Europa Geophysical Explorer (EGE) Mission Concept

Space Technologies and Applications International Forum (STAIF 2006)

February 15, 2005
Albuquerque, NM

Robert Dean Abelson

NASA Jet Propulsion Laboratory

Context

- Europa Geophysical Explorer (EGE) was studied in the Summer of 2005
- Subsequently, JPL continued to investigate issues and details to refine the mission concept. This updated concept is Europa Explorer (EE). Major areas re-assessed:
  - Radiation predictions and mitigations including shield masses
  - Science Data Return approaches
- This presentation focuses on the results of the EGE study and will note where specific modifications were made for EE

Note that though the EE Study was more detailed and reached a modified design point, it re-affirmed all the conclusions reached during the EGE Study

EGE Study-Team Members

Core team

Jacklyn R. Green	Study Leader and Manager
Rob Abelson	Lead Systems Engineer
Pam Chadbourne	Program Systems Engineer
Peter Illsley	Configuration
Elizabeth Kolawa	Technologist
Jan Ludwinski	Mission Design
Lisa Priester	Documentation
Celeste Satter	Systems Engineer
Jim Shirley	Science Advisor
Bill Smythe	Instrument Lead Scientist/Engineer
Tom Spilker	Science Advisor
OPAG Europa Subgroup	Science Requirements

Radiation Assessment

E. Kolawa	Lead
R. Blue	Avionics (X2000)
G.Carr	PMAD (X2000, JIMO)
D.Gear	Avionics (X2000)
F.Deligiannis	Rad hard electronic components (JIMO)
K.Strauss	Memory technology (X2000, JIMO)
M.Mojarradi	PMAD, Radhard electronics
B.Pain	APS technology
J.Patel	Physics of devices
H.Garreth	Radiation environment

RPS Assessment

Team Members

Rob Abelson Lead
Kip Dodge
Rich Ewell
Bill Nesmith

Resources

Jack Chan (Lockheed Martin)
Bill Otting (Pratt and Whitley Rocketdyne)
Bob Wiley (DOE)

Science Assessment and Compliance

Tom Spilker

Science Instruments Definition

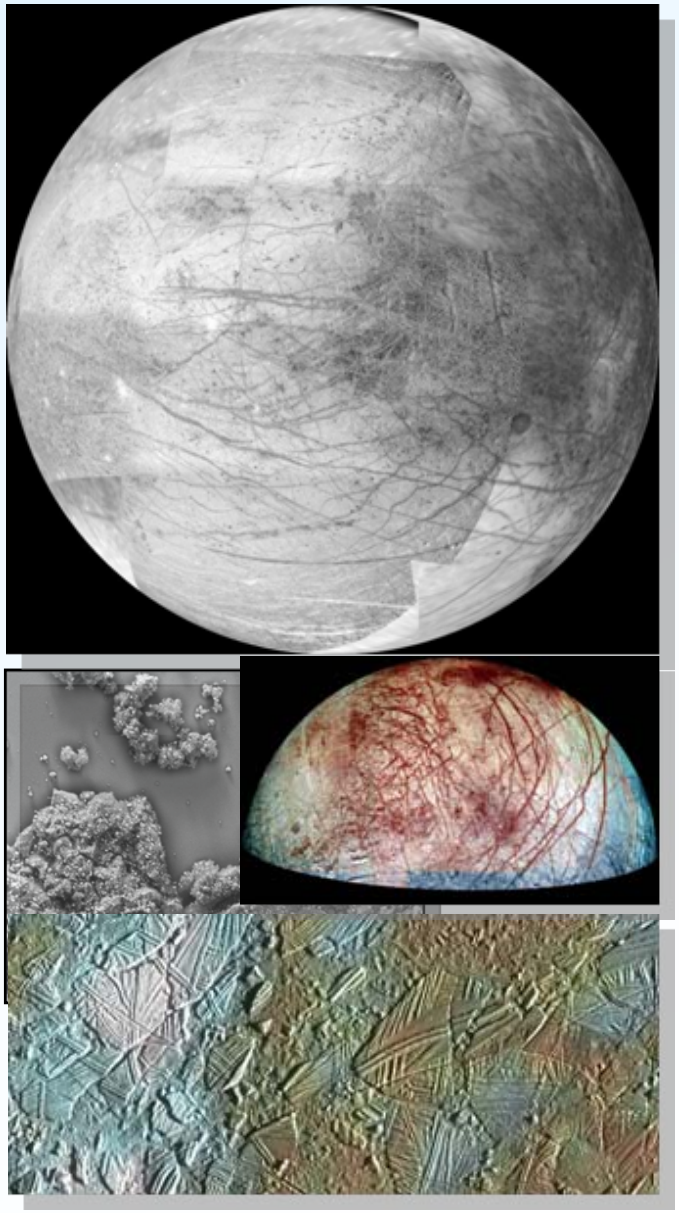
Bill Smythe	Lead
Soren Madsen	Sounder, TopoMapper
Carl Bruce	Cameras and spectrometers
Daniel Winterhalter	Fields and Particles

EGE Study Objectives

- The Strategic Road Map for Solar System Exploration recommended in May 2005 that NASA implement the Europa Geophysical Explorer (EGE) mission as a Flagship mission early in the next decade. This supported the recommendations of the Solar System Decadal Survey and the priorities of the Outer Planets Assessment Group (OPAG).

- **NASA Headquarters Solar System Division initiated a 45-day study of the mission in early May 2005 in order to**
  - Understand new Europa mission possibilities that have emerged since the Europa Orbiter mission was cancelled
  - Define technology and advanced-development needs to support a launch early in the next decade

- **The study is sponsored through technology programs:**
  - Radioisotope Power System Program: Ajay Misra
  - Solar System Chief Technologist: Jim Robinson
  - Science: Curt Niebur



Why do this Study Now? What has Changed?

- **The next step in Europa exploration, the EGE 2005 concept study builds upon previous Europa Orbiter concepts:**
  - ✓ **Earth Gravity Assists (EGA) are on the table (direction from NASA**
  - ✓ Result in a dramatic increase in delivered mass
    - The somewhat longer flight time is deemed acceptable
  - ✓ **Better understanding of the radiation environment**
    - Radiation modeling from Galileo data indicates a smaller total radiation dose
  - ✓ **Advances in radiation-hardened components and subsystems**
    - Results from considerable investments from X-2000 and JIMO
  - ✓ **Developments in radioisotope power systems (RPS)**
    - Technology development for the MMRTG and SRG

