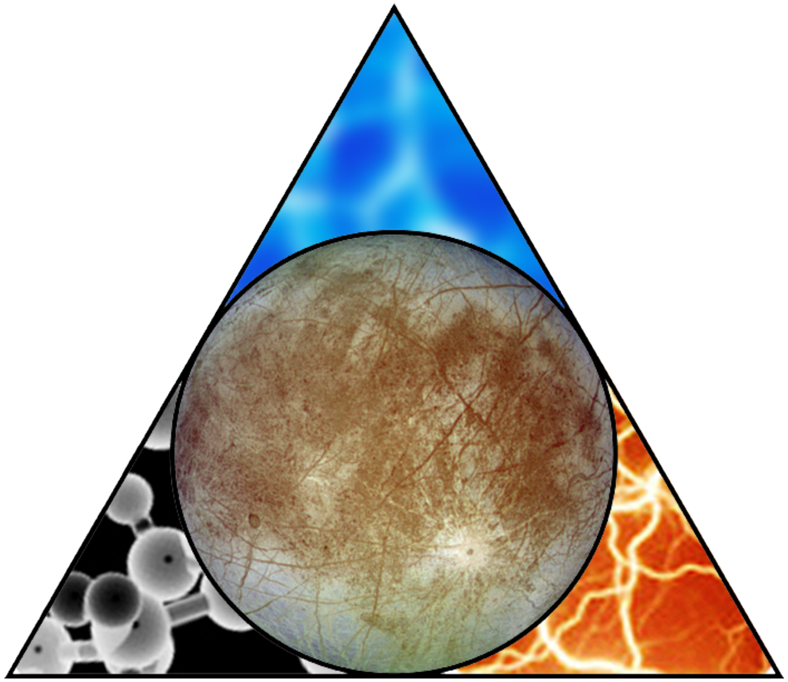


Flyby Element

Kenneth Hibbard

Science as a Driver of Mission Architecture

Science traceability leads to a two element mission concept:

***Orbiter Element:* Geophysical measurements that can be achieved only from orbit**

- Payload focused primarily to address “Ocean” objective:
  - Radio Subsystem (RS)
  - Laser Altimeter (LA)
  - Magnetometer (MAG)
  - Langmuir Probe (LP)
  - Mapping Camera (MC)
- Have readily accommodated those instruments that are:
  - Less massive
  - Lower power
  - Lower data rate

***Flyby Element:* Remote measurements that can be accomplished via multiple flybys**

- Payload focused primarily to address “Chemistry” and “Energy” themes:
  - Ice Penetrating Radar (IPR)
  - ShortWave IR Spectrometer (SWIRS)
  - Ion and Neutral Mass Spectrometer (INMS)
  - Topographical Imager (TI)
- Have readily accommodated those instruments that are:
  - More massive
  - Higher power
  - Higher data rate

