel, including an agenda and list of presenters; key findings of the panel; recommendations by the panel; and RFAs.

Review Objectives

Do we have a sound systems and mission approach to radiation?

1. Is the environment that results from the statistical-GIRE model appropriately applied to predict the radiation environment for this mission?
2. Is the approach to transport analysis and to shielding mass calculation appropriate?
3. Are the parts, material and design assumptions for implementation sound?
4. Do we have a technical approach that handles radiation for the mission/systems?
5. Do we have a technical approach that handles uncertainties?
6. Is our plan for Phase A appropriate?

The board report should also identify:

1. Any major flawed approaches or assumptions
2. Any major omissions
3. Areas for improvement or additional focus in next design phase
4. Statement of perceived residual risk

Participants

- Joe Srour - Chair, Aerospace Corporation
- John Henley, SAIC
- Sammy Kayali, JPL
- Dave Kusnierkiewicz, JHU-APL
- Gentry Lee, JPL
- Duncan Macpherson, JPL
- Ralph McNutt, JHU-APL

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Scope of the Peer Review Material

The following material was presented for review and discussion:

- Executive Summary of the work done to-date
- Radiation Environment Peer Review Board Report
- Transport Analysis and Shielding Peer Review Board Report
- Parts Workshop Board Report
- Materials Peer Review Report
- Discipline Systems and Operations Workshop Board Report
- Future Plans

Here is the agenda followed and the presenters:

Executive Summary/Mission Concept Overview	Guy Man, JPL
Radiation Environment Board Report	Chris Paranicas, JHU-APL
Transport Analysis and Shielding Board Report	Jeff Johnson, ORNL
Parts Workshop Board Report	Ron Lacoe, Aerospace
Materials Peer Review Report	Paul Willis, JPL
Discipline Systems and Operations Board Report	Richard Kingsland
Summary and Future Plans	Guy Man/Karla Clark, JPL

Key Findings

In general, the JPL team is performing high-quality work in preparing for the Europa Explorer mission. At the present review, the Europa team did a very good job of presenting an overview of their progress, recommendations, and plans in radiation-related areas. The visibility of radiation issues and the integration of radiation expertise on the Europa program are commendable and essential for success. Very good teamwork and healthy communications are evident. The inclusion of an excellent peer review process on the program is notable.

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The review panel offers observations and suggestions here for consideration by the Europa team. These comments are intended to augment the outstanding efforts conducted thus far, and may serve to stimulate additional design- and mission-related ideas of value. The present comments reflect, or originate from, the following sources: a) new observations made by the panel; b) observations made by presenters and other attendees that the panel wants to highlight and emphasize because of their potential value to mission success.

1. More analyses and trades are needed regarding the currently baselined mission design, which involves a Jovian tour prior to injection into Europa orbit. The present design minimizes post-launch ΔV by including that tour, and thereby delays Europa orbit insertion. That delay increases mission risk. Further analyses and trades should examine the impact of an earlier exit from the planned Jovian tour on the total radiation dose. Inclusion of radiation dose timelines for different mission scenarios would be beneficial. The cost of the additional ΔV needed for alternative mission profiles should also be considered.

2. Dosimetric adaptability is important for Europa. If the onboard dosimeters reveal that the radiation environment is significantly more severe than expected, then plans must be in place to handle that situation.

3. NASA AOs for Europa Explorer instruments must contain a sufficient amount of detail regarding radiation requirements for the mission. Key areas for inclusion are the radiation environment, shielding guidelines, parts information (e.g., what classes of parts are allowed or excluded, such as FPGAs), and the types of radiation support that will be provided by JPL to instrument suppliers.

4. The Europa Explorer team has made good initial progress toward identifying those technical achievements that will constitute mission success. Additional work is needed in that area to quantify, and obtain concurrence on, the minimum science achievements for a successful Europa mission.

5. Detailed planning is needed for the materials and parts radiation testing program. That planning should include identification of appropriate radiation facilities and their cost, estimation of the number and types of materials and parts to be tested, consideration of irradiation and measurement conditions and approaches, deciding on the types of radiation effects to be examined in parts (i.e., the numerous single-event effects (upset, latchup, burn-out, gate rupture, transients), total ionizing dose effects (including ELDRS), displacement damage effects), and manpower estimates for testing.

6. The panel concurs with the statement made at the review that the radiation environment and parts capabilities in that environment must be known well to avoid significant issues for the Europa Explorer mission.

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7. The area of radiation effects on materials and selection of appropriate materials for the Europa mission needs more work. The presentation made to the review panel provided general information of value, but seemed generic and less focused on the mission at this point than the other areas presented.

8. Displacement damage (DD) effects on parts have not yet been addressed in detail in contrast to total ionizing dose effects. The Europa team is aware of that and plans to address the DD area. This area needs attention early on. A realistic nonionizing dose versus shielding depth curve needs to be developed that includes the following sources of displacement damage: a) the external particle environment; b) secondary neutrons produced in shielding materials by incident protons; c) neutrons produced by onboard RTGs. That curve will help in identifying parts that should be avoided because of their DD sensitivity in specific applications (e.g., instruments).

9. The total ionizing dose deposited at material surfaces by low-energy plasma environments is orders-of-magnitude larger than that typically considered for electronic parts. It is important to address the effects of that very severe environment on surface materials, coatings, windows, etc., through analysis and testing where needed. At the review, the Europa team indicated that they plan to address such effects.

10. Transient radiation effects (i.e., noise) in visible and infrared imaging sensors need more attention. That issue is likely to arise for some of the instruments. Work being performed in that area on other programs, such as the James Webb Space Telescope, may be helpful for the Europa mission.

11. Parts risk reduction activities need to be planned and conducted early (requirements, development, testing, etc.).

12. The feasibility and potential advantages of common buys of parts for instruments should be examined.

13. Additional trades of mass memory size, memory technology, radiation tolerance, and resulting telecommunications requirements are needed. Such trades may lead to a mission concept that provides more capability than that presently envisioned.

14. The Europa team should continue to assess whether FPGAs are appropriate for use on this mission. A stance on that issue will be needed for the instrument AOs (see Item 3) so that candidate suppliers will know if FPGAs are a design option.

15. The Europa team should consider using a CAD/radiation transport analysis tool interface, currently under development, as a means of enhancing the design evolution process.

16. Radiation analysis code verification and validation was recommended in the Transport Analysis and Shielding presentation. Such work is important technically but may consume considerable time and funds. The cost and schedule impact and the technical return on investment should be considered before undertaking such an activity.

17. The degree of conservatism being exercised (e.g., in selecting radiation design margins, performing radiation environment definitions, etc.) appears to need further consideration. That is, in some cases the team may be overly conservative but in other cases may not be conservative enough. A balanced approach should be sought.

18. The approach to failed operations and recovery appears to need more attention. As suggestions, the Europa team should investigate approaches used by the DoD and prior considerations for the NASA Prometheus Project.

19. The Discipline Systems and Operations presentation raised the topic of ITAR concerns for non-US equipment for the Europa mission. The panel concurs that that area needs attention and planning early on.

20. There are large uncertainties associated with the Europa Explorer mission, some of which are radiation-related. Those uncertainties need to be quantified and the mission then tailored to deal with them.

21. As the Europa project moves forward, team leaders should strive to present a bigger-picture view of the mission. That approach will help all key players better understand and appreciate the scientific benefits, the mission trade-offs, risks, and contingency plans.

Recommendations

The following recommendations are offered by the review panel. These suggestions follow directly from the Key Findings given above and are numbered identically for reference purposes.

1. Perform additional analyses and trades to examine alternative mission profiles.

2. Develop plans to handle radiation environments that are more severe than expected.

3. Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments.

4. Quantify and obtain concurrence on minimum science criteria for a successful mission.

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5. Perform detailed planning for the parts and materials radiation testing program.

6. Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring.

7. Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.

8. Address displacement damage effects on parts early on.

9. Address the extremely high total ionizing doses that occur at material surfaces.

10. Give detailed consideration to transient radiation effects in sensors.

11. Plan and conduct parts risk reduction activities early on.

12. Consider common buys of parts for instruments.

13. Conduct mass memory trades in an attempt to improve mission capability.

14. Assess and decide whether FPGAs are appropriate for use on this mission.

15. Consider the use of a CAD/radiation transport analysis tool interface to enhance the design evolution process.

16. Consider the cost and schedule impact and the technical return on investment of code verification and validation before undertaking that activity.

17. Try to achieve a balanced approach to conservatism in the radiation-inclusive design.

18. Give additional attention to the failed operations and recovery approach.

19. Develop plans for handling ITAR concerns.

20. Quantify large uncertainties and tailor the mission to deal with them.

21. Present a bigger-picture view of the mission so that key players better understand and appreciate the scientific benefits, trade-offs, risks, and contingency plans.

6. RFA Disposition Status, June 4, 2007

RFA Status for the EE Radiation Reviews 5/31/07

Review & RFA #	Submitted by	Concerns	Recommendations	Disposition	Date for Closure	Comments
1. Environment						
1.1	R. Thorne	Flux suppression near Europa has not been modeled	Update analysis by using a more realistic model	Advisory	Phase B	
1.2	R. Thorne	>10 MeV electron need looks too conservation	Re-analyze high energy data from Pioneer	Accept	Phase A	
1.3	S. Levine	Divine model is out of date	Consider a fresh start with today's understanding	Advisory		
1.4	R. Thorne	C22-like injection not understood	Try to understand the physics leading to the event	Advisory	Phase B	
1.5	R. Thorne	Need best magnetic field mode for inclusion of curent sheet	Incorporate Kristan Khurana's curent sheet model	Advisory	Phase B	
1.6	T. Armstrong	Modeling scatter	Try using B observed to organize the fluxes	Advisory	Phase B	
2. Transport & Shielding						
2.1	L. Waters	Uncertainty of the transport metnodology cannot be quantified	Establish a code v & v program	Accept	Phase A	Plan needs to be written in Phase A
2.2	J. Johnson	Tracability of tools, models and results have not been established	Establish a configuration management system	Accept	Phase A	Plan needs to be written in Phase A
2.3	J. Johnson	Radiation sources (e.g., GCR, SEP CME, and MMRTG) and the displacement damage and SEEs)could be of equal importance to the shield design optimization and mass calculations	Extend the analyses to investigate these other sources very early on to quantify their effects relative to the Jovian/Europa environments	Accept	Phase B	Can be started in Phase A but realistically probably takes longer

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2.4	R. Kemski & K. Adams	Integration of the radiation group with the system engineering design team is paramount to mission success	Radiation transport analysts need to be integrated on all system engineering design teams impacted by the shielding analyses	Accept	Phase A	In plan from the start of Design work in Phase A
3. Parts & Material						
3.1	R. Lacoe	Need a strategy for ASICs development	In addition to considering ASIC development at rad-hard foundries, approaches that target fabrication at commercial foundries using hardness-by-design techniques should be considered	Advisory	Phase A	All approaches to rad-hard will be pursued. Qualification implications of rad-hard by design approaches will be investigated during Phase A
3.2	R. Lacoe	Reliability of rad hard foundries	Devlop a process to control the reliability of low wafer volume foundry even they suppose to be rad hard	Advisory	Phase A	Will follow JPL guidelines for this, will consider any additional requirements in Phase A/B
4. Systems & Ops						
4.1.1	J. Boldt	Availability of FPGA	Justify and reconsider	Advisory		Current guidelines do not allow FPGAs. This approach is based on limited testing on RTAX FPGAs and the combination of radiation, life and temperature not meetig EE reqiuirmeents. It is more conservative to assume ASICs which require more cost and schedule. In Phase A and B, we will attempt to qualify FPGAs such that they can be used, but the plan needs to cover dollars and schedule in case that effort is not fruitful.
4.1.2	G. Reeves	"		Advisory		see 4.1.1
4.2	J. Boldt	ASIC development for instruments	Revisit decision	Advisory		see 4.1.1

4.3	J. Boldt	Shield mass specification for instruments	Develop a reasonable method	Accept	Phase A	Detailed instructions will be developed to support AO
4.4.1	J. Boldt	Ops interface req for instruments	Develop and communicate an approach in AO	Accept	Phase A	Add spacecraft and instrument communication plan to do in Phase A
4.4.2	G. Reeves	"		Accept	Phase A	see 4.4.1
4.5	J. Boldt	No avonics architecture to support autonomous sys	Need avonics and FP req for insrument	Accept	Phase A	
4.6	S. Leete	DSN limitation	Consider relay satellites	Reject		Too costly
4.7.1	S. Leete	Internal electron charging from high energy electrons	Need a ESD approach	Accept	Phase B	In plan, will attempt to get in Phase A but may go into early Phase B
4.7.2	G. Levanas	"		Accept	Phase B	see 4.7.1
4.7.3	R. Kingsland	"		Accept	Phase B	see 4.7.1
4.8	S. Leete	ITAR is a big concern for foeign participation	Address ITAR early especially due to radiation concerns	Accept	Phase A	
4.9	S. Leete	Resource management is complex	Develop a plan	Advisory		Resource management plan will put special attention on radiation issues
4.10.1	S. Leete	Hardware providers will need a lot of help on radiation issues	Develop an implementation plan	Accept	Phase A	Concern is noted and plan will be developed in Phase A
4.10.2	G. Reeves	"		Accept	Phase A	see 4.10.1
4.11	S. Leete	Not clear what will project provide and what can hardware provide assume available from project	Develop a plan and flow information down	Accept	Phase A	Wiil address in Phase A
4.12	S. Leete	Team communiation	Develop an implementation plan	Accept	Phase B	Will attempt to get in Phase A but may go into early Phase B, radiation control plan will be done in Phase A to support AO along with anything else relating to AO. There is Radiation Advisory Board to facilitate communication.
4.13	G. Reeves	Autonomous recovery requirements	Develop autonomous strategy starting from science	Accept	Phase A	
4.14	G. Reeves	Need a successful implementation plan in phase A	Develop a comprehensive implementation plan	Accept	Phase A	In plan, but are there details he is specifically conecrned about over and above "normal" JPL requirments?

RFA Status for the EE Radiation Reviews

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4.15	G. Levanas	Unclear statistical uncertainty of TID	Clarify statistical uncertainty of TID and communicate with h/w builders	Reject		See Environment peer review
4.16	R. Kingsland	Using today's technology only is too limiting	Remove this restriction in Phase A	Advisory		Any new technologies and developments will be scuritinzed during early project for risk, cost, schedule and performance enhancement. A conscieos decision will be made on individual developments given risk posture of project.
4.17	R. Kingsland	Higher assembly level tests for internal charging	Investigate the use of tests such as cable shield current injection and quadriaxial drive tests	Accept	Phase B	Will look at as a part of 4.7.1
4.18	R. Kingsland	High charge environment	Consider using Faraday shielded modules	Accept	Phase B	In design, commonly done for JPL missions such as these.
4.19	R. Kingsland	Need to develop a knowledgable team to handle FP during ops	Plan for a worm to tumb team for this mission	Accept	Phase B	Plan will be developed for not a womb-to-tomb team to handle the worst case.
4.20.	R. Kingsland	How to create a radiation sensetive culture on EE	Train a core team early including dealing with ITAR	Accept	Phase A	In plan
4.21	R. Kingsland	It is not clear how design engr and parts engr work toghter	Sensitize them to work much closer for this mission and develop needed new processes	Accept	Phase A	In plan

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7. Disposition of Recommendation for the Integrated Systems Peer Review, July 5, 2007

6/21/07

Peer review for EE Radiation Integrated Systems
Review Date: 5/10/07

#	Recommendation	Disposition	Project Response	Date for Closure
1	Perform additional analyses and trades to examine alternative mission profiles.	Accept	Will optimize mission plan to meet science priority and minimize risk.	Phase A
2	Develop plans to handle radiation environments that are more severe than expected.	Advisory	Will develop plan to handle actual radiation that is lower and higher than plan.	Phase A
3	Take steps to ensure that sufficient radiation-related details are included in NASA AOs for instruments.	Accept	In plan	Phase A
4	Quantify and obtain concurrence on minimum science criteria for a successful mission.	Accept	In plan, will address in the EE Study Report	8/30/07
5	Perform detailed planning for the parts and materials radiation testing program.	Accept	In plan	Phase B
6	Take steps to ensure that the radiation environment and parts capabilities are known well enough to minimize the likelihood of significant radiation-related problems occurring.	Advisory	This is on-going. The project intends to work with the Radiation Advisory Board regularly on this and progress will be reviewed in technical peer reviews and all major reviews.	On going
7	Perform more detailed and focused studies of radiation effects on materials and on the identification of materials appropriate for the Europa mission.	Advisory	Much of this work is already done. It was not presented in detail. Results are published and will be used as a part of the Phase A support to the release of the AO.	Phase A
8	Address displacement damage effects on parts early on.	Accept	In plan. We typically deal with displacement damage in paralel with total ionizing dose.	Phase A
9	Address the extremely high total ionizing doses that occur at material surfaces.	Accept	In plan. We plan to follow JPL rigorous design guidelines for ESD and grounding, early testing of materials to define acceptable use for EE, providing mission design guidelines early in the design cycle, and conducting design workshops to train designers on the environment and charging issues.	Phase A
10	Give detailed consideration to transient radiation effects in sensors.	Advisory	Early work will be done to identify sensors for the approved part list in support of the AO. Transient work will be limited until actual sensors are selected for mission.	Phase A
11	Plan and conduct parts risk reduction activities early on.	Accept	In plan.	Phase A

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Peer review for EE Radiation Integrated Systems
Review Date: 5/10/07

12	Consider common buys of parts for instruments.	Accept	We will study the trade for such action and develop plan in support of AO.	Phase A
13	Conduct mass memory trades in an attempt to improve mission capability.	Accept	We plan to revisit status of mass memory technology in Phase A. Any new technologies and developments will be scrutinized during early project for risk, cost, schedule and performance enhancement. A conscious decision will be made on individual developments given risk posture of project.	Phase A
14	Assess and decide whether FPGAs are appropriate for use on this mission.	Advisory	Current guidelines do not allow FPGAs. This approach is based on limited testing on RTAX FPGAs and the combination of radiation, life and temperature not meeting EE reqiuiremeents. It is more conservative to assume ASICs which require more cost and schedule. In Phase A and B, we will attempt to qualify FPGAs such that they can be used, but the plan needs to cover dollars and schedule in case that effort is not fruitful.	Phase A/B
15	Consider the use of a CAD/radiation transport analysis tool interface to enhance the design evolution process.	Accept	Will further assess benefits and cost associated with pursuing this approach.	Phase A/B
16	Consider the cost and schedule impact and the technical return on investment of code verification and validation before undertaking that activity.	Accept	Agreed and planned to be done in Phase A.	Phase A
17	Try to achieve a balanced approach to conservatism in the radiation-inclusive design.	Advisory	In plan. Will balance risk across the project to minimize overall risk as part of systems engineering effort to address mission hazards. Plan to work with the Radiation Advisory Board regularly on risk assessment, trades and status.	On going starting from Phase A
18	Give additional attention to the failed operations and recovery approach.	Accept	In plan	Phase A
19	Develop plans for handling ITAR concerns.	Accept	In plan	Phase A
20	Quantify large uncertainties and tailor the mission to deal with them.	Advisory	In plan, cannot quantify when complete	On going

Peer review for EE Radiation Integrated Systems
Review Date: 5/10/07

21	Present a bigger-picture view of the mission so that key players better understand and appreciate the scientific benefits, trade-offs, risks, and contingency plans.	Advisory	In plan, this is an on-going effort and presentation is constantly being refined as we get input on effectiveness	On going
RFA1	Contact Barry Geldzahler and work out proof-of-concept scenario for end-to-end retrieval of data from Europa.	Reject	For Study, we have clear guidelines from HQ on approach to DSN capabilities. During subsequent efforts, we intend to work in normal channels and sign agreements with the appropriate parties.	
RFA2	Scope out next level of details in facility. Look at time and effort required for ASIC design production, testing, and documentation.	Accept	Preliminary efforts will continue in Phase A, more detailed assessments will need to wait until Phase B	Phase B

8. DRAFT FLIGHT SYSTEM CHARGING REQUIREMENTS

8.1 Surface Charging Requirements

Each conductive layer of thermal blankets and all exposed conductive surfaces on the Flight system shall be grounded. All flight system exterior surfaces near plasma measuring instruments shall be conductive enough to prevent electrostatic fields disruption of the plasma measurements. Confirmation of meeting this requirement shall be made through test or analysis.in accordance with design rules as described in NASA-TP-2361 (Design Guidelines for Assessing and Controlling Spacecraft Charging Effects).

8.2 Internal Charging Requirements

This requirement is driven by the high-energy electron environments of the mission. Some of the following design rules are universal, and some are specifically based on particular known mission environments; the two are made clear in context.

If the worst-case electron flux is less than 5×10^5 electrons per square centimeter per second at the dielectric or conductor in question, then the remaining specifications in this paragraph do not apply.

Design and analysis rules as described in NASA-HDBK-4002 (Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects) shall be used.

There shall be no ungrounded conductors (non-electrical and non-electronic without a conductive bleed path to chassis) of size greater than 3 cm^2 on most parts of the flight system and no ungrounded conductor areas greater than size 0.3 cm^2 on or near circuit boards or cabling or other electronics.

There shall be no ungrounded/unreferenced wiring (for example, spares or wiring isolated by switching activities or pulse transformers without a conductive bleed path to chassis) of length greater than 15 cm. No circuit, including input power leads (or non-circuit conducting elements, including structures) shall measure greater than 20 megohms to chassis.

Circuit boards, integrated circuit lids, transistor cans, and relay cans also shall be designed so that radiation spot shields over integrated circuits have a resistive bleed path to ground with resistance less than 10 megohms (zero ohms is acceptable). Additionally, any metal area greater than 0.3 cm^2 shall have a bleed path with the same Electrostatic Discharge (ESD) grounding limits of 0–10 megohms resistance to ground. Each open dielectric area (not covered by a grounded conductor) shall be verified to be able to store no more than 1 microjoule (1 uJ) of energy or no more than 2×10^{10} electrons accumulated in a 10 hour period.

Circuit boards shall be designed so that there will be no open dielectric surface areas greater than 0.3 cm^2 (assuming 80 mil thick FR4 type circuit board). Open dielectric surfaces with one dimension less than 3 mm need not be grounded. If there is an open dielectric surface area greater than 0.3 cm^2, then place a grounded (by less than 10 megohms) metal patch on the region (a power plane over that region also meets the requirement). Alternatively, if there is a ground or power plane underneath the dielectric surface area, then the permitted dielectric surface area is increased in inverse proportion to the depth of the ground (or power) plane as shown in Figure below. This rule applies to both the front and rear surfaces of dielectric areas.

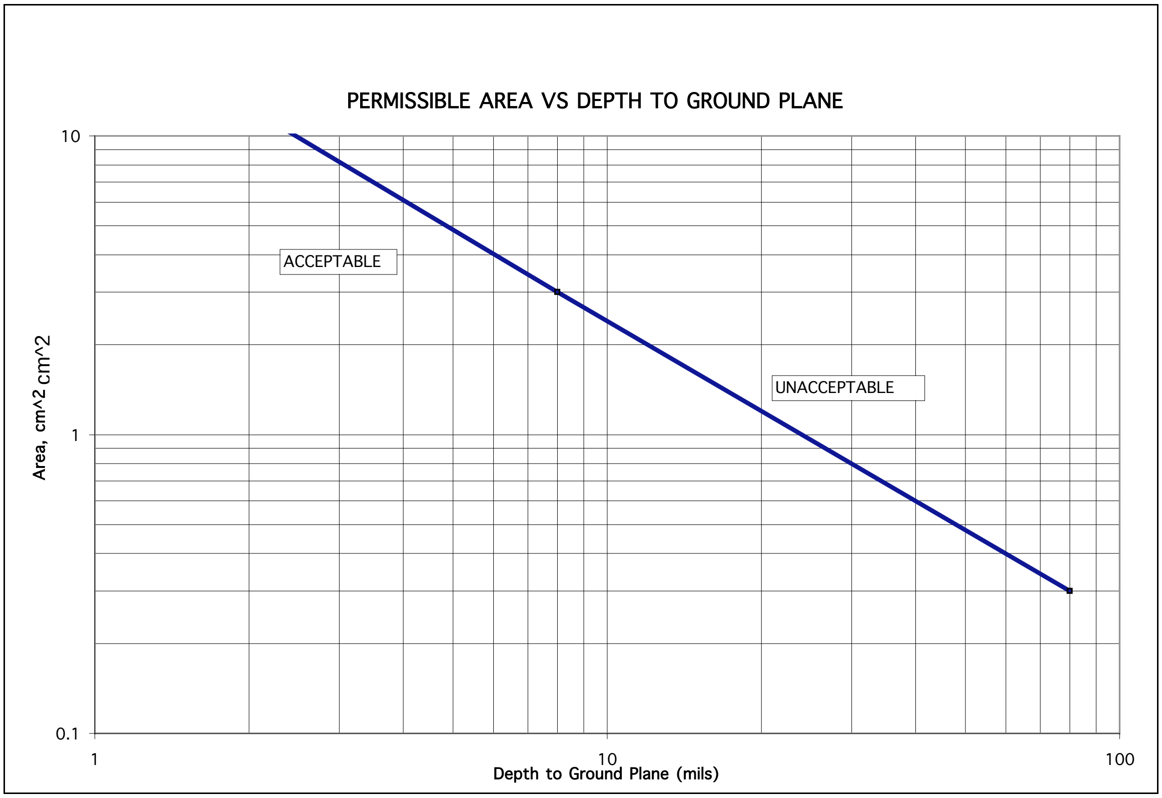


Figure - Permissible exposed dielectric area vs. depth to nearest ground/power plane.

8.2.1 Corona and High Voltage Breakdown

Assemblies and subsystem shall be designed to prevent corona or other forms of electrical breakdown at pressures between 50 to 5×10^{-4} torr and in Earth and Jupiter space plasma environments (see NASA-HDBK-4002 and NASA TP 2361). They all involve a loss of power from a source that has power; the subsequent energy flow can disturb or destroy materials at the location of the arc/discharge leading to a loss of dc power, signal, or RF, depending on the signal being affected by the breakdown.

As a minimum, design per JPL D-8208 Section 3.9, High Voltage Requirements.

Confirmation of meeting this requirement shall be made through test or analysis.

8.2.2 Electrical Isolation, Bonding and Grounding

8.2.2.1 Signal, Command, Data, and Telemetry

Electrical isolation of signal line, command, data, and telemetry interfaces shall exceed 1 megohm DC from chassis. Coupling capacitance shall be less than 400 picofarads per line for isolated interface circuits. Differential circuits shall be balanced with respect to chassis, both AC and DC.

8.2.2.2 Power Supply Input Lines

Electrical isolation of power supply input lines shall exceed 1 megohm DC from each line to chassis. Capacitance from each line to chassis shall be less than 0.1 microfarads.

8.2.2.3 Pyro Supply Lines

The pyro firing system shall be designed so that there can be less than 3 milliamps [TBR] direct chassis return currents as a result of pyro firings. This means that the firing unit itself must be isolated from the flight system power's ground reference, and it means that the firing unit's ground must be isolated from the spacecraft chassis. The firing unit return shall have a resistive reference to chassis such that no more than 3 milliamps of current may flow in the chassis due to a pyro firing event.

The concern is that squibs (EED's, pyros, etc.) have demonstrated that they can have a short circuit from their active pin to chassis in the pyro containment unit (pin-puller, valve actuator, cable cutter, separation nuts, etc.). The current may be as much as the firing unit can deliver through the wiring; this has been 17 amps or more in prior JPL spacecraft. This current may cause disruption of electronic circuits if they are unfortunate enough to have current induced voltages into nearby wiring. We can eliminate this possible problem by proper design of the pyro firing unit.

If the pyro firing system is not designed to prevent chassis return currents caused by pyro firing events, there shall be a system level test to simulate the effect of pyro firing-caused chassis currents.

The test shall consist of a complete flight system (configured as in flight), with simulated pyro ground fault currents. The ground fault current test shall be performed at least once for each pyro event that is planned in flight. The ground fault simulator shall have its return attached at the location of the chassis connection point for the pyro firing unit. The simulated ground fault current shall be injected into the flight system at the location of the each pyro device. The test shall consist of a pulse of current that is 1.25× the maximum available pyro firing current at each location, and the time duration of the simulated current shall be 1.5× the maximum duration of the switch that sends current to the pyro. For each location, the flight system operating mode shall be adjusted so that the operating mode matches that which would exist at the time of the firing event being simulated.

The criterion for a successful test is that no anomalies occur that would adversely interfere with the mission success.

8.2.2.4 Electrical Bonding

All conductive structural elements and conductive assemblies in the flight system shall be bonded together with an impedance not greater than 10 milliohms per joint (measured with a DC voltage). Bonding shall be done using the methods provided in NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment.

8.2.2.5 Electrical Grounding

All electrical/electronic circuitry shall be grounded by a single ground-wire to the chassis. Each electronic assembly may have a separate ground wire, but there shall be only one reference path from circuit to chassis for any given circuit. Ground wires shall not be used to carry current.

D. COST DETAIL

The process for developing the cost estimate is identical for the floor and baseline mission concepts. Unless otherwise noted, the numbers included in the text and tables below pertain to both the baseline and floor mission concepts.

D1. Cost Estimation Process

The process used to develop the cost estimate for EE is shown in **Figure D1-1**. The process was initiated with the publication of a set of EE cost guidelines that included a

- Top level Project milestone schedule and funded schedule reserves requirements,
- WBS and dictionary to level 3
- Baseline technical description as captured in the EE Systems Trade Model (STM)
- Responsibility Assignment Matrix (RAM)
- Assumptions on engineering models and testbeds
- Requirements for radiation and planetary protection design
- Basis of estimate requirements

The cost estimate was developed using a combination of grass roots estimates, parametric cost models including JPL's Parametric Mission Cost Model (PMCM), rules of thumb and cost analogies, and the NICM system cost model, and Headquarters provided launch system and RPS costs. WBS elements 06 Spacecraft System, 10 Project System Integration and Test, and 12 Mission Design were estimated using grassroots techniques including developing an integrated detailed schedule. This process was used for both baseline and floor missions.

Tables D1-1, -2 summarize the baseline and floor EE cost estimates to WBS level 3 for the June 2015 launch opportunity. **Figures D1-2, -3**, and **-4** show the estimated cost by fiscal year for the baseline (June 2015), floor (June 2015) and backup (January 2017) mission concepts respectively. Note that these estimates do not account for anticipated New Obligation Authority realities of fiscal year boundary carry forward requirements.

D2. Cost Estimate Bases of Estimate

The EE cost estimate has an individual cost basis for each WBS element using one of the following six primary costing methods:

- Rules of thumb—factors based on ranges as derived from actual costs for numerous previous projects
- Analogy—direct comparison with one or two projects
- Parametric Cost Models—models based on experience from numerous previous projects with specific high-level input parameters

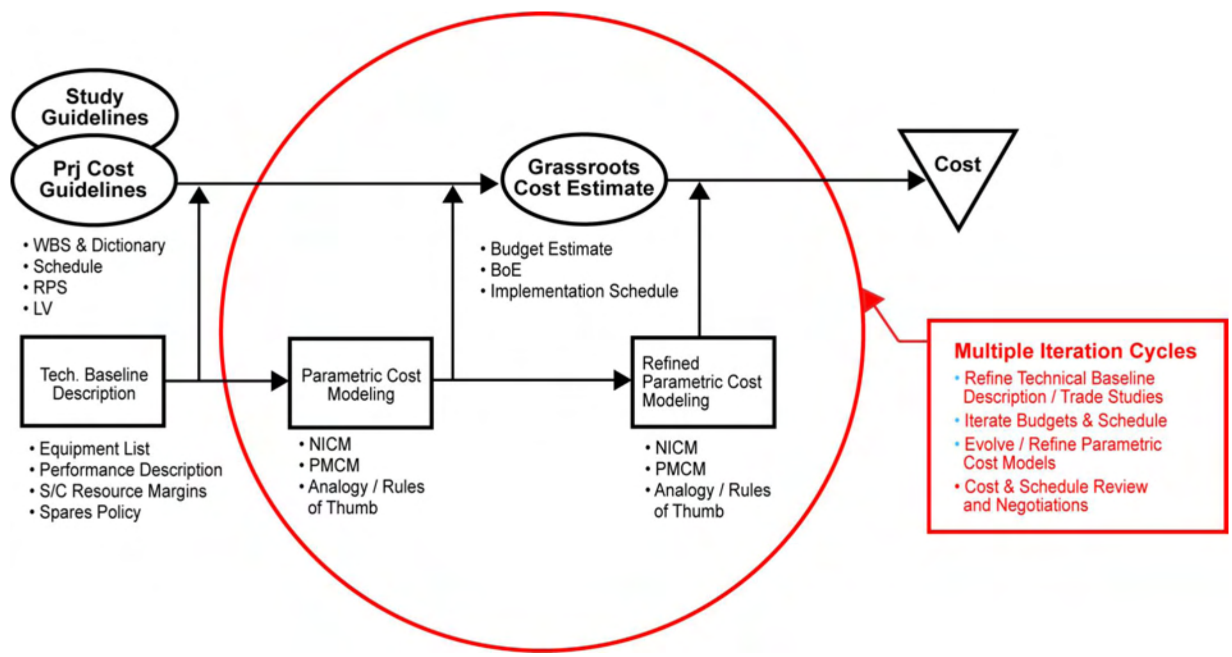


Figure D1-1. *Cost Estimation Process*

Table D1-1. Baseline Europa Explorer Cost Summary to WBS Level 3

Europa Study ($MFY07) Baseline Mission 2015 Launch	Phase A/B	Phase C/D	Phase E	Total ($FY07M)
Phase Duration (Months)	24	58	113	
01 Project Management	24	77	34	135
02 Project System Engineering	13	67	20	100
03 Safety & Mission Assurance	13	67	20	100
04 Science	21	54	203	278
Phase A/B Science	21			21
Phase C/D Science		54		54
Low Science Activity			95	95
High Science Activity			109	109
05 Payload System	45	350		395
05.01 Payload Management	3	8		11
05.02 Payload System Engineering	5	9		14
05.03 Wide-Angle Camera (WAC)	1	13		14
05.04 Medium-Angle Camera (MAC)	3	23		25
05.05 Narrow Angle Camera (NAC)	3	27		30
05.06 IR Spectrometer (IRS)	4	38		42
05.07 UV Spectrometer (UVS)	3	25		28
05.08 Laser Altimeter (LA)	4	32		36
05.09 Ice Penetrating Radar (IPR)	9	82		91
05.10 Thermal Instrument (TI)	3	24		26
05.11 Magnetometer (MAG)	1	7		8
05.12 Ion and Neutral Mass Spectrometer (INMS)	4	40		45
05.13 Particle & Plasma Instrument (PPI)	2	22		25
06 Spacecraft System	88	367		456
06.01 S/C Management	2	7		9
06.02 Spacecraft System Engineering	10	22		32
06.03 Spacecraft Product Assurance				
06.04 Power SS	8	36		43
06.05 C&DH SS	16	35		51
06.06 Telecom SS	6	31		37
06.07 Mechanical SS	15	86		101
06.08 Thermal SS	3	11		14
06.09 Propulsion SS	6	27		33
06.10 AACS	18	58		76
06.11 Harness	1	9		10
06.12 FSW	3	28		31
06.13 SC M&P	1	3		3
06.14 SC Testbeds	0	10		10
06.18 DTM / Trailblazer		5		5
07 Mission Operations System	2	39	234	275
09 Ground Data System	3	41	25	68
DSN Aperture	-	2	120	123
10 Project System Integration & Test	4	38	-	42
11 Education and Public Outreach	1	6	13	20
12 Mission Design	5	10		16
CBE Cost	220	1,118	670	2,008
CBE Reserves	64	414	100	578
CBE + Reserves	283	1,532	770	2,585
Launch System Reserves				-
Launch System Total	-	502	-	502
Radioisotope Power Source Total	22	201	-	223
Total Mission Cost ($MFY07)	306	2,234	770	3,310

Table D1-2. *Floor Europa Explorer Cost Summary to WBS Level 3*

	Phase A/B	Phase C/D	Phase E	Total ($FY07)
Phase Duration (Months)	24	58	107	
01 Project Management	23	65	26	114
02 Project System Engineering	11	55	15	81
03 Safety & Mission Assurance	11	55	15	81
04 Science	13	33	123	168
Phase A/B Science	13			13
Phase C/D Science		33		33
Low Science Activity			61	61
High Science Activity			62	62
05 Payload System	28	211		239
05.01 Payload Management	2	6		8
05.02 Payload System Engineering	3	6		10
05.03 Wide-Angle Camera (WAC)	1	13		14
05.04 Medium-Angle Camera (MAC)	2	18		20
05.05 Narrow Angle Camera (NAC)	-	-		-
05.06 IR Spectrometer (IRS)	3	30		33
05.07 UV Spectrometer (UVS)	-	-		-
05.08 Laser Altimeter (LA)	3	23		26
05.09 Ice Penetrating Radar (IPR)	8	73		81
05.10 Thermal Instrument (TI)	2	15		16
05.11 Magnetometer (MAG)	1	6		6
05.12 Ion and Neutral Mass Spectrometer (INMS)	-	-		-
05.13 Particle & Plasma Instrument (PPI)	2	22		24
06 Spacecraft System	88	364		452
06.01 S/C Management	2	7		9
06.02 Spacecraft System Engineering	9	21		30
06.03 Spacecraft Product Assurance				
06.04 Power SS	8	36		43
06.05 C&DH SS	16	35		51
06.06 Telecom SS	6	31		37
06.07 Mechanical SS	15	86		101
06.08 Thermal SS	3	11		14
06.09 Propulsion SS	6	27		33
06.10 AACS	18	58		76
06.11 Harness	1	9		10
06.12 FSW	3	27		30
06.13 SC M&P	1	3		3
06.14 SC Testbeds	0	10		10
06.18 DTM / Trailblazer		5		5
07 Mission Operations System	2	34	191	227
09 Ground Data System	3	39	23	64
DSN Aperture	-	2	100	103
10 Project System Integration & Test	4	38	-	42
11 Education and Public Outreach	1	5	10	16
12 Mission Design	5	10		16
CBE Cost (Reserves Base)	188	910	504	1,602
CBE Reserves	61	382	76	519
CBE + Reserves	250	1,292	580	2,121
Launch System Reserves				-
Launch System Total	-	176	-	176
Radioisotope Power Source Total	12	109	-	121
Total Mission Cost ($MFY07)	262	1,577	580	2,419

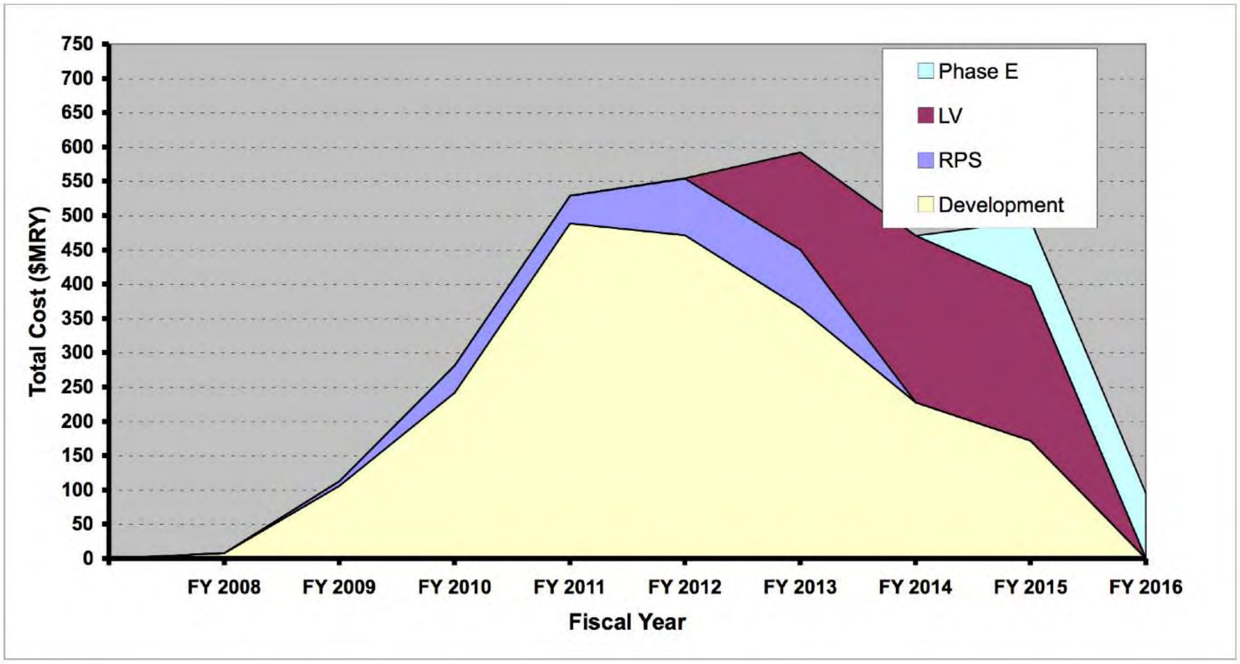


Figure D1-2. *Cost Estimate by Fiscal Year for the Baseline June 2015 Mission Concept*

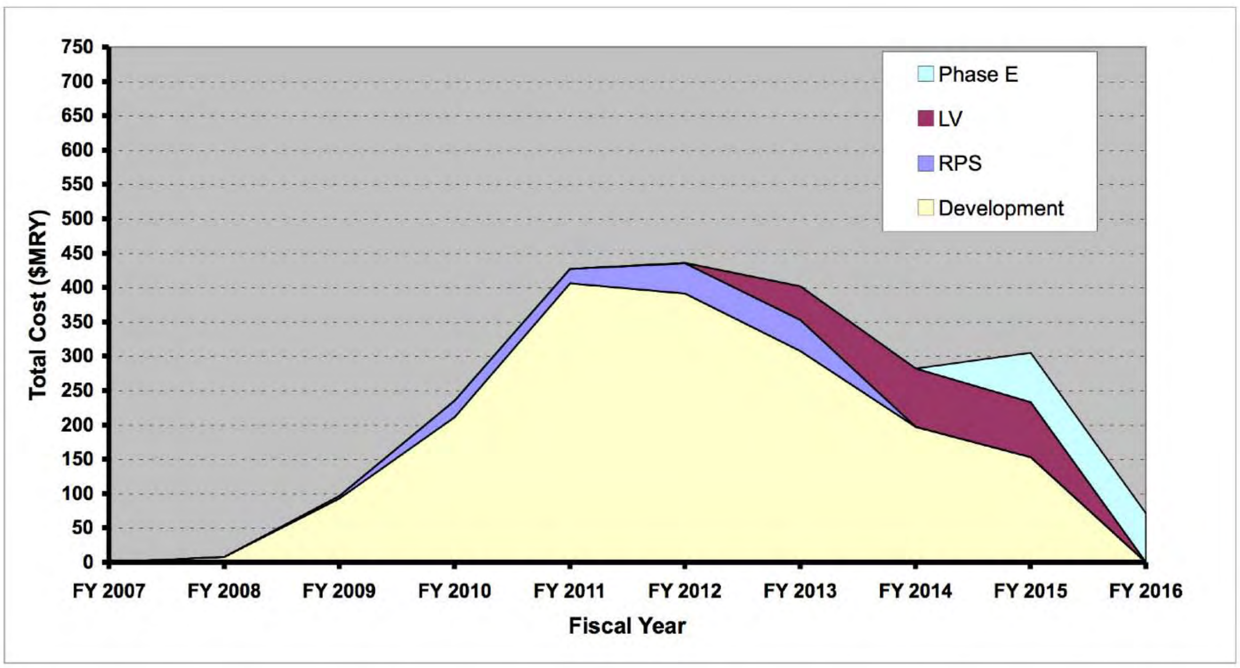


Figure D1-3. *Cost Estimate by Fiscal Year for the Floor June 2015 Mission Concept*

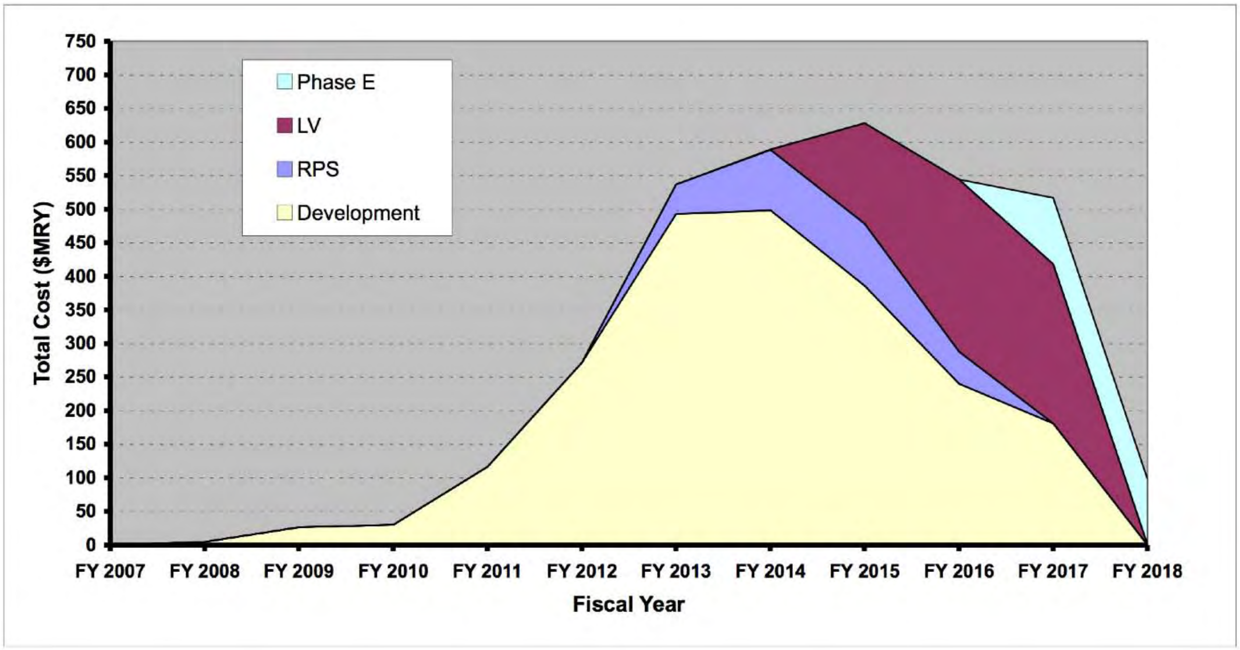


Figure D1-4. *Cost Estimate by Fiscal Year for the Backup January 2017 Mission Concept*

- Grassroots—detailed estimates by implementing organization utilizing schedules, delivery requirements (engineering models, spares, test levels etc), and radiation and planetary protection implementation requirements
- Quasi-grassroots—more detailed requirements input for estimating than in Parametric Cost Modeling but not as detailed an evaluation as a grass roots, usually performed by management level above lowest implementing organization
- NASA provided costs.