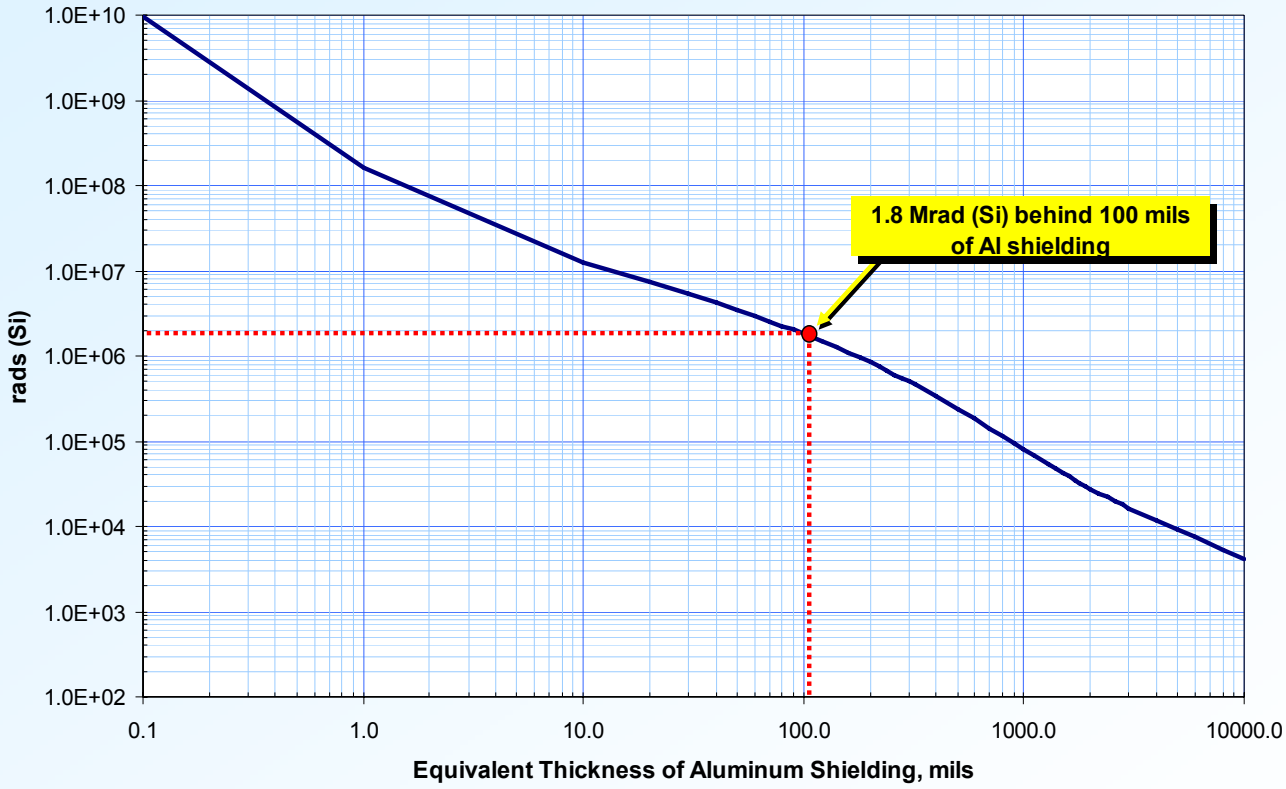
Level 1 EGE Mission Requirements*

- **The mission concepts shall support a science-mission duration of at least 30 days in Europa orbit**
- **The mission concepts shall feature a high-inclination orbit at Europa**
- **The mission concepts shall be designed to launch in 2012**
  - Implied requirement: Same spacecraft should support launch windows in 2013, 2014, etc.
- **The mission concepts shall consider a trajectory design that employs gravity assists, including around Earth**
  - The trade studies shall include the two basic trajectory types that use gravity assists:
    - VEEGA
    - ΔV-EGA
- **The mission concepts shall use either a Delta IV H or Atlas V launch vehicle**
- **The mission concepts shall use chemical propulsion**
- **The trade studies shall consider the following RPSs:**
  - MMRTG
  - SRG
  - Upgraded MMRTG (conceptual 160W, 4W/kg unit)
- **The trade studies shall consider the options for a "bolt-on" lander**
  - The studies must assess which mission options permit a "bolt-on," capable, lander payload

(* Requirements defined by Curt Niebur, NASA HQ)

EGE Radiation Environment

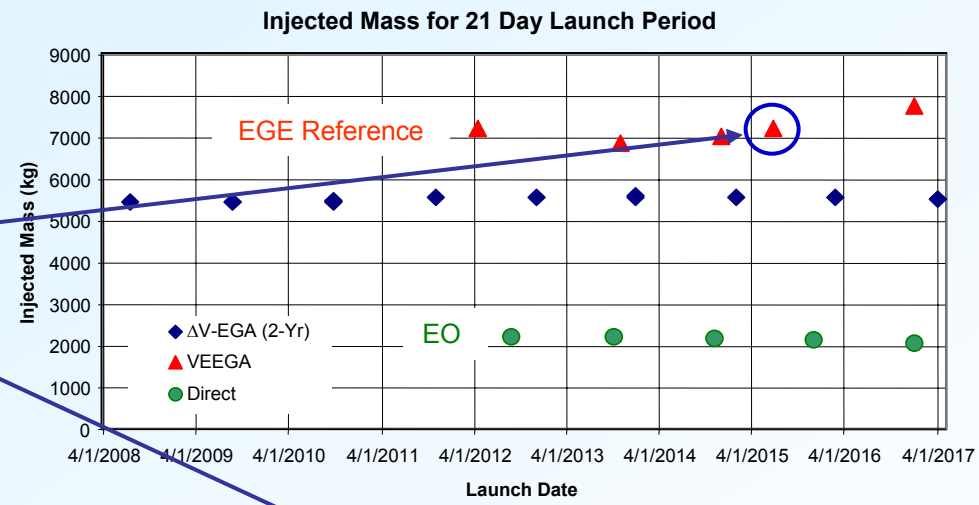
- **The total mission dose is expected to be ~1.8 Mrad behind 100 mils of aluminum, based on the then-current Galileo Interim Radiation Electron (GIRE) model results***
- **Dose from 1.5-year Jovian tour is about the same as 30 days at Europa**
- **Even using hardened parts, radiation vaults are required for certain critical spacecraft systems**

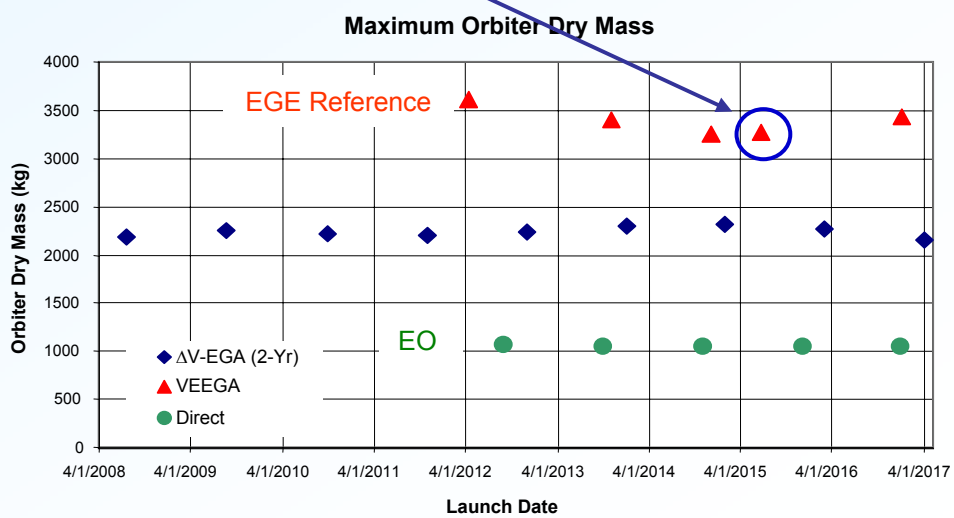


* During the EE Study, this model was updated and used for EE

Reference Case Parameters

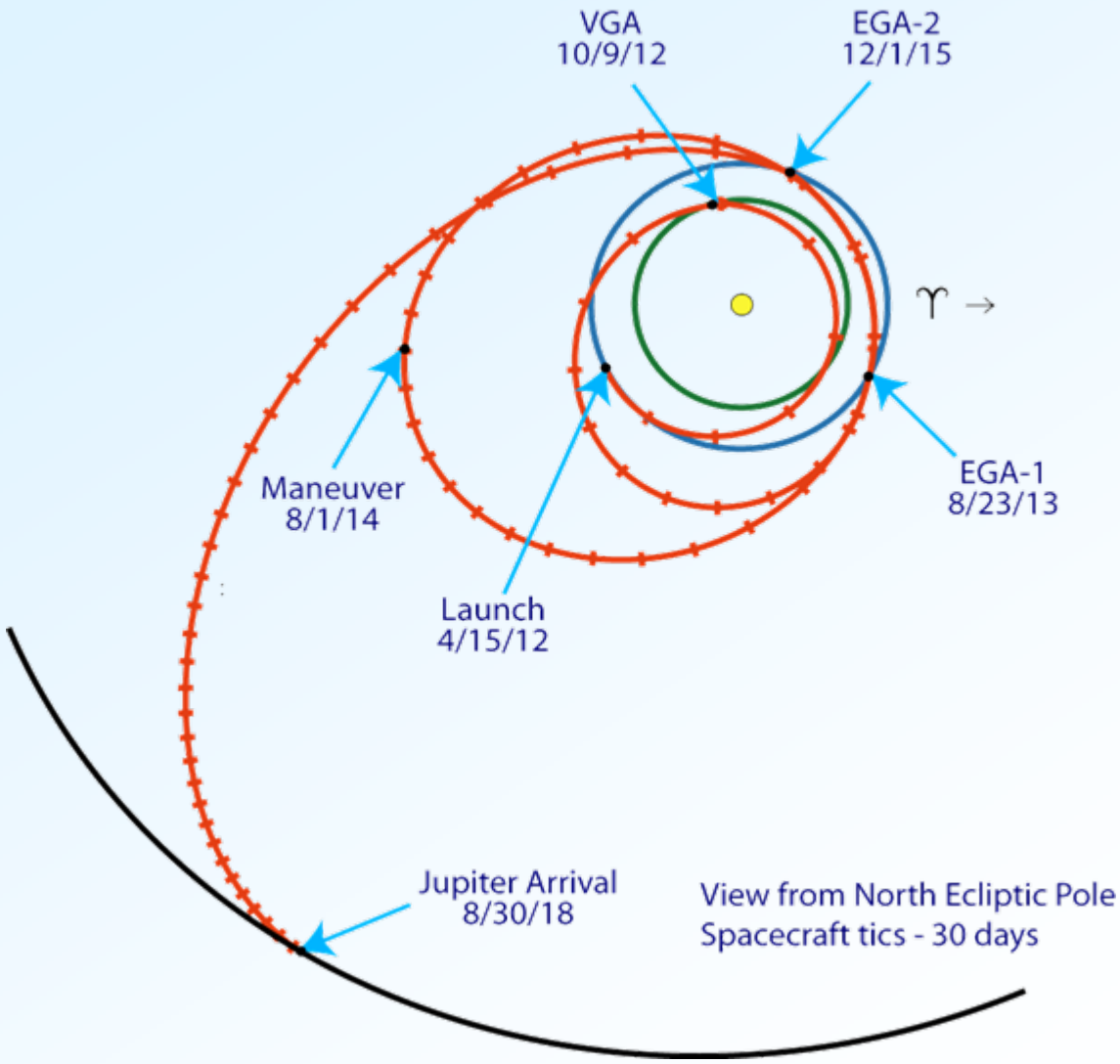
- Launch date: April 15, 2012
  - However, assumed most conservative spacecraft dry mass value between 2012 and 2017
- Trajectory: VEEGA (C_3~14 km^2/s^2)
- Launch vehicle: Delta IV Heavy (4050H)
- Injected mass capability: ~7230 kg
  - Corresponds to most conservative spacecraft dry mass
- Maximum available spacecraft dry mass: ~3250 kg
  - Is the most conservative mass value between 2012 and 2017—corresponds to 2015 value
- Total time to Europa: ~8 years
  - To Jupiter: 6.4 years
  - Jupiter Tour: ~1.5 years
- If the 2012 launch date was selected, it would permit a maximum available dry mass of ~3600 kg (>300 kg more than listed above)
- A one-year launch delay to 2013 would provide a maximum available dry mass of ~3400 kg