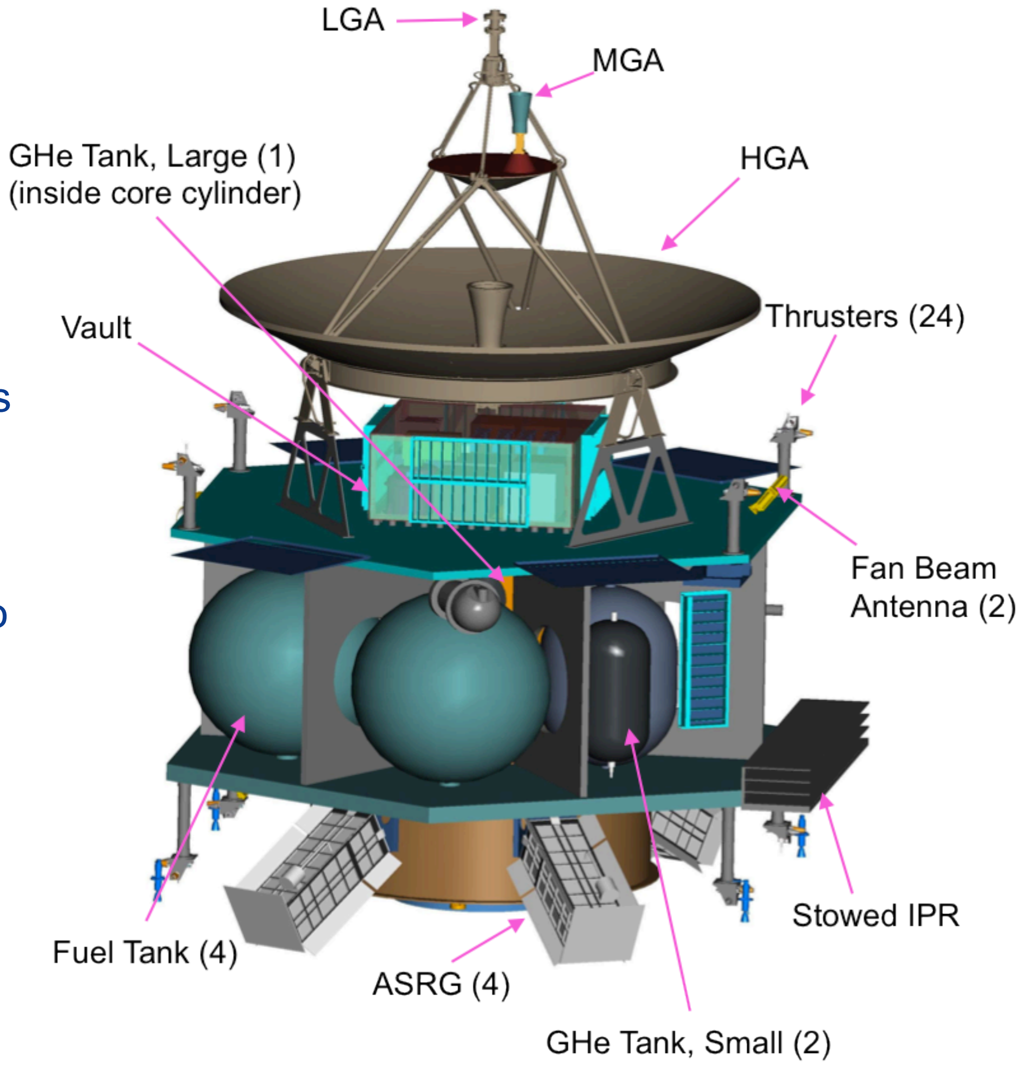
Key Science Drivers & Requirements

Instrument(s)	Key Accommodation Requirements	Element
Radio Subsystem + Laser Altimeter	Low altitude (~100+ km), circular, near-polar orbit, for at least 30 days. Unperturbed orbital arcs (no thrusting) of at least 3 days.	Orbiter
Magnetometer + Langmuir Probe	Low altitude (~100+ km), circular, near-polar orbit, for at least 30 days. Cover approximately 12 hours of Europa local time.	Orbiter
Mapping Camera	Low altitude (~100+ km), ≥ 80% global coverage under near uniform lighting conditions, solar incidence angle > 45° (70° preferred).	Orbiter
Ice Penetrating Radar	≥ 800 km tracks in 11 of 14 globally distributed regions, intersected by at least 1 other track, with track lengths measured from ≤ 400 km alt. ~25–100 km closest approach at ≤ 6 km/s.	Flyby ✓
ShortWave IR Spectrometer	Ability to target specific geologic locations with a wide range of surface locations, lighting between 9:00am and 3:00pm. Attitude stability < ½ IFOV over integration time, flyby speed < 6 km/s.	Flyby ✓
Topographical Imager	High resolution stereo imagery aligned with IPR coverage; lighting conditions solar incidence angle > 20° (70° preferred).	Flyby ✓
Ion and Neutral Mass Spectrometer	Low altitude (< 200 km with lower altitudes desired) at ≤ 7 km/s; long integration times and low altitudes (≤ 100 km) preferred.	Flyby ✓

✓ = areas accommodated in Flyby concept

Flyby Element
Configuration Overview

- Element design based on the latest science requirements from the Europa Science Definition Team (ESDT)
- Level of study was to drive to a single point design that accomplishes the element science at ≤ $1.5B, excluding launch vehicle costs
  - The Europa Study significantly builds upon the level of studies performed for the Planetary Science Decadal Survey last year
- Wide open trade space - objective was to accomplish science and optimize the design for cost to fit within projected NASA budget
- Flyby element optimizes surface coverage over ~15-30 Europa flybys to achieve globally distributed regional observations