Cassini and Juno projects were used in many cases to validate the costs. Cassini is a flagship-class outer planets orbiter mission with 12 instruments. Costs associated with the Huygens Probe were not included where they could be identified; in other cases the costs were inextricably linked with other costs. Cassini had similar Launch Approval/NEPA activities, visibility, reliability requirements and science team integration activities. The spacecraft was very similar to EE, e.g., both (1) have large propellant requirements, (2) are 3-axis stabilized with reaction wheels, (3) have a large payload suite with remote sensing, fields and particles, and radio science investigations and (4) have similar trajectory designs. The major increased requirements for EE over Cassini are: increased requirements for insight/ oversight by HQ, Earned Value Management, planetary protection and radiation (Cassini 150 krad).

Juno is similar to EE in that both are Category 1 Projects per NPR 7120.5D "NASA Space Flight Program and Project Requirements", and both have the additional EVM. Both also have increased radiation requirements, although Juno has a radiation design point of ~500 krad versus a far higher 2.6 Mrad for EE. A key difference between the projects is the approach to meeting the planetary requirements; Juno, a PP Category II mission) will impact Jupiter to avoid Europa while EE (a PP Category IV mission) will be sterilized. Lastly, Juno has a Class B risk classification per NPR 8705.4, "Risk Classification for NASA Payloads", while it would be expected that EE would be Class A.

D2.1 WBS 01 Project Management, WBS 02 Project System Engineering, WBS03 Safety and Mission Assurance, WBS11 Education and Public Outreach

Rules of thumb for level of effort activities were developed from historic project cost data with line organization review. Fourteen JPL missions were used to calculate a recommended wrap factor range for 01 Project Management, 02 Project Systems Engineering, and 03 Safety and Mission Assurance. Due to the project complexity, visibility and the challenges of the radiation and planetary protection environments, the upper end of the recommended wrap factor was chosen to more accurately reflect the increased complexity for this mission.

WBS 01 Project Management includes LA/NEPA which was estimated independently at ~$22M. This WBS also includes all aspects of Earned Value Management (EVM), DPMR, Radiation Advisory Board, and other Review support and would be fully compliant with 7120.5D. An additional estimate for contract burden (~$39M) was added and accounted for in this WBS element to account for an unspecified scope of work (~$260M) which would be contracted out of JPL above that assumed in the current estimate. This is prudent given that the estimates assume all work is performed in-house at JPL though experience shows that a significant portion would ultimately be contracted out. This is only an estimate at this time and the specifics of what scope would be contracted have not been determined. Though bookkept in this WBS element, it would be reasonable that the majority of this scope would fall into other WBS elements such as 03 SMA, 05 Payload, 06 Spacecraft, 07 MOS and 09 GDS.

WBS 02 Project System Engineering would include the Deputy Project System Engineer for Radiation (DPSER). Other distributed costs for radiation team personnel including spacecraft and payload system engineers, configuration engineers, radiation control engineers and radiation parts specialists would be included in separate WBSs.

WBS 03 Safety and Mission Assurance responds to a risk classification of Class A (similar to Cassini) per NPR 8705.4, "Risk Classification for NASA Payloads" with a full reliability and parts programs. All electronics parts would be either verified or tested to radiation levels before use on the flight system. Workforce is included early to provide support to the designers (instrument and spacecraft) in the early phases of the design to mitigate downstream issues.

Additional funding of $9M (baseline, June 2015 launch opportunity) is included ($4M in Pre-Phase A and $5M in Phase A) to support the development of the radiation and planetary protection design guidelines and approved parts lists, specific part evaluation (FPGAs, CCDs, APSs, power converters, etc.) and to support other radiation and planetary protection related issues early in the project. This support starts in Pre-Phase A to provide information in support of the instrument AO process.

WBS 11 Education and Public Outreach was calculated as 0.5% of cost current best estimate excluding launch system and RPS for Phases A–D and 2% of cost current best estimate excluding launch vehicle and RPS during Phase E. This was done as the emphasis of the EPO program is on the scientific results of the mission, though some on-going activity through development and early operations is critical. **Table D2-1** summarizes the wrap factors used.

Table D2-1. *Wrap Factors*

	Phase A–D	Phase E	Range of Historic Missions
01 Project Management	5.0%	3.0%	0.8% to 4.4%
02 Project System Engineering	6.0%	3.0%	0.5% to 5.1%
03 Safety & Mission Assurance	6.0%	3.0%	0.5% to 5.4%
11 Education and Public Outreach	0.5%	2.0%	

D2.2 WBS 04 Science

The New Frontiers-Juno and Cassini missions were used as cost analogies for estimating WBS 04 Science.

The Juno project was selected as the analog for Phase A through D science costs because of the detail and clean mapping of individual science team support to specific instruments. The algorithm relates Science Phase A–D cost to the value of the Phase E Science using the factors defined in **Table D2-2**. The Cassini project was selected as the operations phase analog because of its operations phase applicability to EE. The Cassini science team planned costs in FY07 for each individual instrument and Radio Science were obtained. The "high activity period" data indicates 2

Table D2-2. *Phase A–D Science Team Analogy Cost*

	Phase A/B	Phase C/D
Science as a % of Phase E	10%	27%

fairly distinct "classes" of instrument distinguished by operational cost, complex (~$3.5M/year) and simple (~$2M/year). Based on analogy to the Cassini instruments, the EE planning payload instruments were listed as either complex or simple, as shown in **Tables D2-3** and **-4**. "Low" and "High" Science activities were defined based on the level of support required during the mission phase. Though calibrations during cruise would require additional workforce, the cruise portion was modeled as "low" science activity until 6 months prior to Jupiter Orbit Insertion where the science teams would need to staff up to prepare for full up science activities ("high" activity science). **Table D2-5** summarizes the parameters derived from Cassini mission. It should be noted that no science optimization of the tour design or science activity planning for the tour was costed, consistent with the study guidelines to de-emphasize science during the tour.

Data archival (Phase F) was costed as a linear ramp down of the science teams starting from full staffing at end of Europa Science to no staffing at the end of 6 months.

Table D2-3. *Baseline Mission Instrument Complexity*

Instrument	Simple Instrument	Complex Instrument
Wide-Angle Camera (WAC)	X	
Medium-Angle Camera (MAC)		X
Narrow Angle Camera (NAC)		X
IR Spectrometer (IRS)		X
UV Spectrometer (UVS)		X
Laser Altimeter (LA)	X	
Ice Penetrating Radar (IPR)		X
Thermal Instrument (TI)	X	
Magnetometer (MAG)	X	
Ion and Neutral Mass Spectrometer (INMS)	X	
Particle & Plasma Instrument (PPI)		X
Total	5	6

Table D2-4. *Floor Mission Instrument Complexity*

Instrument	Simple Instrument	Complex Instrument
Wide-Angle Camera (WAC)	X	
Medium-Angle Camera (MAC)		X
IR Spectrometer (IRS)		X
Laser Altimeter (LA)	X	
Ice Penetrating Radar (IPR)		X
Thermal Instrument (TI)	X	
Magnetometer (MAG)	X	
Particle & Plasma Instrument (PPI)	X	
Total	5	3

Table D2-5. *Baseline 2015 Science Phase E Cost Algorithm*

	Simple $MFY07/yr	Complex $MFY07/yr	Duration Months
"Low Science Activity"	1.0	2.0	67
"High Science Activity"	2.0	3.5	42
Project Closeout			6

D2.3 WBS 05 Payload

The NASA Instrument Cost Model (NICM) system cost model was used to estimate instrument costs. **Tables D2-6** and **-7** give the actual inputs to the parametric model and fully wrapped output cost. The NICM input and wrap uncertainty features were not used. The NICM model does not have parameters or characteristics sufficient to describe planetary protection requirements or radiation environments. Therefore, cost scaling factors for planetary protection (10%) and radiation design (25%) impacts were developed based upon line organization review. Two grassroots estimates were developed specifically looking at the impact of these scaling factors. In both cases, the model approach estimated costs above those developed via the grassroots effort (**Table D2-8**). The larger, more conservative estimates were kept to provide margin for alternate approaches to meeting the science objectives. Additionally, the instruments were conservatively estimated as independent, stand alone instruments with individual Principal Investigators (PI) and teams. Once the AO is released and instruments are selected, it is very likely that some of the capability of these individual instruments would be combined under one "instrument suite" with a single PI. This combined instrument would likely be less

Table D2-6. *NICM Model Inputs for Baseline Mission*

Instrument	NICM Instrument Class	Mass (CBE + Contin.)	Power (Peak)	Data Rate (Peak)	BCD Schedule Duration	Design Life	NASA TRL
		kg	W	kbps	Months	Months	Dimensionless
Wide-Angle Camera (WAC)	Optical	3.9	5.0	800	73	107	7
Medium-Angle Camera (MAC)	Optical	13.0	10.0	6,000	73	107	7
Narrow-Angle Camera (NAC)	Optical	19.5	12.0	30,000	73	107	7
IR Spectrometer (IRS)	Optical	32.5	22.0	30,000	73	107	7
UV Spectrometer (UVS)	Optical	19.5	10.0	4,000	73	107	7
Laser Altimeter (LA)	Optical	19.5	21.0	12	73	107	7
Ice Penetrating Radar (IPR)	Active Microwave	46.8	45.0	300	73	107	7
Thermal Instrument (TI)	Optical	10.4	14.0	43	73	107	7
Magnetometer (MAG)	Fields	5.2	2.0	4	73	107	7
Ion and Neutral Mass Spectrometer (INMS)	Particles	19.5	28.0	2	73	107	7
Particle & Plasma Instrument (PPI)	Particles	15.6	10.0	2	73	107	7

Table D2-7. *NICM Model Inputs for Floor Mission*

Instrument	NICM Instrument Class	Mass (CBE + Contin.)	Power (Peak)	Data Rate (Peak)	BCD Schedule Duration	Design Life	NASA TRL
		kg	W	kbps	Months	Months	–
Wide-Angle Camera (WAC)	Optical	3.9	5.0	500	73	107	7
Medium-Angle Camera (MAC)	Optical	9.1	7.0	3000	73	107	7
IR Spectrometer (IRS)	Optical	15.6	20.0	100	73	107	7
Laser Altimeter (LA)	Optical	9.1	15.0	2	73	107	7
Ice Penetrating Radar (IPR)	Optical	40.3	45.0	140	73	107	7
Thermal Instrument (TI)	Optical	6.5	5.0	4	73	107	7
Magnetometer (MAG)	Active Microwave	2.6	1.0	3	73	107	7
Particle & Plasma Instrument (PPI)	Optical	13.0	8.0	2	73	107	7

Table D2-8. *Instrument Comparison to Grass Roots Estimate*

	EE NICM Based Estimate ($MFY07)	EE Grass Roots Estimate ($MFY07)
Ice Penetrating Radar (IPR)	91	62
Narrow-Angle Camera (NAC)	30	19

expensive than the sum of the individual instruments. The NICM cost is reported in $FY04 which is escalated to $FY07 using the NASA New Start Inflation Index. Nominal, scaled, and escalated cost estimates are reported in **Tables D2-9** and **-10**.

WBS 05.01 Payload Management and WBS 05.02 Payload Systems Engineering were estimated using recently completed JPL Team X cost models and augmented to include a radiation system engineer (RSE) for every 2 instruments during Phases A and B and 1 RSE for every 4 instruments in Phases C and D. The Team X cost models use a quasi-grassroots method.

D2.4 WBS 06 Spacecraft

WBS 06 Spacecraft, was estimated using a grassroots technique. The design estimated was the design developed during the EE-2006 internal JPL study with only minor modifications for this study. The EE-2006 design had evolved from studies spanning 8 years and had been evaluated by the design team for meeting the requirements set forth by the science team. This study took the previous design and iterated with the SDT to make changes as required to meet their requirements (e.g., telecom downlink requirements). Also, some minor changes were made to take advantage of the progress in technology (mass

Table D2-9. *NICM Baseline Instrument Cost Estimate*

Planetary Protection Scale Factor =	10%	Cost scale factor for Planetary Protection
Radiation Cost Factor =	25%	Cost scale factor for radiation. Accounts for parts screening, additional analysis, testing ...

Instrument	Fully Wrapped Cost @ 70%	Cost Scaling Factor (PP + Rad)	Scaled Fully Wrapped Cost	Escalated Scaled Fully Wrapped Cost
	$MFY04		$MFY04	$MFY07
Wide-Angle Camera (WAC)	10	35%	13	14
Medium-Angle Camera (MAC)	17	35%	23	25
Narrow-Angle Camera (NAC)	21	35%	28	30
IR Spectrometer (IRS)	28	35%	38	42
UV Spectrometer (UVS)	19	35%	25	28
Laser Altimeter (LA)	24	35%	33	36
Ice Penetrating Radar (IPR)	62	35%	83	91
Thermal Instrument (TI)	18	35%	24	26
Magnetometer (MAG)	5	35%	7	8
Ion and Neutral Mass Spectrometer (INMS)	30	35%	41	45
Particle & Plasma Instrument (PPI)	17	35%	23	25
			Total	370

Table D2-10. *NICM Floor Instrument Cost Estimate*

Instrument	Fully Wrapped Cost @ 70%	Cost Scaling Factor (PP + Rad)	Scaled Fully Wrapped Cost	Escalated Scaled Fully Wrapped Cost
	$MFY04		$MFY04	$MFY07
Wide-Angle Camera (WAC)	10	35%	13	14
Medium-Angle Camera (MAC)	14	35%	19	20
IR Spectrometer (IRS)	23	35%	30	33
Laser Altimeter (LA)	17	35%	24	26
Ice Penetrating Radar (IPR)	55	35%	74	81
Thermal Instrument (TI)	11	35%	15	16
Magnetometer (MAG)	4	35%	6	6
Particle & Plasma Instrument (PPI)	16	35%	22	24
			Total	221

memory). Each estimate was fully reviewed by the implementing JPL organization. Each spacecraft subsystem developed a delivery and test schedule and provided an estimate including the costs associated with radiation and planetary protection implementation. The specific driving requirements include:

- All circuits undergo radiation analysis in Phase B with review by the Radiation System Engineering Team prior to subsystem PDR
- Minimum 100 krad die level radiation hardness for IEEE parts
- No FPGAs and 2 passes on all ASICs
- Provide own shielding to environment unless in 6U chassis, then provide shielding to 300 krad (6U chassis takes it the rest)
- Subsystem boxes must be capable of being sterilized for planetary protection
- Flight spares
- Protoflight development program
- Engineering Models
- Full, dual string system level testbed for C&DH, Power electronics, front end telecom hardware and AACS simulators
- Additional workforce in spacecraft system engineering to support radiation engineering team

The summary bases of estimate are included in **Table D2-11**.

D2.5 WBS 10 Project Systems Integration and Test

WBS element 10 Project Systems Integration and Test was estimated using a grassroots technique. Each estimate was fully reviewed by the implementing JPL organization. The Integration and Test estimate was developed by first creating a schedule for the integration of the flight system including the instruments and RPS. The flow for the integration was based on Cassini since the spacecraft and instrument complement are comparable, but updated with recent experience on Mars Exploration Rovers and current activities on Mars Science Laboratory. The summary bases of estimate are included in **Table D2-11**.

D2.6 WBS 12 Mission Design

The mission design estimate was provided by the implementing organization using a grassroots methodology and based on past experience on Cassini as well as taking advantage of many tools developed since Cassini for current missions. The summary bases of estimate are included in **Table D2-11**.

D2.7 WBS 07 Mission operations System and WBS 09 Ground Data Systems

WBS elements 07 Mission Operations System, 09 Ground Data System and DSN aperture fees were estimated by the JPL Ground Segment Team (Team G) using quasi-grassroots techniques. The Team G estimate uses cost drivers such as:

- Schedule duration (baseline: through 1 year Europa operations plus 6 months project and data archival, floor: through 6 months Europa operations and 6 months project and data)
- Mission class
- Number of instruments and relative complexity
- High level description of spacecraft design
- Complexity of spacecraft operations
- DSN tracking profile

Using these cost drivers, the Team G model generates a quasi-grassroots cost estimate including time phased workforce staffing profiles. DSN aperture fees are generated using the DSN Aperture Tool. **Tables D2-12** and **-13** summarizes the Team G estimate by WBS level 3.

D2.8 WBS 06.16 Radioisotope Power Source and WBS 08 Launch System

The NASA HQ provided cost data for WBS 06.16 Radioisotope Power Source is given in **Table D2-14**. WBS element 08 Launch System cost is reported in **Table D2-15**.

D3 Reserves Approach

The reserves are calculated as:

- Phase A = 10%
- Phase B through D established by Cost Risk Subfactor Analysis
- Phase E = 15%.

The reserves base is the current best estimate cost excluding RPS and Launch System.

The 10% for Phase A and 15% for Phase E are typical approaches for JPL missions. The Cost Risk Subfactor Analysis approach used for Phases B through D has been used internally at JPL for 4 years to internally validate reserves proposed in response to mission AOs. This approach was developed to account for the complexity differences between proposed missions and to provide guidance and consistency for setting reserves. The approach was developed by looking at the required reserves over 15 past projects and determining the major and minor risk factors to cost growth. The algorithm has a fixed reserves level of 20%, with each primary risk subfactor adding 5% and each secondary subfactor adding 2% to the base reserves level. The EE Cost Risk Subfactor Analysis is given in **Table D3-1**. For this study, the Study Leader was instructed to adopt a “conservative costing philosophy” in order to avoid cost growth as the mission became better defined. Recent SMD experience with the overly optimistic initial costing of large flagship missions such as JWST was cited as a model to avoid. Accordingly, this study used the cost risk subfactor analysis to identify risk areas and establish reserves at fairly high level commensurate with the maturity of the mission concept and the modest investment in mission studies to date (< 1% of mission cost). During Phase A, these risk areas will be examined in more detail and its expected that some of them will be retired. As a result, following the Phase A studies the level of reserves will decrease

Table D2-11. Grassroots Bases of Estimate for WBS 06 Spacecraft System, 10 System I&T, and 12 Mission Design

WBS	Basis of Estimate and Cost Element Summary - Baseline Mission 2015 Launch		
01	Project Management		
	1. Methodology:	Rule of Thumb	
	2. Cost Estimate ($kFY07):	134,719	Phase A-D - 5%, Phase E = 3% of CBE cost excluding RPS and LV. Project management, business office and support, Reviews, Indep. Radiation Advisory Board, NEPA/LA, subcontract burden, and Science AO support.
02	Project System Engineering		
	1. Methodology:	Rule of Thumb	
	2. Cost Estimate ($kFY07):	100,364	Phase A-D - 6%, Phase E = 3% of CBE cost excluding RPS and LV. Includes support for Project level systems engineering, Radiation Systems Team Lead, EEIS, Planetary Protection Office, Contamination Control, Project Verification and Validation, risk management
03	Safety & Mission Assurance		
	1. Methodology:	Rule of Thumb	
	2. Cost Estimate ($kFY07):	100,364	Phase A-/D - 6%, Phase E = 3% of CBE cost excluding RPS and LV. Includes Project level SMA and Spacecraft SMA.
04	Science		
	1. Methodology:	Analogy	
	2. Cost Estimate ($kFY07):	278,190	Phase A-D scaled from Juno 2011 launch. Phase E derived from Cassini FY07 operations actual costs.
05	Payload System		
	1. Methodology:	Model Based	
	2. Cost Estimate ($kFY07):	395,101	Instrument costs were estimated using NICM - System Model scaled for planetary protection and radiation. WBS 05.01 Payload Management and 05.02 Payload Systems Engineering estimates used recently completed Team X models. WBS 05.02 is augmented with additional radiation system engineering support
06	SPACECRAFT SYSTEM		
06.01	SC Management		
	1. Methodology:	Rule of Thumb	
	2. Cost Estimate ($kFY07):	9,113	Phase A-D - 2%
06.02	SC Systems Engineering		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	31,709	Includes flight system lead, deputy and technical support; fault protection and radiation system engineering.
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	121	Direct labor
	Labor Cost ($kFY07)	30,408	Fully burdened labor costs
	Procurements ($kFY07)	1,300	DNS chargebacks.
06. 03	SC Product Assurance		
	1. Methodology:	Included in WBS 03 Safety & Mission Assurance	
06. 04	Power Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	43,420	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	77	Direct labor including subsystem management, analyses, design and test
	Labor Cost ($kFY07)	18,419	Fully burdened labor costs
	Procurements ($kFY07)	17,124	Procurements include ASIC retargeting / design, ASIC fabrication parts (1st and 2nd runs) and test; power electronics,
	Service ($kFY07)	7,827	Fabrication builds (prototype / EM, Flight and spares), chassis design, backplane. BTE, qualification testing (vibe & shock, thermo vac, EMI / EMC)

WBS	Basis of Estimate and Cost Element Summary - Baseline Mission 2015 Launch		
	Travel ($kFY07)	51	Miscellaneous vendor travel
06. 05	C&DH Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	51,086	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	70	Direct labor including subsystem management, analyses, design and development (MSIA, MTIF, MREU and SSR), simulators for software development
	Labor Cost ($kFY07)	16,306	Fully burdened labor costs
	Procurements ($kFY07)	31,166	Procurements include RAD750 and ASIC
	Service ($kFY07)	3,598	Fabrication builds (prototype / EM, Flight and spares), chassis design, backplane. EGSE, environmental testing. Includes electronics shielding.
	Travel ($kFY07)	17	Miscellaneous vendor travel
06. 06	Telecom Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	36,513	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	62	Direct labor including subsystem management, analyses, design and test
	Labor Cost ($kFY07)	13,245	Fully burdened labor costs
	Procurements ($kFY07)	22,725	Procurements include radios, power amplifiers, antennas, optical communication, and RFS microwave hardware.
	Service ($kFY07)	497	Design and computer services.
	Travel ($kFY07)	45	Miscellaneous vendor travel
06. 07	Mechanical Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	100,659	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	246	Direct labor including subsystem management, analyses, design and test; Loads / dynamics analysis, support to Telecom, Propulsion, Thermal Subsystems; Shielding, mechanisms, HGA boom and separation, Mag boom and separation, linear separation assembly, MGSE, ATLO and launch support
	Labor Cost ($kFY07)	58,454	Fully burdened labor costs
	Procurements ($kFY07)	5,959	Fabrication services, assembly and test including structural hardware (bus, LV adapter and RPS support structures), mechanisms and actuators
	Service ($kFY07)	35,974	Design and fabrication services, computer services, assembly and test.
	Travel ($kFY07)	272	Miscellaneous vendor travel
06. 08	Thermal Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	13,812	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	35	Direct labor including subsystem management, design, analyses and test
	Labor Cost ($kFY07)	8,360	Fully burdened labor costs
	Procurements ($kFY07)	3,143	Procurements include thermal control hardware, blankets, shunt radiator, louvers.
	Service ($kFY07)	2,144	Fabrication services, assembly and test.
	Travel ($kFY07)	165	Miscellaneous vendor travel
06. 09	Propulsion Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	33,377	
	3. Direct Resources	Total Ph A-D	Description

WBS	Basis of Estimate and Cost Element Summary - Baseline Mission 2015 Launch		
	Labor (WY)	43	Direct labor including subsystem management, design, analyses and test
	Labor Cost ($kFY07)	10,792	Fully burdened labor costs
	Procurements ($kFY07)	19,265	Procurements include propulsion and helium tanks, main engines, thrusters (32.5N, 4.4N), latch, solenoid, service, pyro valves; transducers, and filters; lines, fittings, connectors, consumables
	Service ($kFY07)	2,963	Design and fabrication services, assembly and test.
	Travel ($kFY07)	356	Miscellaneous vendor travel
06. 10	Attitude & Articulation Control Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	75,688	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	104	Direct labor including subsystem management, design, analyses and test, control alogorthm design and test (delivered to Software for coding)
	Labor Cost ($kFY07)	26,047	Fully burdened labor costs
	Procurements ($kFY07)	49,116	Procurements include IMU, Star Tracker, Sun Sensor, and Reaction Wheels.
	Service ($kFY07)	138	Design and computer services
	Travel ($kFY07)	387	Miscellaneous vendor travel
06. 11	Harness Subsystem		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	10,201	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	17	Direct labor including subsystem management, design, analyses and test
	Labor Cost ($kFY07)	4,111	Fully burdened labor costs
	Procurements ($kFY07)	1,512	Procurements including wire and connectors
	Service ($kFY07)	4,578	Fabrication services, assembly and test.
06. 12	Software		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	31,344	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	113	Direct labor including subsystem management, design, analyses and test. C&DH and AACS algorithms, engineering model algorithms, payload and instrument control software; Software test beds, systems services (fault monitors and responses); Software I&T.
	Labor Cost ($kFY07)	28,631	Fully burdened labor costs
	Procurements ($kFY07)	2,660	test stations
	Travel ($kFY07)	53	Miscellaneous vendor travel
06. 13	Materials & Process		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	3,456	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	12	Direct labor including management, design, analyses and test, includes 10 radiation tests with multiple samples
	Labor Cost ($kFY07)	2,889	Fully burdened labor costs
	Procurements ($kFY07)	126	DNS chargebacks.
	Service ($kFY07)	442	Radiation testing services
06. 14	Test beds		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	10,325	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	41	Direct labor including tested management and support

WBS	Basis of Estimate and Cost Element Summary - Baseline Mission 2015 Launch		
	Labor Cost ($kFY07)	9,629	Fully burdened labor costs
	Procurements ($kFY07)	472	DNS chargebacks and miscellaneous procurements
	Service ($kFY07)	192	Clean room, loan pool services
	Travel ($kFY07)	32	Miscellaneous travel for training
06. 17	Radioisotope Power Source		
	1. Methodology:	Cost provided by NASA	
	2. Cost Estimate ($kFY07):	223,000	6 MMRTGs [$7M (Qual by analysis) + 6*$36M = $223M]. Cost values provided in ground rule documentation *RPS Cost Est for Flagship_v4,* 4/10/2007.
06. 18	DTM / Trailblazer		
	1. Methodology:	Scale factor	
	2. Cost Estimate ($kFY07):	4,933	
07	Mission Operations System		
	1. Methodology:	Ground Segment Team (Team G)	
	2. Cost Estimate ($kFY07):	274,943	MOS development and operations (Phase E). Excludes Science.
		122,746	DSN Aperture
08	Launch System		
	1. Methodology:	Cost provided by NASA	
	2. Cost Estimate ($kFY07):	501,552	Delta IV (4050H). Source: *Requirements and Ground rules for Flagship Mission Studies*, Table 1 ROM Launch Services costs for Atlas 5 and Delta IV Heavy launch vehicles. Table values reported in $FY06 and escalated to $FY07 dollars. Includes nuclear payload
09	Ground Data System		
	1. Methodology:	Ground Segment Team (Team G)	
	2. Cost Estimate ($kFY07):	67,789	GDS development and operations (Phase E).
10	Project Systems Integration & Test		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	41,890	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	117	Direct labor including I&T management and support. Includes ATLO manager and deputy, test conductor and I&T support, floor subsystem personnel, and documentarian.
	Labor Cost ($kFY07)	28,279	Fully burdened labor costs
	Procurements ($kFY07)	3,354	EGSE
	Service ($kFY07)	7,375	Includes facilities and environmental and thermal-vacuum testing.
	Travel ($kFY07)	2,090	Launch site travel.
11	Education and Public Outreach		
	1. Methodology:	Rule of Thumb	
	2. Cost Estimate ($kFY07):	20,087	Phase A/D - 0.5%, Phase E = 2% of CBE cost excluding RPS and LV.
12	Mission Design		
	1. Methodology:	Grassroots	
	2. Cost Estimate ($kFY07):	15,865	
	3. Direct Resources	Total Ph A-D	Description
	Labor (WY)	60	Phase A/D only: Direct labor including MDNAV management, trajectory analyst, mission engineer and engineering support, Team Chief, Radio Orbit determination OpNav and maneuver analysts.
	Labor Cost ($kFY07)	13,576	Fully burdened labor costs
	Procurements ($kFY07)	648	DNS chargebacks.
	Service ($kFY07)	1,642	Miscellaneous services for system administration and MD/NAV service center

WBS	Basis of Estimate and Cost Element Summary - Baseline Mission 2015 Launch		
01.RE	Reserves		
	1. Methodology:	Cost Risk Subfactors and Rules of Thumb (Phases A and E)	
	2. Cost Estimate ($kFY07):	577,663	Phase A = 10%, Phase B-D = 37% (established by Risk Subfactor Analysis); Phase E = 15%. Reserves base excludes Launch Services and Radioisotope Power Source

Table D2-12. *Team G Cost Estimate for Baseline Mission*

	Phase A/B	Phase C/D	Phase E	Total ($MFY07)
07 Mission Operations System	2	39	234	275
07.01 MOS Management	1	1	5	7
07.02 MOS System Engineering	1	11	2	14
07.03 Ground Station Tracking	Reported separately			
07.04 Mission Control Team	0	1	7	8
07.05 Spacecraft Team	0	14	126	140
07.06 Navigation Ops Team	0	0	26	26
07.07 Science Planning Team	0	0	20	20
07.08 Mission Planning Team	0	0	14	14
07.09 Sequence Integration Team	0	4	14	18
07.10 Data Management Team (MDAS)	0	2	9	10
07.11 Science Support Team	0	0	0	0
07.12 DSN Scheduling	0	0	1	2
07.13 Training	0	1	1	2
07.14 MOS V&V	0	3	0	4
07.15 Inst & PL MOS	0	0	10	10
09 Ground Data System	3	41	25	68
09.01 GDS Management	0	1	2	4
09.02 GDS System Engineer	1	4	1	6
09.03 TTC&M (MDAS)	0	2	1	4
09.04 SC Analysis (MDAS)	0	1	0	1
09.05 Inst Analysis	0	0	0	0
09.06 Nav Ops HW & SW	0	0	0	0
09.07 Science Planning Subsystem	0	11	5	17
09.08 Mission Planning Subsystem	0	0	0	0
09.09 Sequencing Subsystem	0	0	0	0
09.10 Simulation SS	0	0	0	0
09.11 Data Mngmt & Archive (MDAS)	0	1	1	2
09.12 Radio Science SS	0	0	0	0
09.13 Science Analysis SS	0	0	0	0
09.14 Ground Network Infrast.	0	3	6	9
09.15 Mission Support Area	0	0	0	0
09.16 System Administration	0	2	6	9
09.17 GDS I&T	0	3	1	3
09.18 GDS Deployment	0	5	1	5
09.19 Inst & PL GDS	0	6	0	7
07.03 Ground Station Tracking	0	2	120	123

Table D2-13. *Team G Cost Estimate for Floor Mission*

	Phase A/B	Phase C/D	Phase E	Total ($MFY07)
07 Mission Operations System	2	34	191	227
07.01 MOS Management	1	1	5	7
07.02 MOS System Engineering	1	9	2	12
07.03 Ground Station Tracking	Reported separately			
07.04 Mission Control Team	0	1	6	7
07.05 Spacecraft Team	0	11	103	115
07.06 Navigation Ops Team	0	0	25	25
07.07 Science Planning Team	0	0	13	13
07.08 Mission Planning Team	0	0	9	9
07.09 Sequence Integration Team	0	4	12	16
07.10 Data Management Team (MDAS)	0	2	8	9
07.11 Science Support Team	0	0	0	0
07.12 DSN Scheduling	0	0	1	2
07.13 Training	0	1	1	2
07.14 MOS V&V	0	3	0	3
07.15 Inst & PL MOS	0	0	8	8
09 Ground Data System	3	39	23	64
09.01 GDS Management	0	1	2	4
09.02 GDS System Engineer	1	4	1	6
09.03 TTC&M (MDAS)	0	2	1	4
09.04 SC Analysis (MDAS)	0	1	0	1
09.05 Inst Analysis	0	0	0	0
09.06 Nav Ops HW & SW	0	0	0	0
09.07 Science Planning Subsystem	0	11	5	17
09.08 Mission Planning Subsystem	0	0	0	0
09.09 Sequencing Subsystem	0	0	0	0
09.10 Simulation SS	0	0	0	0
09.11 Data Mngmt & Archive (MDAS)	0	1	1	2
09.12 Radio Science SS	0	0	0	0
09.13 Science Analysis SS	0	0	0	0
09.14 Ground Network Infrast.	0	3	5	8
09.15 Mission Support Area	0	0	0	0
09.16 System Administration	0	2	6	8
09.17 GDS I&T	0	3	1	3
09.18 GDS Deployment	0	5	1	5
09.19 Inst & PL GDS	0	5	0	5
07.03 Ground Station Tracking	0	2	100	103

Table D2-14. *NASA Provided Cost for 06.17 Radioisotope Power Source*

	Qualification Cost ($MFY07)	Unit Cost ($MFY07)	Number of Units	Total Cost ($MFY07)
MMRTG	7	36	6	223
ASRG	26	19	5	121

Table D2-15. *NASA provided Cost for WBS 08 Launch System*

LV	Performance Range (kg)	C_3	Launch Date	Launch Site	LV Cost ($MFY07)	Nuclear Processing ($MFY07)	Total Cost ($MFY07)
Delta IV (4050H)	4251 to 6400	C_3=20	2015	CCAFS	$490.2	$11.4	$501.6
Atlas V 551	4951 to 5250	C_3=10	2015	CCAFS	$185.8	$11.4	$197.1
Atlas V 531	3621-4190	C_3=12.6	2018	CCAFS	$165.1	$11.4	$176.5

Table D3-1. Cost Risk Subfactor Analysis

COST RISK SUBFACTORS		RATIONALE
BASE ALLOCATION Percentage	20	
A. MISSION COMPLEXITY		
1. Mission with multiple flight elements (P)		
2. Mission with multiple objectives	2	Driven by Jupiter System objectives
3. Precision lander mission		
4. Operation in harsh environments (P)	5	Radiation Environment
5. Planetary Protection requirement for heat sterilization	2	Planetary protection is challenging for Europa
B. SIGNIFICANT TECHNICAL DEVELOPMENT		
1. Mission enabling spacecraft technology with TRL<5 (P)	5	ASRG for floor mission, have ability to move to MMRTGs if needed, not applicable to baseline or backup missions
2. Mission critical instrument technology with TRL<5	2	Chosen instrument implementation may drive technical issues related to radiation design
3. Lack of fallback option for mission critical technology		
4. Multiple interfaces affected by mission critical technology		
C. NEW SOFTWARE OR UNVALIDATED SOFTWARE INHERITANCE		
1. New software architecture	2	Operational approach to collect and return data in the scenario of real-time downlink handling large volumes of data
2. New fault protection	2	Rapid identification and resolution on-board for radiation related faults
3. New software team		
4. Undocumented software inheritance without the same development team		
D. TECHNICAL MARGINS		
1. New design with multiple parameters not meeting the margin requirements specified in the design principles (P)		
2. Inherited hardware with any single technical parameter not meeting the technical margin requirements specified in the design principles		
E. SYSTEM ARCHITECTURE		
1. New system architecture (P)		
2. System architecture applied to new environment and technology	2	The basic orbiter architecture is traditional but the radiation environment and the technologies employed are a new application of this basic orbiter architecture
3. Level 1 Requirements not well defined in formulation phase (P)		
4. System with many ACS modes		
5. System with many deployments		
6. Excessive reliability requirements (P)		
7.Pointing control stability requirements beyond state of art		
F. CONTRACTOR CAPABILITIES MATCH		
1. Contractor inexperienced in mission application (P)		
2. Foreign Partner delivering hardware that is mission critical or on critical path		
3. Not enough experienced personnel available.		
G. PROGRAMMATIC /COST &SCHEDULE MARGIN		
1. Less then 12-month Phase A/B		
2. Less than 30-month Phase C/D		
3. Schedule margins below guidelines (P)		
4. Multiple programmatic interfaces		
H. MANAGEMENT AND ORGANIZATION		
1. Inadequate team and management experience (P)		
2. Insufficient workforce		
3. Risk mitigation plan not completed during formulation phase		
4. Selection of science instruments late in phase B (P)		
RESERVES percentage from sum of above scores		37% for baseline mission and 42% for floor mission

(P) = Primary risk subfactors; All others (S) = Secondary risk subfactors. Required budget reserve % = 20% + 5(number of P's)% + 2(number of S's)%

and will continue to do so at subsequent project key decision points. Commensurately, the confidence in implementing the mission within the overall estimate provided here is expected to grow.