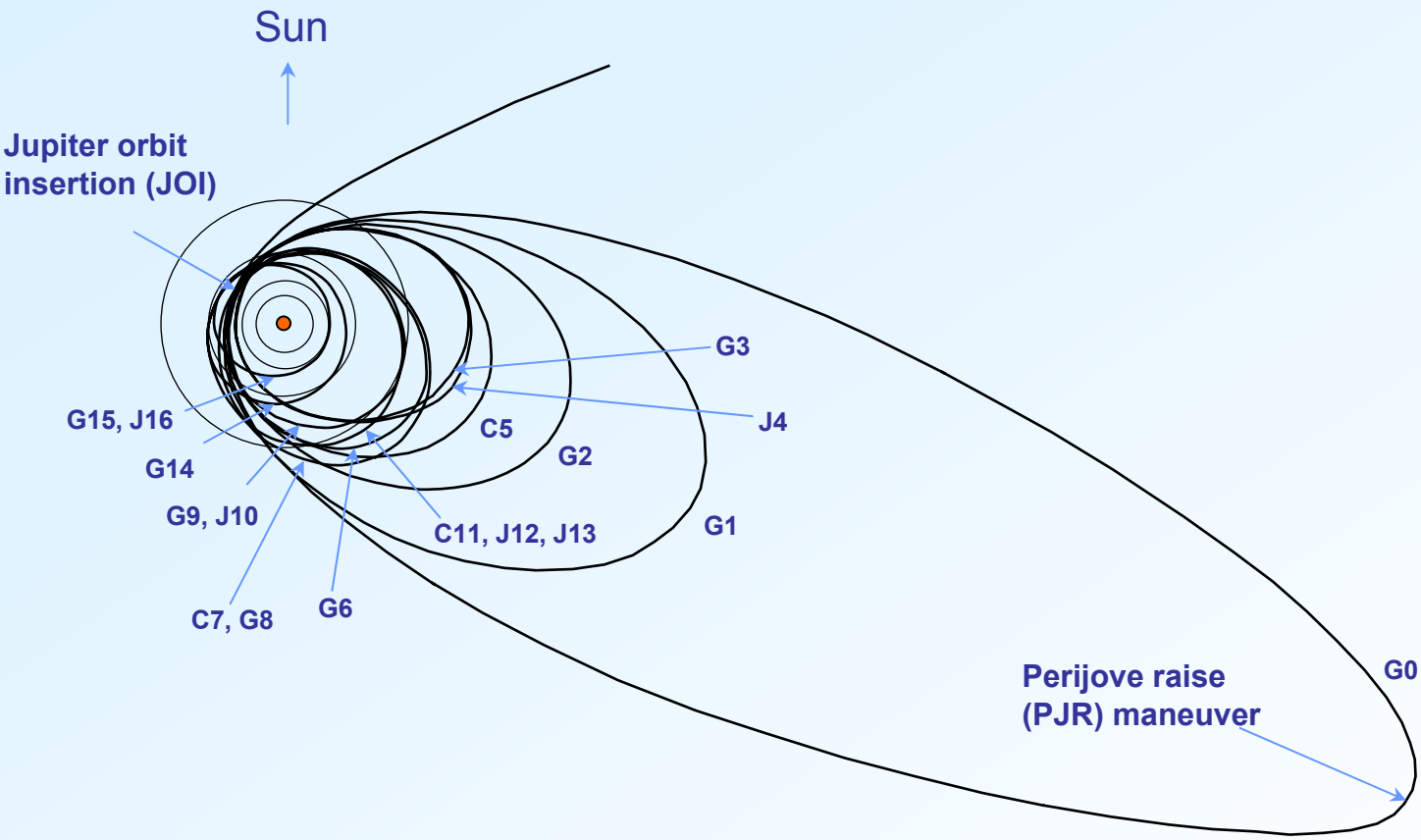


The ΔV-EGA trajectories shown at right have a ~2-year Earth-return period, with the Earth flyby occurring during the inbound leg of the Earth return transfer orbit. A similar ΔV-EGA trajectory (not shown), where the Earth flyby occurs during the outbound leg of the transfer orbit, goes through a perihelion of ~0.9 AU, has a roughly comparable injected mass and orbiter dry mass capability, and launches ~2 months earlier than the inbound case

Interplanetary Trajectory Option: 2012 VEEGA



Representative Jovian Tour



Sun–Jupiter Fixed View

J = Jupiter
C = Callisto
G = Ganymede

Encounter	Days Since Last Encounter
G1	—
G2	50
C3	34
G4	40
G5	21
C6	9
J7	
G8	39
J9	
G10	21
G11	7
J12	
E13	9
J14	
G15	13
J16	
E17	8
J18	
J19	
E20	14
J21	
J22	
J23	
J24	
J25	
EOI	23

Example of an Instrument Suite for the Reference Mission

Subsystem	Daylight Power, W	Nighttime Power, W	Average Power, W	Mass, kg
Instruments (w/o contingency)	**129.3**	**86.7**	**108.0**	**109.7**
Instruments (w/ 43% contingency)	**184.9**	**123.9**	**154.4**	**156.9**
Two-Band Sounder	5	61	33.0	30.0
Laser Altimeter	20.8	0	10.4	12.0
Wide Angle Camera and filters	1.88	1	1.4	7.0
VIS/NIR Mapper, High Resolution	21.3	1	11.2	20.0
VIS/MWIR Spectrometer	30	1	15.5	12.0
MeV Ion Spectrometer	10	10	10.0	10.0
KeV Ion Spectrometer	11.4	11.4	11.4	7.0
Ion and Neutral Spectrometer	27.7	0	13.9	10.0
Magnetometer	1.25	1.25	1.3	1.7

Average Payload Power: ~154 W (w/ contingency)

Payload Mass: ~157 kg (w/ contingency)

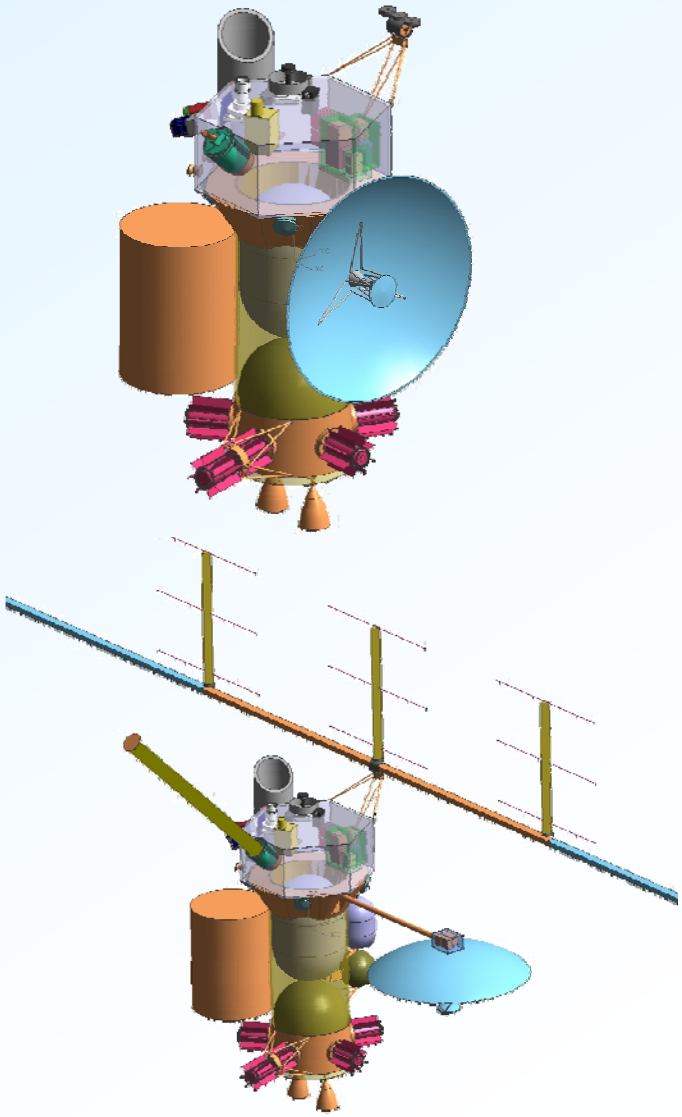
EGE Reference Mission Capability

The reference mission has the following capabilities:

- Launch mass capability: 7230 kg
- Spacecraft wet mass: 6374 kg
- Spacecraft dry mass: 2400 kg
- Power (EOM): 770 W
- Number of MMRTGs: Seven
- Data rate (@5.2 AU): 340 kb/s

- **Unallocated mass:* 856 kg**

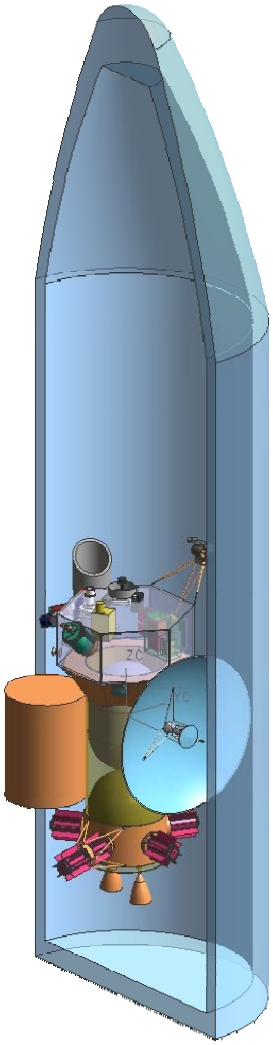
*** NOTE: during the subsequent EE study, this available mass number has been refined and reduced**



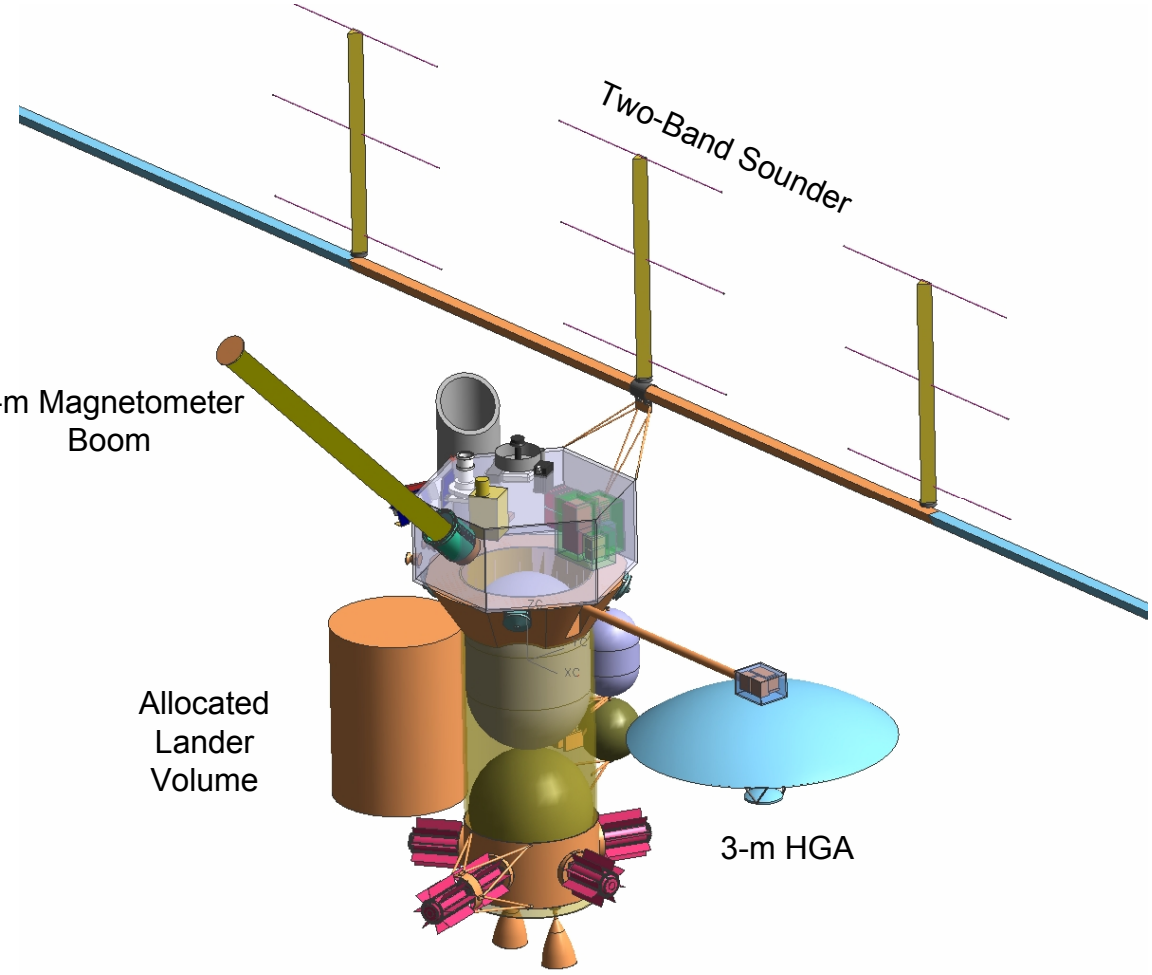
Conceptual Illustrations

Conceptual EGE Spacecraft Configuration

Conceptual Illustrations



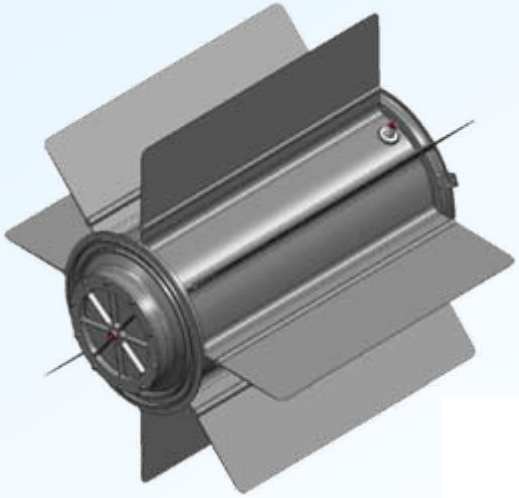
EGE spacecraft within Delta IV-H launch-vehicle fairing



EGE spacecraft in Fully Deployed Configuration

Power System: MMRTGs and Batteries

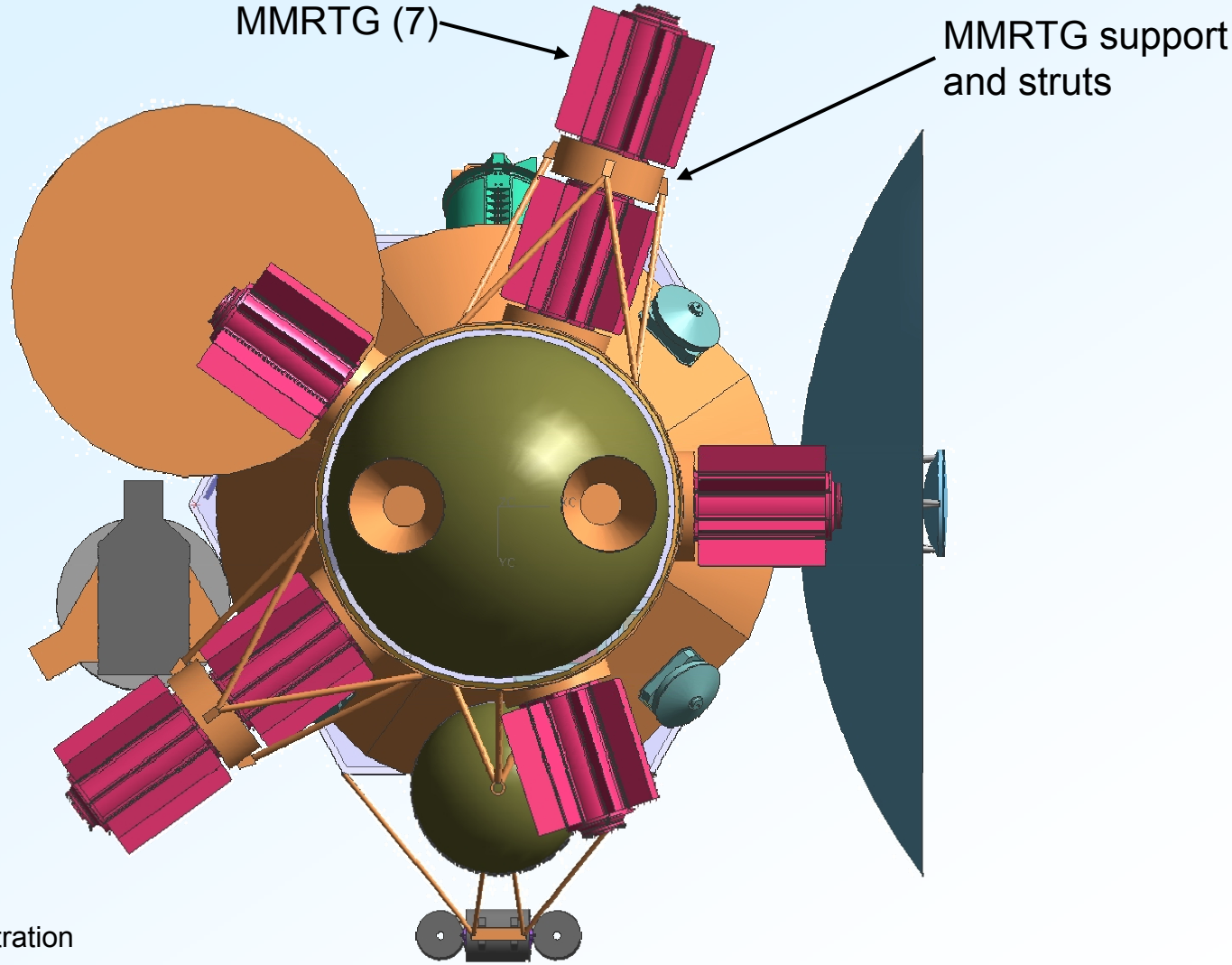
- The reference mission baselines seven MMRTGs
  - Provides a total of ~770 W_e (EOM)
  - Contains 56 GPHS modules, about the same amount of Pu-238 fuel as used on Cassini
  - NASA is proposing to fly an MMRTG on MSL before the 2012 EGE launch date
  - Lowest risk approach compared with other RPS alternatives (SRG and upgraded MMRTG)
- Small secondary batteries are included for load leveling during high power modes (i.e., concurrent telecom and science observations)
  - Could replace the batteries with another MMRTG, but deemed mass and cost inefficient to do so
  - Baseline design is two batteries, 4.8 AH each, 22 cells/battery. Total mass 11.4 kg
- Shunt regulators and shunt radiators are used to regulate bus power by rejecting unused MMRTG electrical power