Mission Architecture Drivers

- Launch in the 2021-2024 timeframe with annual backup opportunity
- Existing launch vehicle: Atlas V 551 (or smaller); sized for Atlas V 431
- Utilize ASRGs: No limit on number, but strong desire to minimize ^{238}Pu usage
- Mission Duration: < 10 years, launch to End Of Mission (EOM)
- Use commercially available 100 krad radiation hardened parts and shield as necessary for Total Ionized Dose (TID)
- Assumed a flyby mission system sized for ~40 flybys total
- Payload Observation Constraints:
  - <5 km/s max velocity at closest approach; limited by radar
  - 25-100 km closest approach altitude; bounded INMS and IPR
  - Examine Europa at different orbit points; ideal lighting is 9:00 am – 3:00 pm
  - IPR requires crossing ground tracks
  - All instruments on ±1000 km from closest approach
  - IPR, TI, and SWIRS co-aligned, nadir pointed during flybys
- Optimized design for cost! We were looking for the lowest cost possible while achieving baseline science

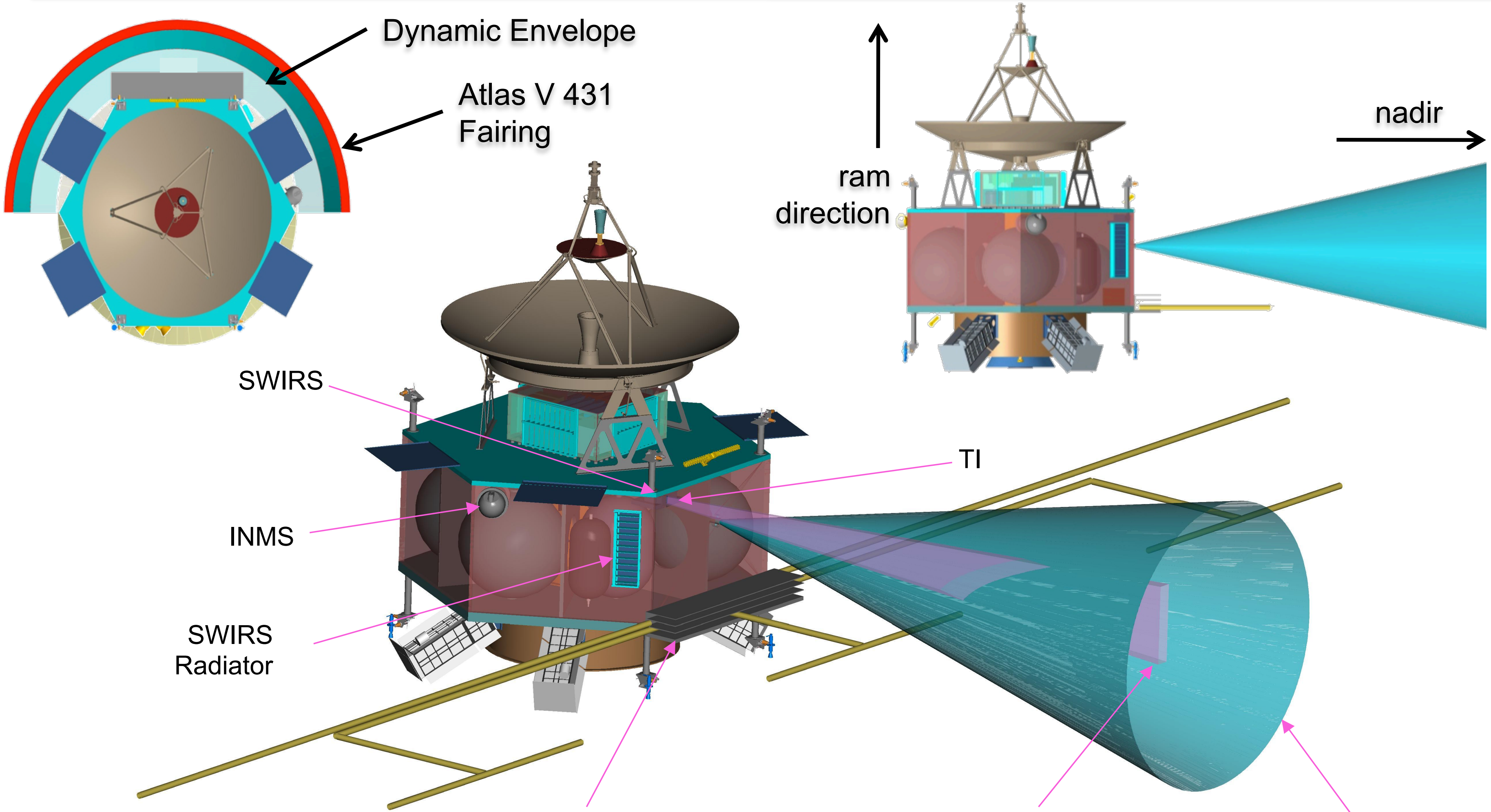
Minimal Mission Cost Design Strategies

- Needed to accommodate radiation in Jovian environment, planetary protection concerns, and minimize Phase E operational costs (hibernation, minimize Time of Flight (TOF), other)
- Flyby concept permits store-and-forward data return strategy, as well as battery use with recharging between encounters