The Cost Risk Subfactor Analysis for the EE baseline mission concept indicates 1 primary risk subfactor and 6 secondary risk subfactors totaling 37% recommended reserve. In addition, a second primary risk factor is identified for the floor mission relating to the level of maturity of the ASRG. It is useful to note, that the floor mission can be implemented on the floor mission on the same launch vehicle (Atlas V 531) but the ASRG was chosen due to its lower projected cost. This additional risk factor increased the recommended reserve for the floor mission to 42%.

D4. Floor Mission Concepts Differences

The major differences between the baseline and floor mission concepts which relate to cost are shown in **Table D4-1**. In addition to these differences, items which are scaled from either these items directly or from the project estimate are also affected but not specifically noted here. Note that the floor mission can technically be done with MMRTGs on the same launch vehicle but ASRGs were selected as they saved approximately $20M.

Table D4-1. *Major technical differences that drive the majority of the cost delta between the baseline and floor mission concepts.*

	Baseline Mission	Floor Mission
Launch Vehicle	Delta IV-H	Atlas V 531
RPS	6 MMRTG	5 ASRG
Payload Complement	5 Simple, 6 Complex	5 Simple, 3 Complex
Europa Mission Duration	12 months	6 months
Reserves on Phases B-D	37%	42%

D5. Cost Uncertainty

The range of uncertainty in the cost estimate was determined by the Study Lead by assessing the level of maturity and cost estimation methodology for each WBS element. These uncertainty ranges were applied to the CBE and then reserves were adjusted accordingly. The ranges used by WBS level and rationale are shown in **Table 4.10-4**.

D6. WBS and Dictionary to Level 3 of the WBS

The EE WBS and dictionary are given in **Table D6-1**.

D7. TMC Requested Tables

The TMC requested tables for the baseline and floor mission concepts are given in **Foldout 10, where the tables for the baseline mission are pages 1 and 2, and for the floor mission are pages 3 and 4.**

Table D6-1. *Europa Explorer WBS and Dictionary*

WBS Num	Element Name	Element Description
01	**Project Management**	**The business and administrative planning, organizing, directing, coordinating, controlling, and approval processes used to accomplish overall Project objectives that are not associated with specific hardware (HW) or software (SW) elements.**
01.01	Proj Mgmt	**Project Management:** Lead and manage the overall flight project for delivery of the project systems to the sponsor. This element also includes being the primary interface to the sponsor. Includes Project Manager, Deputy Project Manager for Radiation (DPMR), Other Deputies (if any), secretaries, and other Project Office support personnel. Also includes expert planning support to the project, preparation of agreements with outside organizations, foreign travel, and technology transfer. Products include Task Plans, Project Plan, and Implementation Plans.
01.02	Business Mgmt	**Business Management:** Lead and manage the business and resource control processes for the project. Includes all Project resource planning and control activities, development and maintenance of the Project schedules, financial control, production of cost estimates, development and operation of the Project performance measurement and reporting system(s), earned value management system, etc. Personnel include Project Business/Control Manager, Financial, Planning and Scheduling personnel.
01.04	Review Support	**Review Support:** Provide the human resources and facility structure for the formal, major internal and external Reviews of the project, and for preparation of the subsequent Board Requests For Actions (RFAs) and Board reports. Includes travel expense for Board members, and conferencing facilities. Includes the labor expense for JPL direct and external Board members. Also includes Radiation Advisory Board support.
01.05	Facilities	**Facilities:** Establish and maintain any project-unique facilities. Excludes office moves, cubicle partitions, or conference room costs.
01.06	Launch Approval	**Launch Approval:** Support NASA HQ in satisfying legal and related requirements associated with assessing and mitigating the potential adverse environmental effects of flight projects and certain terrestrial research and development projects and tasks managed by JPL. Includes performing analyses, drafting and submitting documentation to the appropriate national agencies, interfacing with industrial, foreign, US Agency, NASA Center, and university partners/subcontractors and reviewing their analyses for requirements compliance
01.RE	Project Reserves	**Project Reserves**: Includes all Project Reserves as a non WBS element. Reserves are to be allocated to specific WBS elements for costing as required. Reserves are planned as part of the project baseline budget.
02	**Project System Engineering**	**The technical and management efforts of directing and controlling an integrated engineering effort for the project. Includes the effort to define the Project space-ground system, conducting trade studies; the integrated planning and control of the technical program efforts of design engineering, specialty engineering, and integrated test planning; the effort to transform Project objectives into a description of system requirements and a preferred system configuration; the technical oversight and control effort for planning, monitoring measuring, evaluating, directing, and replanning the management of the technical program. Documentation Products include Project System Requirements Document (PSRD); Interface Control Documents (ICDs); and Verification and Validation (V&V) Implementation Plan.**
02.01	Proj Sys Eng	**Project System Engineering:** The Project System Engineer (PSE) is responsible for project technical integrity including mission risk and performance to meet the driving scientific and technological objectives. The PSE is responsible for the planning and implementation of the system engineering function across the entire scope of the project. The Deputy PSE for Radiation (DPSER) will be responsible for all technical aspects of the radiation design including: risk assessments, mission design options, implementation (mass/parts/materials selection) trades, radiation control and validation etc. The DPSER reports directly to the DPMR who has the ultimate responsibility for making the cost/risk/schedule/performance trades in conjunction with the Project Scientist when Science performance is involved.

WBS Num	Element Name	Element Description
02.02	Proj SW Eng	**Project Software Engineering:** Develop the system SW architecture and provide the Project SW Systems Engineer. Includes developing SW policies & practices; defining SW requirements; designing SW; implementing SW; resolving SW test issues; making flight/ground tradeoffs; providing the project interface (along with SW Quality Assurance (SW QA) Liaison) to NASA's West Virginia (WVa) Independent Verification and Validation (IV&V) Center. The personnel may include a Ground Data System (GDS) SW Engineer if not included within GDS system engineering WBS element 07.03.02. Participates in the Project System Engineering Team.
02.03	EEIS	**End-to-End Information System:** Provide for End-to-End Information System (EEIS) Engineering for the project science and/or technology data stream. Includes analysis and validation of data streams from Instrument/Payload collection points through the Payload-Spacecraft interface; downlinking; collection in the Ground Data System (GDS); data processing; delivery to recipients. Products/deliverables include Level 2 EEIS requirements, Project Data System Design Document, Data Interface Control Documents between the, Science System, Flight system, and Mission System; data product generation and information flows supporting uplink and downlink processes developed by MOS Engineering, EEIS portion of Project V&V Plan. Participates in the Project System Engineering Team.
02.04	Info Sys Eng & Com	**Information System Engineering and Communications:** Provide project team communications, information technology architecture, and data organization, retrieval, and archiving to support the "virtually co-located" project, which includes partners/major subcontractors and international partners. Coordinate and facilitate audio and video conferencing among the remote locations. Identify, integrate, and adapt project-specific and institutional tools and repositories for Project Team use. Assure compliance with: International Standards Organization (ISO) 9001; NASA Procedures and Guidelines (NPG) 7120.5; International Traffic in Arms Regulations (ITAR); Export Administration Regulations (EAR); JPL Institutional Management Requirements. Extend information environment to the launch site.
02.05	Config Mgmt	**Configuration Management:** Provide the interface with and coordinate Configuration Management (CM) activities between the project (that is, JPL) and industrial, foreign, United States (US) agency, NASA Center, and university partners to provide the required change visibility with all interacting and interdependent elements of the project, and to ensure interface control between various project elements. Includes establishing and managing the JPL Project-Level Change Control Board; coordinating change activity between the project and industrial team partners; providing operational guidance on CM issues. Also includes the costs of the EDMG and/or Product Data Management System (PDMS).
02.06	Planetary Protection	**Planetary Protection:** Ensure that the project meets all NASA Planetary Protection (PP) requirements. Includes performing analyses; drafting and submitting documentation to the appropriate national agencies; interfacing with industrial, foreign, US Agency, NASA Center, and university partners/subcontractors, and reviewing their analyses for compliance with requirements.
02.07	Contamination Cntrl	**Contamination Control:** Lead, manage, and coordinate spacecraft and payload CC effort for project. Includes Contamination oversight to spacecraft contractor and Payload providers. Excludes support to detailed contamination analysis; CC program development; support to Planetary Protection (PP) effort; requirements verification; interface documentation; support to thermal vacuum bake-outs. Documents include Contamination Control Plan. Products include Contamination Materials Identification and Flowpath Analysis. Provides level 2 contamination control requirements. Participates in the Project System Engineering Team.
02.08		**Purposely left blank**
02.09	Launch Sys Eng	**Launch System Engineering:** Provide the liaison interface between Launch System and all other Project Systems, and the primary interface between the project and the Launch Services provider. Participates in the Project System Engineering Team. Launch services costs are excluded.
02.10	Proj V&V	**Project Verification and Validation:** Implement the verify and validate function at the project level throughout the project lifecycle. Produce the following products: 1) Incompressible Test List, 2) project verification & validation requirements at level 2, 3) project verification & validation implementation plan. Review project V&V results. Produce the 2.10 work agreement and manage the task.

WBS Num	Element Name	Element Description
02.11	Risk Mgmt	**Risk Management:** Provide for the Project Risk Engineer and Risk Management subcontract/services that coordinate Project Risk Management processes. Includes creation and maintenance of Project Master Risk List, interfacing with the Project Business personnel for development and maintenance of the Project Soft Lien List. Products include Project Risk Management Plan (Written by the PSE or MAM), Significant Risk List and metrics on risk items.
03	**Safety & Mission Assurance**	**The technical and management efforts of directing and controlling the Safety & Mission Assurance Elements of the project. Includes design, development, review, and verification of practices and procedures intended to assure that the delivered Spacecraft System and Instruments/payloads meet performance requirements and function for their intended lifetimes. Excludes Mission and Product Assurance efforts at partners/ subcontractors other than a review/oversight function, and the direct costs of environmental testing.**
03.01	SMA Mgmt	**Safety & Mission Assurance Management:** Lead and manage the overall Safety & Mission Assurance (SMA) effort for the project and provide the primary SMA interface to partners and subcontractors, with responsibilities distributed among the staff. Includes SMA Manager; Deputy (as applicable). Documentation products include Safety & Mission Assurance Plan (included in the PIP).
03.02	Sys Safety	**System Safety:** Provide Systems Safety engineering to the project. Includes monitoring subcontractors and payload providers; launch campaign, system safety facility surveys; etc.
03.03	Environ Eng	**Environmental Engineering:** Provide Environmental Engineering for the project, including for example: Radiation, Internal Charging, Thermal; Vibro-Acoustic; Natural Space Environments and EMC/EMI; test monitoring; etc. Excludes costs of Environmental Testing. Products include Radiation Control Plan; Environmental Requirements Document (ERD).
03.04	Rel Eng	**Reliability Engineering:** Provide reliability (circuit and mechanism) design and analysis support to project elements at JPL and at partners/subcontractors (as applicable). Includes Reliability Plan (may be part of Mission Assurance Plan), performing and reviewing Electronic Parts Stress Analyses; Circuit Worst Case Analyses; interface failure modes, effects and criticality analyses (FMECAs) and Single-Event Effects (SEE) analyses on spacecraft electronics; Fault Tree Analyses, and Probabilistic Risk Assessment; review/assessment for spacecraft contractor problem reports; review and closeout of problem/failure reports (P/FRs). Also includes Orbital Debris Assessment
03.05	Parts Eng	**Parts Engineering:** Provide Electrical, Electronic, and Electromechanical (EEE) Parts Engineering support to project elements at JPL and at partners/subcontractors (as applicable). Includes parts list reviews; waivers; Monthly Management Review (MMR) / PDR / CDR / HRCR support; document/status reviews (implementation plans, Radiation Lot Acceptance Testing (RLAT), Non-Standard Parts Approval Request (NSPAR); Materials Review Board (MRB) support; limited Alert review; parts list in Electronic Parts Information System (EPINS). Also includes: costs associated with upscreening and testing. Excludes cost of the EEE parts themselves, which are distributed throughout the subsystem (SS) accounts.
03.06	HW QA Eng	**Hardware Quality Assurance:** Provide JPL on-site and itinerant Hardware Quality Assurance (HQA) support to partners/subcontractors, and oversight into partners/ subcontractor's Quality Assurance (QA) effort to ensure that proper HQA processes are selected and used for flight hardware.
03.07	SW QA Eng	**Software Quality Assurance Engineering:** Provide JPL on-site and itinerant SQA support to partners/subcontractors, and oversight into partners/subcontractor's Quality Assurance (QA) effort to ensure that proper SQA processes are selected and used for flight software.
03.08	SW IV&V	**Software Independent Verification and Validation:** Provide IV&V for Project software systems. Includes bypass funding for software IV&V performed by the NASA West Virginia facility. Also includes JPL SW QA support to IV&V activities.
03.09	MO Assur	**Mission Operations Assurance**: Ensure operations staff follows proper processes and procedures during operations phase. Includes pre-launch preparation activities; support from the Operations Assurance Manager and specified MA activities that assure continuing capability of the PRS; operations software product assurance

WBS Num	Element Name	Element Description
04	**Science**	**Science: The technical and management efforts of directing and controlling the Science investigation aspects of the project. Includes the efforts associated with defining the science requirements; ensuring the integration of the science requirements with the Instruments, Payloads, Flight and Ground Systems; providing the algorithms and software for science data processing and analyses; science data analysis and archiving. Excludes hardware and software for on-board science investigative Instruments / Payloads.**
04.01	Sci Mgmt	**Science Management:** Provides scientific management of the entire mission, comprised of a suite of science instruments. The Project Scientist manages relationships between other elements of the project and the science investigators. The Project Scientist is on a par with the Project Manager in making decisions affecting the mission. Includes maintaining a science office, setting up and participating in reviews, implementing and monitoring science support contracts, planning science operations and data analyses; science implementation schedules; science document configuration control; managing the data archiving process, serving as the scientific spokesperson for the project. Document products include Science Management Plan; Science Data Management and Archiving Plans. Include travel, workshops, and publications. Provides for setting up and attendance at project science meetings
04.02	Sci Implement	**Science Implementation:** The fundamental project science activities, as distinct from management, and personnel associated with the project's science investigations who provide scientific direction. Excludes Instrument/Payload development costs. Activities include data processing, calibration, validation, analysis, and interpretation.
04.03	Sci Suppt	**Science Support:** Provide support to the Project Science Team(s).
05	**Payload System**	**Payload System: The equipment provided for special purposes in addition to the normal equipment integral to the spacecraft. Includes experimental and scientific data gathering equipment placed on board the flight system.**
05.01	PL Sys Mgmt	**Payload System Management:** Coordinate support to Announcement of Opportunity (AO). Function as the Contract Technical Managers (CTMs) for Instrument/Payload contracts. Provide the primary interface between the project and Instrument/Payload providers.
05.02	PL Sys Eng	**Payload System Engineering: Payload System Engineering:** Implement the JPL system engineering functions for the instrument[s]: 1) develop architecture, 2) develop and maintain requirements, 3) define interfaces, 4) manage technical resources, 5) analyze the technical design, 6) manage and control risk, 7) conduct technical peer reviews, 8) manage and control the design, 9) verify and validate and 10) manage the task. Provide for ad hoc expert division support to the Payload System Engineering element. (This includes specialist-engineering support, such as stray light analysis, contamination analysis, parts qualification, and parts radiation testing.) Participates in the Project System Engineering Team. Includes radiation system engineering to facilitate radiation design information coordinatioon for instrument.
05.03 - end		**Individual Instruments**
06	**Spacecraft System**	**The Spacecraft that serves as the platform for carrying payload, instruments and other mission-oriented equipment in space to the mission destination(s) to achieve the mission objectives. The Spacecraft includes subsystems such as: power, C&DH, telecom, mechanical, thermal, propulsion, AACS, and harness. Does not include support to the Project level I&T activity.**
06.01	SC Mgmt	**Spacecraft System Management:** Manage and provide leadership for the Spacecraft development, and control schedule and cost.Includes liaison with the Project Office to: define interfaces within the Spacecraft and to other Project Systems; define requirements, define and perform system-level Spacecraft tests; support design team meetings and Project reviews; lead Spacecraft System design reviews.

WBS Num	Element Name	Element Description
06.02	SC Sys Eng	**Spacecraft System Engineering:** The technical and management effort that direct and control an integrated engineering effort for the Spacecraft System. Includes effort to define the system and the integrated planning and control of the technical program efforts of design engineering, specialty engineering, production engineering, and integrated test planning; effort to transform an operational need into a description of system requirements and a preferred system configuration; technical and control effort for planning, monitoring, measuring, evaluating, directing, and replanning the management of the technical program. Excludes actual design engineering and the production engineering directly related to the WBS element with which it is associated. Participates in the Project System Engineering Team.
06.03	SC Prod Assur	**Spacecraft Product Assurance:** Provide for significant Product Assurance costs associated with a spacecraft system. Excludes itinerant product assurance support and travel.
06.04	Power SS	**Power Subsystem:** The complex of equipment, data, services, human resources, and facilities required to develop, produce, test, and deliver an integrated Power Subsystem that meets Subsystem and Flight System requirements. Includes requirements generation, planning, breadboards, brassboards, STMs, EMs, Proto-Flight Models (PFMs), flight hardware, spares, and Subsystem integration. Includes subcontracts as relevant. Excludes all direct effort associated with integrating the Subsystem into the Spacecraftt System.
06.05	C&DH SS	**Command and Data Handling Subsystem:** The complex of equipment, data, services, human resources, and facilities required to develop, produce, test, and deliver an integrated Command and Data Handling Subsystem (C&DH), which meets Subsystem and Flight System requirements. Includes breadboards, EMs, PFMs, and spares. Includes subcontracts as needed. Excludes all direct effort associated with integrating the Subsystem into the Spacecraft System.
06.06	Telecom SS	**Telecommunications Subsystem:** The Human Resources, equipment, data, services, and facilities required to develop, test, and deliver an integrated Telecom Subsystem that meets Subsystem and Flight System requirements. Includes breadboards; brassboards; STMs; EMs; PFMs; spares. Excludes all direct effort associated with integrating the Subsystem into the Flight System.
06.07	Mech SS	**Mechanical Subsystem:** The human resources, equipment, data, services, and facilities required to develop, test, and deliver an integrated Mechanical Subsystem that meets Subsystem and Flight System Requirements. Includes breadboards; brassboards; STMs; EMs; PFMs; spares. Excludes all direct effort associated with integrating the Subsystem into the Flight System.
06.08	Thermal SS	**Thermal Subsystem:** The resources required to provide a validated Thermal Subsystem design, and to develop, produce, test, and deliver an integrated Thermal Subsystem that meets Flight System requirements.
06.09	Prop SS	**Propulsion Subsystem:** The human resources, equipment, data, services, and facilities required to develop, test, and deliver an integrated Propulsion (Prop) Subsystem that meets Subsystem and Flight System requirements. Includes breadboards; brassboards; STMs; EMs; PFMs; spares. Excludes all direct effort associated with integrating the Subsystem into the Flight System.
06.10	AAC SS	**Attitude and Articulation Control Subsystem:** The complex of equipment, data, services, human resources, and facilities required to develop, produce, test and deliver an integrated SS that meets its requirements. Includes breadboards; STMs; EMs; PFMs; spares. Includes subcontracts as relevant. Excludes all direct effort associated with integrating the SS into the flight system.
06.11	Harness	**Harness:** Design, develop/fabricate/procure, assemble and test the primary cabling that interconnects all Spacecraft Subsystems.
06.12	Flt SW	**Flight Software:** The human resources, equipment, data, services, and facilities required to develop, produce, test, and deliver the Flight Software System to meet Software System and Flight System requirements. The Flight Software System includes: operating system; health monitoring system; command and control system; telemetry system; data storage and handling system; software required to interface, command, and control Instruments and Payloads; software for the various Subsystems of the Flight System. Excludes Science/investigative and other software delivered with the Instruments/Payloads. Documents include Flight Software Management Plan, Summary Work Agreement; materials for Monthly Management Reviews.

WBS Num	Element Name	Element Description
06.13	Materials & Proc	**Materials and Processes:** Provide for spacecraft M&P support for the project design and implementation phases, including: oversight into JPL and contractor M&P efforts and the review and assessment of the subsystems' M&P listing to ensure that proper materials and processes are selected and used for flight HW. Excludes costs for materials, fasteners, thermal vacuum bakeouts; any required M&P development, qualification, testing.
06.14	SC Testbeds	**Spacecraft System Testbeds:** The human resources, equipment, data, services, and facilities required to develop, produce, test, and deliver integrated Spacecraft System Testbeds to meet the Spacecraft System Test / V&V requirements. Includes simulation hardware and software producing a flight-like environment within which flight hardware and software may be integrated and tested; interconnectivity to Mission Operations System (MOS) elements for command/control checkout.
06.15, 16		**Purposely left blank**
06.17	Radioisotope Power Source	**Radioisotope Power Source as provided by the Department of Energy.**
06.18	DTM / Trailblazer	**DTM/Trailblazer:** The workforce to perform the early activities related to the integration of RPS at the launch site. Includes storyboarding the integration, planning the Ground Support Equipment, and practicing the integration at the facilities prior to RPS and flight system arrival at launch facility.
07	**MOS**	**The Mission Operations System (MOS) is the ground-based system required to conduct project mission operations and consists of the following key components: Note that some of these elements are developed and maintained under WBS Element 09 Ground Data System.** **a) Human resources: Trained and certified personnel** **b) Procedures: Documented, tested procedures to ensure that operations are conducted in a reliable, consistent and controlled manner** **c) Facilities: Offices, conference rooms, operations areas, testbeds and other space to house the personnel and perform the operations** **d) Hardware: Ground-based communications and computing hardware and associated documentation required to perform mission operations** **e) Software: Ground-based software and associated documentation required to perform mission operations** **f) DSN: The tracking stations of the Deep Space Network** **The purpose of the MOS development is to plan the activities required to perform the mission, and to implement the associated facilities, hardware and software and procedures. Mission Operations System (MOS) development costs include Launch +30 days of flight operations.**
07.01	MOS Mgmt	**MOS Management:** Manage and provide leadership, schedule and cost control for the development and operations of the Mission Operations System. Includes: MOS planning, liaison with the all elements of the Project to define the interfaces between the MOS and other Project Systems; defining MOS requirements; designing and performing MOS tests; supporting design team meetings and Project reviews; leading MOS design reviews, providing management practices for all elements of the MOS. Personnel include: MOS Manager; Deputy MOS Manager (if any); administrative support. Documents include: Mission Operations Plan; Flight System Operations Handbook; Flight rules.
07.02	MOS Sys Eng	**MOS System Engineering:** The integrated system engineering effort for the MOS and GDS. Includes definition and documentation of system requirements, architecture, design, and V&V requirements; monitoring data system and operations implementation; specialty engineering as may be identified; supporting technical efforts performed in planning, monitoring, measuring, evaluating, directing, and replanning the project's technical program. Excludes actual design engineering and the production engineering directly related to the WBS element with which it is associated. Products include operations concept; level-2 and 3 MOS and GDS requirements; V&V requirements, operational interface agreements; flight operations plan; sequence activity plan, review of and contribution to other project documents (including MOUs), DSMS service Agreement (DSA), ICDs, data archive, security, SW management, and configuration management. May include the MOS CM and MOS security plans if they are not provided by the project.

WBS Num	Element Name	Element Description
07.03	Gnd Station Trckng	**Ground Station Tracking:** Provides ground station tracking time and costs. For example, for Discovery missions determine the DSN (or equivalent) costs for tracking support throughout the mission.
07.04	Mssn Cntrl Team	**Mission Control Team:** Provides personnel to monitor and control the spacecraft. Tasks may include sending commands; monitoring spacecraft and instrument health; implementing contingency actions in response to detected anomalies; scheduling tracking-station support. Development tasks include develop team level-4 requirements, design operating procedures; support development of the flight operations plan; develop contingency plans. Depending on the mission, this element may also include a DSN scheduling team and/or a mission control team.
07.05	SC Team	**Spacecraft Team:** Provides personnel to analyze spacecraft health and performance and plan future spacecraft activities. Tasks may include thermal analysis and prediction; telecom analysis; flight SW maintenance; consumable management; operation of flight testbeds. Development tasks include develop team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.06	Nav Ops Team	**Navigation Operations Team:** Provides personnel to determine the spacecraft trajectory and/or position, and plan spacecraft trajectory changes as required. Development tasks include: develop team level-4 requirements; design operational procedures; support development of the Flight Operations Plan; develop contingency plans. Includes trajectory, orbit determination, maneuver analysis, launch support, NAIF/ SPICE, target body orbit/ ephemeris updates, and a navigation liaison in residence at contractor site. Includes system engineering and administration, travel, procurements, and by-pass funding. Train, test and certify team for navigation flight operations, and participation in Operational Readiness Tests (ORTs). Develop and update navigation team procedures and interfaces. Participate in the planning, status, anomaly resolution, mission change requests analysis and staff meetings (and others as required). Prepare for and participate in reviews, both internal and external to the project. Generally starts in phase D and goes through Phase E.
07.07	Sci Plng Team	**Science Planning Team:** Provides personnel to plan science activities. Development tasks include develop team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.08	Mssn Plng Team	**Mission Planning Team:** Provides personnel to plan mission activities. Development tasks include develop team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.09	Sequencing Team	**Sequencing Team:** Provides personnel to develop and integrate the sequence of commands to control spacecraft and instrument activities. Tasks may include constraint checking and testing sequences on a testbed simulator before sending commands to the spacecraft. Development tasks include develop team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.10	Data Mgmt Team	**Data Management Team:** Provides personnel to process, manage, and transfer data to the users. Tasks may include preparing and transferring data to an archive facility. Development tasks include develop team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.11	Sci Suppt Team	**Science Support Team:** Provides personnel to support science activities. Tasks may include monitoring instrument health; preparing command files; transferring science data. Development tasks include develop of team level-4 requirements; design operational procedures; support development of the flight operations plan; develop contingency plans.
07.12	DSN Scheduling	**DSN Scheduling:** Represent the project to the resource allocation review board (RARB) and the joint users review allocation planning (JURAP) process to ensure that critical resource changes are negotiated and effected. Input project requirements and view periods into the RARB planning process. Negotiate DSN tracking resources to meet project requirements and maintain accurate allocation files of resources scheduled. Distribute allocation files to other teams for inclusion in their processes.
07.13	Training	**Training:** Prepare, coordinate, and conduct operations training and tests. Train and certify operations personnel. Tasks include prepare the operations training plan; coordinate and conduct team training; produce training reports; train personnel in GDS tool usage. Support validation of the operations readiness test (ORT) activity. Provides the operations training engineer.

WBS Num	Element Name	Element Description
07.14	MOS V&V	**Mission Operations System Verification and Validation:** The complex of personnel and services required to validate that the MOS is prepared to operate (track, analyze, plan, and command) the spacecraft and instruments.
07.15	Inst MOS	**Instrument MOS:** Personnel, procedures, equipment and services for testing and operating the instrument MOS
08	**Launch Sys**	**Launch System: The primary means for providing initial thrust to place the flight system directly into its operational environment or on a trajectory towards its intended target. Includes launch Vehicle; associated launch services.**
08.01	Launch Services	**Launch Services:** Launch services provide the goods and services necessary to place the flight system directly into its operational environment, or on a trajectory towards its intended target. Includes launch vehicle; launch vehicle integration; launch operations; and any other associated launch services. Frequently includes an upper-stage propulsion system. Prepare the Launch Services Implementation Plan
09	**Ground Data Sys**	**Ground Data System:** The complex of equipment, HW, SW, and facilities required to assemble, integrate, test, and operate the GDS. Includes the computers, communications, operating systems, and networking equipment needed to interconnect and host the MOS SW. May include spacecraft and instrument testbeds post-launch; flight SW development equipment, or interfaces to such capability if provided by corresponding spacecraft or instrument areas**.**
09.01	GDS Mgmt	**Ground Data System Management:** The technical and management efforts to direct and control the GDS. Includes support of systems engineering efforts that define and document the GDS requirements, architecture, design, and integration and test requirements; oversight of GDS implementation; specialty engineering as may be identified; the technical oversight and control effort for planning, monitoring, measuring, evaluating, directing, and replanning the technical program as necessary. Excludes actual design engineering. Products include SW interface specifications, test plans, user manuals, review of and contribution to other project documents (including MOUs, PSLA, ICDs), security, SW, and configuration management.
09.02	GDS Sys Eng	**Ground Data System Engineering:** Develop and implement the GDS architecture and system engineering effort. Apply GDS technical resources to develop and verify the system requirements, develop the design, maintain configuration management, perform security, and validate the GDS. Provides for the GDS system engineers and other staff as may be determined necessary. May include a GDS SW engineer if not included within project SW engineering WBS 02.03. Roles include manage/lead GDS development while controlling schedule and cost; maintain liaison with the MOS and other project elements to ensure the interfaces between them and the GDS are fully defined; define and document requirements, and obtain approval; perform test and validation according to the requirements; support design team meetings and project reviews; lead GDS design reviews.
09.03	TTC&M SS	**Tracking, Telemetry, Command and Monitoring Subsystem:** The ground complex of HW and SW used to track the spacecraft, receive and process telemetry from the spacecraft, format and send commands to the spacecraft, and report the status and metrics of the tracking stations and ground network. Includes SS management and engineering.
09.04	SC Anls SS	**Spacecraft Analysis Subsystem:** The ground complex of HW and SW used to analyze spacecraft health and status and plan spacecraft activity. Includes SS management and engineering.
09.05	Inst Anls SS	**Instrument Analysis Subsystem:** The ground complex of HW and SW used to analyze instrument health and activity. Includes SS management and engineering.
09.06	Nav Ops HW & SW Dev	**Navigation Operations Hardware and Software Development:** The ground complex of hardware and software used to analyze a spacecraft trajectory and position and plan maneuver activity. Includes subsystem management and engineering. Includes software development to support operations in the domains of: trajectory, orbit determination, maneuver analysis, launch support, NAIF/ SPICE adaptation, and target body ephemeris development. Includes system engineering and administration, travel, procurements, and by-pass funding. Generally starts in Phase B and can go through Phase E.
09.07	Sci Plng SS	**Science Planning Subsystem:** The ground complex of HW and SW used to plan science instrument activity. Includes SS management and engineering.
09.08	Mssn Plng SS	**Mission Planning Subsystem:** The ground complex of HW and SW used to plan the mission activity. Includes SS management and engineering.

WBS Num	Element Name	Element Description
09.09	Sequencing SS	**Sequencing Subsystem:** The ground complex of HW and SW used to develop and integrate sequences of spacecraft and instrument commands. Includes SS management and engineering.
09.10	Simulation SS	**Simulation Subsystem:** The ground complex of HW and SW used to simulate ground and spacecraft events for purposes of testing ground HW and SW, and training operations personnel. May include flight SW simulators / test beds. Includes SS management and engineering.
09.11	Data Mgmt & Archive SS	**Data Management and Archiving Subsystem:** The ground complex of HW and SW used to process, configuration manage, and transfer project data to an archive facility. Includes computers; operating and application SW; science and telemetry data capture, conditioning and processing SW; network HW and SW systems; telecommunications links; data distribution HW and SW systems; data mass storage systems; data storage facilities. Includes SS management and engineering.
09.12	Radio Sci SS	**Radio Science Subsystem:** The ground complex of HW and SW used to process and support the analysis of radio science data. Includes SS management and engineering.
09.13	Sci Anls SS	**Science Analysis Subsystem:** The ground complex of HW and SW used to process and support the analysis of science data. Includes SS management and system engineering.
09.14	Gnd Net Infrastructr	**Ground Network Infrastructure:** Engineer and maintain the communication and interconnection equipment to link the various elements of the GDS. design, implement, procure, and maintain all required HW and SW. May include replenishment of equipment required to support the mission throughout the project life cycle.
09.15	Mssn Suppt Area	**Mission Support Area:** Provides the facility(s) to house operations personnel during the mission. Includes local and remote facilities; all required space, equipment, and furnishings.
09.16	Sys Admin	**System Administration:** Provides administration, configuration, and control of the ground computers and SW. Provides the GDS system Administrator(s).
09.17	I&T	**Integration and Test:** Provides integration and testing of the GDS. Tasks include prepare GDS I&T plan; coordinate and conduct GDS system-level tests; produce test reports; support training of test personnel in GDS tool usage. Provides a GDS test engineer.
09.18	GDS Deployment	**Ground Data System Deployment:** Deploys the complex of human resources, services, and facilities required to assemble, integrate, and test the ground system and spacecraft according to the mission plan.
09.19	Inst GDS	**Instrument GDS:** Ground SW, computers, networks, data storage, HW peripherals, facilities, services, documentation, instrument/payload flight SW (post-launch), and instrument /payload EGSE (post-launch) required for commanding the instrument/payload and processing instrument/payload data through the GDS. Includes establishing and maintaining project interfaces; design, implementation, testing, and documentation of tools and data system. Post-launch funding for instrument/payload FSW and EGSE is for maintenance and required upgrades.
10	**Project Systems I&T**	**Project Systems Integration and Test (ATLO): The human resources, equipment, data, services, and facilities required to assemble, integrate, test, and deliver to the Launch Site the Integrated Spacecraft, Payload, Launch Vehicle, MOS and GDS systems that meet Project System requirements. Includes mechanical and electrical assembly; functional testing; performance testing and environmental testing; transportation/logistics; Launch Site support.**
10.01	Proj Sys I&T Mgmt	**Project Systems I&T Management:** Lead and manage the Project Systems I&T through Launch + 30 days. Personnel includes: Project Systems I&T Manager; Deputy Manager (if needed).
10.02	Proj Sys I&T Eng	**Project Systems I&T Engineering:** Lead and perform overall ATLO System Engineering to meet Project requirements. Includes generating integration and test storyboard; reviewing test configurations, plans, and procedures; reviewing facility requirements; providing interface to Mission Operations technical personnel. Documents include Work Agreement; functional and detailed requirements; ICDs for mechanical, electrical, and information interfaces; Equipment POs; associated documentation (such as ATLO specifications, Drawings, Test Plans, and Test Procedures for System Functional and Performance Tests), and Test Reports from Functional Tests during ATLO. Excludes Subsystem engineering support to ATLO

WBS Num	Element Name	Element Description
10.03	I&T Facilities	**Project Systems I&T Facilities:** Provide for modification and maintenance of system test Facilities for the duration of use by the project. Includes, for example; labor, services, and equipment unique to project requirements.
10.04	PS Env Testing	**Project Systems Environmental testing:** Environmental testing of the fully integrated Flight System. Includes costs of EMC/EMI; acoustic, vibration, and thermal-vac facilities; and labor directly associated with the function and operation of those facilities. Excludes Integration & Test engineering and technical support labor.
10.05	SS Eng Suppt	**Subsystem Engineering Support:** Provide Subsystem Engineering Support to ATLO after each Spacecraft Subsystem is delivered to ATLO. Includes technical representatives and discipline experts from each delivered Flight Subsystem as needed to support environmental tests, data analysis, design trouble-shooting, modifications, and ATLO activities.
10.06	SC I&T	**Spacecraft Integration and Test:** Mechanical integration and functional test of the Subsystems of the Spacecraft System without Instruments and/or Payloads, excluding Environmental Test costs. Includes Labor; test chief; technicians.
10.07	Inst & PL Eng Suppt	**Instrument and Payload Engineering Support:** Provide Engineering Support to Project Systems I&T after each Instrument and Payload is delivered. Includes technical representatives and discipline experts from each delivered Instrument and Payload as needed to support environmental tests, data analysis, design trouble-shooting, modifications, and ATLO activities.
10.08	Proj Sys I&T	**Project Systems Integration and Test:** Mechanical integration and functional test of the Instruments/Payloads with the Spacecraft System, the Launch System the MOS and the GDS, excluding Environmental Test costs. Includes Labor; test chief; technicians.
10.09	FS EGSE	**Spacecraft Electrical Ground Support Equipment:** Provide system-level Electrical Ground Support Equipment. Includes system-level cabling equipment necessary for system Integration & Test that is not delivered with Subsystems, Instruments, and Payloads. (Notes: (1) Substantial contributions of ATLO EGSE from the Subsystems and GDS are costed elsewhere. (2) This is a coordinated activity.
10.10	FS MGSE	**Flight System Mechanical Ground Support Equipment:** Provide shipping containers, support fixtures, lift fixtures, and all other Mechanical Ground Support Equipment. Includes (Notes: (1) Substantial contributions of ATLO MGSE from the Subsystems and GDS are costed elsewhere. (2) This is a coordinated activity.
10.11	Logistics& Transport	**Logistics and Transport:** Provide labor and transportation for shipment of the Flight System to its Launch Site. Includes travel costs for personnel during shipment; expenses for common carrier or other transportation means.
10.12	Launch Site Suppt	**Launch Site Support:** Provide Labor and travel associated with on-site support of post-ship checkout, any Launch Vehicle Interface Compatibility Tests, and integration of the Flight System with the Launch System. Includes time period from arrival of the Flight System at the Launch Site to Launch + 30 days.
11	**Educ & Pub Outreach**	**Education and Public Outreach: Provide for the Education and Public Outreach (EPO) responsibilities of JPL's missions, projects, and programs in alignment with NASA's Strategic plan for Education. Includes management and coordinated activities, formal education, informal education, public outreach, media support, and web site development.**
12	**Mission Design**	**Mission Design: Manage and develop the project mission and navigation designs. Includes all mission analysis; mission engineering; and navigation design. Also includes management of Mission Design schedules, cost and performance, liaison with all elements of the project, and support of Project design teams and reviews.**
12.01	Mssn Dsgn Mgmt	**Mission Design Management:** Manage and provide leadership for Mission and Navigation design, development, schedule and cost activities for the project. Includes liaison with the project to ensure the interfaces between the Mission and Navigation Design Teams and all elements of the project are defined; ensuring level 3 mission design requirements are defined and tests are performed; supporting design team meetings and Project reviews; leading Mission and Navigation design reviews. Includes PEM or team lead; Deputy (if any); and administrative support.

WBS Num	Element Name	Element Description
12.02	Mssn Anls	**Mission Analysis:** Perform trajectory and mission analysis (including aero/ EDL, low-thrust, n-body, tour design, etc.), mission planning, mission analysis software, and special studies (Launch Approval/ NEPA, Planetary Protection, Entry Vehicle Breakup, Orbital Debris, etc.). Includes launch vehicle performance. Plan and develop the Project's end-to-end mission scenarios. Includes, for example: developing planning and operational guidelines and constraints for the mission; supporting DSN requirements and interface definition; developing Earth-relative departure targets for the launch vehicle upper-stage; evaluating utilization of the launch period; analyzing the trajectory and orbit design of the various mission phases for compliance with planetary protection requirements; providing system administration support for Unix computers owned and operated by the Mission Design Team. The main products are: Mission Requirements Document; Target Specification; Mission Plan; Trajectory Characteristics Document. Generally starts in Phase A and goes through Phase D.
12.03	Mssn Eng	**Mission Engineering:** Develop mission requirements; conduct trade studies on cross-system issues of operating the spacecraft, payload and ground systems; develop operating scenarios and resource budgets, and document the Mission Plan.
12.04	Nav Dsgn	**Navigation Design:** Includes radiometric and optical orbit determination, maneuver analysis, launch support, and navigation design software. Perform maneuver and orbit determination analyses in support of the Mission and Navigation Design Team. Includes, for example: performing maneuver analyses to determine propulsive maneuver locations; statistical Delta-V, propellant budgets, probabilities of impact and delivery errors at the target body; developing launch vehicle injection targets biased for planetary protection purposes; developing an end-to-end baseline trajectory for the entire mission; analyzing the spacecraft design for operability (ephemeris prediction requirements) in the primary science orbit; provide system administration support for Unix computers owned and operated by the Mission and Navigation Design Team. The main products are: Navigation Plan; Performance Assessment Report. Generally starts in Phase A and goes through Phase D. Products include Navigation Plan and Performance Assessment Report.