MMRTG

RPS parameters for the reference mission case	
Number of RPSs	**7**
Mission duration, years	**8**
Power output per RPS at BOM, We	**125**
Power at BOM, We	**875**
Power at EOM, We	**769**

MMRTG Configuration of the Reference Spacecraft

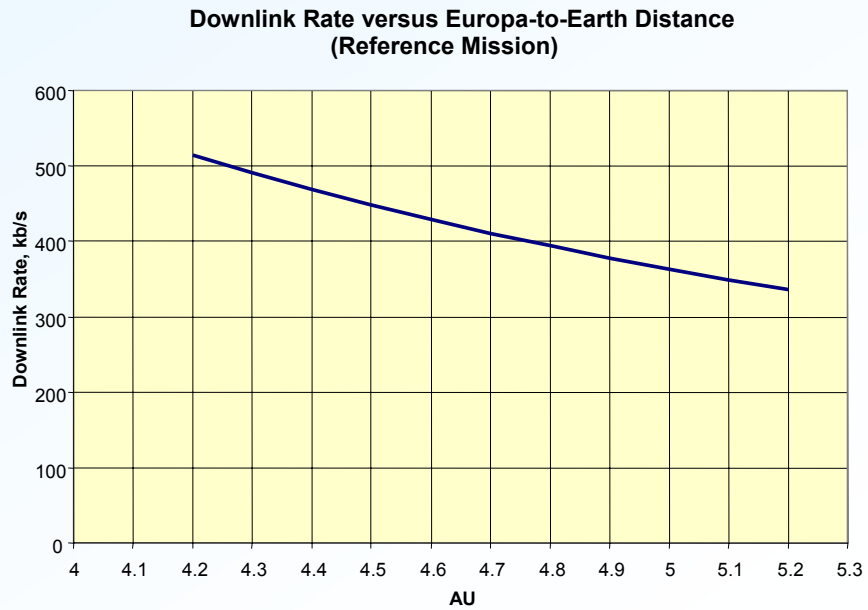


Conceptual Illustration

Aft end of spacecraft

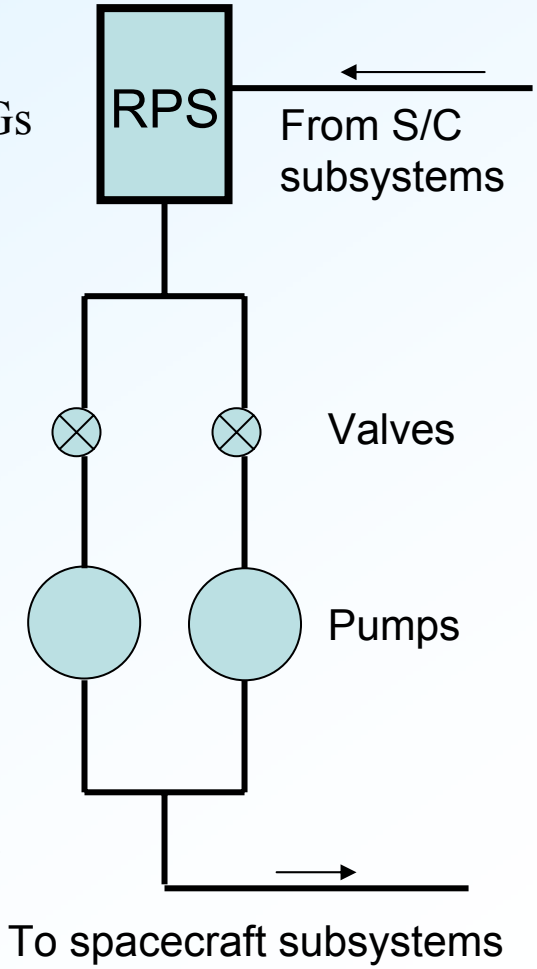
Telecommunications and DSN

- The short mission duration (30 days at Europa) and the high instrument data rate necessitates a high-rate telecommunications system.
- An articulating (2-DOF) 3-m-diameter Ka-band high-gain antenna (HGA) is used with redundant 50-W (RF) amplifiers.
- Ka-band is used for downlink and X-band is used for uplink.
- Assume 24/7 ground system coverage during 30d science mission using existing DSN 34-m antennas.
- Downlink rate is 340 kb/s at 5.2 AU, using 34-m DSN antennas.
  - Assumes 3×34-m antennas at Goldstone, and 2×34-m antennas at Canberra and Madrid.
  - 20° elevation angle, 90% weather Canberra site.
  - Canberra's 34-m antenna is assumed to be upgraded to Ka-band by mission time.
  - 60% non-occulted, record occulted and playback interleaved in dayside.
  - Science data restricted by limits of DSN rate.
- Europa orbit period is 2.05 hours (at 100 km altitude), with 40% occultation.



Thermal Control Subsystem

- The EGE thermal subsystem would use the heat produced by the MMRTGs to maintain spacecraft operating temperatures.
  - Would reduce the amount of electrical heaters that would otherwise be used, thus minimizing the number of MMRTGs required for the mission.
- About 300 W of thermal power would be required to keep the spacecraft at operating temperature.
  - Each MMRTG produces ~1875 W_{th} (BOM) - would need only a small portion of this to supply all S/C thermal needs.
  - The spacecraft cooling loop would be directly connected to the MMRTG cooling tubes for heat redistribution.
- Thermal-control louvers would be used to prevent spacecraft subsystems from exceeding their operating temperatures.
- Passive thermal-control elements, such as coatings, low absorptivity paint, multilayer insulation, and reflective surfaces, would be included in the thermal system design.



Propulsion Subsystem

- The EGE propulsion system would utilizes existing flight-proven technology.
- It would use a dual-mode bipropellant (N_2H_4 and NTO) system.
  - Minimizes propellant mass associated with the large mission ΔV
- Two Aerojet 900N HiPAT bipropellant main engines (including one backup) would be used for:
  - Deep-space maneuvers
  - JOI, perijove raise, and Europa orbit insertion
- Eight Aerojet 36-N monopropellant engines would be used for attitude control authority during deep-space maneuvers, JOI, perijove raise, and Europa Orbit insertion.