Flagship TMC Cost Table1 for Baseline
FY Costs in Millions of Fixed Year FY07 Dollars (to nearest thousand)

Europa Explorer Cost Element	Proposed Costs – NASA																							Contributions	TOTAL
																									0
		Pre-A	Phase A/B			Phase C/D							Phase E											Phase B-E	
Phase A/B/C/D (Development)	**Total**	FY2008	FY2009	FY2010	**Total**	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	**Total**	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025		
Proj. Mgmt/Safety & MA/Sys. Eng./Msn Design	**56.328**	**8.000**	**19.082**	**29.246**	**221.151**	**5.857**	**42.346**	**45.755**	**49.575**	**44.493**	**33.125**														**277.480**
Payload Mgmt & Payload Systems Engr.	**7.752**		3.101	4.651	**16.913**	0.502	5.733	5.237	3.371	1.412	0.657														24.665
Wide-Angle Camera (WAC)	**1.435**		0.574	0.861	**12.915**	0.384	4.378	3.999	2.574	1.078	0.502														14.350
Medium-Angle Stereo Camera (MAC)	**2.509**		1.004	1.505	**22.580**	0.671	7.654	6.991	4.501	1.885	0.877														25.089
Narrow-Angle Camera (NAC)	**3.033**		1.213	1.820	**27.301**	0.811	9.255	8.453	5.442	2.280	1.061														30.334
IR Spectrometer (IRS)	**4.194**		1.678	2.516	**37.747**	1.121	12.796	11.687	7.524	3.152	1.467														41.941
UV Spectrometer (UVS)	**2.781**		1.112	1.668	**25.027**	0.743	8.484	7.749	4.989	2.090	0.972														27.808
Laser Altimeter (LA)	**3.592**		1.437	2.155	**32.324**	0.960	10.958	10.008	6.443	2.699	1.256														35.916
Ice Penetrating Radar (IPR)	**9.113**		3.645	5.468	**82.016**	2.436	27.802	25.394	16.349	6.848	3.187														91.129
Thermal Instrument (TI)	**2.635**		1.054	1.581	**23.713**	0.704	8.039	7.342	4.727	1.980	0.921														26.348
Magnetometer (MAG)	**0.781**		0.312	0.468	**7.025**	0.209	2.381	2.175	1.400	0.587	0.273														7.805
Ion & Neutral Mass Spectrometer (INMS)	**4.484**		1.794	2.691	**40.360**	1.199	13.681	12.496	8.045	3.370	1.568														44.844
Particle & Plasma Instrument (PPI)	**2.487**		0.995	1.492	**22.384**	0.665	7.588	6.931	4.462	1.869	0.870														24.872
Instrument Integration, Assembly and Test	Included in individual Instrument costs																								
Subtotal - Instruments	**44.796**	**0.000**	**17.918**	**26.878**	**350.305**	**10.405**	**118.749**	**108.463**	**69.828**	**29.249**	**13.611**													**0.000**	**395.101**
Spacecraft Bus	**88.210**		35.284	52.926	**367.426**	10.914	124.553	113.763	73.241	30.679	14.276														455.636
Flight System Integration, Assembly and Test	**4.354**		1.741	2.612	**37.536**	3.094	4.652	2.292	6.728	10.923	9.848														41.890
Launch Ops (Launch+30 days)	Included in Flight System Integration & Test																								
Subtotal - Spacecraft	**92.564**	**0.000**	**37.025**	**55.538**	**404.962**	**14.007**	**129.205**	**116.055**	**79.969**	**41.602**	**24.125**													**0.000**	**497.526**
Science Team Support	**20.754**		8.302	12.453	**54.019**	1.605	18.312	16.725	10.768	4.510	2.099														74.773
Pre-Launch GDS/MOS Development	**4.250**		1.700	2.550	**79.563**	3.189	9.392	10.772	14.508	16.736	24.966														83.813
DSN/Tracking Support	**0.000**				**2.397**						2.397														2.397
E/PO	**1.099**		0.440	0.659	**5.590**	0.166	1.895	1.731	1.114	0.467	0.217														6.689
Other (4)																									0.000
Subtotal Phase B/C/D before Reserves	**219.791**	**8.000**	**84.467**	**127.324**	**1,117.988**	**35.230**	**319.899**	**299.501**	**225.762**	**137.057**	**100.539**													**0.000**	**1,337.779**
Total Reserves	**63.520**		15.880	47.640	**413.656**	13.035	118.362	110.815	83.532	50.711	37.200														477.175
Total Phase B/C/D	**283.310**	**8.000**	**100.347**	**174.963**	**1,531.643**	**48.265**	**438.261**	**410.316**	**309.293**	**187.769**	**137.739**													**0.000**	**1,814.954**
Phase E (Operations)																									
Mission Operations & Data Analysis (including Project Management)												**332.753**	33.169	32.034	30.941	30.427	36.361	36.066	36.005	35.760	39.938	21.472	0.581		332.753
DSN/Tracking Network												**120.349**	11.996	11.586	11.191	11.005	13.151	13.044	13.022	12.933	14.445	7.766	0.210		120.349
Science Team												**203.417**	20.277	19.583	18.915	18.600	22.228	22.048	22.010	21.860	24.415	13.126	0.355		203.417
E/PO												**13.398**	1.336	1.290	1.246	1.225	1.464	1.452	1.450	1.440	1.608	0.865	0.023		13.398
Subtotal Phase E before Reserves												**669.917**	**66.777**	**64.493**	**62.293**	**61.257**	**73.203**	**72.611**	**72.486**	**71.994**	**80.406**	**43.228**	**1.170**	**0.000**	**669.917**
Reserves												**100.488**	10.017	9.674	9.344	9.189	10.980	10.892	10.873	10.799	12.061	6.484	0.175		100.488
Total Phase E												**770.405**	**76.794**	**74.166**	**71.637**	**70.445**	**84.184**	**83.502**	**83.359**	**82.793**	**92.467**	**49.712**	**1.345**	**0.000**	**770.405**
Launch Services					**501.552**			0.536	120.007	200.263	180.746														**501.552**
RPS	**22.300**		6.690	15.610	**200.700**	20.700	36.000	72.000	72.000																**223.000**
Total NASA Phase A-E	**305.610**	**8.000**	**107.037**	**190.573**	**2,233.895**	**68.965**	**474.261**	**482.852**	**501.301**	**388.032**	**318.485**	**770.405**	**76.794**	**74.166**	**71.637**	**70.445**	**84.184**	**83.502**	**83.359**	**82.793**	**92.467**	**49.712**	**1.345**	**0.000**	**3,309.910**
Phase F (Extended Mission)																									**0.000**
PSP																									**0.000**
DAP																									**0.000**
Total NASA	**305.610**	**8.000**	**107.037**	**190.573**	**2,233.895**	**68.965**	**474.261**	**482.852**	**501.301**	**388.032**	**318.485**	**770.405**	**76.794**	**74.166**	**71.637**	**70.445**	**84.184**	**83.502**	**83.359**	**82.793**	**92.467**	**49.712**	**1.345**	**0.000**	**3,309.910**

Flagship TMC Cost Table 2 for Baseline

FY Costs in Millions of Fixed Year FY07 Dollars (to nearest thousand)

Europa Explorer Cost Element	Proposed Costs NASA																							TOTAL
																								0
		Pre-A	Phase A/B		Phase C/D							Phase E												
Phases A/B/C/D/E	**Total**	FY2008	FY2009	FY2010	**Total**	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	**Total**	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	
01 Project Management	**24.467**	**8.000**	**11.117**	**5.350**	**76.615**	**2.029**	**14.670**	**15.851**	**17.175**	**15.414**	**11.476**	**33.638**	**3.353**	**3.238**	**3.128**	**3.076**	**3.676**	**3.646**	**3.640**	**3.615**	**4.037**	**2.171**	**0.059**	**134.719**
02 Project System Engineering	**13.187**		**3.297**	**9.891**	**67.079**	**1.777**	**12.844**	**13.878**	**15.037**	**13.496**	**10.047**	**20.098**	**2.003**	**1.935**	**1.869**	**1.838**	**2.196**	**2.178**	**2.175**	**2.160**	**2.412**	**1.297**	**0.035**	**100.364**
03 Safety & Mission Assurance	**13.187**		**3.297**	**9.891**	**67.079**	**1.777**	**12.844**	**13.878**	**15.037**	**13.496**	**10.047**	**20.098**	**2.003**	**1.935**	**1.869**	**1.838**	**2.196**	**2.178**	**2.175**	**2.160**	**2.412**	**1.297**	**0.035**	**100.364**
04 Science	**20.754**		**8.302**	**12.453**	**54.019**	**1.605**	**18.312**	**16.725**	**10.768**	**4.510**	**2.099**	**203.417**	**20.277**	**19.583**	**18.915**	**18.600**	**22.228**	**22.048**	**22.010**	**21.860**	**24.415**	**13.126**	**0.355**	**278.190**
05 Payload System	**44.796**		**17.918**	**26.878**	**350.305**	**10.405**	**118.749**	**108.463**	**69.828**	**29.249**	**13.611**													**395.101**
05.01 Payload Management	2.983		1.193	1.790	8.070	0.240	2.736	2.499	1.609	0.674	0.314													11.054
05.02 Payload System Engineering	4.769		1.908	2.862	8.842	0.263	2.997	2.738	1.763	0.738	0.344													13.612
05.03 Wide-Angle Camera (WAC)	1.435		0.574	0.861	12.915	0.384	4.378	3.999	2.574	1.078	0.502													14.350
05.04 Medium-Angle Camera (MAC)	2.509		1.004	1.505	22.580	0.671	7.654	6.991	4.501	1.885	0.877													25.089
05.05 Narrow Angle Camera (NAC)	3.033		1.213	1.820	27.301	0.811	9.255	8.453	5.442	2.280	1.061													30.334
05.06 IR Spectrometer (IRS)	4.194		1.678	2.516	37.747	1.121	12.796	11.687	7.524	3.152	1.467													41.941
05.07 UV Spectrometer (UVS)	2.781		1.112	1.668	25.027	0.743	8.484	7.749	4.989	2.090	0.972													27.808
05.08 Laser Altimeter (LA)	3.592		1.437	2.155	32.324	0.960	10.958	10.008	6.443	2.699	1.256													35.916
05.09 Ice Penetrating Radar (IPR)	9.113		3.645	5.468	82.016	2.436	27.802	25.394	16.349	6.848	3.187													91.129
05.10 Thermal Instrument (TI)	2.635		1.054	1.581	23.713	0.704	8.039	7.342	4.727	1.980	0.921													26.348
05.11 Magnetometer (MAG)	0.781		0.312	0.468	7.025	0.209	2.381	2.175	1.400	0.587	0.273													7.805
05.12 Ion and Neutral Mass Spectrometer (INMS)	4.484		1.794	2.691	40.360	1.199	13.681	12.496	8.045	3.370	1.568													44.844
05.13 Particle & Plasma Instru.(PPI)	2.487		0.995	1.492	22.384	0.665	7.588	6.931	4.462	1.869	0.870													24.872
06 Spacecraft System	**88.210**		**35.284**	**52.926**	**367.426**	**10.914**	**124.553**	**113.763**	**73.241**	**30.679**	**14.276**													**455.636**
06.01 S/C Management	1.764		0.706	1.059	7.349	0.218	2.491	2.275	1.465	0.614	0.286													9.113
06.02 Spacecraft System Engineering	9.702		3.881	5.821	22.006	0.654	7.460	6.814	4.387	1.837	0.855													31.709
06.03 Spacecraft Product Assurance	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													0.000
06.04 Power SS	7.896		3.158	4.737	35.525	1.055	12.043	10.999	7.081	2.966	1.380													43.420
06.05 C&DH SS	15.762		6.305	9.457	35.324	1.049	11.974	10.937	7.041	2.949	1.373													51.086
06.06 Telecom SS	5.563		2.225	3.338	30.949	0.919	10.491	9.583	6.169	2.584	1.203													36.513
06.07 Mechanical SS	15.152		6.061	9.091	85.508	2.540	28.986	26.475	17.045	7.140	3.322													100.659
06.08 Thermal SS	2.925		1.170	1.755	10.887	0.323	3.691	3.371	2.170	0.909	0.423													13.812
06.09 Propulsion SS	6.234		2.494	3.740	27.143	0.806	9.201	8.404	5.410	2.266	1.055													33.377
06.10 AACS	17.908		7.163	10.745	57.781	1.716	19.587	17.890	11.518	4.824	2.245													75.688
06.11 Harness	0.982		0.393	0.589	9.219	0.274	3.125	2.854	1.838	0.770	0.358													10.201
06.12 FSW	3.028		1.211	1.817	28.316	0.841	9.599	8.767	5.644	2.364	1.100													31.344
06.13 SC M&P	0.835		0.334	0.501	2.621	0.078	0.889	0.812	0.523	0.219	0.102													3.456
06.14 SC Testbeds	0.460		0.184	0.276	9.865	0.293	3.344	3.055	1.967	0.824	0.383													10.325
06.18 DTM / Trailblazer	0.000		0.000	0.000	4.933	0.147	1.672	1.527	0.983	0.412	0.192													4.933
07 Mission Operations System	**1.672**		**0.669**	**1.003**	**39.027**	**1.564**	**4.607**	**5.284**	**7.116**	**8.209**	**12.246**	**234.244**	**23.350**	**22.551**	**21.781**	**21.419**	**25.596**	**25.389**	**25.346**	**25.173**	**28.115**	**15.115**	**0.409**	**274.943**
09 Ground Data System	**2.578**		**1.031**	**1.547**	**40.536**	**1.625**	**4.785**	**5.488**	**7.391**	**8.527**	**12.720**	**24.675**	**2.460**	**2.375**	**2.294**	**2.256**	**2.696**	**2.675**	**2.670**	**2.652**	**2.962**	**1.592**	**0.043**	**67.789**
DSN Aperture	**0.000**		**0.000**	**0.000**	**2.397**						**2.397**	**120.349**	**11.996**	**11.586**	**11.191**	**11.005**	**13.151**	**13.044**	**13.022**	**12.933**	**14.445**	**7.766**	**0.210**	**122.746**
10 Project System Integration & Test	**4.354**		**1.741**	**2.612**	**37.536**	**3.094**	**4.652**	**2.292**	**6.728**	**10.923**	**9.848**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**41.890**
11 Education and Public Outreach	**1.099**		**0.440**	**0.659**	**5.590**	**0.166**	**1.895**	**1.731**	**1.114**	**0.467**	**0.217**	**13.398**	**1.336**	**1.290**	**1.246**	**1.225**	**1.464**	**1.452**	**1.450**	**1.440**	**1.608**	**0.865**	**0.023**	**20.087**
12 Mission Design	**5.487**		**1.372**	**4.115**	**10.378**	**0.275**	**1.987**	**2.147**	**2.326**	**2.088**	**1.554**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**15.865**
Subtotal before Reserves	**219.791**	**8.000**	**84.467**	**127.324**	**1,117.988**	**35.230**	**319.899**	**299.501**	**225.762**	**137.057**	**100.539**	**669.917**	**66.777**	**64.493**	**62.293**	**61.257**	**73.203**	**72.611**	**72.486**	**71.994**	**80.406**	**43.228**	**1.170**	**2,007.696**
Reserves	**63.520**		**15.880**	**47.640**	**413.656**	**13.035**	**118.362**	**110.815**	**83.532**	**50.711**	**37.200**	**100.488**	**10.017**	**9.674**	**9.344**	**9.189**	**10.980**	**10.892**	**10.873**	**10.799**	**12.061**	**6.484**	**0.175**	**577.663**
Total A/B/C/D/E w/ Reserves (w/o LV or RPS)	**283.310**	**8.000**	**100.347**	**174.963**	**1,531.643**	**48.265**	**438.261**	**410.316**	**309.293**	**187.769**	**137.739**	**770.405**	**76.794**	**74.166**	**71.637**	**70.445**	**84.184**	**83.502**	**83.359**	**82.793**	**92.467**	**49.712**	**1.345**	**2,585.358**
Launch Services	**0.000**				**501.552**	**0.000**	**0.000**	**0.536**	**120.007**	**200.263**	**180.746**	**0.000**												**501.552**
RPS	**22.300**		**6.690**	**15.610**	**200.700**	**20.700**	**36.000**	**72.000**	**72.000**	**0.000**	**0.000**	**0.000**												**223.000**
Total NASA Phase A-E Cost	**305.610**	**8.000**	**107.037**	**190.573**	**2,233.895**	**68.965**	**474.261**	**482.852**	**501.301**	**388.032**	**318.485**	**770.405**	**76.794**	**74.166**	**71.637**	**70.445**	**84.184**	**83.502**	**83.359**	**82.793**	**92.467**	**49.712**	**1.345**	**3,309.910**

Flagship TMC Cost Table1 for Floor
FY Costs in Millions of Fixed Year FY07 Dollars (to nearest thousand)

Europa Explorer	Proposed Costs																							
Cost Element	**NASA**																							**TOTAL**
																								-
	Phase A/B				**Phase C/D**							**Phase E**												
Phase B/C/D (Development)	**Total**	FY2008	FY2009	FY2010	**Total**	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	**Total**	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	
Proj. Mgmt/Safety & MA/Sys. Eng./Msn Design	**50.832**	**8.000**	**17.708**	**25.124**	**184.393**	**4.884**	**35.307**	**38.150**	**41.335**	**37.098**	**27.619**													**235.225**
Payload Mgmt & Payload Systems Engr.	**5.535**		2.214	3.321	**11.978**	0.356	4.060	3.709	2.388	1.000	0.465													17.513
Wide-Angle Camera (WAC)	**1.435**		0.574	0.861	**12.915**	0.384	4.378	3.999	2.574	1.078	0.502													14.350
Medium-Angle Stereo Camera (MAC)	**2.025**		0.810	1.215	**18.226**	0.541	6.178	5.643	3.633	1.522	0.708													20.251
Narrow-Angle Camera (NAC)	**-**		-	-	**-**	-	-	-	-	-	-													-
IR Spectrometer (IRS)	**3.323**		1.329	1.994	**29.907**	0.888	10.138	9.260	5.961	2.497	1.162													33.230
UV Spectrometer (UVS)	**-**		-	-	**-**	-	-	-	-	-	-													-
Laser Altimeter (LA)	**2.578**		1.031	1.547	**23.200**	0.689	7.865	7.183	4.625	1.937	0.901													25.778
Ice Penetrating Radar (IPR)	**8.113**		3.245	4.868	**73.018**	2.169	24.752	22.608	14.555	6.097	2.837													81.131
Thermal Instrument (TI)	**1.633**		0.653	0.980	**14.696**	0.437	4.982	4.550	2.929	1.227	0.571													16.329
Magnetometer (MAG)	**0.621**		0.248	0.372	**5.585**	0.166	1.893	1.729	1.113	0.466	0.217													6.206
Ion & Neutral Mass Spectrometer (INMS)	**-**		-	-	**-**	-	-	-	-	-	-													-
Particle & Plasma Instrument (PPI)	**2.420**		0.968	1.452	**21.780**	0.647	7.383	6.744	4.342	1.819	0.846													24.200
Instrument Integration, Assembly and Test	Included in individual Instrument costs																							
Subtotal - Instruments	**27.682**	**-**	**11.073**	**16.609**	**211.306**	**6.276**	**71.630**	**65.425**	**42.121**	**17.643**	**8.210**													**238.988**
Spacecraft Bus	**87.933**		35.173	52.760	**364.429**	10.825	123.537	112.835	72.643	30.429	14.160													452.362
Flight System Integration, Assembly and Test	**4.354**		1.741	2.612	**37.536**	3.094	4.652	2.292	6.728	10.923	9.848													41.890
Launch Ops (Launch+30 days)	Included in Flight System Integration & Test																							
Subtotal - Spacecraft	**92.287**	**-**	**36.915**	**55.372**	**401.965**	**13.918**	**128.189**	**115.127**	**79.371**	**41.351**	**24.008**													**494.251**
Science Team Support	**12.541**		5.016	7.525	**32.641**	0.970	11.065	10.107	6.507	2.725	1.268													45.182
Pre-Launch GDS/MOS Development	**4.199**		1.680	2.519	**72.655**	2.912	8.576	9.837	13.248	15.283	22.798													76.854
DSN/Tracking Support	**-**				**2.397**						2.397													2.397
E/PO	**0.942**		0.377	0.565	**4.550**	0.135	1.542	1.409	0.907	0.380	0.177													5.492
Other (4)																								-
Subtotal Phase B/C/D before Reserves	**188.484**	**8.000**	**72.769**	**107.715**	**909.907**	**29.096**	**256.310**	**240.054**	**183.488**	**114.481**	**86.478**													**1,098.390**
Total Reserves	**61.069**		15.267	45.802	**382.161**	12.220	107.650	100.823	77.065	48.082	36.321													443.229
Total Phase B/C/D	**249.552**	**8.000**	**88.036**	**153.516**	**1,292.067**	**41.316**	**363.960**	**340.877**	**260.553**	**162.563**	**122.798**													**1,541.620**
Phase E (Operations)																								
Mission Operations & Data Analysis (including Project Management)												**270.619**	26.975	26.052	25.164	24.745	29.571	29.332	29.282	29.082	32.481	17.462	0.473	270.619
DSN/Tracking Network												**100.438**	10.012	9.669	9.339	9.184	10.975	10.886	10.868	10.794	12.055	6.481	0.175	100.438
Science Team												**122.917**	12.252	11.833	11.429	11.239	13.431	13.323	13.300	13.209	14.753	7.931	0.215	122.917
E/PO												**10.081**	1.005	0.971	0.937	0.922	1.102	1.093	1.091	1.083	1.210	0.651	0.018	10.081
Subtotal Phase E before Reserves												**504.055**	**50.244**	**48.525**	**46.870**	**46.091**	**55.079**	**54.633**	**54.540**	**54.169**	**60.499**	**32.525**	**0.880**	**504.055**
Reserves												**75.608**	7.537	7.279	7.030	6.914	8.262	8.195	8.181	8.125	9.075	4.879	0.132	75.608
Total Phase E												**579.663**	**57.781**	**55.804**	**53.900**	**53.004**	**63.341**	**62.828**	**62.721**	**62.294**	**69.574**	**37.404**	**1.012**	**579.663**
Launch Services					**176.472**			0.482	41.898	69.919	64.174													**176.472**
RPS	**12.100**		3.630	8.470	**108.900**	13.900	19.000	38.000	38.000															**121.000**
Total NASA Phase A-E	**261.652**	**8.000**	**91.666**	**161.986**	**1,577.439**	**55.216**	**382.960**	**379.359**	**340.451**	**232.481**	**186.972**	**579.663**	**57.781**	**55.804**	**53.900**	**53.004**	**63.341**	**62.828**	**62.721**	**62.294**	**69.574**	**37.404**	**1.012**	**2,418.755**
Phase F (Extended Mission)																								**-**
PSP																								**-**
DAP																								**-**
Total NASA	**261.652**	**8.000**	**91.666**	**161.986**	**1,577.439**	**55.216**	**382.960**	**379.359**	**340.451**	**232.481**	**186.972**	**579.663**	**57.781**	**55.804**	**53.900**	**53.004**	**63.341**	**62.828**	**62.721**	**62.294**	**69.574**	**37.404**	**1.012**	**2,418.755**

FOLDOUT 10 (4 OF 4)
FLAGSHIP TMC COST TABLE 2—FLOOR

Flagship TMC Cost Table 2 for Floor
FY Costs in Millions of Fixed Year FY07 Dollars (to nearest thousand)

Europa Explorer Cost Element	Proposed Costs NASA																							TOTAL
		Pre-A	Phase A/B		Phase C/D							Phase E												0
Phases A/B/C/D/E	**Total**	FY2008	FY2009	FY2010	**Total**	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	**Total**	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025	
01 Project Management	**22.728**	**8.000**	**10.682**	**4.046**	**64.826**	**1.717**	**12.413**	**13.412**	**14.532**	**13.042**	**9.710**	**26.185**	**2.610**	**2.521**	**2.435**	**2.394**	**2.861**	**2.838**	**2.833**	**2.814**	**3.143**	**1.690**	**0.046**	**113.738**
02 Project System Engineering	**11.309**		**2.827**	**8.482**	**54.594**	**1.446**	**10.454**	**11.295**	**12.238**	**10.984**	**8.177**	**15.122**	**1.507**	**1.456**	**1.406**	**1.383**	**1.652**	**1.639**	**1.636**	**1.625**	**1.815**	**0.976**	**0.026**	**81.025**
03 Safety & Mission Assurance	**11.309**		**2.827**	**8.482**	**54.594**	**1.446**	**10.454**	**11.295**	**12.238**	**10.984**	**8.177**	**15.122**	**1.507**	**1.456**	**1.406**	**1.383**	**1.652**	**1.639**	**1.636**	**1.625**	**1.815**	**0.976**	**0.026**	**81.025**
04 Science	**12.541**		**5.016**	**7.525**	**32.641**	**0.970**	**11.065**	**10.107**	**6.507**	**2.725**	**1.268**	**122.917**	**12.252**	**11.833**	**11.429**	**11.239**	**13.431**	**13.323**	**13.300**	**13.209**	**14.753**	**7.931**	**0.215**	**168.099**
05 Payload System	**27.682**		**11.073**	**16.609**	**211.306**	**6.276**	**71.630**	**65.425**	**42.121**	**17.643**	**8.210**													**238.988**
05.01 Payload Management	2.043		0.817	1.226	5.564	0.165	1.886	1.723	1.109	0.465	0.216													7.607
05.02 Payload System Engineering	3.492		1.397	2.095	6.414	0.191	2.174	1.986	1.279	0.536	0.249													9.906
05.03 Wide-Angle Camera (WAC)	1.435		0.574	0.861	12.915	0.384	4.378	3.999	2.574	1.078	0.502													14.350
05.04 Medium-Angle Camera (MAC)	2.025		0.810	1.215	18.226	0.541	6.178	5.643	3.633	1.522	0.708													20.251
05.05 Narrow Angle Camera (NAC)	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													0.000
05.06 IR Spectrometer (IRS)	3.323		1.329	1.994	29.907	0.888	10.138	9.260	5.961	2.497	1.162													33.230
05.07 UV Spectrometer (UVS)	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													0.000
05.08 Laser Altimeter (LA)	2.578		1.031	1.547	23.200	0.689	7.865	7.183	4.625	1.937	0.901													25.778
05.09 Ice Penetrating Radar (IPR)	8.113		3.245	4.868	73.018	2.169	24.752	22.608	14.555	6.097	2.837													81.131
05.10 Thermal Instrument (TI)	1.633		0.653	0.980	14.696	0.437	4.982	4.550	2.929	1.227	0.571													16.329
05.11 Magnetometer (MAG)	0.621		0.248	0.372	5.585	0.166	1.893	1.729	1.113	0.466	0.217													6.206
05.12 Ion and Neutral Mass Spectrometer (INMS)	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													0.000
05.13 Particle & Plasma Instru.(PPI)	2.420		0.968	1.452	21.780	0.647	7.383	6.744	4.342	1.819	0.846													24.200
06 Spacecraft System	**87.933**		**35.173**	**52.760**	**364.429**	**10.825**	**123.537**	**112.835**	**72.643**	**30.429**	**14.160**													**452.362**
06.01 S/C Management	1.759		0.703	1.055	7.289	0.216	2.471	2.257	1.453	0.609	0.283													9.047
06.02 Spacecraft System Engineering	9.431		3.772	5.658	20.805	0.618	7.053	6.442	4.147	1.737	0.808													30.236
06.03 Spacecraft Product Assurance	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													0.000
06.04 Power SS	7.896		3.158	4.737	35.525	1.055	12.043	10.999	7.081	2.966	1.380													43.420
06.05 C&DH SS	15.762		6.305	9.457	35.324	1.049	11.974	10.937	7.041	2.949	1.373													51.086
06.06 Telecom SS	5.563		2.225	3.338	30.949	0.919	10.491	9.583	6.169	2.584	1.203													36.513
06.07 Mechanical SS	15.152		6.061	9.091	85.508	2.540	28.986	26.475	17.045	7.140	3.322													100.659
06.08 Thermal SS	2.925		1.170	1.755	10.887	0.323	3.691	3.371	2.170	0.909	0.423													13.812
06.09 Propulsion SS	6.234		2.494	3.740	27.143	0.806	9.201	8.404	5.410	2.266	1.055													33.377
06.10 AACS	17.908		7.163	10.745	57.781	1.716	19.587	17.890	11.518	4.824	2.245													75.688
06.11 Harness	0.982		0.393	0.589	9.219	0.274	3.125	2.854	1.838	0.770	0.358													10.201
06.12 FSW	3.028		1.211	1.817	26.979	0.801	9.145	8.353	5.378	2.253	1.048													30.007
06.13 SC M&P	0.835		0.334	0.501	2.621	0.078	0.889	0.812	0.523	0.219	0.102													3.456
06.14 SC Testbeds	0.460		0.184	0.276	9.600	0.285	3.254	2.972	1.914	0.802	0.373													10.059
06.18 DTM / Trailblazer	0.000		0.000	0.000	4.800	0.143	1.627	1.486	0.957	0.401	0.186													4.800
07 Mission Operations System	**1.672**		**0.669**	**1.003**	**33.991**	**1.363**	**4.012**	**4.602**	**6.198**	**7.150**	**10.666**	**191.499**	**19.089**	**18.435**	**17.807**	**17.511**	**20.925**	**20.756**	**20.721**	**20.580**	**22.984**	**12.357**	**0.334**	**227.162**
09 Ground Data System	**2.527**		**1.011**	**1.516**	**38.664**	**1.550**	**4.564**	**5.235**	**7.050**	**8.133**	**12.132**	**22.692**	**2.262**	**2.185**	**2.110**	**2.075**	**2.480**	**2.460**	**2.455**	**2.439**	**2.724**	**1.464**	**0.040**	**63.883**
DSN Aperture	**0.000**		**0.000**	**0.000**	**2.397**						**2.397**	**100.438**	**10.012**	**9.669**	**9.339**	**9.184**	**10.975**	**10.886**	**10.868**	**10.794**	**12.055**	**6.481**	**0.175**	**102.836**
10 Project System Integration & Test	**4.354**		**1.741**	**2.612**	**37.536**	**3.094**	**4.652**	**2.292**	**6.728**	**10.923**	**9.848**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**41.890**
11 Education and Public Outreach	**0.942**		**0.377**	**0.565**	**4.550**	**0.135**	**1.542**	**1.409**	**0.907**	**0.380**	**0.177**	**10.081**	**1.005**	**0.971**	**0.937**	**0.922**	**1.102**	**1.093**	**1.091**	**1.083**	**1.210**	**0.651**	**0.018**	**15.573**
12 Mission Design	**5.487**		**1.372**	**4.115**	**10.378**	**0.275**	**1.987**	**2.147**	**2.326**	**2.088**	**1.554**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**15.865**
Subtotal before Reserves	**188.484**	**8.000**	**72.769**	**107.715**	**909.907**	**29.096**	**256.310**	**240.054**	**183.488**	**114.481**	**86.478**	**504.055**	**50.244**	**48.525**	**46.870**	**46.091**	**55.079**	**54.633**	**54.540**	**54.169**	**60.499**	**32.525**	**0.880**	**1,602.445**
Reserves	**61.069**		**15.267**	**45.802**	**382.161**	**12.220**	**107.650**	**100.823**	**77.065**	**48.082**	**36.321**	**75.608**	**7.537**	**7.279**	**7.030**	**6.914**	**8.262**	**8.195**	**8.181**	**8.125**	**9.075**	**4.879**	**0.132**	**518.838**
Total A/B/C/D/E w/ Reserves (w/o LV or RPS)	**249.552**	**8.000**	**88.036**	**153.516**	**1,292.067**	**41.316**	**363.960**	**340.877**	**260.553**	**162.563**	**122.798**	**579.663**	**57.781**	**55.804**	**53.900**	**53.004**	**63.341**	**62.828**	**62.721**	**62.294**	**69.574**	**37.404**	**1.012**	**2,121.283**
Launch Services	**0.000**				**176.472**	**0.000**	**0.000**	**0.482**	**41.898**	**69.919**	**64.174**													**176.472**
RPS	**12.100**		**3.630**	**8.470**	**108.900**	**13.900**	**19.000**	**38.000**	**38.000**	**0.000**	**0.000**													**121.000**
Total NASA Phase A-E Cost	**261.652**	**8.000**	**91.666**	**161.986**	**1,577.439**	**55.216**	**382.960**	**379.359**	**340.451**	**232.481**	**186.972**	**579.663**	**57.781**	**55.804**	**53.900**	**53.004**	**63.341**	**62.828**	**62.721**	**62.294**	**69.574**	**37.404**	**1.012**	**2,418.755**

E. EARTH-JUPITER INTERPLANETARY TRAJECTORY OPTIONS

E1. Introduction

The VEEGA trajectories were chosen for the EE baseline and backup missions because of their high delivered mass, moderate flight times, and frequent availability. There are, of course, many different combinations of gravity assists with Earth, Venus, and/or Mars that can deliver a mission to Jupiter. A search was performed for trajectories from Earth to Jupiter for launch dates ranging from 2015 through 2024. While the search was fairly thorough, it was certainly not exhaustive. In addition, many of the trajectories can be modified by trading flight time and ΔV; this study did not have the resources to perform those types of options.

E2. Analysis Assumptions

The Atlas V 551 launch vehicle injected mass capabilities came directly from data on the NASA Launch Services Program Launch Vehicle Performance web site (http://elvperf.ksc.nasa.gov/elvMap/index.html). Post launch ΔVs are assumed to be accomplished with a high-thrust system with an Isp of 325 s, and only deterministic ΔVs are taken into account for the mass performance in these figures. The period of the orbit following Jupiter Orbit Insertion (JOI) is 200 days, and we did not account for a satellite flyby on approach for these mass performances.

E3. Trajectory Results

Examples of the results are shown in **Figures E-1**, **E-2**, and **E-3**. **Figure E-1** shows that there is significant overlap between the performances of the different trajectory types. Loose groupings emerge after brief examination, however. The trajectories with the shortest time-of-flight (TOF) are the single Earth gravity assists, although those have poor delivered mass performance. While the largest delivered mass over the 10-year period studied is by a VEVE trajectory, in all but that one case, the VEEGA, VVEE, and VEME trajectories produced better delivered mass performance for a given TOF than the VEVE trajectories. In the category of performance > 3500 kg, the VEEGAs have a significant advantage in TOF over the otherwise similar delivery mass performance of the VEME and VVEE trajectories.

There is a wealth of information buried in these plots, but given the challenges of delivering sufficient mass to Jupiter, the VEEGAs generally offer the best performance for trajectories over 5.5 years in TOF to Jupiter.

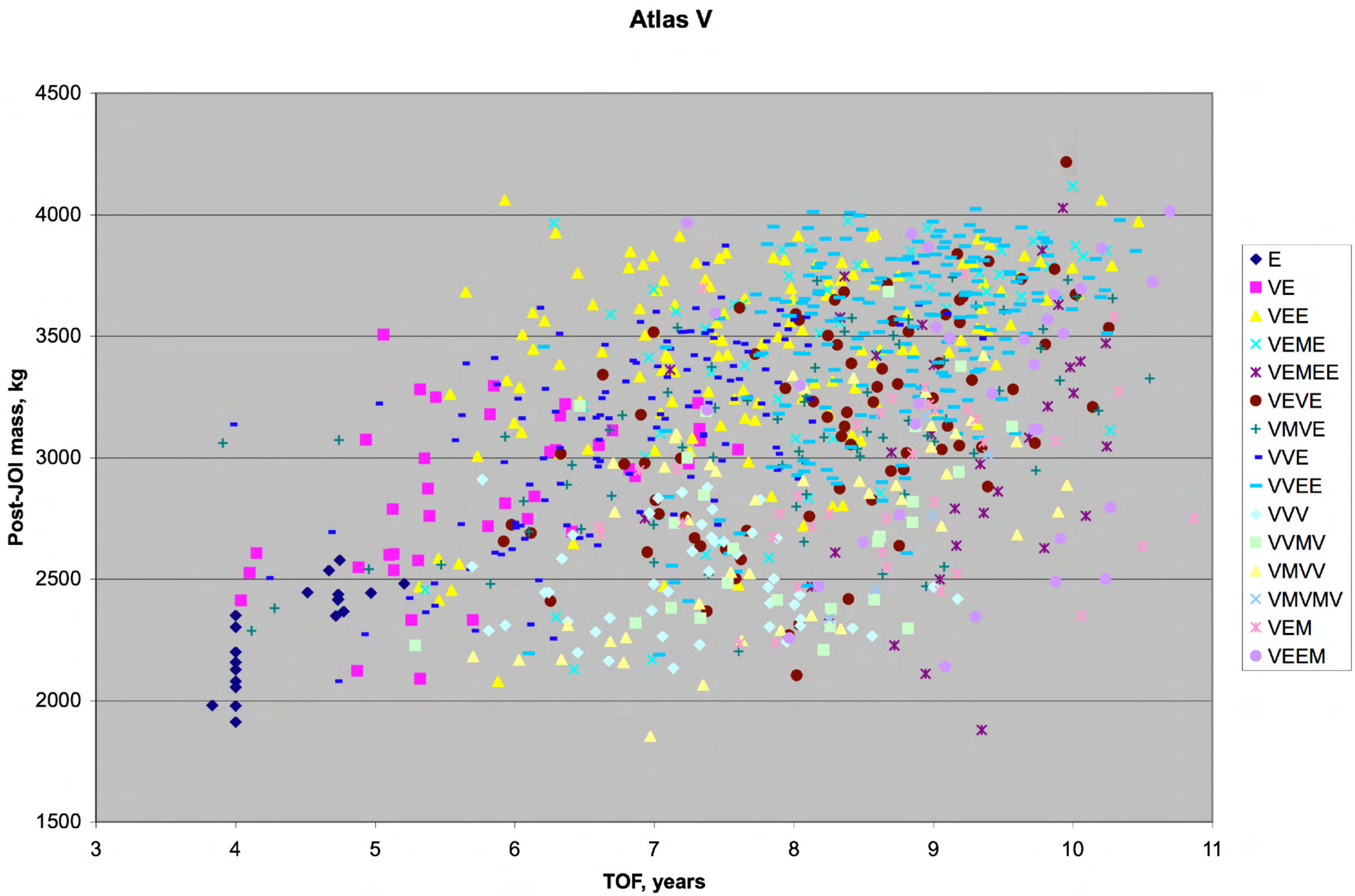


Figure E-1. Mass delivered to 200-day orbit around Jupiter versus flight time from Earth to Jupiter for an Atlas V 551 launch vehicle.

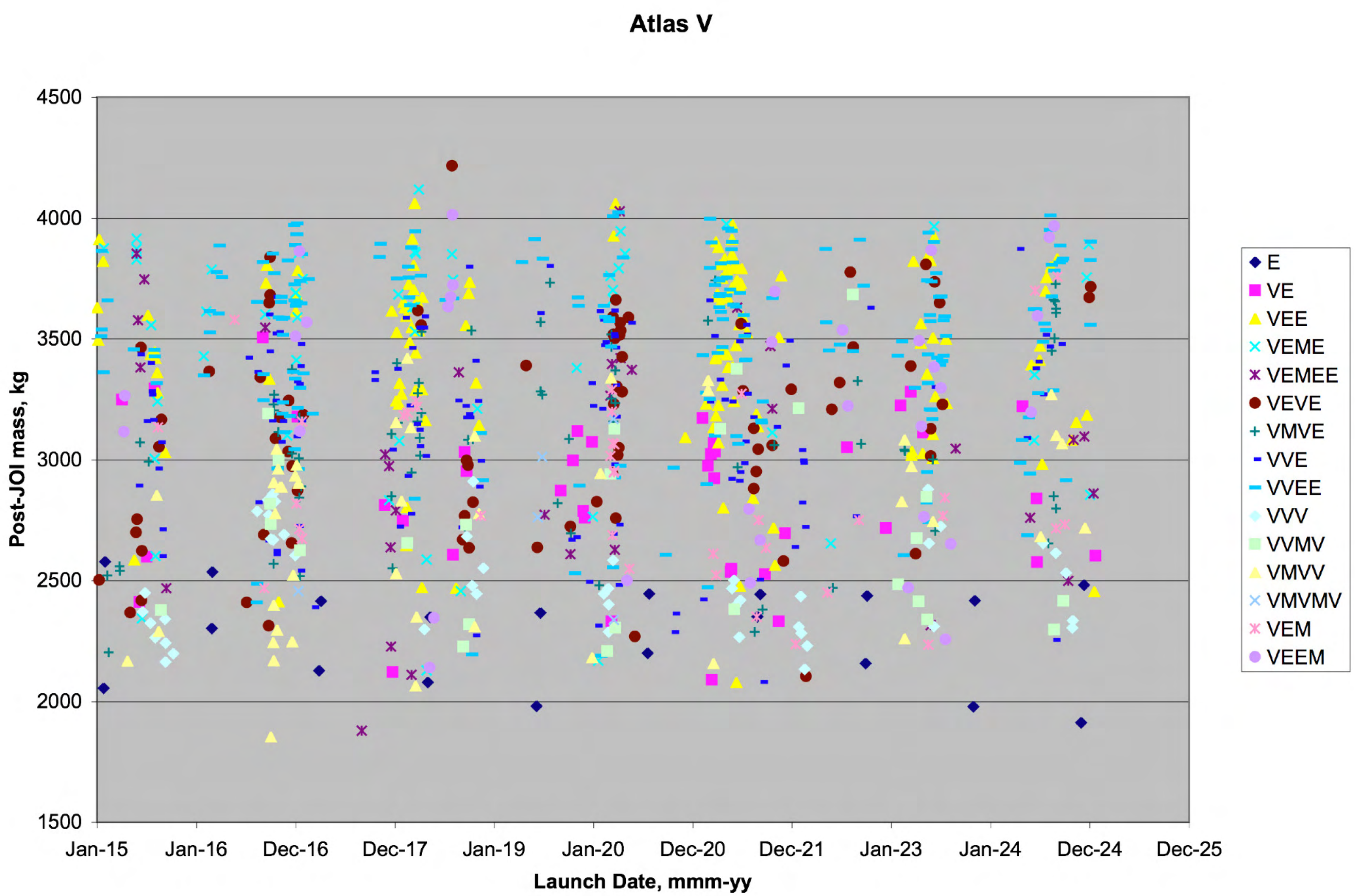


Figure E-2. Mass delivered to 200-day orbit around Jupiter versus launch date for an Atlas V 551 launch vehicle.

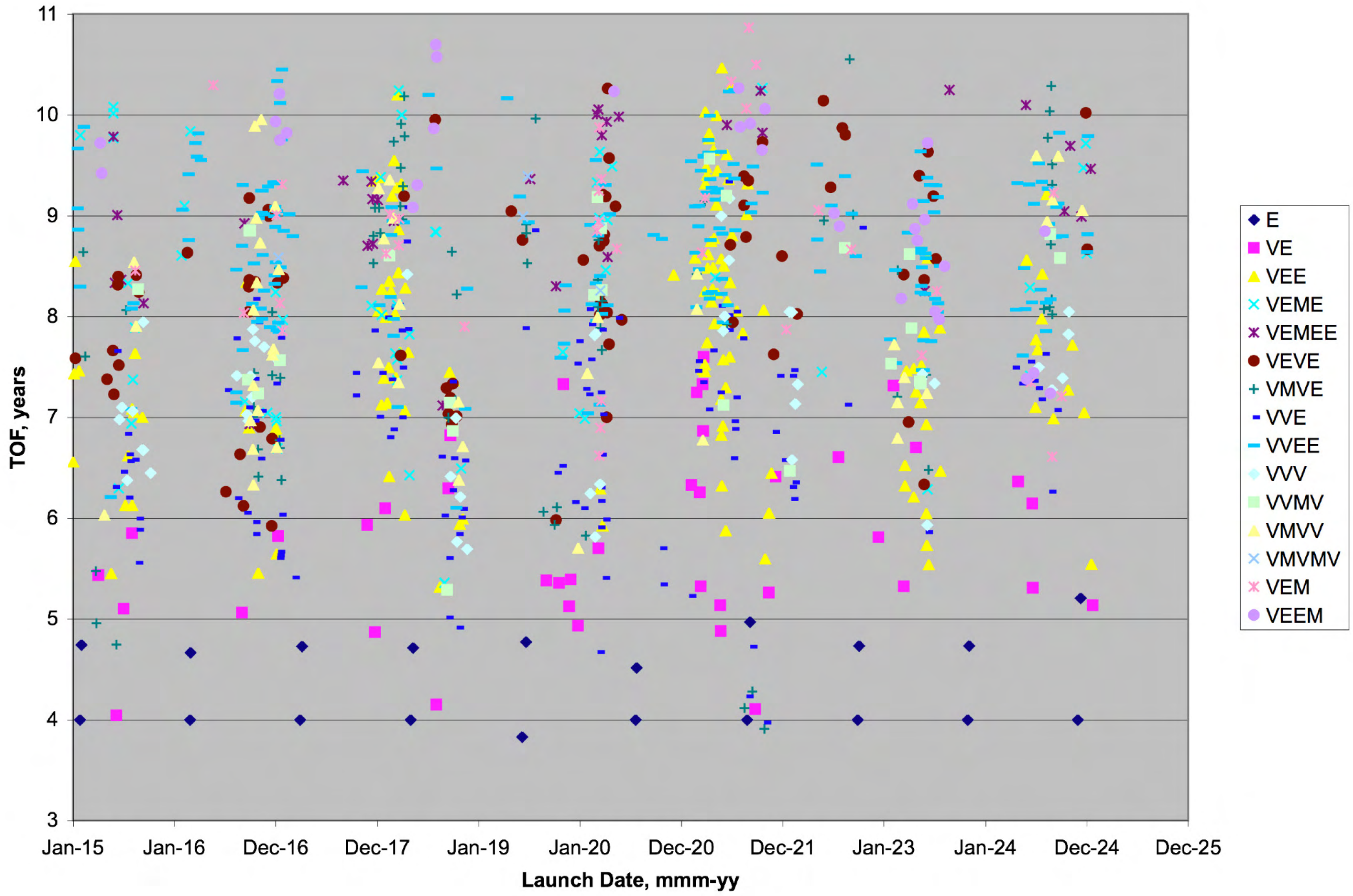


Figure E-3. Flight time from Earth to Jupiter versus launch date.

F. FLIGHT SYSTEM DESIGN SUPPORTING DETAIL

F1. Mass Equipment List (MEL)

The detailed Mass Equipment List is presented in **Table F1-1** for the baseline EE flight system concept. This table provides the instrument and assembly-level mass breakdown for the flight system.

Table F1-1. *Detailed Mass Equipment List for Baseline EE Flight System*

Subsystem / Component	Mass/Unit (CBE) kg	# Units	Total Mass (CBE) kg	Cont., %	Total Mass (CBE+Cont.) kg
Payload			158.00		205.40
Wide-Angle Camera (WAC) - color	3.00	1	3.00	30%	3.90
Medium-Angle Stereo Camera (MAC)	10.00	1	10.00	30%	13.00
Narrow Angle Camera (NAC)	15.00	1	15.00	30%	19.50
IR Spectrometer	25.00	1	25.00	30%	32.50
UV Spectrometer	15.00	1	15.00	30%	19.50
Laser Altimeter (LA)	15.00	1	15.00	30%	19.50
Ice Penetrating Radar (IPR)	36.00	1	36.00	30%	46.80
Thermal Imager (TI)	8.00	1	8.00	30%	10.40
Magnetometer (MAG)	2.00	2	4.00	30%	5.20
Ion and Neutral Mass Spectrometer (INMS)	15.00	1	15.00	30%	19.50
Particle and Plasma Instrument (PPI)	12.00	1	12.00	30%	15.60
ACS			50.80		69.80
IMU (Litton Scalable SIRU)	7.10	1	7.10	37%	9.76
SunSens (GalileoAvionica APS)	1.00	2	2.00	37%	2.75
Sun Acquisition Detectors	0.03	4	0.10	37%	0.14
Star Trackers (Jenna Optonik APS)	6.00	2	12.00	37%	16.49
Reaction Wheels (Teldix RSI 25Nms)	7.40	4	29.60	37%	40.67
C&DH			42.32		55.90
RAD750 w/ 128MB SRAM	2.00	2	4.00	20%	4.80
MSAP System Interface Assembly	0.90	2	1.80	20%	2.16
MSAP Telecommunications Interface Card	0.90	2	1.80	20%	2.16
MAGIC Card	0.90	2	1.80	20%	2.16
MSAP Remote Engineering Unit (RT receiving)	0.90	4	3.60	20%	4.32
HGA Gimbal Drive Electronics	0.50	2	1.00	30%	1.30
Power Converter Unit (see note)	1.00	2	2.00	30%	2.60
NVM Card (1.2 Gb CRAM)	1.00	2	2.00	30%	2.60
Computer Backplane	0.30	2	0.60	30%	0.78
Computer Chassis	4.00	2	8.00	30%	10.40
Cables	4.21	2	8.42	39%	11.67
Science Mass Memory SSR (1.2 Gb CRAM)	2.43	3	7.30	50%	10.95
Power			50.35		64.02
Chassis 1			20.40		26.21
Power Control Slice - PCS	0.80	2	1.60	35%	2.16
Power Switching Slice - PSS - general loads	0.90	4	3.60	30%	4.68
Power Switching Slice - PSS - Pyro	0.90	3	2.70	30%	3.51
Power Switching Slice - PSS-Propulsion	0.90	4	3.60	30%	4.68
RTIU - RTG Int. Card	1.00	1	1.00	30%	1.30
Power Converter Assembly - PCA	1.10	1	1.10	50%	1.65
Back Plane	1.40	1	1.40	25%	1.75
Chassis	5.40	1	5.40	20%	6.48

Subsystem / Component	Mass/Unit (CBE) kg	# Units	Total Mass (CBE) kg	Cont., %	Total Mass (CBE+Cont.) kg
Chassis 2			29.95		37.81
Power Control Slice - BCS	1.00	2	2.00	35%	2.70
Power Switching Slice - PSS - general loads	0.90	4	3.60	30%	4.68
Power Switching Slice - PSS - Pyro	0.90	3	2.70	30%	3.51
Power Switching Slice - PSS - Propulsion	0.90	4	3.60	30%	4.68
RTG Int. Card	1.00	1	1.00	30%	1.30
Power Converter Assembly- PCA	1.10	1	1.10	50%	1.65
Back plane	1.40	1	1.40	25%	1.75
Chassis	5.40	1	5.40	20%	6.48
LI-Ion Battery	8.80	1	8.80	20%	10.56
Cabling/ harness (box level)	0.35	1	0.35	43%	0.50
RPSs			291.00		305.55
MMRTGs	44.00	6	264.00	5%	277.20
Adapters	3.00	6	18.00	5%	18.90
Struts (Outboard RPSs only)	3.00	3	9.00	5%	9.45
Cabling			129.80		168.74
Cabling	129.80	1	129.80	30%	168.74
Propulsion			296.92		389.84
PCA Subsystem			5.05		5.81
High Pressure Latch Valve - 1/4"	0.34	2	0.68	30%	0.88
High Pressure Solenoid Valve - 1/4"	0.34	4	1.36	30%	1.77
Filter-GHe large capacity	0.40	2	0.80	2%	0.82
Pressure Transducer - High - 4000 psi	0.17	2	0.34	20%	0.41
Service Valve Low Pressure - 1/4"	0.15	2	0.31	5%	0.32
Service Valve High Pressure - 3/8"	0.21	2	0.42	5%	0.44
NC Pyro Isolation Valve-1/4"	0.12	6	0.72	2%	0.73
NO Pyro Isolation Valve-1/4"	0.12	2	0.24	2%	0.24
NSI	0.01	14	0.14	2%	0.14
Test Ports	0.01	4	0.04	20%	0.05
PIA Subsystem			6.82		7.30
NC Pyro Isolation Valve-3/8"	0.23	2	0.46	2%	0.47
NSI	0.01	9	0.09	2%	0.09
NC Pyro Isolation Valve-1/4"	0.12	2	0.24	2%	0.24
Service Valve Low Pressure - 1/4"	0.15	3	0.46	5%	0.49
NTO/N_2H_4 Latch Valve-3/8"	0.64	4	2.54	2%	2.59
Fuel/Oxid Venturi	0.03	4	0.12	20%	0.14
Adjustable Liquid Regulator, ALR - JPL	1.20	0	0.00	15%	0.00
Filter-Propellant-NTO/N_2H_4	0.40	3	1.20	2%	1.22
Pressure Transducer - Low - 400 psi	0.17	10	1.70	20%	2.04
Test Ports	0.01	1	0.01	20%	0.01
Tanks - N_2H_4, N_2O_4, GHe			244.38		327.14
Fuel Tank - 48.9in ID × 105in	153.25	1	153.25	30%	199.22
Oxidizer Tank - 48.9in ID × 67in	43.94	1	43.94	30%	57.13
Propellant Tank PMD's	0.00	2	0.00	30%	0.00
NTO GHe Tank	17.43	1	17.43	50%	26.14
N_2H_4 GHe Tank	29.77	1	29.77	50%	44.65
Main Engine Assembly			23.88		29.95

Subsystem / Component	Mass/Unit (CBE) kg	# Units	Total Mass (CBE) kg	Cont., %	Total Mass (CBE+Cont.) kg
Main Engine, 900N (200 lbf) 200:1 Area ratio	10.90	2	21.80	25%	27.25
Heat Shield	0.94	2	1.88	30%	2.44
Main Engine Valve Heaters	0.01	8	0.08	30%	0.10
Main Engine Injector Heaters	0.02	8	0.12	30%	0.16
Thruster Cluster Assemblies			10.96		12.06
32.5 N (7.32 lbf) TVC Thrusters	0.38	8	3.04	10%	3.34
4.4 N (1 lbf) ACS Thrusters	0.33	24	7.92	10%	8.71
PROP System Integration			5.83		7.58
1/4" Fittings & transition tubes (Ti & SST)	0.99	1	0.99	30%	1.29
1/4" × 0.035" SSt. GHe lines - 12 ft	0.40	1	0.40	30%	0.52
1/4" × 0.020" SSt. N_2H_4 lines - 32 ft	0.81	1	0.81	30%	1.05
1/4" × 0.020" Titanium N_2H_4 lines - 18 ft	0.31	1	0.31	30%	0.40
3/8" × 0.020" Ti, NTO/N_2H_4 lines - 33 ft	0.83	1	0.83	30%	1.08
3/8" Fittings (Ti) - tee's, elbows, crosses	0.54	1	0.54	30%	0.71
Fuel line augmentation	1.94	1	1.94	30%	2.53
Structures and Mechanisms			567.88		738.24
Spacecraft Structure	502.88	1	502.88	30%	653.74
LV Adapter (S/C Side - Includes Lin. Sep)	8.00	1	8.00	30%	10.40
Mechanisms	40.00	1	40.00	30%	52.00
3m Boom	17.00	1	17.00	30%	22.10
Telecom			58.92		75.79
X/Ka-Band HGA	30.00	1	30.00	30%	39.00
X-LGA Horn	0.45	2	0.90	30%	1.17
X-MGA Horn	1.00	1	1.00	30%	1.30
SDST X-up/X/Ka	2.90	2	5.80	15%	6.67
Ka-Band Transponder	2.90	1	2.90	50%	4.35
X4 multiplier	0.07	2	0.15	30%	0.19
X-Band 50W TWTA	2.60	2	5.20	20%	6.24
X-Band TWTA Isolator	0.50	2	1.00	30%	1.30
Ka-Band 3.5W SSPA	1.00	1	1.00	30%	1.30
Ka-Band Isolator	0.20	1	0.20	30%	0.26
X-Band Diplexer	0.73	2	1.46	30%	1.90
Ka-Band Diplexer	0.25	1	0.25	30%	0.33
Rotary Joints	0.15	2	0.30	30%	0.39
Waveguide Transfer Switch	0.38	3	1.14	30%	1.48
X-Band Waveguide	0.23	12	2.76	30%	3.59
Ka-Band Waveguide	0.09	6	0.54	30%	0.70
Coax Transfer Switch (CXS)	0.13	1	0.13	30%	0.17
X-Band Receive Filter, low power	0.25	2	0.50	30%	0.65
X-Band Transmit Filter, high power	0.34	2	0.68	30%	0.88
Ka-Band Receive Filter, low power	0.10	1	0.10	30%	0.13
Ka-Band Transmit Filter, high power	0.15	1	0.15	30%	0.20
Coax Cable, flex (190)	0.02	10	0.17	30%	0.22
X-Band Hybrid	0.02	1	0.02	30%	0.03
Ka-Band Hybrid	0.02	2	0.04	30%	0.05
Attenuators	0.01	4	0.03	30%	0.04
USO	1.00	1	1.00	30%	1.30

Subsystem / Component	Mass/Unit (CBE) kg	# Units	Total Mass (CBE) kg	Cont., %	Total Mass (CBE+Cont.) kg
Other (connectors, transitions, etc)	1.50	1	1.50	30%	1.95
Radiation Monitoring Subsystem			8.00		10.40
Radiation Monitoring Subsystem	8.00	1	8.00	30%	10.40
Thermal			78.40		101.80
Multi-layer Insulation	25.00	1	25.00	30%	32.50
Thermal surfaces	1.40	1	1.40	30%	1.82
Thermal cond. control	2.80	1	2.80	30%	3.64
Thermal louvers (internal)	4.00	1	4.00	30%	5.20
Thermal louvers (telecom mod)	1.00	1	1.00	30%	1.30
Venus flyby shield	10.00	1	10.00	30%	13.00
Thermostats (52)	0.10	52	5.20	30%	6.76
Line heaters (26)	0.10	26	2.60	30%	3.38
Misc heaters (4)	0.20	4	0.80	30%	1.04
Temperature sensors (60)	0.01	60	0.60	10%	0.66
Shunt radiator	8.00	1	8.00	30%	10.40
Fixed RHU's (20)	0.10	20	2.00	30%	2.60
Variable RHU's			15.00		19.50
Thruster cluster VRHUs (8)	0.60	8	4.80	30%	6.24
Delta-V thruster VRHUs (2)	0.60	2	1.20	30%	1.56
Instrument suite VRHUs (10)	0.60	11	6.60	30%	8.58
Telecom (4) VRHUs	0.60	4	2.40	30%	3.12
Radiation Shielding			122.46		159.20
Instruments Shielding	17.30	1	17.30	30%	22.49
AACS Subsystem Shielding	25.73	1	25.73	30%	33.45
C&DH Subsystem Shielding	13.19	1	13.19	30%	17.15
Power (w/o RPS) Subsystem Shielding	5.00	1	5.00	30%	6.50
Propulsion Subsystem Shielding	23.68	1	23.68	30%	30.78
Structures & Mechanisms Subsystem Shielding	0.00	1	0.00	30%	0.00
Telecom Subsystem Shielding	37.55	1	37.55	30%	48.82
Thermal Subsystem Shielding	0.00	1	0.00	30%	0.00
System Level Margin					307.00
Spacecraft Total Dry			1855		2652
Propellant			4360.00		4360.00
Spacecraft Total Wet			6215		7012
Launch Vehicle Adapter (LV-Side)			25.00	30%	33.00
Launch Mass Wet			6240		7045

F2. Power Equipment List (PEL)

The detailed Power Equipment List is provided in **Table F2-1**. This table provides the assembly-level power usage for the flight system.

Table F2-1. *Detailed Power Equipment List for Baseline EE Flight System*

Subsystem / Component	Comm Mode Power, W	Non-Comm. Mode Power, W
Payload	110.1 W	98.0 W
Payload (11 instruments)	110.1 W	98.0 W
ACS Subsystem	95.0 W	95.0 W
IMU (Litton Scalable SIRU)	28.7 W	28.7 W
SunSensor (GalileoAvionica APS)	1.0 W	1.0 W
Sun Acquisition Detectors	0.3 W	0.3 W
Star Tracker (Jenna Optonik APS)	5.0 W	5.0 W
Reaction Wheels (Teldix RSI 25Nms)	60.0 W	60.0 W
C&DH Subsystem	67.5 W	67.5 W
RAD750 w/ 128MB SRAM	18.0 W	18.0 W
MSAP System Interface Assembly	5.1 W	5.1 W
MSAP Telecommunications Interface Card	3.6 W	3.6 W
MSAP Remote Engineering Unit (RT receiving)	3.0 W	3.0 W
MAGIC Card	7.0 W	7.0 W
NVM Card (1.2 Gb)	4.0 W	4.0 W
HGA Gimbal Drive Electronics	4.0 W	4.0 W
Power Converter	3.8 W	3.8 W
Sci/Eng Mass Memory	19.0 W	19.0 W
Power Subsystem	25.9 W	25.9 W
Power Control Slice - PCS	5.0 W	5.0 W
Battery Control Slice - BCS	4.0 W	4.0 W
Power Switching Slice - PSS - general loads	9.6 W	9.6 W
Power Switching Slice - PSS - Pyro	1.2 W	1.2 W
Power Switching Slice - PSS-Propulsion	1.6 W	1.6 W
RTG Interface Card	2.4 W	2.4 W
Power Converter Assembly - PCA	2.1 W	2.1 W
Propulsion Subsystem	13.0 W	13.0 W
Orbital average thruster power	13.0 W	13.0 W
Structures and Mechanisms Subsystem	11.0 W	0.0 W
HGA Gimbal Motors	11.0 W	0.0 W
Cabling Subsystem	16.0 W	12.7 W
Cabling	16.0 W	12.7 W
Telecom Subsystem	98.4 W	30.3 W
X-band SSPA	63.6 W	10.0 W
Ka-band SSPA	11.5 W	0 W
SDST (X and Ka)	21.3 W	18.3 W
USO	2.0 W	2.0 W
Thermal Subsystem	18.0 W	18.0 W
Line heaters	13.0 W	13.0 W
Misc heaters	5.0 W	5.0 W
Radiation Monitoring Subsystem	4.0 W	4.0 W
Radiation Monitoring Subsystem	4.0 W	4.0 W
Power Mode Total (CBE)	458.8 W	364.3 W
Average Orbit Power (CBE)	427.6 W	
Contingency	30%	
Average Orbit Power (CBE+Contingency)	555.8 W	
Available RPS Power (@EOM)	618.0 W	

F3. Configuration Views

Figures F3-1 through **F3-6** illustrate different aspects of the EE flight system.

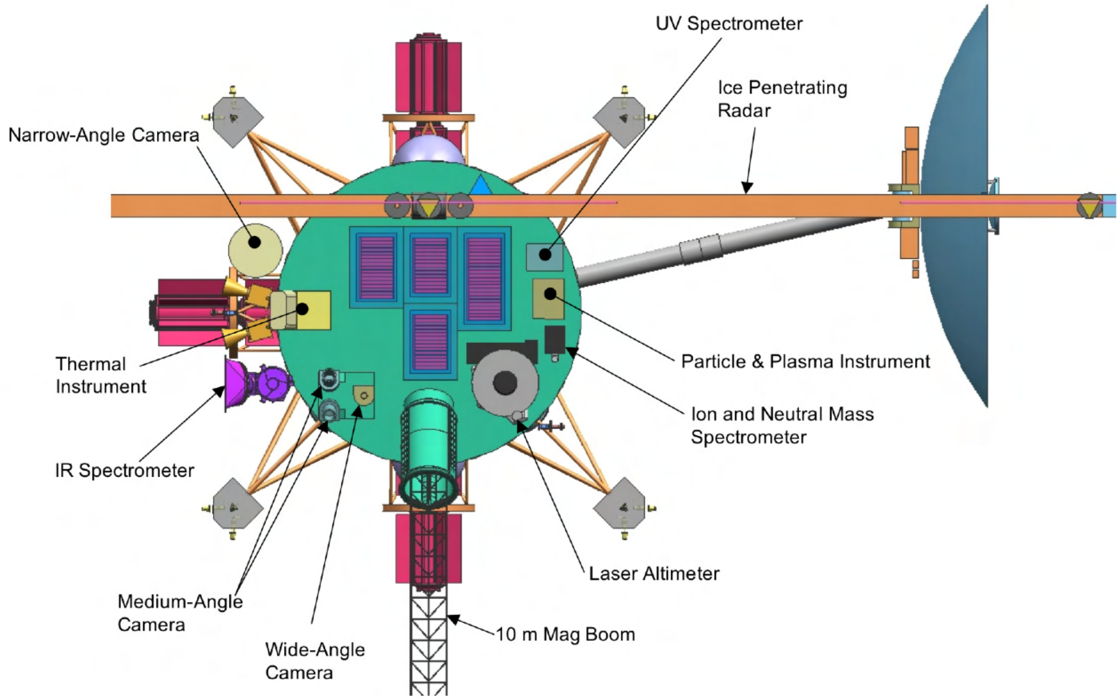


Figure F3-1. *Science Configuration of the EE Flight System*

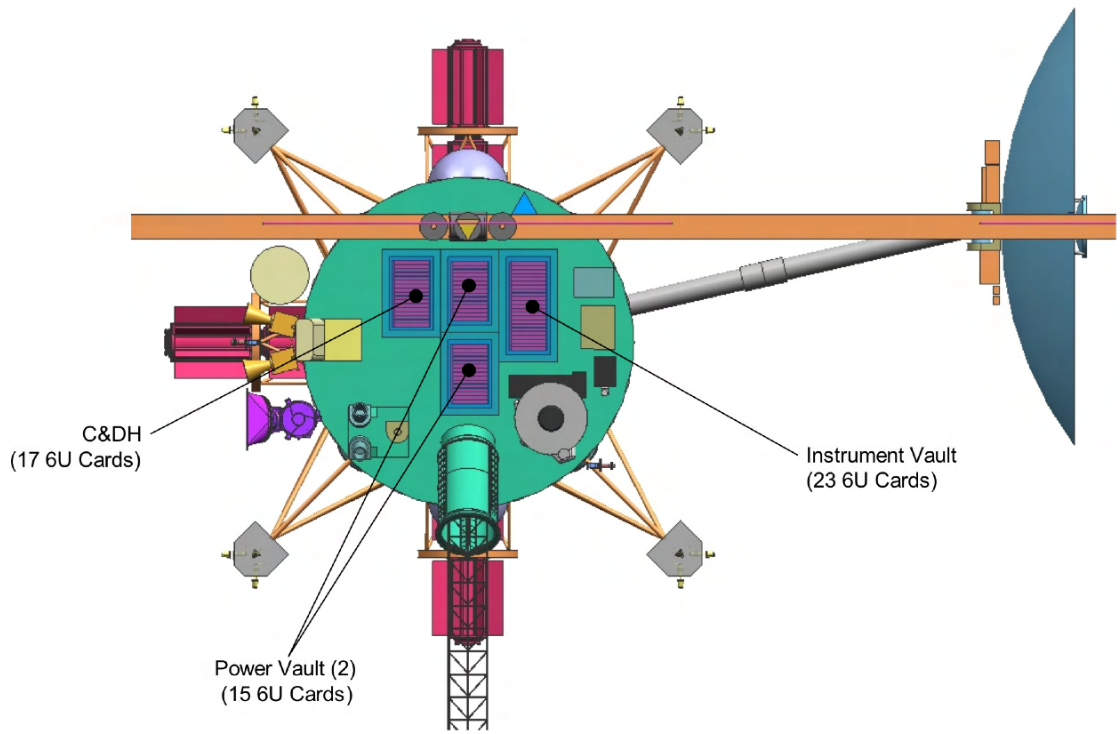


Figure F3-2. *Shielded Electronics (Bus Mounted) Configuration of the EE Flight System*

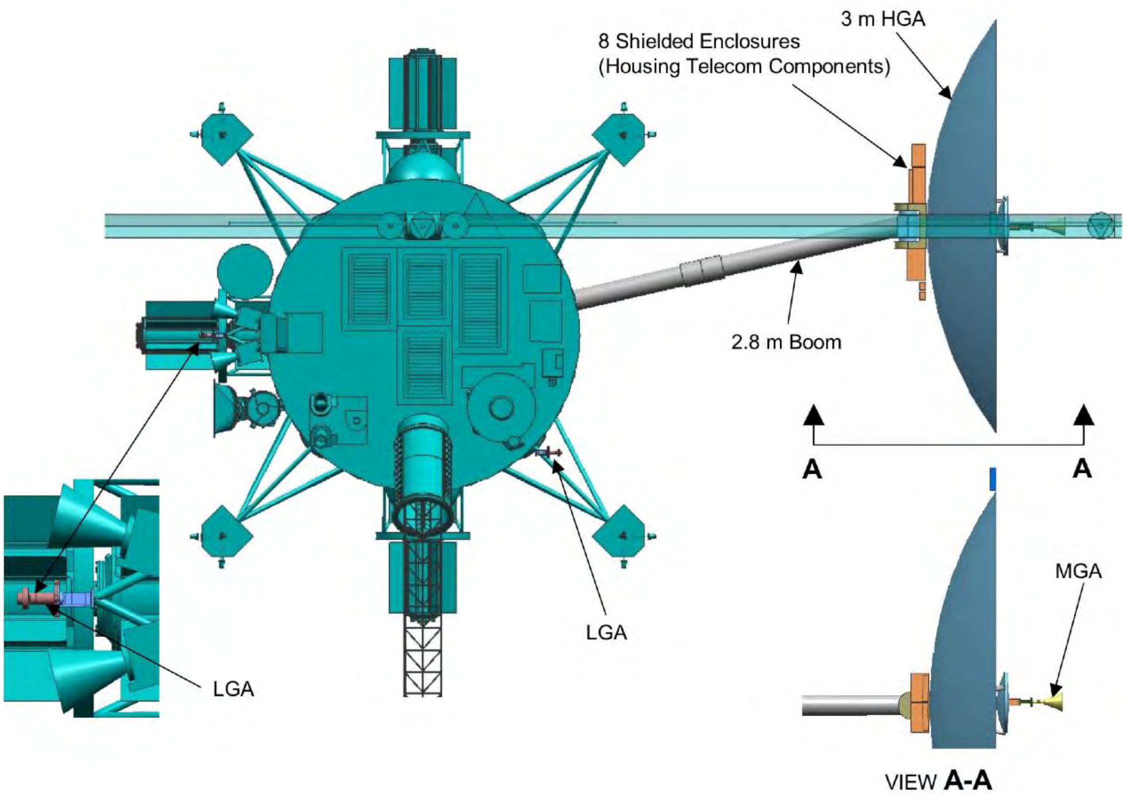


Figure F3-3. Telecom Configuration of the EE Flight System

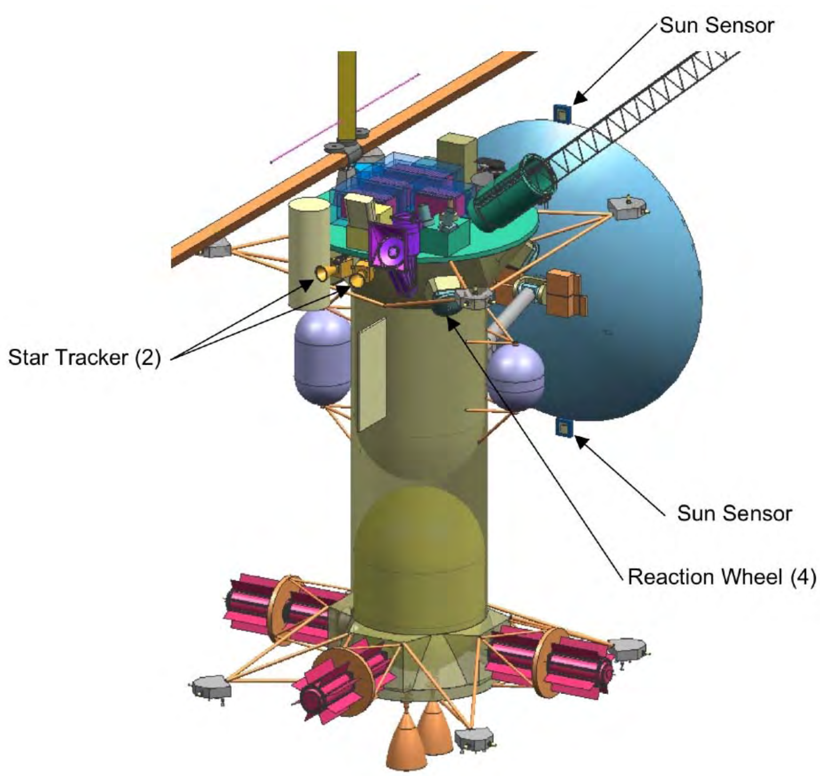


Figure F3-4. AACS Configuration of the EE Flight System

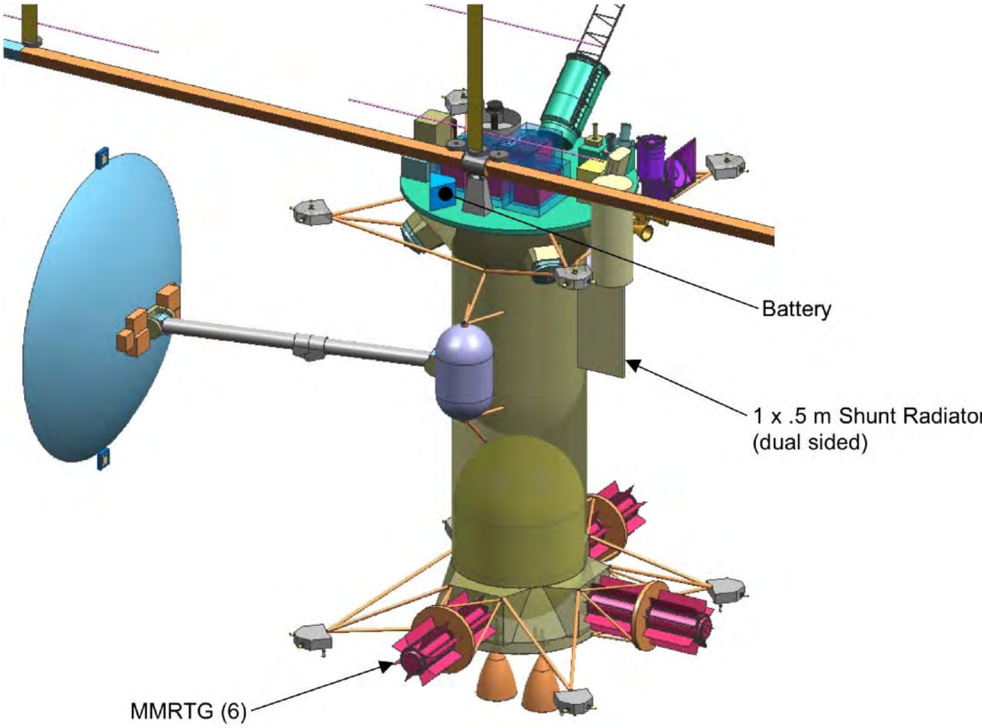


Figure F3-5. *Power Subsystem Configuration of the EE Flight System*

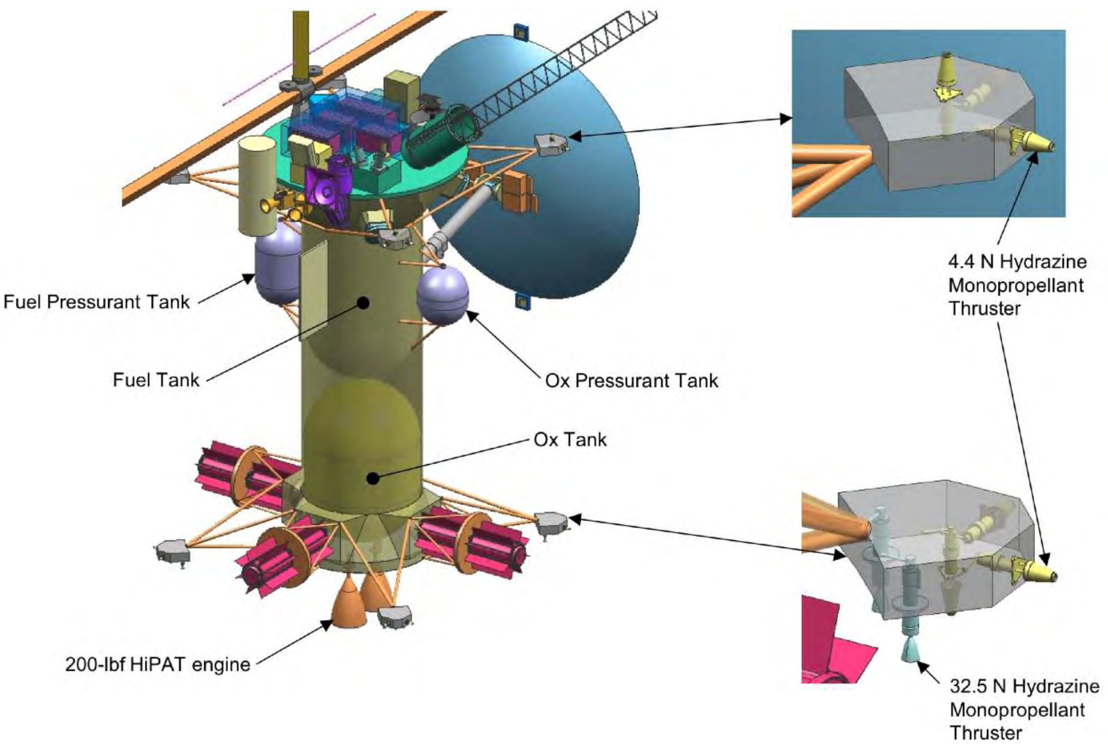


Figure F3-6. *Propulsion Configuration of the EE Flight System*

F4. Floor Flight System Design

The floor EE flight system design is derived from the baseline EE configuration, and includes many of the same flight system components as the baseline design. That is, the floor EE flight system is a redundant, 3-axis stabilized flight system powered by Radioisotope Power Systems (RPSs). The conceptual block diagram for the floor configuration is shown in **Figure F4-1**. The flight system includes an articulated 3-m high-gain antenna (HGA), using X-band, for high rate science downlink. Key differences are that the floor flight system has 8 instruments and relies solely on the X-band system (i.e., no Ka-band) for the gravity science investigation. Additionally, no Ultrastable Oscillator (USO) is included for correlation of Radar and Laser Altimeter investigations. Five Advanced Stirling Radioisotope Generators (ASRGs) would power the flight system (four prime and one hot backup) providing about 514 watts of electrical power at End of Mission (EOM). An Atlas V 531 launch vehicle would be used in place of the more expensive (and capable) Delta IV-H. The Maximum Expected Value (MEV) of the flight system mass at launch, including contingency, is 3903 kg with respect to the currently quoted Atlas V 531 capability of 4030 kg.

A majority of the floor flight subsystems are similar or identical to those of the baseline configuration, including:

- C&DH
- AACS
- Propulsion (excluding tank sizing and fuel loading)
- Thermal
- Power (excluding RPSs)
- Telecom (X-band only), and
- Radiation monitoring subsystem

The floor areas that differ significantly from the baseline configuration are:

- Payload – Eight instruments are used in the floor configuration, resulting in significant mass and power savings.
- RPS – ASRGs are used; resulting in significant mass reduction but higher risk posture compared with MMRTGs.
- Cabling – Same architecture as baseline, but lighter and with less power loss due to Floor's smaller flight system.
- Propulsion (Tanks and prop load) – Less massive than baseline due to lower propellant requirements for the same ΔV requirements.
- Structures and Mechanisms – Same general approach as baseline but less massive overall due to the Floor's smaller flight system.
- Telecom – Floor uses X-band only for communications and gravity science, and a lower power TWTA is incorporated due to the smaller data volume requirements. Overall result is significant power savings and moderate mass savings compared with telecom baseline configuration.

A summary of the key differences between the baseline and floor configurations is presented in **Table F4-1**.

***Table F4-1.** Comparison of Baseline and Floor Mission Configurations*

Parameter	Baseline	Floor
# Instruments	11	8
Mission Duration in Europa Orbit	1 Year	6 Months
P/L Mass (CBE)	158 kg	77 kg
P/L Power (CBE)	106 W	58 W
Launch Vehicle	Delta IV-H	Atlas V 531
Inj. Mass Cap.	7230 kg	4030 kg
Wet Launch Mass (w/ cont.)	7045 kg	3903 kg
RPSs	6 MMRTGs	5 ASRGs
Gravity Science Technique	X and Ka band	X-band only
USO	Included	None
Data Volume	20 Gb/day	7 Gb/day
Remaining Avail Mass	185 kg	127 kg

The mass and power summaries for the floor flight system are presented in **Tables F4-2** and **F4-3**.