Notional HiPAT thruster

- Sixteen Aerojet 0.7-N minimum impulse thrusters (MITs) would provide:
  - Redundant coupled three-axis control
  - Momentum wheel desaturation
  - Functional redundancy for each other

Propulsion: ΔV and Propellant Usage

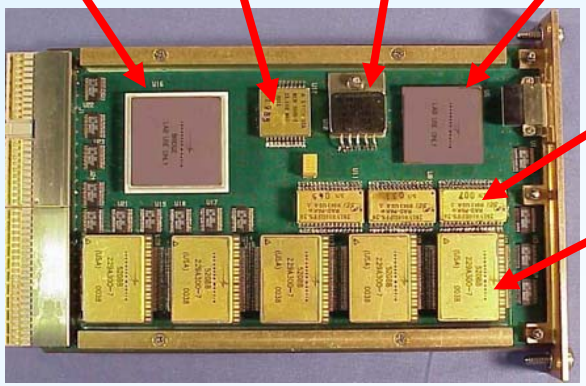
Estimates of ΔV and propellant usage are for propulsive maneuvers planned during the reference mission

Activity	Delta V (m/s)	Prop Mass (kg)	Description
Deep Space Maneuvers	139	308	Deep space maneuvers during cruise phase.
Earth Biasing	50	108	Prior to each Earth flyby
JOI DV (with Ganymede GA)	1081	1959	Jupiter Orbit Insertion
Gravity Losses	27	41	
PJR and Endgame	820	1092	PeriJove Raise and Europa Orbit Insertion
Statistical DV (JOI/EOI Cleanup)	150	171	For cleanup maneuvers during Jupiter and Europa orbit insertion
Europa Altitude Change	40	44.3	From 200km to 100km altitude
Statistical DV (Remainder)	100	152	For orbital maintenance at Europa and other TCMs during the mission
Oxidizer and Residual Propellant	0	78	Holdup volume / residual margin of propellant and oxidizer.
Pressurant	0	20	
Total	**2407**	**3974**	

* ΔV allocation does not explicitly account for propellant required for Europa atmospheric-drag makeup or to correct for an unstable spacecraft orbit around Europa; however, this ΔV is expected to be small (totaling tens of m/s)

Command and Data Handling Subsystem

- The EGE command and data handling subsystem would use a dual-string, PCI-bus-based computer system that contains:
  - BAE Systems RAD750 with ~50 Mbyte of local, onboard, SRAM.
  - X2000 systems interface assembly for connection to science instruments, telecom, and attitude control sensors.



- An SRAM-based solid state recorder would be used to store science data.
  - The SSR design assumes tentative performance requirements of ~18 Gbits of total storage (BOM) and 11 Mbits/sec peak data rate.
    - Original 18-Gb requirement based on using the upgraded DSN (180 12-m antennas) and a 100-W (RF) Ka-band system.
    - Updated SSR storage requirement for the reference mission concept is ~2 Gbits and assumes the use of the existing DSN and a 50-W (RF) Ka-band system. This new storage requirement is not reflected in the current SSR design.
  - A new ATMEL 80-Mbit device is the current SSR baseline; however, subsequent analyses indicates it may not meet mission requirements because of its low SEU tolerance (1 MeV).
    - NOTE: This approach was re-assessed during the EE Study and a more robust approach adopted

EGE Radiation Vaults

Radiation environment

- The total mission dose is predicted to be ~1.8 Mrad (100 mils Al).
  - Even using hardened parts, radiation vaults would be required.

Subsystem radiation tolerance levels (RDF=1):

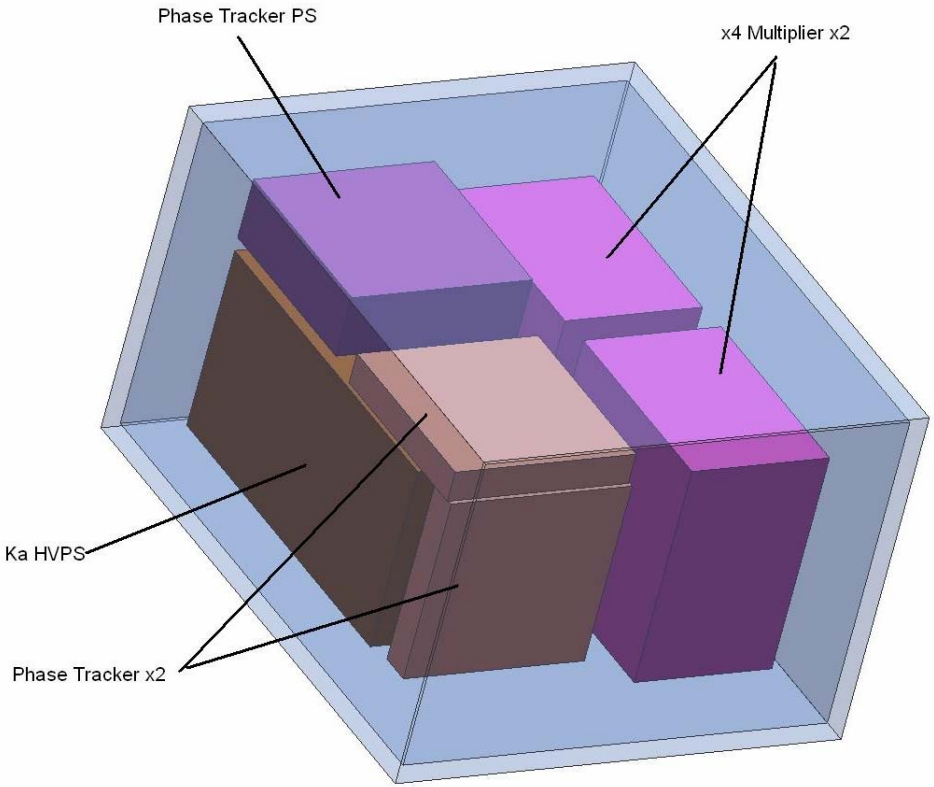
- Telecom: generally 300 krads, with one 1 Mrad part
- Power distribution system: 1 Mrad
- Instruments: 100 krads
- C&DH: combination of 300 krad and 1 Mrad parts
- AACS: combination of 300 krad and 1 Mrad parts

Two radiation vaults would be required:

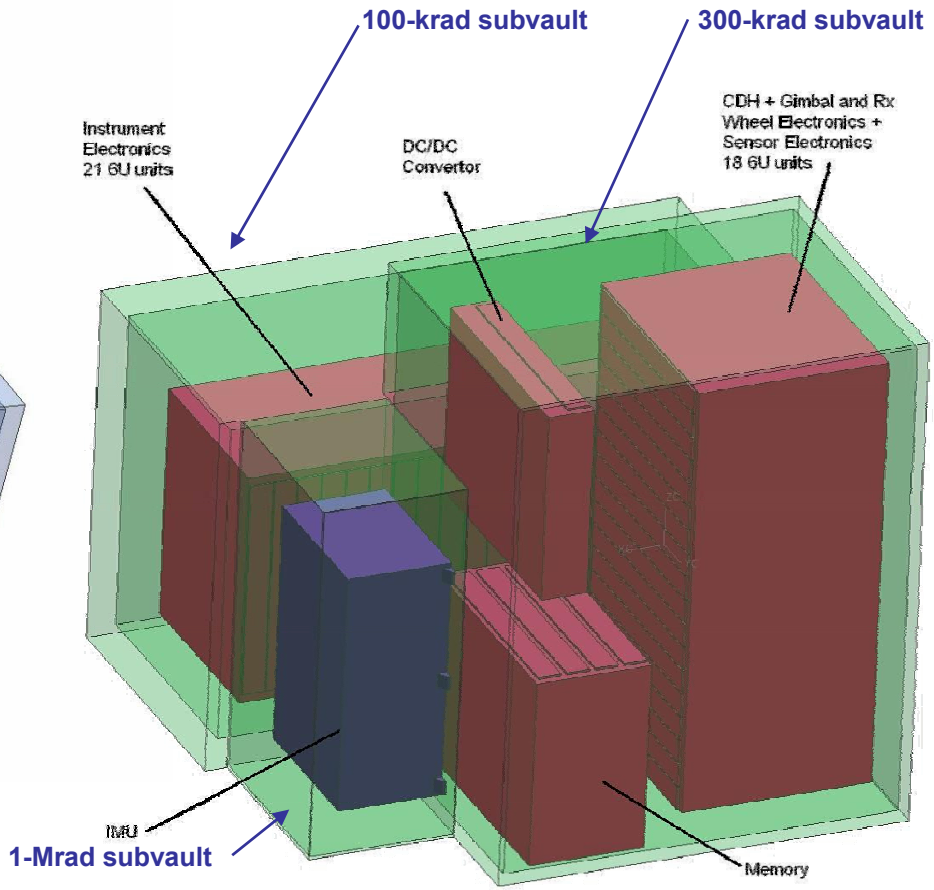
- Telecom vault (25.7 kg, including contingency)
  - 300-krad telecom components, 350-mil-thick Al
- Main vault with three subvaults (125 kg, including contingency)
  - Instruments (100-krad components, 900-mil-thick Al)
  - C&DH and AACS (300-krad components, 350-mil-thick Al)
  - C&DH and AACS (1-MRad components, 80-mil-thick Al)