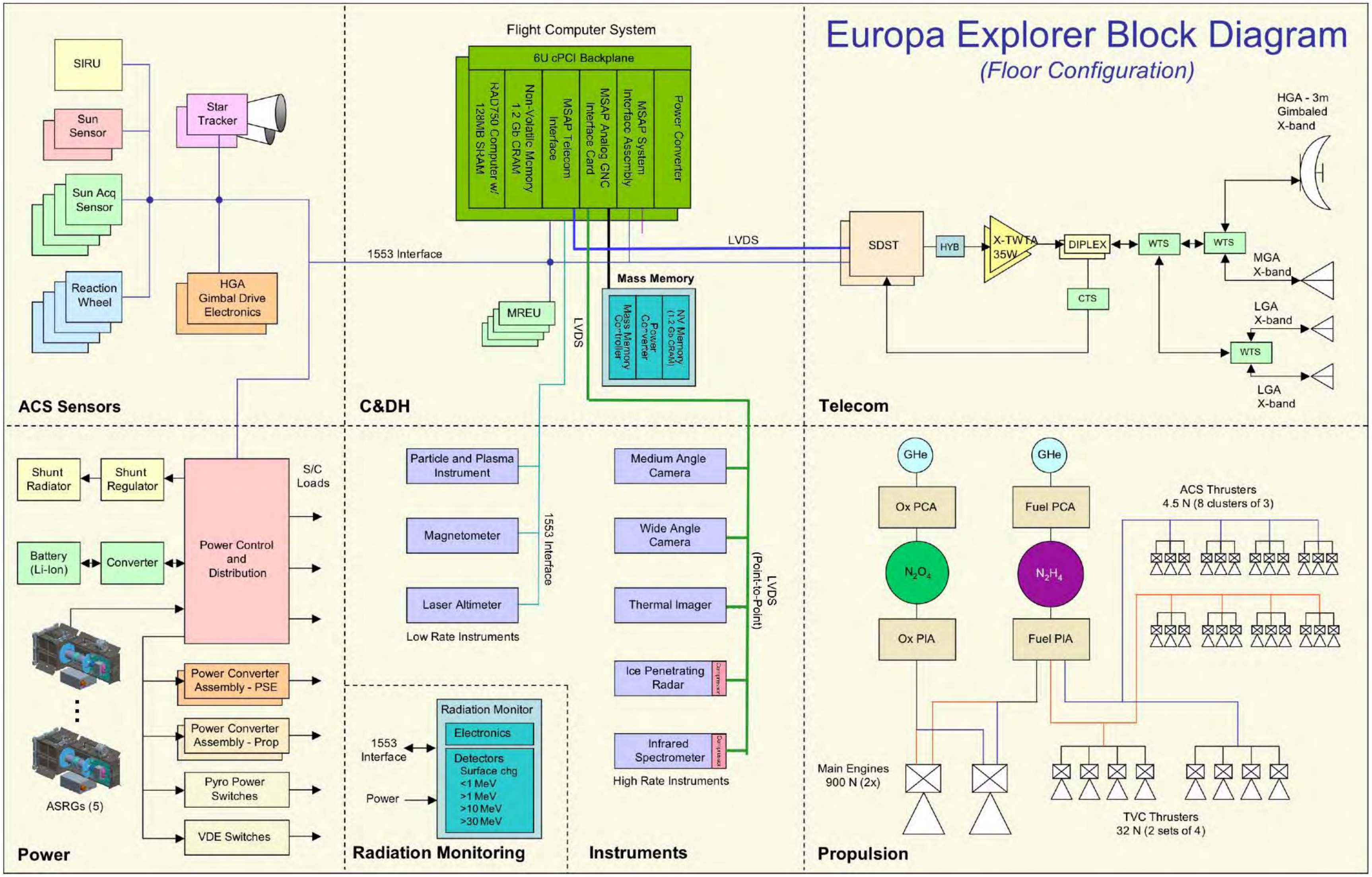


Figure F4-1. *System Functional Block Diagram for Floor EE Flight System*

Table F4-2. *Mass Summary for the Floor Europa Explorer Configuration*

Subsystem	Flight System Mass, kg			Notes
	CBE	Cont.	CBE + Cont.	
Payload	**77**	**30%**	**100**	**Excludes radiation shielding mass.**
Instruments	77.0	30%	100.1	8 instruments.
Bus	**889**	**30%**	**1158**	**Excludes radiation shielding mass.**
AACS	50.8	37%	69.8	Includes SIRU, star trackers, and sun sensors
CDH	42.3	32%	55.9	Includes redundant Rad 750 flight computer and 2.4 Gb NVM
Power (w/o RPSs)	50.4	27%	64.0	Includes power distribution, switches, and power converters
RPS System w/ Adapters	150.1	30%	195.2	Five ASRGs and associated struts and adapters
Cabling	74.7	30%	97.2	CBE value equals 7% of CBE Spacecraft Total Dry mass (including radiation shielding mass)
Propulsion	130.5	30%	170.3	Includes 900N main engines, ACS and RCS thrusters, tanks and associated plumbing.
Structures & Mechanisms	263.7	30%	342.8	Includes S/C structure, HGA gimbals and motors, magnetometer boom, and SC side LVA. Worst case value equals 12.5% of LV injected mass capability minus RPS & LV struts/adapters and LV-side LVA and augmented to account for a different LV-side LVA.
Telecom	52.6	27%	67.0	Includes 3m HGA, MGA, and LGAs
Radiation Monitoring System	8.0	30%	10.4	Allocation
Thermal	65.5	30%	85.1	Includes MLI, heaters, and RHUs. Assumes temp sensors feed into C&DH for processing, and heaters use thermostats or S/W control.
Radiation Shielding	**102.2**	**30%**	**132.8**	
Spacecraft Total Dry	**1068**	**30%**	**1390**	**Includes Payload, Bus, Shielding, and System Contingency.**
Additional System Margin	-	**13%**	**135**	Additional contingency added to obtain specified 30% margin (43% contingency) at system level for the S/C bus and PL.
Spacecraft Total Dry	**1068**	**43%**	**1524**	**Includes Payload, Bus, Shielding, and System Contingency.**
Propellant	2345		2345	Worst case prop mass based on Injected Mass Capability minus LV adapter (LV side) using CBE+Cont. values. Uses 21d worst case DSM Delta V value and includes allocation for uncertainties. Accounts for LV adapter (LV-side) that stays behind with LV
Spacecraft Total Wet (e.g., Separated Wet Mass)	**3412**		**3869**	**Includes Payload, Bus, Shielding, System Contingency, and Propellant.**
LV Adapter (LV Side)	25	30%	33	
Launch Mass Wet	**3437**		**3903**	**Includes entire wet spacecraft, all adapters, and contingencies.**
Injected Mass Capability			4030	**For Atlas V-531 with C_3=14.1 km^2/s^2.**
Remaining LV Capability			**127**	**Accounts for mass contingencies and additional system margins as indicated above.**
Flight System Dry Mass Contingency per Study Guidelines		**30.1%**		(MEV-CBE)/CBE
Flight System Dry Mass Margin per Study Guidelines		**18.5%**		(MPV-MEV)/MEV
Flight System Dry Mass Margin per JPL Design Principles		**35.2%**		(MPV-CBE)/MPV

Table F4-3. *Power Summary for the Floor Europa Explorer Configuration*

Subsystem	Flight System Power, W		Notes
	Comm. Mode	Non-Comm. Mode	
Payload	**62.9**	**47.0**	**Average over two consecutive science orbits**
Instruments	62.9	47.0	Two-orbit average orbital power of 57.7W (CBE). .
Bus	**283.7**	**257.0**	**Average over two consecutive science orbits**
AACS	95.0	95.0	Includes star tracker, star sensor, and SIRU.
CDH	67.5	67.5	Includes RAD750 and 2.4 Gb of NVM
Power	25.9	25.9	Power for switches and power converters
Propulsion	13.0	13.0	Average thruster power calculation including catbed heaters, valve power, and pressure transducers
Structures and Mechanisms	11.0	0.0	Includes power for gimbal motors and resolvers
Cabling	12.1	10.6	Equals 3.5% of total spacecraft power (CBE)
Telecom	37.2	23.0	Average telecom power estimate for X band system.
Thermal	18.0	18.0	Power for electrical heaters
Radiation Monitoring	4.0	4.0	Allocation
Total Power Level (CBE), W	**346.6**	**304.0**	
Contingency%	**30%**		
Total Power Level w/ Contingency, W	**450**	**395**	
Orbit Period, hrs	2.3		Based on 200km altitude circular orbit.
Mode Duration per Orbit, hrs	1.54	0.76	
Energy Used per Mode, W-hr	693	300	
Energy Used/Orbit, W-hr	**993**		Does not account for battery charge/discharge losses.
RPS Type	ASRG (w/ Redundancy)		Floor Configuration
RPS Unit Output at EOM, W	128.5		Value based on age of fuel and generators at EOM (12 years from BOL, 9 years from BOM).
Avg Total Power Used per Orbit w/o cont., W	**333**		**CBE Value**
Avg Total Power Used per Orbit w/ cont., W	**432**		**Max Expected Value (MEV)**
Required # of RPSs (w/o redundancy)	**4**		
Total RPS Power Produced at EOM, W	**514**		**Max Possible Value (MPV)**
Excess RPS power available	**82.3**		**Unused RPS power after accounting contingency**

Flight System Power Contingency per Study Guidelines	**29.9%**	(MEV-CBE)/CBE
Flight System Power Margin per Study Guidelines	**19.1%**	(MPV-MEV)/MEV
Flight System Power Margin per JPL Design Principles	**35.3%**	(MPV-CBE)/MPV

G. OPERATIONS SCENARIO ANALYSIS

G1. Introduction

The purpose of Appendix G of the Europa Explorer (EE) study report is to document the work and methods used to develop the operations scenarios for the EE study and describe detailed operations context for several aspects of the mission. The key conclusions and summary descriptions of the baseline data acquisition and return scenarios and Jupiter system scenarios are included in the main body of the report. Tool and methodology descriptions and some key analysis results for the baseline science scenarios, floor science scenarios, and a quick look feasibility study for the Jupiter system tour are described in this appendix. Context descriptions including mission operations system architecture and DSN scheduling methods are also provided.

G2. Study Approach

The development of the operations scenarios was a central part of the EE Mission Concept Study from the start. The development was an interactive collaboration among all of the members of the Science Definition Team (SDT) led by Bob Pappalardo and Ron Greeley, the study lead, Karla Clark, and engineers from the operations scenario study team. The team members were Rob Lock, Greg Welz, Ken Klaasen, Rob Abelson, and Rob Sharrow at JPL and Nick Pinkine at APL.

The starting point for the operations scenarios development was the work done in the previous study (2006) since most of the key elements of the mission, including science payload, mission design, and flight system design, were similar to those from the previous study. The 2006 study did not develop detailed operations scenarios but did develop operations concepts for single orbits that dealt with challenges in collection and return of large data volumes with constrained on-board data storage. The results of the previous study directly supported the operations scenario development and can be found in [*Europa Explorer Data Return Issue Report 2006*].

Working in concert with the SDT, and in parallel with the SDT's development of the science value matrix, key mission capabilities and constraints were examined and challenged. Science goals were discussed and options were considered for data collection scenarios.

The first scenarios to be considered were the floor mission scenarios. The SDT was developing the floor science goals and value matrix and the scenarios were needed to determine the science achievement and validate the science value estimates. Basic instrument operations constraints, interactions, and coverage estimates were developed and presented in the first sessions. Once the flight system capabilities were determined and orbit-by-orbit scenarios were developed, higher order scenarios for science campaigns were sketched out to estimate the progress of achievement of the science goals during the mission. This was needed for the science value matrix being developed separately by the SDT. Key system parameters estimated and traded were instrument power, mass and data rate, telecom rate, Solid State Recorder (SSR) capacity, instrument data volume allocations, operations timing constraints, co-observing issues, data reduction and compression factors and phasing of campaign goals.

Following the development of goals, operations scenarios and the science value matrix for the floor mission, the process was repeated for the baseline mission. During this process the strategy for data allocation for coordinated targets was developed based on coverage and resolution for the instruments rather than direct allocation of data volume. The baseline and floor scenarios were updated based on desired coordinated target strategy.

Due to the study guidelines to primarily focus on Europa science, a limited effort was made to understand the feasibility of, and constraints on, science data collection of the Jupiter system tour. Simple coordinated target observing strategies similar to those used for Europa science scenarios were used as place holders for imaging campaigns that might be used in a system tour. Trajectories for the tour which had been designed for minimum ΔV and radiation dose, were not optimized for tour science. The feasibility study used those trajectories as is to estimate the coarse science return for the mission. High-level conclusions and recommendations are given to indicate where deeper studies and system architecture modifications might be most beneficial.

G3. Ground System Architecture Context

The description of the ground system architecture in this appendix is intended to provide detailed information for the ground system elements, mission operations system, and the DSN scheduling rationale aspects of the mission not presented in the main body of the report. The descriptions of the mission design and flight system design are provided in §4 of the report and are not repeated here.

The ground system elements are the Deep Space Mission System (DSMS), which includes the DSN and several data processing and transport systems, and the mission operations system (MOS) for the project including the science planning, analysis, and archive functions. These descriptions are generic for JPL missions of the scope of EE and were used for cost estimation purposes. They are included for here for context.

The DSN scheduling rationale is described for all phases of the mission and is used for mission cost analysis and for Jupiter system tour and Europa science data return scenarios.

G3.1 Ground System

The ground system is illustrated in **Figure G-1**, and is made up of the people, processes,

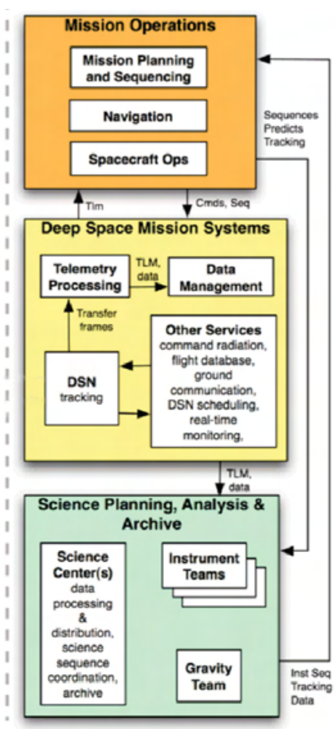


Figure G-1. *Ground System Data Flow Diagram*

software, and hardware necessary to successfully operate the mission. This figure shows the three major elements that make up the ground system, the NASA wide common services and capabilities provided through the DSMS; the project specific MOS with its underlying ground data system; and the science support elements.

G3.1.1 Deep Space Mission System

The DSMS handles the communication interface between the flight and ground systems. DSMS includes the DSN, the underlying interconnecting ground network, and the related services. The services support initial processing of the telemetry and the related data management and distribution of the telemetry data to specific interfaces, such as the science processing organization and spacecraft analysis teams.

The DSN will perform all tracking for this mission, starting shortly after launch. For launch support up through final injection burn the tracking system will consist of NASA Ground Network 9–12 m X-band ground stations used to support launches from Cape Canaveral Florida. The actual stations used depend significantly on the ascent trajectory. Once the DSN takes over the tracking duties it will follow a profile along the lines as described in **Table G-1**. The DSN currently consists of three complexes (Goldstone, USA; Canberra, Australia; Madrid, Spain), each with several 34 m stations and one 70 m station.

There is some concern about the availability of the 70 m stations during the science activities. The current 70 m stations were built in the 1960's and updated for many missions since then but have been, until recently, approaching their projected end-of-life. With the recent launch of New Horizons, funding has been provided to refurbish the 70 m stations, extending their projected end-of-life to 2025. In addition, there are plans in development to implement the 70 m equivalent capabilities, likely via arrays of smaller antennas, with implementation starting around 2010 with the goal of being operational by 2020. While opportunities will exist to increase mission performance using future capabilities, the operations scenarios assume only current or nearly delivered capabilities for the DSN.

***Table G-1.** Planned DSN coverage as a function of Mission Phase*

DSN Coverage					
Description	Subnet	Year	Hours/ track	Tracks/ week	Duration (weeks)
Interplanetary Phase June 2015 to July 2021					
<u>Launch and Early Operations:</u> Begins with the launch countdown. Activities include initial acquisition by the DSN, checkout and deployment of all critical flight system systems and a major maneuver to clean-up trajectory errors from launch vehicle injection				June/July 2015 30 day duration	
Launch to L+30	34m	2015	8	21	4
<u>Cruise:</u> Activities include science instrument calibrations, Venus and Earth gravity assist flyby science operations, trajectory correction maneuvers, and operations readiness testing.				July/August 2015 to December 2018	
Maneuvers & VEEGA	34m	2015–2019	8	10	11
Annual health checks	34m	2015–2019	8	7	5
Eng telemetry + Nav (through VEGA)	34m	2015–2016	8	3	41
Eng telemetry + Nav (till JOI – 30m)	34m	2016–2018	8	2	124
<u>Jupiter Approach:</u> Activities include final preparations, training, and ORTs for all mission elements in preparation for JOI and Jovian moon flybys, and an optical navigation campaign to determine satellite ephermerides prior to pre-JOI Ganymede flyby.				January 2019 to JOI (July 2021)	
Eng telemetry + Nav (till JOI – 2m)	34m	2019–2021	8	3	123
JOI Approach Heavy tracking**	34m	2021	8	21	3
JOI Approach Light tracking**	34m	2021	8	14	3
JOI	34m	2021	8	20	2*
	70m		8	1.5	
Jovian Tour July 2021 to June 2023					
The phase is characterized by continuous science observations of the Jovian system and multiple (20+) flybys of major Jovian satellites. The final month of the phase is dedicated to targeting maneuvers in preparation for EOI.				JOI to EOI (July 2021 – June 2023)	
Jupiter System Science	34m	2021–2023	8	7	55
Fly-by Prep & Science	34m	2022–2023	8	14	44*
(22 fly-bys)	70m		8	3	
Europa Science June 2023 to June 2024					
Begins after achieving the primary science orbit and continues for 100 Eurosols (1 year). All high priority science goals are achieved in this phase.				June 2023 – June 2024 (1 year)	
EOI	34m	2023	8	20	2*
	70m		8	1.5	
Campaigns 1,2,3	70m	2023	8	21	13*
Ka-band Radio Science	34BWG		8	7	
Campaign 4	70m	2023–2024	8	7	39
Extended Europa Science June 2024 +					
Begins after the Focused Europa science phase ends. End date is dependent on negotiated funding period, flight system health, and remaining propellants.				June 2024 +	
Extended Orbital Science	70m	2024+	8	7	+
*Coverage by both 34m and 70m antennas during this time span. **ΔDOR tracking would be used during approach and as needed during cruise, not called out separately.					

In addition to the DSN, DSMS also provides services for working with the DSN. These services include telemetry processing and distribution, commanding, real-time monitoring and control, scheduling, and ground communications infrastructure. The telemetry services will take the bit-stream as received at the DSN stations and convert it to level 0 formats (as the data appeared on the flight system prior to transmission). The telemetry system also performs additional processing to separate the instruments data from the spacecraft data, stores the data in the project database for non-real-time analysis, and distributes telemetry data to the appropriate customers. The command service takes the command files generated by the MOS and radiates them to the flight system. The real-time monitoring and control team, also known as the mission control team, act as the interface between the mission and the DSN operations, and provide ongoing monitoring of the telemetry being received and of the command radiation activities, ensuring timely responses to problems in communications. Scheduling services ensure the project is able to get the DSN tracking resources needed routinely and for emergencies and are key to resolving conflicts with other missions over the limited resources of the DSN. Finally a critical, but often overlooked service is the ground communications network support. This final service provides as a minimum the communications between JPL and each of the DSN complexes and voicenets used by the project. More frequently this service is also extended to implement and support remote science or spacecraft operation centers. A key part of this support are network system administrators that ensure the continued functioning of the network, network security, and voice communications.

G3.1.2 Mission Operation System

The MOS is made up of the project specific people, processes, software, and hardware used to operate the spacecraft and instruments, and for processing, storing and archiving the data associated with operating the spacecraft and instruments. Key elements of the project specific elements of the MOS include: the infrastructure support, spacecraft operations and analysis, navigation support, mission planning and sequence development, and training. **Figure G-2** shows the functions are flow of products among the MOS elements in the project.

The infrastructure support includes the system administrators, developers, and supporting hardware. Prior to launch the multi-mission Ground Data System (GDS) is adapted across all elements of the ground system to handle the mission specific functions and requirements. In addition, after launch the underlying multi-mission GDS undergoes periodic revision, about every 18 months, changes to the GDS will need to be made and tested as needed by supporting programmers. Typically every 3 to 4 years the GDS

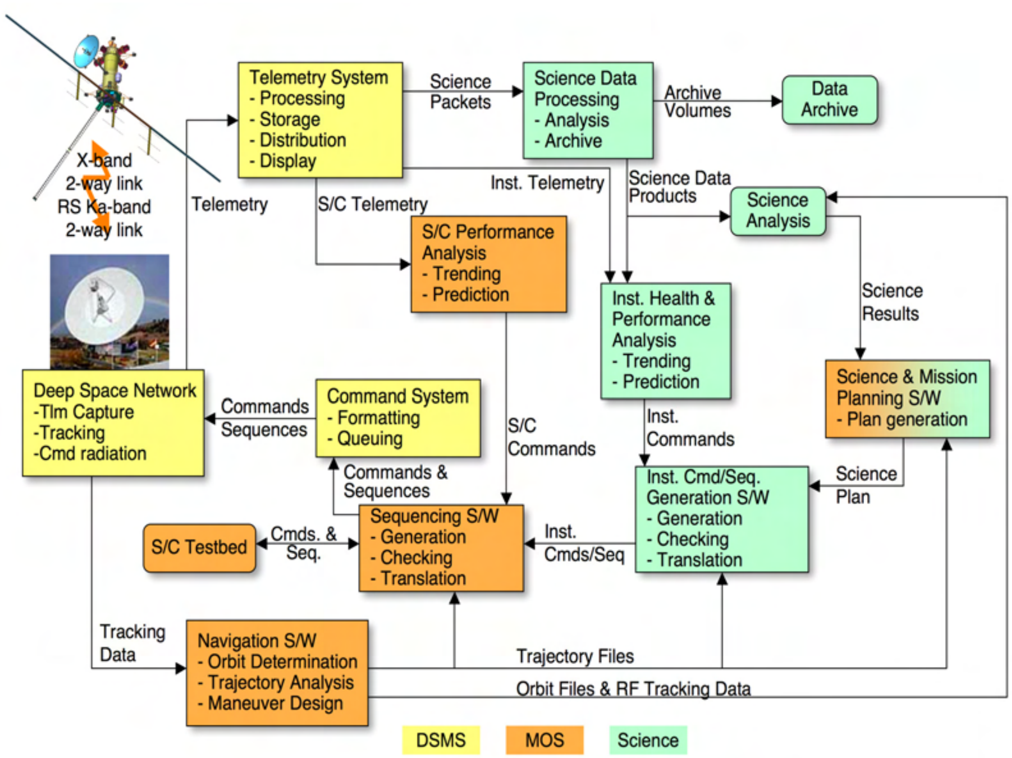


Figure G-2. MOS Function and Product Flow Diagram computers and related hardware will need to be replenished to ensure that the hardware and operating systems support will be available during flight operations.

Spacecraft operations teams monitor spacecraft health and develop sequences for the spacecraft. The spacecraft subsystem engineers use the spacecraft engineering telemetry to perform general spacecraft health analysis and trending. The spacecraft subsystem engineers also participate in fault diagnosis, anomaly resolution, and prediction of future behavior, and sequence development and review.

The navigation team performs trajectory analysis and design, and will also support in the Europa Gravity mapping. The navigation team performs the orbit determination and trajectory analysis for the flight system using DSN RF data and, if needed, on-board imaging data. The navigation team also coordinates with instrument and spacecraft teams to implement planned propulsive maneuvers and reaction wheel de-saturation burns, predict flyby geometry and timing parameters, and plan future mission phase trajectories.

Mission planning is an ongoing function for the life of the mission and involves the cross-project coordination, planning and analysis of the trajectory design, mission timelines, and the major activities during each of the mission phases. This is performed with membership across the project including support from spacecraft, navigation, instrument and science teams. Once the flight system is operational, mission planning coordinates the refining of trajectories and activities to compensate for changing plans and evolving flight system characteristics, and to fine-tune specific events such as flybys, checkouts and instrument calibrations.

Training activities are required to maintain personnel skill levels and to prepare for mission operations. Activity planning, uplink product generation, flight and ground system software updates and testing, operations rehearsals and Operation Readiness Tests (ORT) support personnel training and readiness. These activities validate procedures and prepare the teams for upcoming critical events. During ATLO, missions typically conduct ORTs and other test and training activities for launch, the first major maneuver, and for any mission critical event that could cause a loss of mission if done incorrectly. For the long duration of EE mission skill retention issues will necessitate additional training. Team training activities will be planned at regular intervals and will include post launch training activities and ORTs for each of the gravity assist encounters, the first Ganymede flyby, JOI, Europa approach, EOI, and Europa mapping campaigns.

Sequences will be developed by many teams and will be centrally integrated and tested. The spacecraft team develops the sequences for the spacecraft based on the mission plan, inputs from navigation, and the results of subsystem analysis and trends. The instrument operations teams create sequences for the instrument based on mission plans and science observation plans, coordinating with other instrument teams and the spacecraft team to ensure proper sharing of resources. These sequences are integrated together and tested to ensure that they do not violate flight rules, endanger the flight system, and will function correctly.

Science teams perform quick analysis of the returned science products within hours of data receipt. The quick analysis products would be used to support near term data collection strategies and to guide the longer-range observation plan updates.

The project science working group (PSG) leads science teams in setting up the overall science observation plan that will be used for the development and operation of the mission. Science observation planning is likely to evolve over the life of the mission as conditions change and spacecraft and instrument health change.

Instrument operations teams bridge the science teams and spacecraft operations. The science teams provide the direction for what the instrument observations are to be based on the mission and science plans. The spacecraft team provides the information on the spacecraft state and attitude, resources available, and any potential conflicts that may be encountered. The instrument operations team ensures that all instrument sequences meet science goals, are fully integrated, tested and successfully uplinked to the flight system.

G3.2 DSN Scheduling Rationale

The amount of tracking for this mission is significant due to the duration of the mission and the science volumes collected at Europa. The duration of 9 years is illustrated in **Figure G-3**. The DSN tracking profile used for the current trajectory is summarized in **Table G-1**. The profile, like the trajectory, is notional and provided only as a way of demonstrating the proof-of-concept, both will change and evolve over the course of project development.

Launch and Early Operations

Immediately after launch is an intense month of flight system deployment, checkout, and critical maneuvers. This period will use round-the-clock tracking by the DSN 34 m subnet to support the commanding, flight system telemetry, and RF navigation data needed for these tasks. During this phase the flight system developers are monitoring the deployments and performing their final in space tests and handing the flight system over to the flight team. The navigation team compares the actual launch performance versus the predicted, reviews RF data and alters the maneuver design to ensure the flight system will achieve the planned trajectory that will take it to Jupiter.

Cruise

The duration of cruise drives the tracking to be economical and still ensure safe delivery to Jupiter orbit. For the first year, three passes per week would provide the necessary tracking needed for navigation analysis and flight system characterization activities. For gravity assists or maneuvers the tracking will be augmented around the event to provide at least twenty 8-hour passes for the 2 weeks surrounding the event. Fly-bys will also be used to test science and instrument operating procedures, in early preparation for the Jovian tour. After the first year tracking can generally be decreased to 2 or fewer 8-hour passes per week. With annual weeklong intensive spacecraft and instrument health checks, to ensure all is well. These health checks usually require 1 week of daily 8-hour passes. Though not explicitly called out, ΔDOR tracks will be scheduled periodically and prior to planet and satellite encounters.

About 18 months before JOI, tracking frequency is increased to handle the operational needs for JOI and the tour. This tracking will be used for flight software loads and provide RF tracking data to support increased orbit determination and trajectory analysis work for JOI, as well as some early Jovian system science. Approach to JOI is accompanied by significantly increased tracking including ΔDOR. At the time of JOI, 70 m tracking support will be used to augment 34 m tracking to provide the best reception available at burn attitudes.

Tour

Once in Jupiter orbit, tracking goes to a steady state of daily 8-hour 34 m passes, intended to support Jovian system science data collection and navigation. This routine is augmented around fly-bys to support the final navigation analysis and increased science. During and right after each fly-by, tracking is augmented with DSN 70 m antennas to maximize science return and improve navigation analysis accuracy.

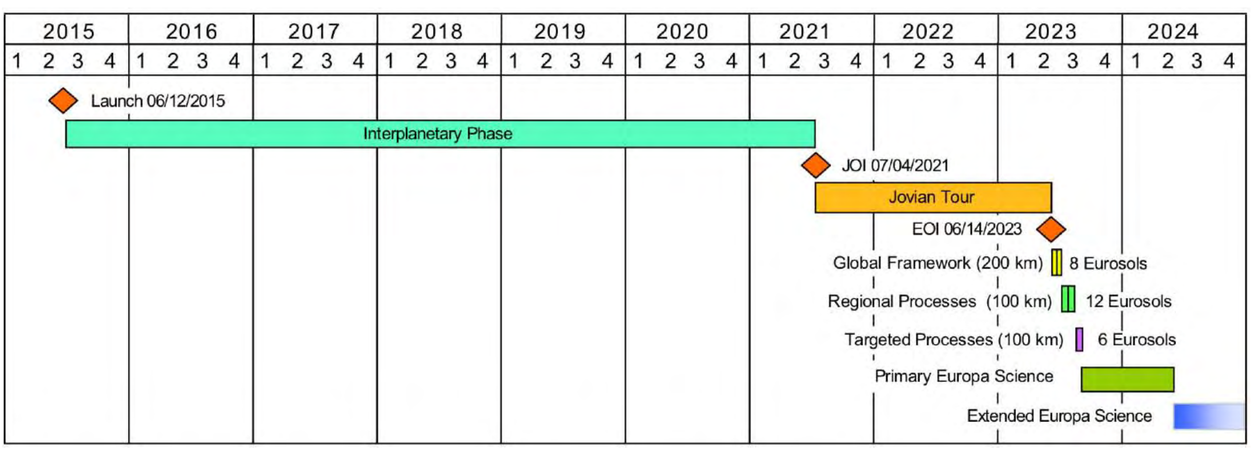


Figure G-3. *Europa Explorer Mission Phase Timeline*

Europa Mapping

The tour ends with Europa orbit insertion. Once in orbit, DSN tracking is increased to continuous 70 m tracking for 3 months to maximize science return. Focused Europa science will continue beyond the initial 3 months of science but with reduced tracking. The next 9 months will be targeted science and will provide key Europa science but use less tracking; one 70 m pass per day versus round the clock tracking.

In addition to the instrument based science observations, Europa gravity science will be performed during first 12 months in Europa orbit using the radio science capabilities of the flight system and DSN. Gravity science will use coherent, two-way Ka and X-band Doppler data. The 70 m can support the coherence X-band up and down, however, the Ka-band uplink passes currently require Goldstone's 34 m BWG, DSS-25, with the only Ka-band transmitter in the DSN.

Extended Europa Science (not costed)

At the end of the one-year prime Europa science activities the flight system will still have significant radiation margin available to enable months of additional operation around Europa. To make use of this opportunity, daily 8-hour 70 m passes could be used to support the continued observations (not yet planned or costed). These tracks would return the science observations made and support the navigation activities needed to maintain a stable orbit around Europa. This phase could continue until the flight system becomes inoperable or until the project is terminated. The present notional concept does not have additional Ka-band radio science and so the 34 BWG is not scheduled in this period.

G4. Scenario Analyses

The 2006 EE study examined operations concepts for the collection and return of large volumes of science data with highly constrained on-board data storage. The current study has a planning payload that can generate similar data volumes with a similar variety of data types and rates. Conclusions from the earlier study were applied as needed to the current study. The data collection tool used for the earlier study was updated and modified for the new planning payloads and used to develop operations scenarios for science data collection and return.

The current study also has similar issues with mass memory depth. While emerging CRAM memory components are somewhat less massive and power hungry than last year's baselined SRAM components, their performance is still unknown and they make large, massive and power hungry SSRs. The decision was made to allocate 1 Gb of SSR in the system design to science for data collection and return. Because of this, the operations constraints needed by the previous study were carried forward. They include (for the Europa Science phase):

- Downlink all data on the orbit collected
- Collect data mainly during downlink sessions
- Preclude mass memory allocations for data retransmission
- Schedule continuous DSN 70 m tracking (or equivalent)
- Use X-band for highest link reliability (based on weather)

These operations constraints remove consideration for data retransmission, discontinuous DSN coverage, and prioritizing and queuing of data products. On-the-fly data reduction, compression, processing, packetization and management can still be accommodated and is necessary in most cases. Analysis based on these recommendations showed that mass memory allocations of significantly less than one Gbit could be used while allowing considerable flexibility in data collection among instruments.

The simulation tool used for scenario analysis was adapted from the tool used last year. The planning payload instruments and instrument characteristics were incorporated and a second orbit was added to the minute-by-minute simulation. Methods for evaluating different orbit periods for different science campaigns, different data rates for each orbit, and data set asides for coordinated target data collection were incorporated.

G4.1 Floor Scenarios

During SDT meetings, science objectives were developed and instrument characteristics for the floor planning payload were developed.

Simulations were run to determine how well scenarios under discussion were performing. In this way, it was discovered that instrument data rates were too high for single orbit strategies but by alternating orbits for certain instruments, global imaging coverage and profile distribution would meet science goals. **Table G-2** shows the instrument characteristics of raw data rate, data reduction factor, observation duty cycle and generated data volumes per orbit for the floor planning payload. The example shown is for Campaign 1 at 200 km orbit altitude. Campaigns 2, 3, and 4 have similar characteristics but are at 100 km orbit altitude. Some instrument rates are twice as fast at the lower altitudes as the pixel rates are faster due to range and ground speed.

Figures G-4 through **G-6** show the floor data flow simulation results for Campaigns 1, 2 and 3. The red plot line shows the available accumulated downlink data volume (occultations are shown and include DSN lockup times). The green line shows the data collected as an accumulation to compare to the downlink capability. The dark blue line shows the state of the SSR at each minute. Each instruments data collection scenario is represented in the plot and the simultaneous and accumulated impacts are characterized.

The examples show accumulation in the SSR only during occultations. Operations constraints allow only a few low rate instruments to operate during occultations. These scenarios show only a 10–15% depth of use on the SSR and only during occultations. There is ample room for coordinated target data collection for either the ~400 Mb imaging type or the 900 Mb radar type on most orbits.

Table G-2. *Floor Scenario Instrument Inputs – Rates, Reduction Factors, Duty Cycles*

Inputs		WAC	MAC	IRS	IPR	TI	LA	PPI	MAG
Raw data rate (Mb/s)		0.1	1.5	0.03	30	0.004	0.002	0.002	0.0025
Mapping orbit duty cycle		40%	0%	40%	25%	100%	100%	100%	100%
Data reduction rate		4	4	2.5	215	2	1	1	1
Uncompressed Dvol (Mb)		336	0	99	62100	33	17	17	21
Compressed Rate (Mb/s)		0.025	0.38	0.012	0.140	0.002	0.0020	0.0020	0.0025
Total Dvol/Orbit #1 (Mb)	(0.11)	84.0	0.0	40.3	0.0	16.6	16.6	16.6	20.7
Total Dvol/Orbit #2 (Mb)	(0.11)	0.0	0.0	40.3	293.0	16.6	16.6	16.6	20.7
Total Dvol/2Orbit (Mb)		84.0	0.0	80.6	293.0	33.1	33.1	33.1	41.4

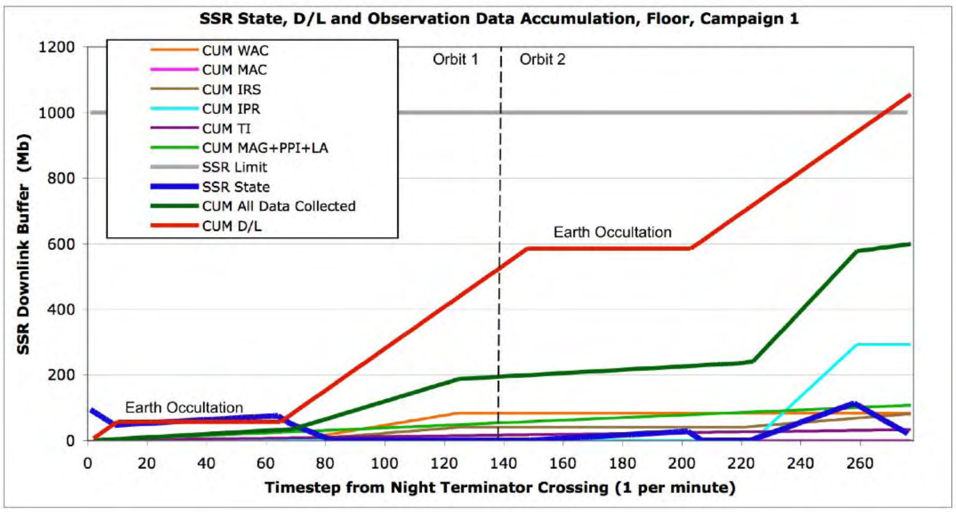


Figure G-4. *Floor Data Flow Simulation Results for Campaign 1*

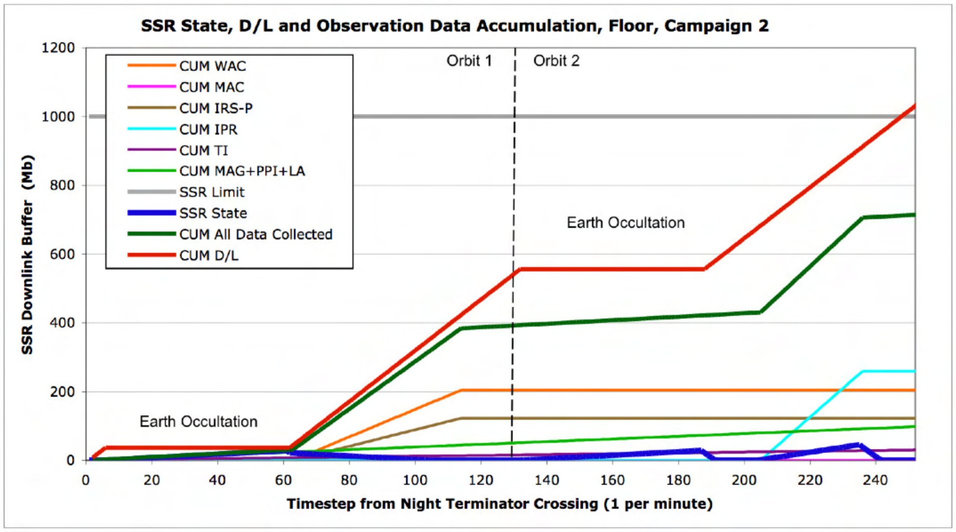


Figure G-5. Floor Data Flow Simulation Results for Campaign 2

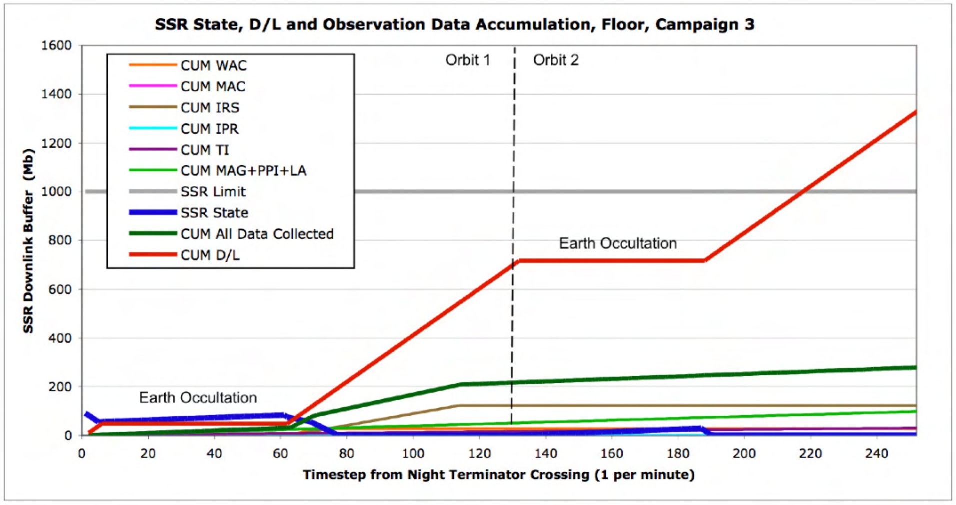


Figure G-6. Floor Data Flow Simulation Results for Campaign 3

The small difference between the downlink capacity and the accumulated data collected (red and green lines) shows that at the beginning of Campaign 2 (**Figure G-5**), few targets can be collected. This is due to the change in orbit period (from changing altitude from 200 km to 100 km) and occultation duration (they are relatively longer due to the lower period and closer orbit geometry). Campaign 3, on the other hand, shows most of its data as available for coordinated target observing. Campaign 4 was developed very late in the study and was not simulated. Its behavior is very similar to Campaign 3.

The mission performance of the floor mission is shown in **Table G-3**. Performance in this context is represented by measures of daily data volume for global mapping and profiling goals and for coordinated targets and the totals of same for each campaign. The number of targets per day and per campaign are also shown as are percentage distributions for the different representative instruments.

G4.2 Baseline Scenarios

After the floor scenarios were developed, the SDT began developing the baseline science scenarios. The planning payload and instrument characteristics were augmented to be able to meet the baseline science goals. Simulations were run to determine how well scenarios under discussion were performing. **Table G-4** shows the instrument characteristics of raw data rate, data reduction factor, observation duty cycle and generated data volumes per orbit for the baseline planning payload. The example shown is for Campaign 1 at 200 km orbit altitude. Campaigns 2, 3, and 4 have similar characteristics but are at 100 km orbit altitude. Some instrument rates are twice as fast at the lower altitudes as the pixel rates are faster due to range and ground speed.