EGE Radiation Vault Concepts

Telecom vault



Main vault



Conceptual Illustrations

EGE Trade Study Results

Trade Space Overview

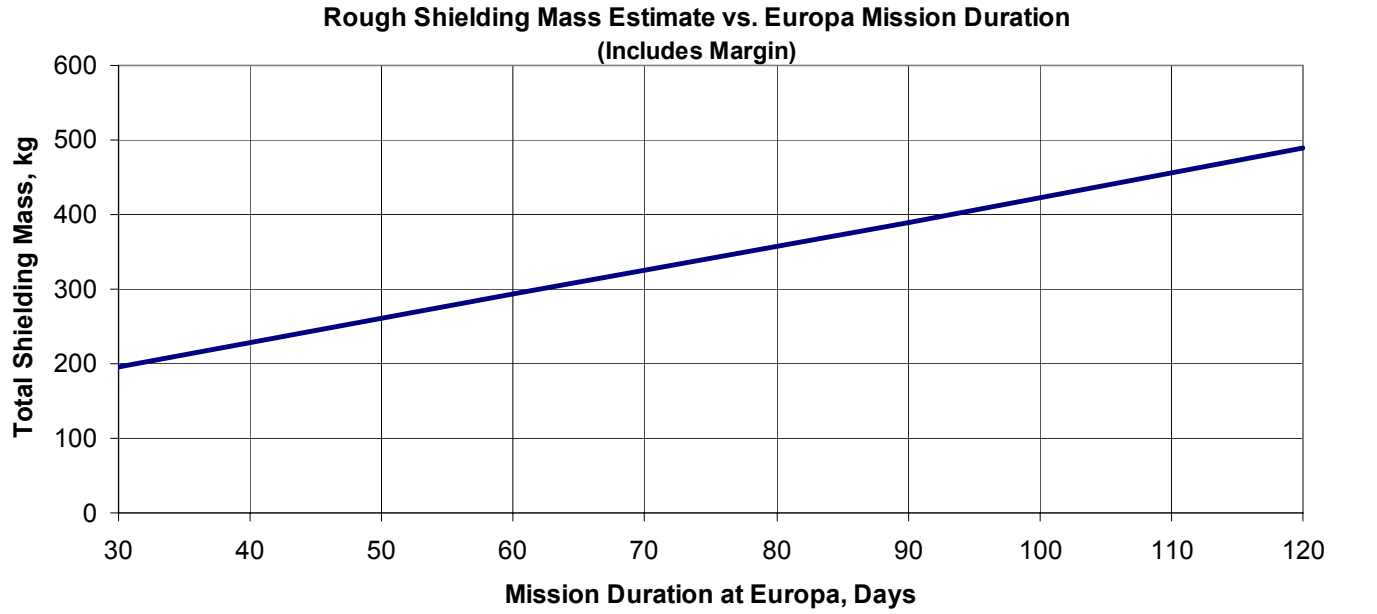
Ten Mission-Concept Cases were Investigated in the Trade Space

EGE Options	Launch Vehicle	Trajectory	Launch Mass Capability, kg	# Instruments	RPS	Power level @ EOM, W	Wet Mass w/ Contingency, kg	Dry Mass w/ Contingency, kg	Unallocated Mass, kg
Reference Mission	Delta 4050H	VEEGA	7230	9	7 MMRTGs	769	6374	2400	856
With Upgraded DSN	Delta 4050H	VEEGA	7230	9	7 MMRTGs	769	6374	2400	856
With SRG	Delta 4050H	VEEGA	7030	9	**8 SRGs**	761	6409	2436	**749**
With Upgraded MMRTG	Delta 4050H	VEEGA	7230	9	**5 upgraded RTGs**	703	6155	2182	**1075**
With Altas 551	**Altas 551**	VEEGA	**4920**	9	7 MMRTGs	769	4911	2200	9
With ΔV-EGA	Delta 4050H	**ΔV-EGA**	**5580**	**8** (No sounder)	**6 MMRTGs**	**660**	5486	2147	94
Augmented Mission	Delta 4050H	VEEGA	7230	15	9 MMRTGs	990	6890	2916	340
With Upgraded DSN	Delta 4050H	VEEGA	7230	15	9 MMRTGs	990	6890	2916	340
With SRG	Delta 4050H	VEEGA	7030	15	**10 SRGs**	**980**	6908	2935	**250**
With Upgraded MMRTG	Delta 4050H	VEEGA	7230	15	**7 Upgraded RTGs**	**984**	6655	2682	**575**

Green background indicates key trade or result

Trade Study: Mission Duration at Europa

- The mission duration at Europa is driven by the ambient radiation environment, the configuration and the radiation tolerance of the spacecraft's subsystems and components
- Preliminary estimates were made of the shielding required for a ≥30 day mission for the EGE reference design
- Each month at Europa exposes the spacecraft to ~900 krad (behind 100 mils of aluminum)
- To increase the mission duration from 30 to 60 days at Europa, the shield thickness and mass would need to increase by ~50%
  - Analysis assumed that, to first order, shielding thickness and mass were linearly related to radiation dose. Detailed radiation and spacecraft accommodation analyses need to be performed to generate a more accurate shield mass estimate.



For EGE, each 30 day mission extension requires ~100 kg of additional shielding

Trade Study Summary

- The reference mission satisfies all science goals and has ~860 kg of unallocated mass
  - The augmented mission permits additional science (temperatures, surface composition, dust particles), higher sampling rates, higher downlink data rates, but has only 340 kg of unallocated mass
- The VEEGA trajectory (8-year trip duration) permits the injected mass needed
  - The ΔV-EGA trajectory may not support the injected mass of the EGE reference mission
  - The direct trajectory definitely cannot support the EGE reference mission
- The Delta IV-H (4050) launch vehicle permits ~860 kg of unallocated mass for the reference mission, using a VEEGA trajectory
  - The Atlas V permits only ~10 kg of unallocated mass for the same trajectory
- The standard MMRTG mission option has lower risk and a greater amount of unallocated mass relative to the SRG
  - The upgraded MMRTG could provide >100 kg more unallocated mass relative to the standard MMRTG
- The reference mission allows a 30-day science mission at Europa
  - More radiation shielding could be used to extend Europa mission duration. Each 30-day extension of the mission at Europa would require ~100 kg more shielding, at least for a duration of 120 days.
- Using the existing DSN architecture (34-m antennas) would provide an EGE downlink rate of ~340 kb/s at 5.2 AU
  - The upgraded DSN (180 12-m dishes) would increase the downlink rate by >10 times

The reference EGE mission provides the greatest amount of unallocated mass and uses the most conservative assumptions in technology and architecture

EGE Study Conclusions

- The results of the 45-day EGE study indicate that a Europa orbiter mission using RPSs and conventional propulsion is potentially feasible.
- The reference EGE mission concept meets all science requirements as defined by the Europa Subgroup of the Outer Planets Assessment Group (OPAG).
- The use of the Venus Earth Earth Gravity Assist (VEEGA) trajectory drastically increases the amount of delivered mass to Europa compared with a direct trajectory (unfeasible for EGE) or the ΔV-EGA trajectory (highly limiting for EGE).
- A better understanding of the Jovian radiation environment and advances in radiation-hardened components and subsystems has lead to a reduction in the amount of shielding required for a Europa mission.
  - Galileo data indicates a lower total radiation dose than previously believed.
  - X2000 development has resulted in 300 krad to 1 Mrad part tolerance levels.
  - This combination permits more mass for payload and mission growth.
  - Can conceive of missions lasting 90 days or longer in Europa orbit.
- The reference EGE mission potentially has a significant amount of additional, unallocated mass. This could be used for:
  - Mission growth and additional margin to cover uncertainties in the EGE design
  - More power (RPSs) and upgraded telecom system for greater downlink data rates
  - Enhanced science payload
  - A Europa lander

Europa Explorer Highlights

Europa Explorer Study Highlights

- Following the EGE study, an internally-funded Europa Explorer (EE) study was performed by JPL.
  - This study began in November 2005 and concluded in February 2006.