Figures G-7 through **G-9** show the baseline data flow simulation results for Campaigns 1, 2 and 3. The red plot line shows the available accumulated downlink data volume (occultations are shown and include DSN lockup times). The green line shows the data

Table G-3. *Floor Mission Performance – Data Volume and Number of Targets*

	Campaign 1						Campaign 2						Campaign 3						All Campaigns		
Reference S/C (Floor)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Targ per day	Cam Tot Targ	Cam Tot Vol (Gb)	Total Targets	% total vol	Total Vol (Gb)
Data Volume	3.1	2.5				**158**	3.1	2.7				**284**	2.1	5.6				**161**			**603**
WAC	0.4		8%			**12**	0.4	0.0	7%			**66**	0.6		8%			**13**		15%	**92**
MAC[1]	0.0	0.2	4%	11 T	**295**	**7**	0.0	0.3	5%	12 T	**291**	**17**	0.0	0.1	1%	1 T	**21**	**1**	**606 T**	4%	**25**
IRS[2]	0.4	1.4	32%	11 T	**301**	**50**	0.4	1.6	34%	12 T	**295**	**67**	0.7	0.1	11%	1 T	**21**	**17**	**617 T**	22%	**135**
IPR[3]	1.5	0.9	43%	1 T	**28**	**68**	1.5	0.9	42%	1 T	**42**	**102**	0.0	5.4	70%	6 T	**126**	**113**	**196 T**	47%	**284**
TI	0.2		3%			**5**	0.2		3%			**7**	0.2		2%			**4**		3%	**16**
LA	0.2		3%			**5**	0.2		3%			**7**	0.2		2%			**4**		3%	**16**
PPI	0.2		3%			**5**	0.2		3%			**7**	0.2		2%			**4**		3%	**16**
MAG	0.2		4%			**6**	0.2		4%			**9**	0.2		3%			**5**		3%	**20**

[1] MAC targets are 1 minute duration (71 km/min @200 km, 78 km/min @100 km)
[2] IRS targets are each 400x400 pixels, 128 Mb
[3] IPR targets are each 30 Mb/s x 30 s, 900 Mb

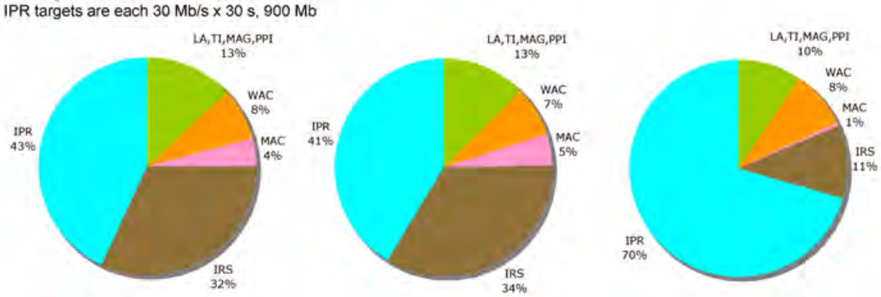


Table G-4. *Baseline Scenario Instrument Inputs – Rates, Reduction Factors, Duty Cycles*

Inputs		WAC	MAC	NAC	IRS-P	IRS-I	IPR	TI	UVS-PL	UVS-I	LA	MAG	INMS	PPI
Raw data rate (Mb/s)		0.4	3	15	0.03	30	30	0.043	0.005	4	0.012	0.004	0.0015	0.002
Mapping orbit duty cycle		40%	0.0%	0.0%	40%	0.0%	45%	80%	100%	0.0%	100%	100%	100%	100%
Data reduction rate		4	4	4	2.5	2.5	107	2	1	2	1	1	1	1
Uncompressed Dvol (Mb)		1344	0	0.0	99	0	111780	285	41	0	99	33	12	17
Compressed Rate (Mb/s)		0.100	0.75	3.7500	0.012	12.000	0.280	0.022	0.0050	2.0000	0.0120	0.0040	0.0015	0.0020
Total Dvol/Orbit #1 (Mb)	(0.32)	336.0	0.0	0.0	40.3	0.0	0.0	143.2	41.4	0.0	99.4	33.1	12.4	16.6
Total Dvol/Orbit #2 (Mb)	(0.32)	0.0	0.0	0.0	40.3	0.0	1059.8	143.2	41.4	0.0	99.4	33.1	12.4	16.6
Total Dvol/2Orbit (Mb)		336.0	0.0	0.0	80.6	0.0	1059.8	286.4	82.8	0.0	198.7	66.2	24.8	33.1

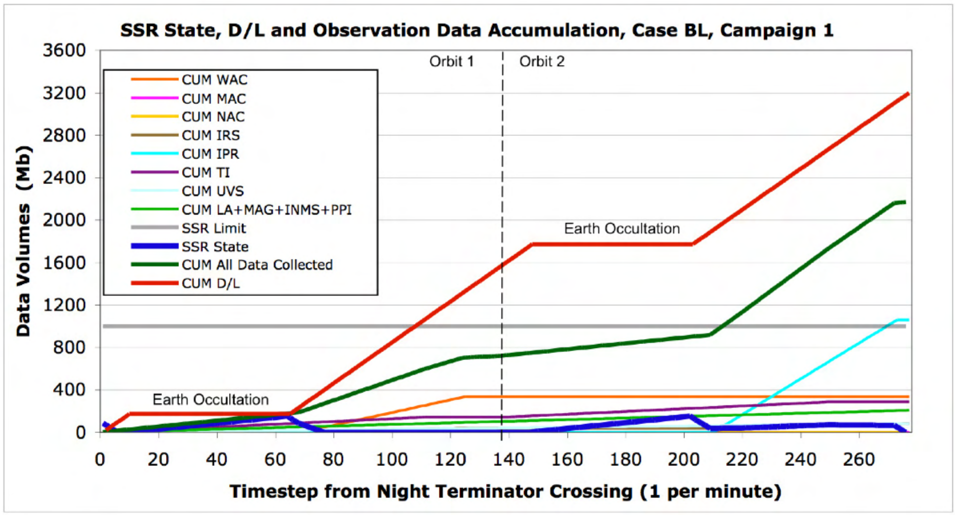


Figure G-7. Baseline Data Flow Simulation Results for Campaign 1

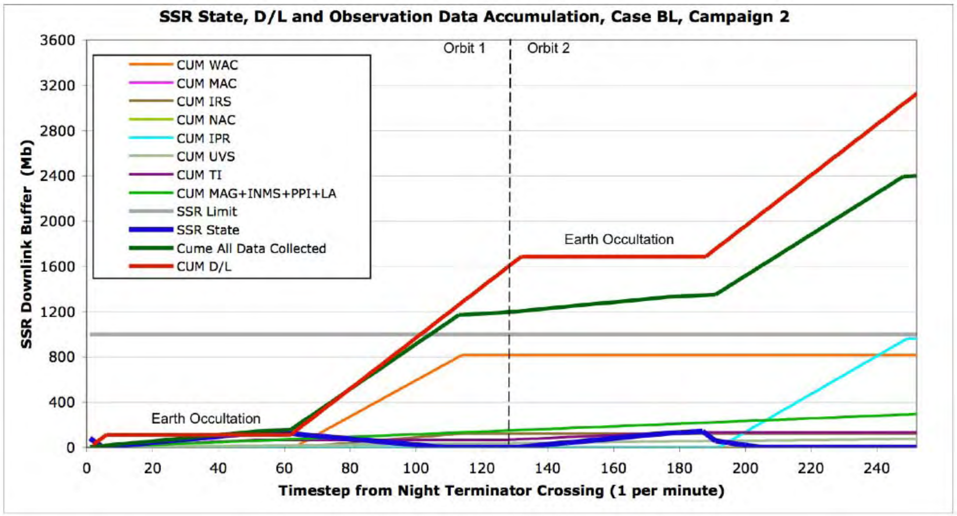


Figure G-8. Baseline Data Flow Simulation Results for Campaign 2

collected as an accumulation to compare to the downlink capability. The dark blue line shows the state of the SSR at each minute. Each instruments data collection scenario is represented in the plot and the simultaneous and accumulated impacts are characterized.

The examples show accumulation in the SSR only during occultations when only a few low rate instruments are operating during. These scenarios show only a 10–15% depth of use on the SSR and only during occultations. There is ample room for coordinated target data collection for either the ~400 Mb imaging type or the 900 Mb radar type on most orbits.

The small difference between the downlink capacity and the accumulated data collected (red and green lines) shows that at the beginning of Campaign 2 (**Figure G-8**), few targets can be collected (once every other orbit). This is due to the change in orbit period (from changing altitude from 200 km to 100 km) and occultation duration (they are relatively longer due to the lower period and closer orbit geometry). By the middle of Campaign 2, data rate improvements (due to Earth Europa range reductions) and the completion of global color mapping, cause the available data volume to increase and the WAC data volume needs to decrease. Daily

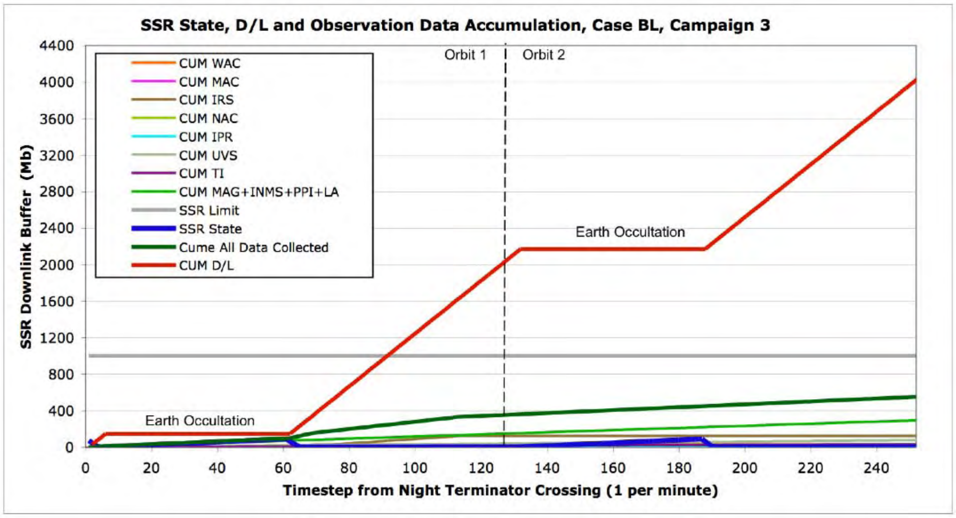


Figure G-9. Baseline Data Flow Simulation Results for Campaign 3

targeting will increase to an average more than one per orbit in this timeframe and beyond. Campaign 3 shows most of its data as available for coordinated target observing. Campaign 4 was developed very late in the study and was not simulated. Its behavior is very similar to Campaign 3.

Coordinated targets are collected only when analysis of upcoming data takes and downlink data volume shows there is sufficient data to collect one. Target locations will be selected based on lists of preselected targets by type and extent and can be automatically selected to fill data volumes as they become available. This planning occurs on the ground approximately with sequence uplink once per week, and with ephemeris updates several times per week.

The mission performance of the baseline mission is shown in **Table G-5**. Performance in this context is represented by measures of daily data volume for global mapping and profiling goals and for coordinated targets and the totals of same for each campaign. The number of targets per day and per campaign are also shown as are percentage distributions for the different representative instruments. The totals column shows that the baseline scenario enables collection of data over more than the desired 1000 targets in the first 3 campaigns. The values for IPR, UVS and NAC are different reflecting different goals for their targets. IPR takes very large observations (900 Mb) and cannot collect at the same time as the imagers (a larger SSR would enable simultaneous targeting for a subset of the total target set). UVS collects 2 stellar occultation targets at the limb of Europa each day. The NAC will collect high resolution target sets for characterizing potential future landing sites. This occurs in Campaign 3 and is likely to extend well into Campaign 4.

For both the floor and baseline missions (they have the same trajectory profile), the coverage of Europa is similar. Examples of global coverage for the WAC in baseline Campaign 1 is shown in **Figure G-10**. Global color coverage is complete in 3 eurosols or about 10 days. Global stereo coverage can be achieved in another 10 days, leaving 8 days in Campaign 1 for margin. This margin is useful for orbiter and instrument checkout and trim maneuvers immediately after EOI. A delay in mapping startup of several days can be tolerated and still achieve the Campaign 1 science goals.

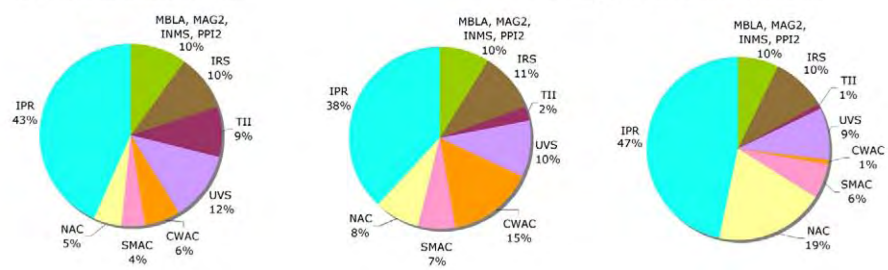
The WAC coverage for Campaign 2 is shown in **Figure G-11**. Because the WAC swaths are narrower due to lower orbit altitude, 7 eurosols are needed to achieve global coverage. Global stereo goals can be achieved in the remainder of Campaign 2. Small gaps in coverage are planned into the data allocations for Campaign 3.

Figure G-12 shows the ground track coverage for the 200 km orbit used in Campaign 1. This notional orbit has a 4 eurosol repeat pattern. This can be seen in the narrow spacing between adjacent ground tracks in the figure. Other repeat patterns will be considered in future studies. The ground track pattern can be used as a surrogate for LA, TI, IR spectral profiles, UV spectral profiles and IPR observations. The white box in the figure represents 10 × 10 degrees on the surface. Each degree on the surface is about 27 km in distance for both latitude and longitude near the equator. The ground track separation in the first campaign will be 60–70 km at the widest points.

Table G-5. *Baseline Mission Performance – Data Volume and Number of Targets*

	Campaign 1: Global Framework						Campaign 2: Regional Processes						Campaign 3: Targeted Processes								
Reference S/C (Baseline)	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Avg Targ per day	**Cam Tot Targ**	**Cam Tot Vol (Gb)**	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Avg Targ per day	**Cam Tot Targ**	**Cam Tot Vol (Gb)**	Glob data per day (Gb)	Targ data per day (Gb)	% tot vol	Avg Targ per day	**Cam Tot Targ**	**Cam Tot Vol (Gb)**	Total Targets	% total vol	**Total Vol (Gb)**
Data Volume	10.7	6.6				**483**	11.7	7.5				**804**	3.1	20.0				**486**			**1773**
WAC	1.1		6%			**31**	2.9		15%			**122**	0.2		1%			**3**		9%	**156**
MAC[1]	0.0	0.7	4%	12 T	**333**	**15**	0.0	1.3	7%	11 T	**441**	**53**	0.0	1.5	6%	12 T	**254**	**30**	**1028 T**	6%	**98**
NAC[2]	0.0	0.9	5%	12 T	**329**	**18**	0.0	1.6	8%	11 T	**441**	**66**	0.0	4.5	19%	30 T	**630**	**95**	**1400 T**	10%	**179**
IRS[3]	0.4	1.3	10%	12 T	**328**	**54**	0.7	1.3	11%	11 T	**441**	**86**	0.7	1.6	10%	12 T	**254**	**47**	**1024 T**	11%	**187**
IPR[4]	5.5	1.8	43%	3 T	**70**	**218**	5.5	1.8	38%	2 T	**84**	**306**	0.0	10.8	47%	12 T	**252**	**227**	**406 T**	42%	**750**
TI	1.5		9%			**42**	0.5		2%			**19**	0.2		1%			**4**		4%	**65**
UVS	0.4	1.6	12%	14 T	**383**	**58**	0.4	1.5	10%	13 T	**525**	**81**	0.4	1.7	9%	14 T	**298**	**45**	**1205 T**	10%	**184**
LA	1.0		6%			**29**	1.0		5%			**44**	1.0		4%			**22**		5%	**94**
MAG	0.3		2%			**10**	0.3		2%			**15**	0.3		1%			**7**		2%	**31**
INMS	0.1		1%			**4**	0.1		1%			**5**	0.1		1%			**3**		1%	**12**
PPI2	0.2		1%			**5**	0.2		1%			**7**	0.2		1%			**4**		1%	**16**

[1] MAC targets are 1 minute duration (71 km @200 km, 78 km @100 km)
[2] NAC targets are 15 seconds duration
[3] IRS targets are each 400x400 pixels, 128 Mb
[4] IPR targets are each 30 Mb/s x 30 s, 900 Mb



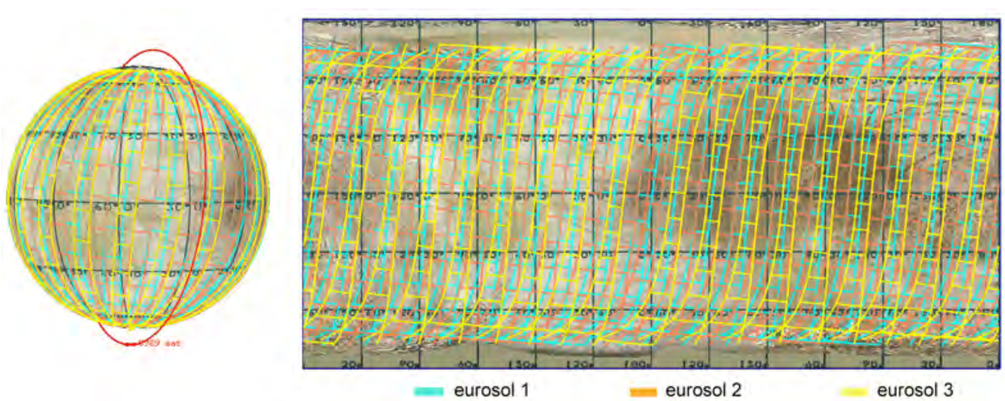


Figure G-10. *WAC Coverage for 3 Eurosols in Campaign 1*

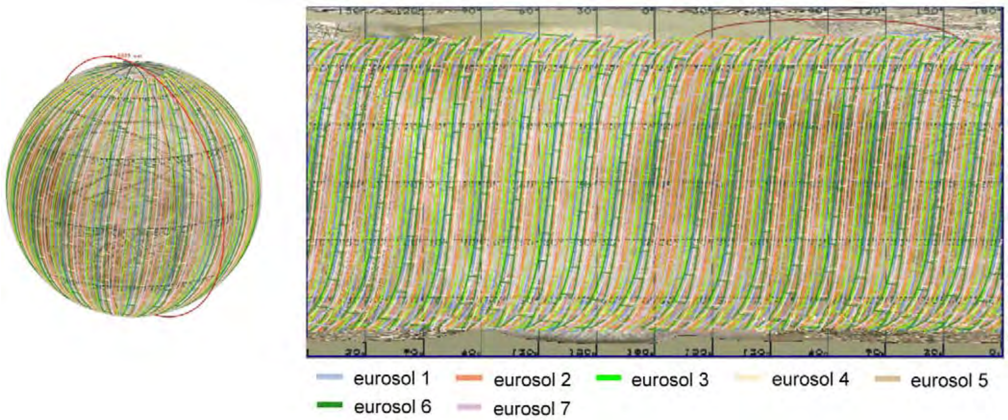


***Figure G-11**. WAC Coverage for 7 Eurosols in Campaign 2*

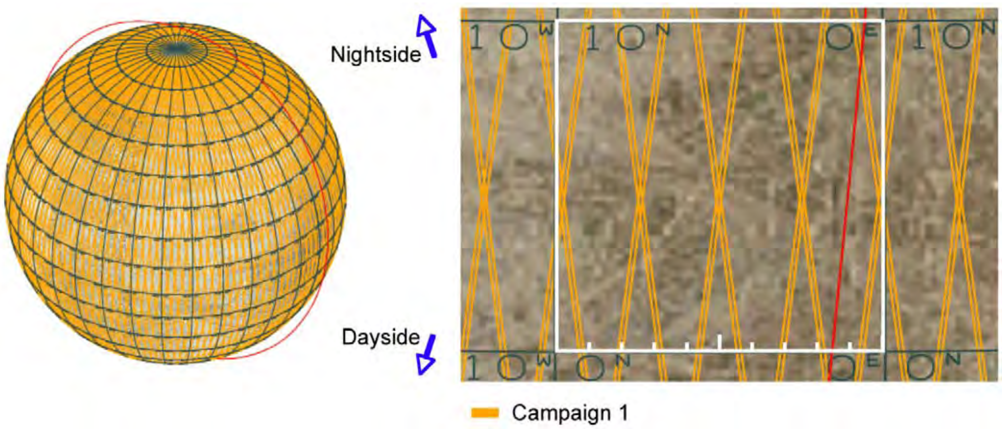


***Figure G-12.** Ground-track Coverage in Campaign 1*

By the end of Campaign 3, the ground tracks will be densely scattered across Europa. Laser altimeter, thermal and spectral profiles will have grids finer than 1 degree on the surface and the radar sounder will have grids about half as fine. **Figure G-13** shows the ground track spacing for Campaigns 1–3. The colors show how the ground tracks build up by campaign.

Other repeat cycles will have considerably better performance as these have very close spacing at the repeat intervals. This allows for larger gaps in the grid. Other repeat cycles can be devised to reduce the gap size with small impacts to orbit altitude and period. Other considerations include alternating orbit repeat patterns vs repeat geometry for swath coverage and gap fill, and ideal repeat patterns for repeat pass stereo coverage.

G4.3 Jupiter System Science Analysis

The Jupiter system science opportunities exist as a result of the trajectory needed to reduce the required ΔV for EOI to feasible levels. The trajectory gradually reduces the flight system's orbital energy through 2 years of gravity assist flyby maneuvers at Ganymede, Callisto, and Europa. While not fully optimized, the tour portion of the end-to-end trajectory is typical of trajectories that have been optimized to minimize ΔV and radiation total dose. No consideration for encounter geometry for science was made. The resulting trajectory contains encounters with Callisto, Ganymede and Europa that can be considered typical for such trajectories. It is very likely that future studies will be able to design science optimized targeted and non-

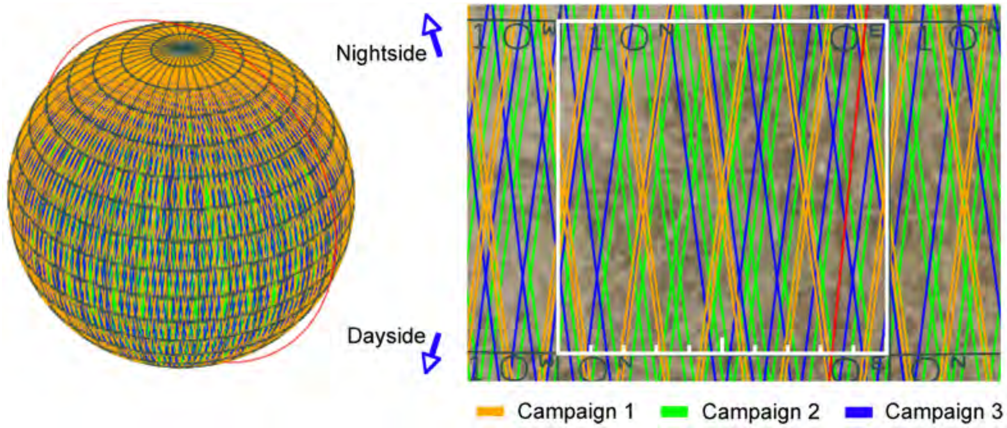


Figure G-13. *Ground-track Coverage in Campaigns 1–3*

targeted encounters for a small penalty of ΔV, radiation dose, and/or trip time.

The following analysis is representative of the types of geometries that could be used for observing during a Tour. The analysis is a cursory look at typical geometries and how they might be used with the EE planning payload to survey Jupiter and the Jovian satellite system. While the flight system is in Jupiter orbit during the tour, each gravity assist flyby typically happens within a day or two of a Jupiter closest approach. EE's ability to collect tour science is determined by the planning payload, on-board storage space, downlink rate, and DSN time. Gravity assist flybys have additional DSN tracking coverage scheduled, including 70 m stations, to increase data volume returned and navigation accuracy during an encounter. While the additional data volume is increased, the close ranges and high resolutions occur over such a short time period that on-board data storage becomes the most significant limiting constraint.

Around any given satellite encounter, the range to the surface will be less than 10,000 km for about 1 to 3 hours depending on the range and relative speed of the flight system to the target. At 10,000 km the narrow angle camera (NAC), for example will get 100m/pixel resolution, similar to the WAC in a 100 km Europa orbit. **Figure G-14** shows the pixel resolution vs range for the three imaging payloads.

During the closest approach portions of the encounter, where ranges of less than 10,000 km occur, the 1 Gb SSR science data allocation can support collection and return of around 2–3 Gb. In a week where a satellite encounter and Jupiter flyby occurs, the tracking coverage and associated telecom rates typically support downlink of 10–30 Gb for the entire week.

In addition to the data volume that can be collected during the closest approach, the remaining downlink data volume capacity over the week can be divided between far encounter observations (between 10,000 and 100,000 km), Jupiter observation opportunities, and non-targeted opportunities to observe other satellites at ranges of between 100,000 and 500,000 km, where NAC can get resolutions of 1–5 km/pixel. "Non-targeted" means that they are geometrically opportunistic and have no impact on the vehicle flight path.

Table G-6 summarizes the number and characteristics of the Jupiter observing, gravity assist encounter, and not-targeted observing opportunities during the tour.

Jupiter Opportunities

The Jupiter opportunities are well distributed across the Tour, facilitating observation of changing phenomena that span the length of the 2-year tour. Jupiter observing opportunities at less than 1 million km are relatively evenly spaced in time and occur on every orbit whether there is a satellite encounter or not. **Table G-7** summarizes the characteristics of 40 Jupiter opportunities during the tour that have range less than one million km.

Planned DSN coverage allows about 1.8 Tb to be downlinked during the tour. Of this, about half of the downlink is focused around

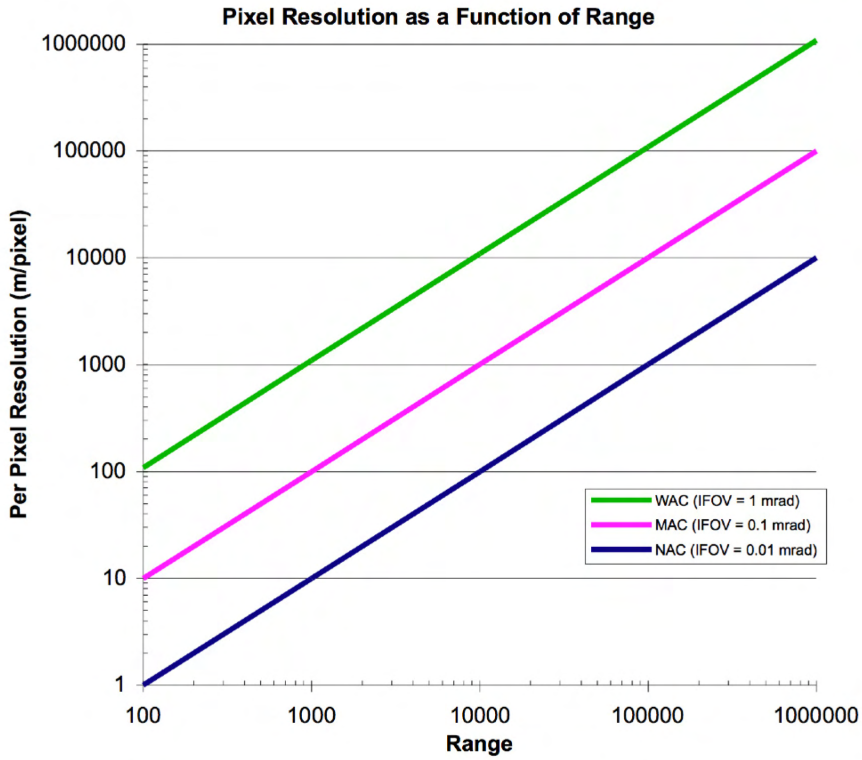


Figure G-14. *Pixel Resolution as a Function of Range*

Table G-6. *System Science Observing Opportunities*

	Opportunities	Ranges (km)	Phase angles (deg)	Ground Speeds (km/s)
Jupiter	40	560,000 – 1,000,000	10 – 100	
Encounters				
Callisto	4	370 – 3,600	80 – 120	2.8 – 4.7
Europa	5	100 – 2,800	60 – 100	0.4 – 1.9
Ganymede	14	450 – 8,050	70 – 170	1.2 – 6.9
Non-Targetted				
Callisto	1	325,000	70	
Europa	13	107,000 – 460,000	5 – 135	
Ganymede	7	28,000 – 430,000	55 – 114	
Io	17	276,000 – 490,000	8 – 174	

***Table G-7**. Summary of opportunities to observe Jupiter at less than 1 million km*

Date	Closest Approach (km)	SC Speed wrt Jupiter (km/s)	Closest Approach Latitude	West Longitude of Closest Approach	Closest approach East Longitude	phase angle sun-body-sc (deg)
7/4/21	821906	140.6	1.7	90.24	269.8	70.9
1/6/22	781700	133.5	0.6	99.70	260.3	61.3
3/19/22	719104	122.5	0.2	215.14	144.9	67.2
4/17/22	687226	116.4	-4.2	334.34	25.7	70.7
5/8/22	709349	120.8	0.5	285.48	74.5	65.6
6/2/22	708185	120.6	0.5	343.49	16.5	62.3
7/5/22	831104	143.1	2.4	277.07	82.9	70.6
8/10/22	857370	148.1	-0.1	325.13	34.9	69.8
9/15/22	808258	139.2	-4.0	240.20	119.8	76.4
10/6/22	796495	137.4	-0.1	252.16	107.8	78.1
10/25/22	922784	160.6	-0.4	116.27	243.7	64.6
11/18/22	922222	160.5	-0.4	129.41	230.6	62.2
12/2/22	862301	149.9	-3.1	115.65	244.3	41.8
12/16/22	899888	155.9	-7.5	27.46	332.5	47.8
12/30/22	930657	162.8	-0.5	32.88	327.1	38.3
1/14/23	954224	167.1	-0.5	247.04	113.0	36.9
1/24/23	894137	156.7	-0.6	258.37	101.6	10.8
2/4/23	894673	156.8	-0.6	233.01	127.0	9.4
2/11/23	736722	128.2	-0.3	145.63	214.4	44.7
2/16/23	566657	96.2	0.1	79.73	280.3	84.0
2/21/23	566703	96.2	0.1	254.27	105.7	83.4
2/27/23	567210	96.3	0.1	60.85	299.2	84.5
3/4/23	561412	95.3	0.5	340.74	19.3	90.4
3/10/23	562689	95.5	0.5	294.37	65.6	91.3
3/15/23	557309	94.6	0.8	30.60	329.4	97.3
3/20/23	557445	94.6	0.8	168.69	191.3	96.7
3/25/23	570145	97.1	0.8	336.05	24.0	96.5
3/28/23	994399	179.1	-0.2	175.28	184.7	97.6
3/31/23	700706	122.0	-2.3	255.58	104.4	67.8
4/6/23	701205	122.1	-2.4	205.86	154.1	67.6
4/12/23	699964	121.8	-2.4	147.39	212.6	68.2
4/17/23	699502	121.7	-2.4	88.71	271.3	68.6
4/23/23	699191	121.7	-2.5	29.55	330.5	68.6
4/28/23	595786	101.2	-0.3	64.58	295.4	83.1
5/4/23	593902	101.6	-0.6	301.45	58.6	94.3
5/9/23	598058	102.3	-0.5	273.39	86.6	94.2
5/14/23	598832	102.5	-0.2	49.30	310.7	74.3
5/20/23	592948	101.8	-0.1	356.32	3.7	68.6
5/25/23	601298	103.5	-0.1	147.29	212.7	69.1
5/29/23	600973	103.4	-0.1	308.18	51.8	69.9

flybys at high resolutions. During the rest of the tour the data volume can be used to downlink data of non-targeted opportunities of Jupiter and its satellites as they become available within suitable ranges.

Non-Targeted Encounters

Non-targeted encounters are opportunities to observe satellites in the Jupiter system at less than 500,000 km range. These opportunities are not specifically targeted in the mission design and the timing and number of encounters could be adjusted at varying cost in ΔV. The details of these non-targeted encounters are shown below in **Table G-8** through **Table G-10**.

Table G-8. *Summary of Europa non-targeted opportunities at < 500,000 km*

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Europa	7/4/21	233126	2.1	8.3	167.48	84.0
Europa	7/5/22	262308	3.7	8.5	206.77	41.8
Europa	8/10/22	337577	5.5	1.0	218.80	22.9
Europa	9/14/22	227714	3.4	-12.9	198.77	56.1
Europa	10/6/22	341508	6.0	0.3	229.75	10.7
Europa	12/29/22	382669	8.6	-0.9	200.85	4.8
Europa	2/15/23	458108	2.7	-0.1	73.73	57.6
Europa	2/18/23	400261	12.2	0.1	163.20	66.9
Europa	3/19/23	364031	2.6	1.8	78.01	73.1
Europa	3/21/23	341080	10.7	-3.0	165.16	57.3
Europa	3/31/23	107362	2.7	-16.2	170.55	58.8
Europa	4/9/23	383542	11.3	14.0	187.43	135.6
Europa	4/19/23	344411	10.3	-9.6	171.18	75.2

Table G-9. *Summary of Ganymede and Callisto non-targeted opportunities at < 500,000 km*

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Ganymede	7/6/22	47984	5.5	50.0	68.38	111.2
Ganymede	8/10/22	119666	5.6	-0.1	25.72	114.1
Ganymede	12/16/22	184608	3.4	-78.1	0.43	104.3
Ganymede	2/15/23	351931	7.0	0.1	341.57	57.2
Ganymede	3/9/23	428925	9.4	0.7	358.26	75.9
Ganymede	5/17/23	27507	2.0	10.1	189.90	96.0
Ganymede	6/1/23	112068	0.8	1.5	353.39	54.6
Callisto	12/5/22	327140	3.4	68.8	325.59	68.9

Table G-10. *Summary of Io non-targeted opportunities at < 500,000 km*

Satellite	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	West Longitude of Closest Approach	Phase Angle sun-body-sc (deg)
Io	2/10/23	437398	22.1	-0.1	190.41	95.1
Io	2/15/23	423989	22.4	0.1	199.48	174.0
Io	3/19/23	460398	24.8	1.0	194.12	145.3
Io	3/24/23	392239	20.9	2.7	196.20	163.1
Io	4/1/23	455307	23.3	-14.0	172.36	22.8
Io	4/6/23	364381	18.6	-10.9	174.74	41.0
Io	4/11/23	367361	19.1	4.3	186.69	104.6
Io	4/16/23	465107	23.8	12.7	191.12	152.0
Io	4/24/23	483054	25.0	-13.0	174.92	29.0
Io	4/29/23	439731	23.5	3.0	166.15	10.9
Io	5/5/23	435073	23.2	3.0	165.66	9.4
Io	5/10/23	393818	20.9	-0.3	166.03	16.4
Io	5/15/23	363469	19.1	-0.4	164.17	7.7
Io	5/21/23	340247	18.1	0.4	163.81	16.8
Io	5/23/23	441646	23.9	-0.3	190.22	165.3
Io	5/26/23	488939	26.6	0.3	174.96	73.4
Io	5/29/23	276099	14.4	-0.4	189.52	116.7

Encounter Opportunities

Several feasibility level analyses were conducted to explore the usefulness of EE payloads during gravity assist flybys or encounters. The EE payload is intended to collect data in a low altitude, near-circular orbit of Europa where ground speed, altitude and lighting conditions are very similar orbit-to-orbit. In the tour, however, ground speeds, altitudes, and lighting conditions vary drastically through each encounter. For most encounters, these conditions are within reasonable limits for the types of instruments in the planning payload, particularly if they have been designed for the expected ranges. To effectively use some of the instruments, flight system slews may be needed. Two bounding case flyby examples were studied to determine how, generally, the observations might be acquired. For the two representative cases, slew rates to maintain tracking of the ground with the instruments and the gimbal rates needed to keep the HGA pointed on the Earth were also within reasonable limits compared to conditions in Europa orbit. Because of data volume storage constraints, a strategy of alternating imaging and IPR sub-surface sounding was employed to ensure reasonable observations of each type. This only becomes an issue when the flyby range was close enough to use the IPR and there are many encounter geometries with poor lighting that are useful for radar coverage.

Table G-11 summarizes the dates and geometry of the flyby encounters. Details of these encounters with potential for science observations are provided including latitude and longitude, closest approach altitude, ground speed, and lighting phase angle.

Figures G-15 through **G-17** show 30-minute ground tracks centered on closest approach for the targeted encounters of Callisto, Europa, and Ganymede. In total there are 14 Ganymede encounters, 4 Callisto Encounters, and 5 Europa encounters before EOI.

Table G-11. *Summary of the dates and geometry of the flyby encounters*

Satellite Encounter	Date	Closest Approach (km)	SC speed wrt body (km/s)	Latitude of Closest Approach	East Longitude of Closest approach	phase angle sun-body-sc (deg)	Ground Speed (km/s)
G0	4-Jul-2021	500	8.15	0.15	235.80	81.0	6.8
G1	6-Jan-2022	1500	7.00	30.70	242.70	70.0	4.4
G2	18-Mar-2022	120	7.00	8.00	251.00	72.0	5.5
G3	16-Apr-2022	100	7.00	64.60	269.80	87.7	6.7
G4	7-May-2022	100	6.95	-75.40	89.24	93.0	6.7
G5	14-Sep-2022	100	5.70	48.60	251.60	93.0	5.6
G6	5-Oct-2022	1190	5.40	-77.85	228.53	88.0	3.9
G7	19-Nov-2022	958	4.38	-12.00	298.70	141.0	1.8
G8	3-Dec-2022	100	4.55	-73.35	193.70	98.0	4.2
G9	15-Jan-2023	2695	3.34	2.30	300.77	172.0	1.7
G10	5-Feb-2023	1312	3.51	3.69	275.69	156.0	2.3
G11	12-Feb-2023	2594	3.34	3.03	248.50	127.2	1.7
G12	28-Mar-2023	1139	3.17	-55.84	33.24	70.0	2.9
G13	25-Apr-2023	200	3.16	47.00	340.70	101.0	1.2
C1	4-Jun-2022	400	6.51	44.00	83.00	82.0	4.7
C2	8-Jul-2022	1909	6.37	-86.00	12.00	87.0	2.8
C3	23-Oct-2022	3095	5.38	2.30	100.80	119.0	2.8
C4	27-Dec-2022	1159	4.23	-66.10	133.70	109.0	4.0
E1	27-Feb-2023	6069	2.70	33.40	309.20	77.0	0.5
E2	10-Mar-2023	8773	2.70	24.40	307.70	69.0	0.4
E3	28-Apr-2023	1451	2.45	-7.30	357.00	99.0	1.8
E4	9-May-2023	1500	2.39	22.10	175.82	86.0	1.9
E5	20-May-2023	669.5	1.96	15.50	213.00	46.0	0.6

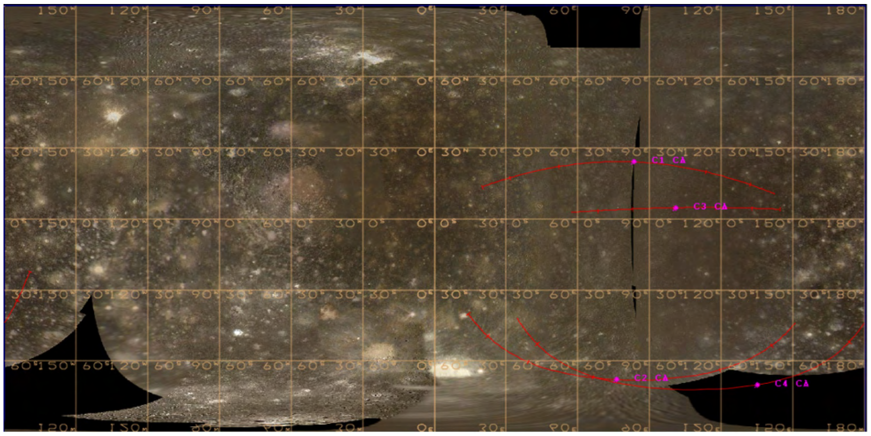


Figure G-15. *Callisto Flyby encounters*

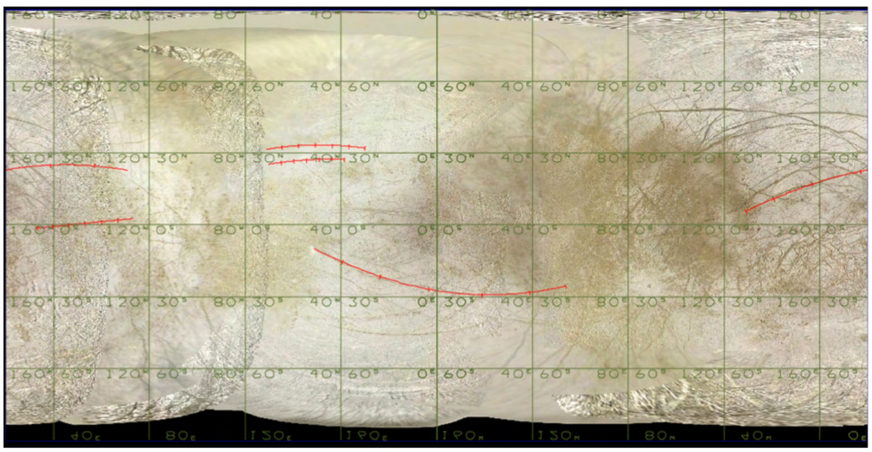


Figure G-16. *Europa Flyby encounters*

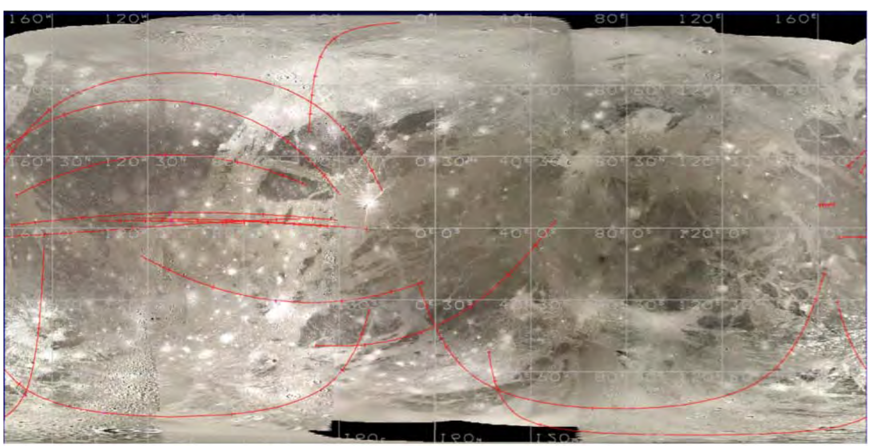


Figure G-17. *Ganymede Flyby encounters*

Representative Encounter Data Collection Strategy

Depending on flight system speed relative to the encounter body, time between 10,000–100,000 km, varies but there is generally sufficient time below 10,000 km to empty and drain the 1 Gb science allocation two to three times.