- The EE study went into much greater detail in key areas compared with the EGE, including:
  - Communications and data return architecture
  - Command and Data Handling (C&DH) subsystem architecture, especially the use of mass memory
  - Environmental radiation modeling and mitigation strategies

- The key differences between the EE and EGE studies are presented in the following table. Areas include:
  - Mission duration
  - Spacecraft mass and science payload
  - Power requirements
  - Telecom architecture, data rate, and data storage

- While there were notable differences between the mission architectures of the EE and EGE reference missions, both concluded the same result:

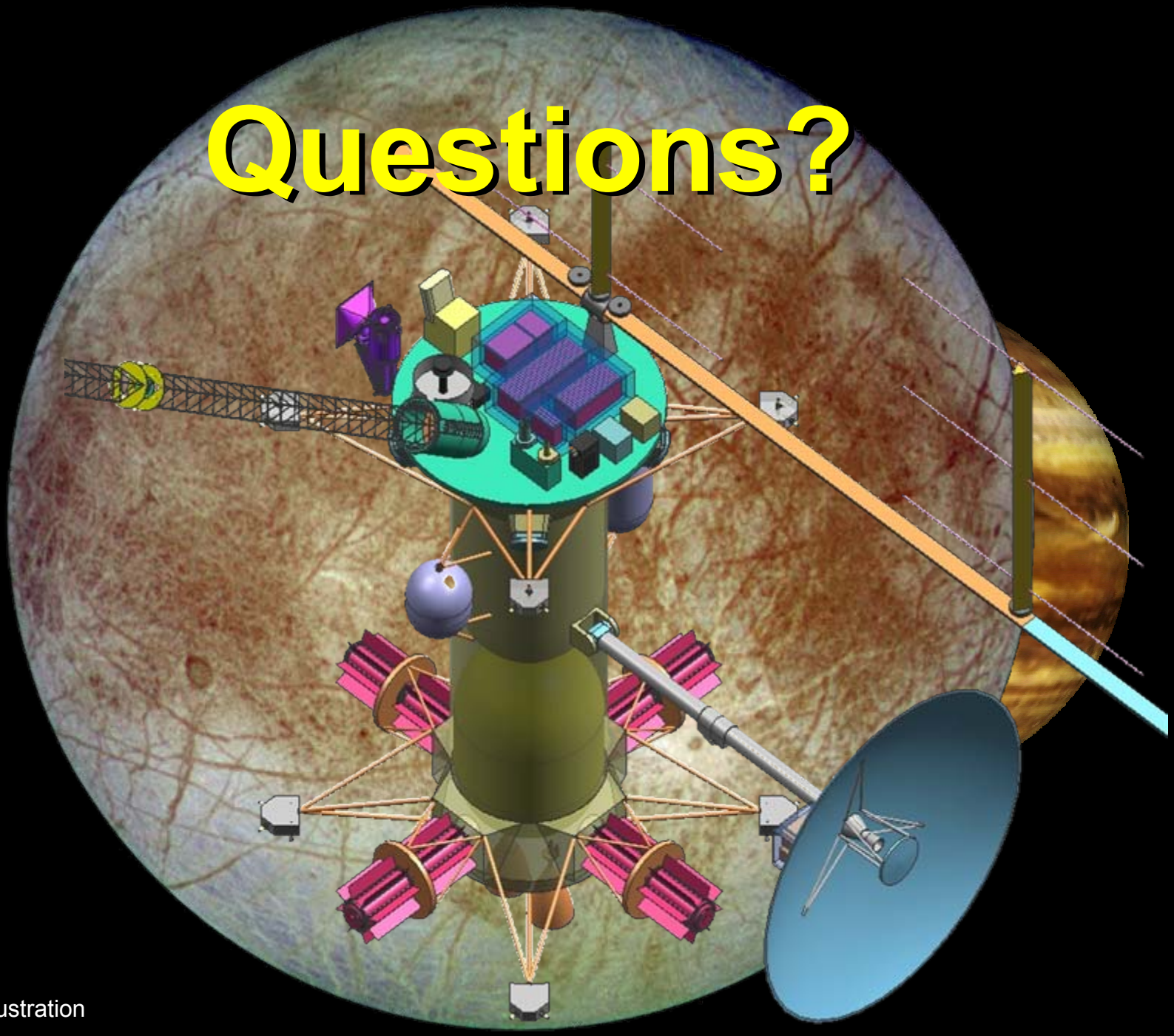
A Europa Orbiter mission appears feasible using RPSs, conventional propulsion, and existing technology.

Key Differences between EE and EGE Studies

Parameter	Europa Geophysical Explorer (EGE) - 2005	Europa Explorer (EE) - 2005-2006
Prime Mission Duration*, days	30	90
Orbit	100 km circular, 80° inclination	100 km nearly circular, inclination between 70° and 110°
Wet Mass, kg	6374 (w/ full LV allocation)	6888 (w/ full LV allocation)
Dry Mass, kg	2404 (w/ full LV allocation)	2608 (w/ full LV allocation)
Number of Instruments	9	10
Payload Complement	Radar sounder, Laser Altimeter, WAC, VIS/NIR HiRes, VIS-MWIR Spec, INMS, keV Ion Spectrometer, MeV Ion Spectrometer, Magnetometer	Radar sounder, Laser Altimeter, WAC, MAC, IR Mass Spec, INMS, keV Ion Spectrometer, MeV Ion Spectrometer, Magnetometer, Thermal Imager
RPS	7 MMRTGs	8 MMRTGs
Telecom Antenna for Science D/L	3-m, 2-axes articulated, Ka-band	3-m, 2-axes articulated, X-band
Downlink Rate	~340 kbps (~5.2 AU)	~400 kbps (~5.5 AU)
Returned Data Volume in Prime Mission, Gb	529	2900
Data Storage	18 Gbits	750 Mb (Science SSR) 500 Mb (Flight SSR)
Predicted Radiation Environment	1.8 Mrad (behind 100 mils Al)	3.4 Mrad (behind 100 mils Al)
Shielding Mass, kg	195	233
Unallocated Available Mass, kg	856	342

* Prime mission is defined to start upon reaching Europa orbit, and does not include the ~1.5 year Jovian tour duration (common to both the EGE and EE studies) where scientific observations and measurements would be made of targets of opportunity. Additionally, the mission is expected to last longer than the 30 days (EGE) and 90 days (EE) specified above.

Questions?



Conceptual Illustration

Backup

Mission Architecture Selection

Trade Element *(decision driver)*	Trade Study Investigations		
Launch Vehicle *(delivered mass)*	***Delta IV-H (4050H-19)***	Atlas V 521	
Trajectory Type *(delivered mass)*	2012 ΔV-EGA	***2012 VEEGA***	Direct
RPS Approach *(delivered mass)*	SRG	***MMRTG***	Advanced MMRTG
Telecom Architecture *(infrastructure investment)*	***Current DSN***	Upgraded DSN Architecture	
Mission Duration at Europa *(reliability, mass)*	***30 days***	> 30 days	
Science Payload *(complexity)*	***Initial 150 Kg payload***	Augmented 350Kg payload	
Potential Lander Allocation *(complexity)*	<500 Kg	***None***	>500 Kg

Key: ***Selected*** Not Selected

System Summary for the Reference Mission Case

	Mass Fraction	Mass (kg) Opt 4 - Reduced Science	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Safing	Mode 2 Power (W) Light side science (Plus telecom, no radar)	Mode 3 Power (W) Dark side science (no telecom, no imaging)	Mode 4 Power (W) Cruise (in years)	Mode 5 Power (W) Launch	Mode 6 Power (W) Jupiter Tour (in years)
Power Mode Duration (hours)					48	1.07	1.07	6.4	3.0	1.5
Payload										
Instruments	6.0%	109.1	43%	156.0	0.0	129.3	86.7	50.4	0.0	103.6
Radiation Vault	6.4%	107.5	43%	153.7	0.0	0.0	0.0	0.0	0.0	0.0
Payload Total	12.4%	216.6	43%	309.7	0.0	129.3	86.7	50.4	0.0	103.6
Bus										
Attitude Control	2.9%	48.4	30%	62.9	82.6	82.6	82.6	82.6	31.0	82.6
Command & Data	2.1%	34.3	30%	44.6	19.0	40.5	40.5	28.0	28.0	28.0
Power	20.2%	336.9	9%	367.9	39.6	57.4	37.1	41.1	24.5	49.3
Propulsion1	15.3%	255.2	26%	322.6	51.3	3.3	3.3	3.3	51.3	3.3
Structures & Mechanisms	29.6%	494.5	30%	642.8	0.0	0.0	0.0	0.0	0.0	0.0
S/C Adapter	3.7%	61.4	30%	79.8						
Cabling	4.2%	70.0	30%	91.0						
Telecomm	4.6%	76.8	23%	94.6	120.0	155.0	40.0	120.0	35.0	120.0
Thermal	5.0%	84.1	29%	108.7	35.2	35.2	35.2	35.2	45.2	45.2
Bus Total		1461.6	24%	1815.1	347.7	374.0	238.7	310.2	215.0	328.3
Spacecraft Total (Dry)		1678.2	27%	2124.8	347.7	503.3	325.3	360.6	215.0	431.9
Subsystem Heritage Contingency		446.6	27%	27%						
System Contingency		275.0	16%	16%	149.5	216.4	139.9	155.1	92.4	185.7
Spacecraft with Contingency		**2399.8**	of total	w/o addl pld	**497.2**	**719.7**	**465.2**	**515.6**	**307.4**	**617.7**
Propellant & Pressurant1	62.5%	3974.1		For S/C mass =	7230		Delta-V, Sys 1	2407	m/s	
Spacecraft Total (Wet)		**6373.9**								
L/V Adapter		0.0								
Launch Mass		**6373.9**								
Launch Vehicle Capability		**7230.0**	Delta IV Heavy							
Launch Vehicle Margin		**856.1**	12%							

Dry Mass

Wet Mass

Contingencies

	Mass	Power
Instruments	43%	43%
Other	43%	0%
Additional Payload	0%	0%
Spacecraft Bus, dry	43%	43%

Per JPL design principles, 43% contingency (mass and power) is included in the spacecraft design

Mass available for spacecraft growth, more payload, more shielding, and/or a lander