Since some encounter closest approaches do not get close enough to get meaningful data from the radar (~2000 km altitude), and other closest approaches occur partially or completely during eclipse, there are ample opportunities to alternate the primary focus for data volume collection of the various flybys between the IPR sub-surface soundings and the imaging payloads. Representative target strategies for Jupiter system encounters showing both an imaging focused flyby and a radar focused flyby are shown in **Table G-12**. They are similar in data volume to comparable target strategies used in orbit with the addition of a WAC image for context on the imaging focused encounters, and a MAC image to provide context to the radar driven encounters.

Analysis of several Ganymede flybys was performed to look at two bounding cases: a fast, close encounter with 70 km closest approach and 6.7 km/s speed with respect to Ganymede; and a distant, slow encounter with 2700 km closest approach and 3.2 km/s speed with respect to Ganymede. These provide bounding cases are representative of encounters at Ganymede.

For the first case of closest approach of 70 km, the range is less than 100,000 km for about 11 hours, while the closest approach is less than 10,000 km for only a little over one hour. At less than 100,000 km, the NAC and MAC can image with resolutions of 1 km/pixel and 10 km/pixel, respectively. At 10,000 km the resolution has improved to 100 m/pixel for the NAC and 1 km/pixel for the MAC. **Figure G-18** shows a timeline of the observing strategy and **Figure G-19** shows example coverage during a flyby with 15 minutes centered on encounter where range is below 2000 km using only imaging focused targets.

Table G-12. *Representative target strategies for encounters for both imaging focused and radar focused observations*

Payload	Duration	Volume (compressed)
WAC	70 s	7 Mb
MAC	60 s	45 Mb
NAC	6 s	60 Mb
IRS	10 s	128 Mb
UVS	8 s	120 Mb
	Total	360Mb

Payload	Duration	Volume (compressed)
MAC	60 s	45 Mb
IPR	30 s	900 Mb
	Total	945Mb

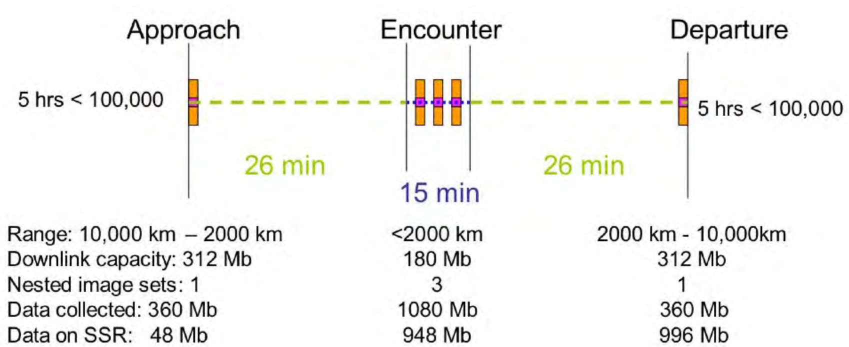


Figure G-18*. Shows the general imaging strategy during a 70 km altitude closest approach for ranges less than 10,000 km using imaging coordinated targets*

Figure G-19 shows how this strategy described would cover the surface using only the imaging coordinated targets at encounter. NAC is shown with purple swaths, MAC with orange swaths, and WAC with white swaths. The 15 minutes centered around closest approach is shown projected nadir as a ground trace in the dashed blue line. The star shaped patterns from the WAC are due to the projection of the edges of the square FOV onto the curved surface. The oval shaped MAC FOVs occur when the edges of the square FOV are above the limb of Ganymede. A constant pitch rate of 0.1 deg/s has been applied to the flight system to get reasonable ground speeds and keep the target in the FOV around closest approach.

These close encounter ranges are also favorable for the radar so both observation strategies were examined. **Figures G-20** and **G-21** show how a similar encounter with closest approach at 70 km could be modified to focus the closest approach altitudes below 2000 km on radar measurements. **Figure G-20** shows the target spacing with radar targets used at altitudes less than 2000 km. During approach and departure, imaging coordinated targets are shown.

Figure G-21 shows how the strategy would cover the surface for imaging focused encounter. NAC is shown with purple swaths, MAC with orange, and WAC with white swaths. In the center of the ground track shown in blue there is a long narrow radar measurement shown. The same constant pitch rate of 0.1 deg per second has been applied here.

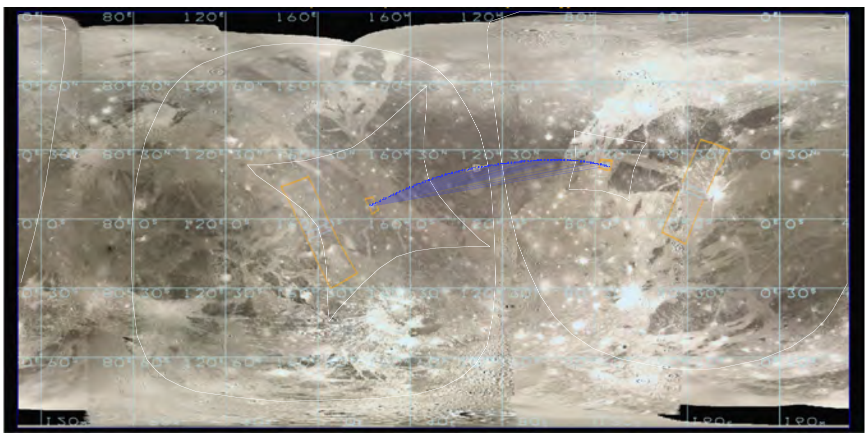


Figure G-19. *Representative Coverage of Ganymede during a close flyby using the imaging coordinated targets*

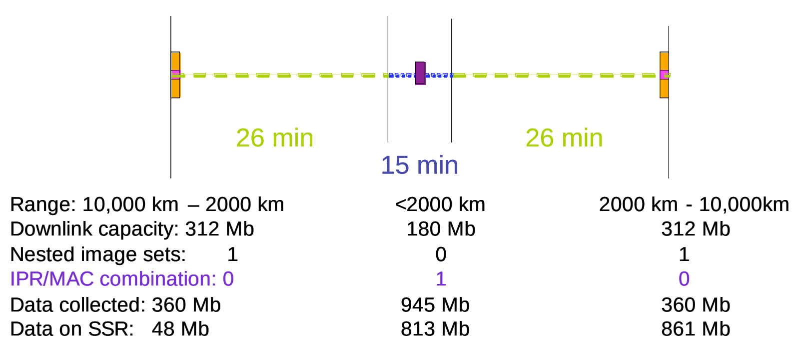


Figure G-20. *Shows the general imaging strategy during closest approach where ranges are less than 10,000 km for IPR targets during closest approach*

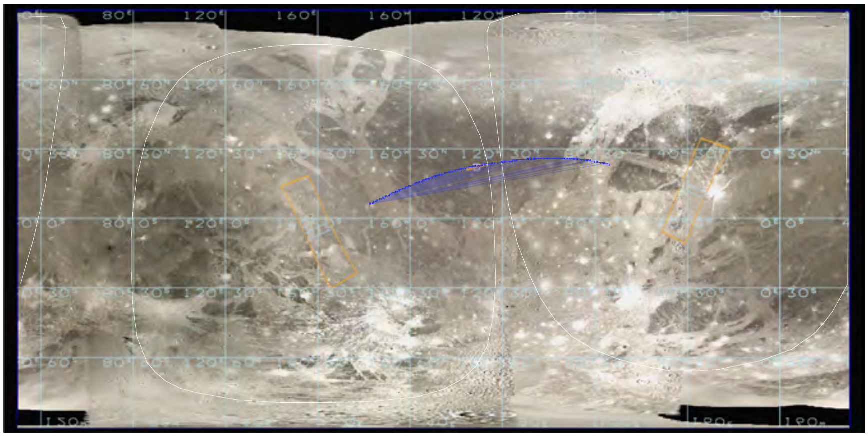


Figure G-21. *Representative Coverage of Ganymede during a close flyby using imaging coordinated targets at ranges greater than 2000 km, and the radar sub-surface sounding target during closest approach at ranges of less than 2000 km*

The other bounding case showing the more distant approach of 2700 km has slower relative velocity with respect to Ganymede and is too far away for meaningful radar observations. The imaging focused closest approach analysis resulted in a similar representative data collection strategy for ranges less than 10,000 km, though the lower speeds permit more targets since there is more time to downlink data.

The range is less than 100,000 km for over 20 hours and closest approach ranges of less than 10,000 km lasts for almost 2.5 hours. Assuming the SSR is emptied of stored data before reaching 10,000 km on approach, and nearly full at 10,000 km on departure, a total of seven 360 Mb coordinated imaging targets can be collected, totaling about 2.5 Gb. **Figure G-22** shows a representative strategy for how the seven image sets could be spread out at altitudes of less than 10,000 km.

During the 60-minute approach, assuming an average downlink rate of 200 kbps, two 360 Gb image sets, totaling 720 Mb, are taken and downlinked. The empty SSR is then filled completely during the 20-minute encounter. During departure, as storage capacity on the SSR is made available, additional targets are collected. The 18 hours between 10,000 km and 100,000 km allows up to about 13 Gb more to be collected for a total of 15.5 Gb. A constant pitch rate of 0.015 deg/s has been assumed for this encounter to keep a constant tracking angle throughout the flyby and keep ground speeds and lighting conditions within reasonable limits.

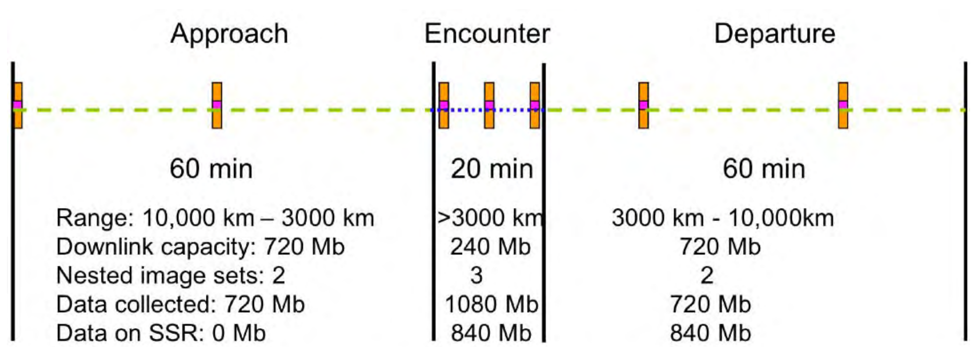


Figure G-22. *Shows the general imaging strategy during a 2700 km altitude closest approach for ranges less than 10,000 km using imaging coordinated targets*

This map of Ganymede in **Figure G-23** shows that during encounter there is excellent coverage at less than 10,000 km range. NAC is shown with purple swaths, MAC with orange, and WAC with white swaths.

Jupiter System Science Conclusions

The EE tour of the Jupiter System (required for propulsive reasons) provides ample opportunities to respond to the Priority 2 science objectives (§2) to determine how the components of the Jovian system operate and interact, leading to potentially habitable environments in icy moons. Dozens of opportunities exist to observe Jupiter and each of its Galilean satellites. These opportunities are important for placing Europa in the context of the Jovian satellite system. This larger context directly applies to interpreting measurements obtained at Europa, but it also allows measurements at Europa to be understood in the broader context as a member of the Jupiter system.

The planning payload instruments would provide strong capability for accomplishing Jupiter system science. The SDT has not optimized the EE payload nor resources to achieve Priority 2 science objectives during the tour, but assuming coverage strategies similar to Galileo's, EE could expect a typical satellite flyby or perijove pass to achieve optical remote sensing with about an order of magnitude higher resolution. Instruments not included in the Galileo payload would be trained on the satellites, notably the radar sounder. As a result, the composition, structure, origin, history, and present dynamics of Jupiter and its system would be addressed over a 2-year time scale. Moreover, fields and particles instruments operate continuously, allowing study of the interactions between Jupiter's magnetosphere and its satellites. Processes controlling satellite habitability are better understood as a result of the science accomplished during this Jupiter System tour.

For improved areal coverage of the surface at the highest resolutions during the relatively brief encounters, a larger capacity SSR would significantly increase the amount of data collected over a short period of time, which could then be downlinked over the following DSN contacts. For example, assuming data is also downlinked during the 30–60 minute satellite encounter, a tripling of the science SSR allocation to 3 Gb would about double the amount of areal coverage at less than 10,000 km range (which could be shared by the optical remote sensing instruments). For the brief duration at the closest ranges and highest resolutions, the time available to downlink is small, so the areal coverage would increase linearly with the increase in science SSR memory available.

G4.4 Trade Studies

G4.4.1 DSN Trades

The DSN sensitivity study examined the trades among DSN resources and the impacts to the flight system and operations scenarios to maintain the science mission goals. The study considered the Europa Science mission phase with particular emphasis on the goals for the first 92 days. Primary consideration was given to options to reduce 70 m tracking needs. The cases considered are shown in **Table G-13**. In each tracking case, the 2 scenarios examined

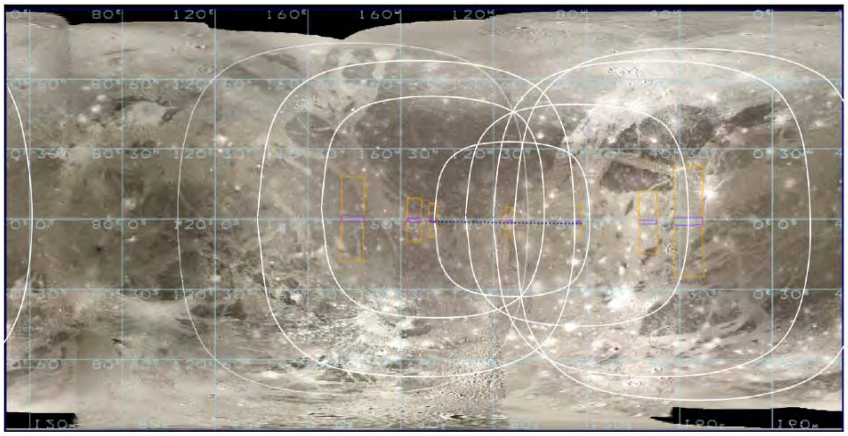


Figure G-23. *2700 km encounter*

improvements to the flight system or increases to the mission duration.

The study showed (**Table G-14**) that operations scenarios are unaffected by short term scheduling issues. In the event of planned short term outages, onboard downlink priorities can be used to reduce targeting activities, then IPR swaths, then mapping data collection. There is no need to reduce Laser Altimeter or fields and particles data collection if tracking gaps are less than a day or two.

A small increase in mission duration could occur if tracking gaps are chronic (> 1 per week). Larger SSR capacities are needed for significant, routine, and scheduled DSN tracking gaps: 3 times larger if two 70 m tracks per day (with one 34 m for radio science and data) are used; 5 times larger if only one 70 m track per day (+ one 34 m) is scheduled.

For the Focused Science campaign (after 92 days) with one 70-m and one 34-m track per day, 5–15 targets per day are achievable depending on SSR capacity.

If the 70 m or equivalent capability is not available and is known prior to CDR, the flight system power could be increased by 1 RPS and the HGA diameter could be increased to preserve the science data acquisition scenario. The Ka-band system could be improved to send telemetry (slight power increase) and the mission increased to 6 months.

Table G-13. *DSN trade study cases*

Case	Tracking Schedule	Description
Baseline	70 m × 3 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka) Doppler only	35 W TWTA 1 Gb SSR 92-day scenario
Case 1A	70 m × 2 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler &Telemetry	Increase TWTA power Increase SSR capacity 92-day scenario
Case 1B	70 m × 2 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler &Telemetry	35 W TWTA Increase SSR capacity Increase Mission Duration
Case 2A	70 m × 1 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler &Telemetry	Increase TWTA power Increase SSR capacity 92-day scenario
Case 2B	70 m × 1 per day (X/X) Telemetry + 34 m × 1 per day (Ka/Ka/X) Doppler &Telemetry	35 W TWTA Increase SSR capacity Increase Mission Duration

Table G-14. *DSN Trade Study Results*

CASE	Baseline	Case 1A	Case 2A	Case 1B	Case 2B
DSN Tracking (Passes/day)	4 (3x70m + 1x34m)	3 (2x70m + 1x34m)	2 (1x70m + 1x34m)	3 (2x70m + 1x34m)	2 (1x70m + 1x34m)
Mission Duration (days)	92	92	92	**119**	**190**
Data rate @5.5 AU to 70m (kb/s)	320	**414**	**590**	320	320
Needed science SSR allocation (Gb)	1	**4.5**	**9.2**	**4.6**	**9.4**
Needed SSR cards	1	**3**	**5**	**3**	**5**
Needed average power increase (W)	-	**18**	**46**	**8**	**16**
Avg Daily downlink (Gb)	19.3	19.3	19.3	**14.9**	**9.3**
Mission Data Volume (Tb)	1.8	1.8	1.8	1.8	1.8
Total Number of Targets	1030	1030	1030	1030	1030
Comments			Doppler tracking gaps		Campaign 2 will stretch out due to low daily volume. Doppler tracking gaps

Red text indicates a dependent parameter

If the 70 m or equivalent capability is not available and is not known until after CDR, the science operational scenarios will be redesigned and the 34 m meter network will be used, with some use of arrays, and the mission would need to increase duration to 9–12 months. In this case the highest priority goals would be achieved after 4–6 months.

G4.4.2 Mass Memory Trades

The mass memory trade study examined the breakpoints in the mission operations scenarios where increased SSR capacity enabled useful capabilities. The study considered additions to the SSR design concept as units at the card level. The cards in the design concept have 1 Gb of useful mass memory per side for a total of 2 Gb per card. Each card added to the SSR adds 3 kg and 11 W.

The breakpoints examined were the mass memory needed to enable large gaps in DSN tracking coverage, science data collection opportunities, or operability improvements.

Tracking gaps of two hours, four hours, and increments of eight hours were considered as representing one orbit, two orbits and whole tracking passes respectively.

Science opportunities were limited to the size of coordinated targets. In the baseline mission, imaging targets are less than 400 Mb whereas radar targets are 900 Mb and the baseline SSR cannot store both at the same time. The next useful breakpoint is the ability to collect and store both target types simultaneously. The sensitivity to increased target size was not considered. No incremental improvements in satellite encounter science were analyzed other than the general position that more is better and SSRs in the 8–10 Gb size range are considered adequate.

The operability improvements are generally considered to be retransmission of data lost in downlink due to flight system or ground system mishap, the capability to post process data on-board for data editing or prioritization. These issues were lumped together and treated as retransmission. Retransmission has large latencies due to light time, DSN complexity, and decision making process times. The best retransmission schemes that make maximum use of automation and limited decision points take as little as 8 hours.

The results of the trades study (see **Figure G-24**) are that for the addition of a single card, bringing the science data allocation to 3 Gb, the simultaneous collection of imaging and radar targets and the accommodation of 2-hour tracking gaps is enabled. With 2 added cards

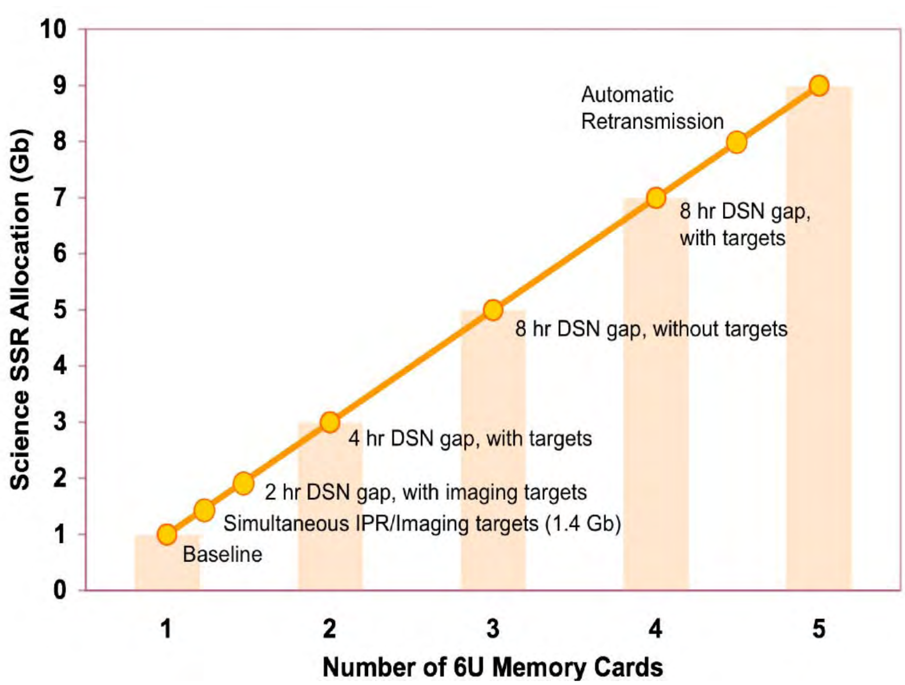


Figure G-24. Benefits of Adding Memory Cards

(5 Gb), the mission can perform routine mapping and accommodate a planned gap of 8 hours (one full DSN pass). Another added card brings the science allocation to 7 Gb and allows routine mapping and full target data acquisition in the presence of an 8 hour tracking gap. The maximum case of 5 cards in the SSR gives a 9 Gb science allocation. This enables retransmission of data.

G5. Findings

The science objectives set by the SDT can be easily met with the flight and ground system design set in the study. With the 26 eurosol, 92-day mission for which the analysis was performed, the science goals are met with margin. For the impacts of a 100 sol mission, aging 70 m subnet, and emerging CRAM high volume SSR design, the mission design has many options to improve science performance or balance the flight system design and resources for a longer mission with smaller DSN apertures, potentially Ka-band telecom, and deeper on-board storage.

The science scenarios developed by the SDT meet all science goals with margin. The highest priority goals are met in the first weeks of the mission. Higher resolution data sets and finer profile grids in later mission campaigns exceed the stated science goals. Future studies can trade performance for such issues as ground track repeat patterns, instrument FOV, alternating orbit strategies, observation duty cycles to optimize performance against goals or re-work the goals for strategic needs.

The scenario studies have shown that floor and baseline missions can be considered with the developed tools and science performance can be optimized across the flight and ground system scope.

G6. Next Steps

For future studies, anticipated changes in study goals should be factored into the operations scenarios, such as:

- Longer mission life capability
- Planning payload changes
- Tour science goals
- More mature SSR concept performance
- Additional Telecom system design trades (X-Ka vs DSN optimization)

The interaction between telecom, C&DH (throughput, compression, and mass memory), instrument characteristics (rates, compression, timing) and ground resources like DSN stations and retransmission, suggest that further optimization should be performed. The operations scenarios should inform and respond to those design iterations.

H. TELECOMMUNICATIONS LINK ANALYSIS

H1. Introduction

This appendix contains the performance estimates for the EE telecommunication links. The telecommunications subsystem is described in §4.4. The following paragraphs detail the assumptions within the link analysis, as well as present the results of the analysis with charts and link design control tables where appropriate.

H2. Requirements

The link shall provide for Command, Telemetry, and Radiometric Navigation:

Radiometric Navigation Performance

1. Doppler: < 0.1 mm/sec in 60 sec
2. Ranging: 4 m in 10 min
3. ΔDOR (VLBI): 0.12 ns

Command Performance at BER < 1E-5

4. Minimum rate: 7.8 bps
5. Maximum rate: 2000 bps

Engineering Telemetry Performance BER < 1E-6

6. Minimum rate: 10 bps
7. Maximum rate: ~800 kbps at EOI +6 mo

Key Functions

8. Initial Acquisition
9. Safemode Telecom & Command
10. Critical Event Data & Monitoring
11. Single fault immunity

H3. Telecommunications Subsystem Overview

The maximum range is 5.5 AU for the Europa science phase since it is constrained to > 50 deg SEP angle for Doppler quality (science requirement).

In order to minimize transmit circuit losses, the telecom hardware is mounted on the back of the HGA which reduces the loss between the output of the high-power amplifiers and the 3 m, X/Ka-band HGA.

Flight system communication is primarily via X-band, with limited use of Ka-band for carrier-only science. Dual string, cross-strapped SDSTs and 35-W TWTAs provide X up/X down command and telemetry capability. In addition, a single string Ka-band transponder and 3.5 W SSPA provides a Ka up/Ka-down carrier-only reference signal for gravity and radio science experiments. If the Ka-band transponder fails, the SDST can provide a Ka-band downlink (referenced to the X-band uplink) which can be used for somewhat lower sensitivity gravity science as compared to Ka/Ka, but still better than X/X alone. The Ka band link can only be operated with the HGA, but the X-band link can be operated with the HGA, MGA, or either LGA.

The high rate links are designed to communicate to DSN 70 m antennas. Link performance for cruise and Jupiter system tour does not constrain the design. The MGA link example is for safe modes during Europa science phase to a 70 m antenna. The MGA 13 deg ½ angle is larger than the Jupiter SEP angle of ~11 deg. The 200 b/s rate shows excess margin above the required 3 dB design margin at 40 b/s.

H4. Assumptions

Assumptions made for the link analysis include:

- 90% Cumulative Weather Distribution
- 15 deg station elevation (20 deg Ka-band)
- 40K receiver noise temperature
- Jupiter Hot body noise in the antenna field of view (13K)
- QPSK suppressed carrier modulation
- Turbo 1/6 encoding
- 8920 bit frame length
- Ranging is OFF for QPSK modulation

H5. Link Design Control Tables

The link Design Control Tables (DCT) were derived from the telecom concept and design assumptions. Because the detailed design has not yet been determined, some parameters, such as circuit losses, were assumed based on actual designs from previous projects. In this case, parameter assumptions were derived from the MRO Telecom design, which has a very similar design concept, configuration and operations scenario. **Tables H5-1** through **H5-3** show the DCTs adapted from the 2006 Europa Explorer Study [Europa Explorer Design Team Report, JPL D-34109, April 27, 2006]. The Telecom subsystem design concept is nearly identical to the current study with the exception of the TWTA power. The previous analysis used a 50 WRF TWTA whereas the current concept specifies a 35 WRF TWTA.

Table H5-1. *35 W X-band TWTA, 3 m HGA, 70 m DSN, Turbo 1/6, 3 mradian pointing*

35.0 W TWTA

X-Band HGA, 3 m antenna diameter, 0.20° off-point
DSN 14 station /Configuration: X/X
Goldstone/15 deg. elevation/90% CD Weather (Year Average)
Hot body noise = 13 K
1 way
Block V receiver/residual carrier mode/TLM-21 Models
Tlm channel/ (Turbo 1/6, 8920 bit frame)/ FER=10^-4

Carrier Loop Bandwidth = 10.0 Hz
Symbol Rate to the SDST= 1175046 sps
Data Bit Rate beofre Encoding= 195841 bps

8.228E+08	Range, km
5.5000	Range, AU
0.76	OWLT, hrs
0.00	SEP, deg
15	Elev. Angle, deg

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	S		
									X	RF band
									8420	Freq, MHz
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	45.44	0.20	-0.20	45.44	0.0067	T	35.0	Xmtr Pwr, W (BOL)
2	Total Circuit Loss	dB	-1.50	0.20	-0.20	-1.50	0.0134	U		
3	Antenna Gain (on boresight)	dBi	45.86	0.50	-0.20	45.96	0.0217	T	0.83	3 dB Beamwidth
4	Ant Pointing Loss	dB	-0.70	2.26	-2.26	-0.70	1.7038	U	HGA	S/C Antenna
5	EIRP (1+2+3+4)	dBm				89.20	1.7455			
	PATH PARAMETERS									
6	Space Loss	dB	-289.26	0.00	0.00	-289.26	0.0000	D		
7	Atmospheric Attn	dB	-0.17	0.00	0.00	-0.17	0.0000	D	Year Average	Weather %
									1	Distribution Type
	RECEIVER PARAMETERS								Goldstone: 70m, DSS14	
8	DSN Antenna Gain	dBi	74.35	0.10	-0.10	74.35	0.0017	T	n/a	
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	X/X	NA Selection
10	Polarization Loss	dB	-0.02	0.00	0.00	-0.02	0.0000	U	1	DSS Config
	TOTAL POWER SUMMARY									
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm				-125.99	1.7472	G		
12	Noise Spec Dens	dBm/Hz	-182.56	0.11	-0.11	-182.56	0.0012	G		
	System Noise Temp	K	40.21	1.00	-1.00			G		
	Vacuum, zenith	K	14.23	1.00	-1.00			T	1	WAY
	Elevation	K	2.56	0.00	0.00			G		
	Atmosphere	K	10.42	0.00	0.00			G		
	Hot Body Noise	K	13.00	0.00	0.00			G	Calculate Threshold!	
13	**Received Pt/No**	**dB-Hz**				**56.57**	**1.7484**	**G**		
13a	**Received Pt/No - 2sigma**	**dB-Hz**				**53.92**				
	CARRIER PERFORMANCE (actual)									
14	Tlm Carrier Supp	dB	-10.15	0.64	-0.70	-10.17	0.0746	T	0 deg	TLM ON?
15	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	1	RNG MI?
16	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR ON?
17	Required Pc/No (13+14+15+16)	dB-Hz				43.39	1.8230	T		
18	Carrier Loop Bandwidth, Bl	dB-Hz	10.00	0.00	0.00	10.00	0.0000	T	10.0	Carrier Bl, Hz
19	Carrier Loop SNR	dB				33.39	1.8230	U	Type 2. SuperCritically Damped	Noise
20	Required Carrier Loop SNR	dB				10.00	0.0000	D		
21	Carrier Loop SNR Margin	dB				23.39	1.8230	U		
	SUBCARRIER PERFORMANCE at Req. Pt/No									
22	SubCar. L. SNR	dB				52.36				
23	Required Loop SNR	dB				20.00			500	SubCarr Bl, mHz
24	SubCarrier Loop SNR Margin	dB				32.36			0.25	SubCarr window f.
	SYMBOL LOOP PERFORMANCE at Req. Pt/No									
25	Sym. Loop SNR	dB				51.82			50	Sym Bl, mHz
26	Required Loop SNR	dB				15.00			0.25	Sym window f.
27	Symbol Loop SNR Margin	dB				36.82			Calculate Threshold!	
	TELEMETRY PERFORMANCE at Required Pt/No									
28	Tlm Data Supp	dB	-0.44	0.07	-0.07	-0.44	0.0008	T	71.9	tlm MI, deg
29	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	peak rng MI, deg
30	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	1,175,046	ch symbol rate, bps
31	Data Rate	dB	52.92	0.00	0.00	52.92	0.0000	D	195,841	data bit rate, bps
32	Radio Loss	dB	-0.09			-0.09		T		
33	SubCarrier Demod. Loss	dB	-0.01			-0.01		T		
34	Symbol Sync. Loss	dB	-0.01			-0.01		T		
35	Waveform Distortion Loss	dB	-0.15			-0.15		T	Turbo 1/6, 8920 bit fr	
37	Threshold Eb/No	dB				-0.10		D	25	Coding
38	Required Eb/No	dB				0.20			FER=10^-4	BER at BVR output
39	**Required Pt/No**	**dB-Hz**				**53.56**	**0.3033**	**U**		
40	**Performance Margin (39-13)**	**dB**				**3.00**				
41	Sigma	dB				1.43				
42	Margin - 2 sigma	dB				0.14			0	
	Wind Loading Loss	dB	0.00	0.00	0.00	0.00	0.0000	U	1	wind speed, mph
	Pointing Loss due to Wind (BWG)		0.00	0.00	0.00	0.00	0.0000	U	99	wind CD %
	Adjusted Performance Margin	**dB**				**3.00**				

Table H5-2. 35 W X-band TWTA, MGA, 70 m DSN

35.0 W TWTA

X-Band MGA, 13.0° off-point
DSN 43 station /Configuration: X/X
Canberra/15 deg. elevation/90% CD Weather (Year Average)
Hot body noise = 13 K
1 way
Block V receiver/residual carrier mode/TLM-21 Models
Tlm channel/ (k=7, r=1/2+RS (I=5))/ FER=10^-4

Carrier Loop Bandwidth = 3.0 Hz
Symbol Rate to the SDST= 86 sps
Data Bit Rate beofre Encoding= 38 bps

8.228E+08	Range, km
5.5000	Range, AU
0.76	OWLT, hrs
13.00	SEP, deg
15	Elev. Angle, deg

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	S	X 8420	RF band Freq, MHz
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	45.44	0.20	-0.20	45.44	0.0067	T	35.0	Xmtr Pwr, W (BOL)
2	Total Circuit Loss	dB	-2.40	0.50	-0.50	-2.40	0.0835	U		
3	Antenna Gain (on boresight)	dBi	19.24	0.50	-0.20	19.34	0.0217	T	13.00	Boresight Angle, deg
4	Ant Pointing Loss	dB	-5.74	0.52	-0.52	-5.74	0.0897	U	MGA	S/C Antenna
5	EIRP (1+2+3+4)	dBm				56.63	0.2016			
	PATH PARAMETERS									
6	Space Loss	dB	-289.26	0.00	0.00	-289.26	0.0000	D		
7	Atmospheric Attn	dB	-0.22	0.00	0.00	-0.22	0.0000	D	Year Average	Weather %
									1	Distribution Type
	RECEIVER PARAMETERS								Canberra: 70m, DSS43	
8	DSN Antenna Gain	dBi	74.38	0.10	-0.10	74.38	0.0017	T	n/a	8
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	X/X	LNA Selection
10	Polarization Loss	dB	-0.09	0.00	0.00	-0.09	0.0000	U	1	DSS Config
	TOTAL POWER SUMMARY									
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm				-158.65	0.2033	G		
12	Noise Spec Dens	dBm/Hz	-182.22	-0.10	0.10	-182.22	0.0010	G		
	System Noise Temp	K	43.42	-1.00	1.00			G		
	Vacuum, zenith	K	14.69	-1.00	1.00			T	1	WAY
	Elevation	K	2.24	0.00	0.00			G		
	Atmosphere	K	13.49	0.00	0.00			G		
	Hot Body Noise	K	13.00	0.00	0.00			G	Calculate Threshold!	
13	**Received Pt/No**	**dB-Hz**				**23.57**	**0.2044**	**G**		
13a	**Received Pt/No - 2sigma**	**dB-Hz**				**22.67**				
	CARRIER PERFORMANCE (actual)									
14	Tlm Carrier Supp	dB	-4.96	0.24	-0.25	-4.96	0.0101	T	0 deg	TLM ON?
15	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	1	RNG MI?
16	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR ON?
17	Required Pc/No (13+14+15+16)	dB-Hz				15.90	0.2145	T		
18	Carrier Loop Bandwidth, Bl	dB-Hz	4.77	0.00	0.00	4.77	0.0000	T	3.0	Carrier Bl, Hz
19	Carrier Loop SNR	dB				11.13	0.2145	U	Type 2. SuperCritically Damp	ase Noise
20	Required Carrier Loop SNR	dB				10.00	0.0000	D		
21	Carrier Loop SNR Margin	dB				1.13	0.2145	U		
	SUBCARRIER PERFORMANCE at Req. Pt/No									
22	SubCar. L. SNR	dB				22.49				
23	Required Loop SNR	dB				20.00			500	SubCarr Bl, mHz
24	SubCarrier Loop SNR Margin	dB				2.49			0.25	SubCarr window f.
	SYMBOL LOOP PERFORMANCE at Req. Pt/No									
25	Sym. Loop SNR	dB				23.48			50	Sym Bl, mHz
26	Required Loop SNR	dB				15.00			0.25	Sym window f.
27	Symbol Loop SNR Margin	dB				8.48			Calculate Threshold!	
	TELEMETRY PERFORMANCE at Required Pt/No									
28	Tlm Data Supp	dB	-1.67	0.11	-0.12	-1.67	0.0022	T	55.6	tlm MI, deg
29	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	peak rng MI, deg
30	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	86	ch symbol rate, bps
31	Data Rate	dB	15.77	0.00	0.00	15.77	0.0000	D	38	data bit rate, bps
32	Radio Loss	dB	-0.46			-0.46		T		
33	SubCarrier Demod. Loss	dB	-0.36			-0.36		T		
34	Symbol Sync. Loss	dB	-0.16			-0.16		T		
35	Waveform Distortion Loss	dB	-0.15			-0.15		T	k=7, r=1/2+RS (I=5)	
37	Threshold Eb/No	dB				2.29		D	7	Coding
38	Required Eb/No	dB				3.43			FER=10^-4	BER at BVR output
39	**Required Pt/No**	**dB-Hz**				**20.87**	**0.3047**	**U**		
40	**Performance Margin (39-13)**	**dB**				2.71				
41	Sigma	dB				0.71				
42	Margin - 2 sigma	dB				1.28				
									0	
	Wind Loading Loss	dB	0.00	0.00	0.00	0.00	0.0000	U	1	wind speed, mph
	Pointing Loss due to Wind (BWG)		0.00	0.00	0.00	0.00	0.0000	U	99	wind CD %
	Adjusted Performance Margin	**dB**				**2.71**				

Table H5-3. *3.5 W Ka-band SSPA, HGA, 34 m DSN, carrier only*

Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var
TRANSMITTER PARAMETERS						
1. S/C Transmitter Power	dBm	35.44	0.1	-0.1	35.44	0.0017
2. S/C Xmit Circuit Loss	dB	-1.5	0.5	-0.5	-1.5	0.0833
3. S/C Antenna Gain	dBi	57.52	0.5	-0.5	57.52	0.0417
4. Degrees-off-boresight (DOFF) Loss	dB	0	0	0	0	0
5. S/C Transmit Pointing Loss	dB	-10.82	0	0	-10.82	0
6. EIRP (1+2+3+4+5)	dBm	80.64	1.07	-1.07	80.64	0.1267
PATH PARAMETERS						
7. Space Loss	dB	-300.92	0	0	-300.9	0
8. Atmospheric Attenuation	dB	-1.18	0	0	-1.18	0
RECEIVER PARAMETERS						
9. DSN Antenna Gain	dBi	78.84	0.3	-0.3	78.84	0.015
10. DSN Antenna Pnt Loss	dB	-0.11	0.1	-0.1	-0.11	0.0033
11. Polarization Loss	dB	-0.03	0.1	-0.1	-0.03	0.0033
TOTAL POWER SUMMARY						
12. Tot Rcvd Pwr (6+7+8+9+10+11)	dBm	-142.76	-1.16	1.16	-142.8	0.1483
13. SNT in Vacuum	K	21.33	-1	2	21.66	0.3889
14. SNT due to Elevation	K	1.47	0	0	1.47	0
15. SNT due to Atmosphere	K	66.08	0	0	66.08	0
16. SNT due to the Sun	K	0	0	0	0	0
17. SNT due to other Hot Bodies	K	37.27	0	0	37.27	0
18. SNT (0+14+15+16+17)	K	126.15	-1	2	126.65	0.25
19. Noise Spectral Density	dBm/Hz	-177.59	-0.03	0.07	-177.6	0.0003
20. Received Pt/No (12-19)	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
21. Received Pt/No, mean-3 dB	dB-Hz	31.81	0	0	31.81	0
CARRIER PERFORMANCE						
25. Recovered Pt/No (20+[AGC+BPF])	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
26. Telemetry Carrier Suppression	dB	0	0	0	0	0
27. Ranging Carrier Suppression	dB	0	0	0	0	0
28. DOR Carrier Suppression	dB	0	0	0	0	0
29. Carrier Power (AGC) (12+26+27+28)	dBm	-142.76	-1.16	1.16	-142.8	0.1483
30. Received Pc/No (25+26+27+28)	dB-Hz	34.81	1.16	-1.16	34.81	0.1486
31. Carrier Loop Noise BW (this loop BW is very wide)	dB-Hz	10	0	0	10	0
32. Carrier Phase Error Var (from 30,31,xpond,solar)	rad^2	0.0048	0	0	0.0048	0
33. Carrier Loop SNR (CNR) (from 32)	dB	23.23	1.16	-1.16	23.23	0.1486
34. CNR, mean-3 dB	dB	20.23	0	0	20.23	0
35. Recommended CNR	dB	10	0	0	10	0
36. CNR Margin (33-35)	dB	13.23	1.16	-1.16	13.23	0.1486
37. CNR Margin, mean-3 dB (34-35)	dB	10.23	0	0	10.23	0

I. NASA ASTROBIOLOGY INSTITUTE LETTER

Dear Karla, Bob, Ron, and Mitch:

In a Dec. 12, 2001 letter to Dr. Michael Belton (Chair of the NRC Steering Committee developing the decadal strategy for Solar System Exploration), the NASA Astrobiology Institute placed a Europa orbiter in its highest priority mission category. The envisioned orbiter featured a payload capable of confirming the presence of a subsurface ocean, characterizing the subsurface, and obtaining remote sensing observations pertinent to Europa's surface composition, geological history, and biological potential.

The current concept for the Europa Explorer mission, as presented on May 8, 2007 to the NAI Executive Council by Mitch Sogin for the mission Science Definition Team, appears to meet these measurement objectives.

The NAI Executive Council reaffirms that such a mission is in its highest priority mission category for advancing the astrobiological goals of Solar system exploration.

Sincerely,

Carl Pilcher, Director of the NAI
for the NAI Executive Council