- Design for the lightest, compact spacecraft
- Design for low-maintenance low-cost operations
- Simplify implementation and integration using modular designs
- Use a combined radiation vault/thermal design for electronics
  - 100 krad parts
- Balance radiation exposure and science requirements
- Standard designs over custom
  - Draw off of internal experience from previous missions
- Minimize mechanisms (e.g. no gimbals on high gain antenna, fixed Leros engine)

Flyby Model Payload Resource Summary

Instrument	Unshielded Mass (kg)	Shielding Mass (kg)	Total Mass (kg)	Power (W)	Data Volume (Gb)/ flyby	Comments
Ice Penetrating Radar (IPR)	28.0	5	33.0	55	25.2	Bringing down data between ± 400 km from surface only (35 Gbit for ± 1000 km)
Topographical Imager (TI)	2.5	4.5	7.0	5.9	3.1	3:1 lossy compression; each additional 4 k x 4 k image is 0.07 Gbit compressed
ShortWave IR Spectrometer (SWIRS)	11.6	9.1	20.7	19.1	1.5	2.5:1 lossy compression; 2 full disk scans on approach; 2 full images during flyby
Ion and Neutral Mass Spectrometer (INMS)	14.0	10.1	24.1	32.5	0.002	2 Kbps rate, acquiring data between ± 1000 km from surface
Totals:			**84.8**	**112.5**	**29.9**	

EHM Flyby Configuration



Dynamic Envelope

Atlas V 431
Fairing

ram
direction

nadir

SWIRS

TI

INMS

SWIRS
Radiator

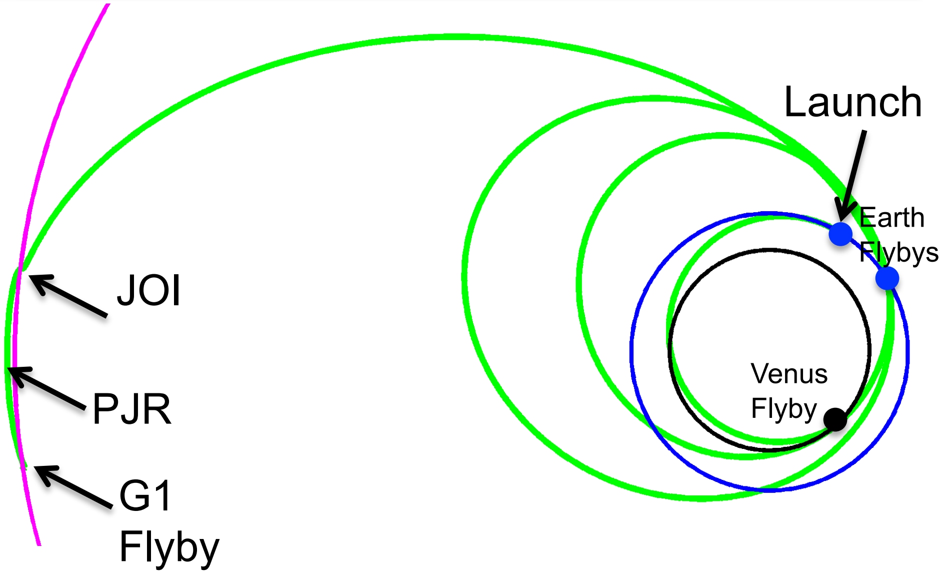
IPR

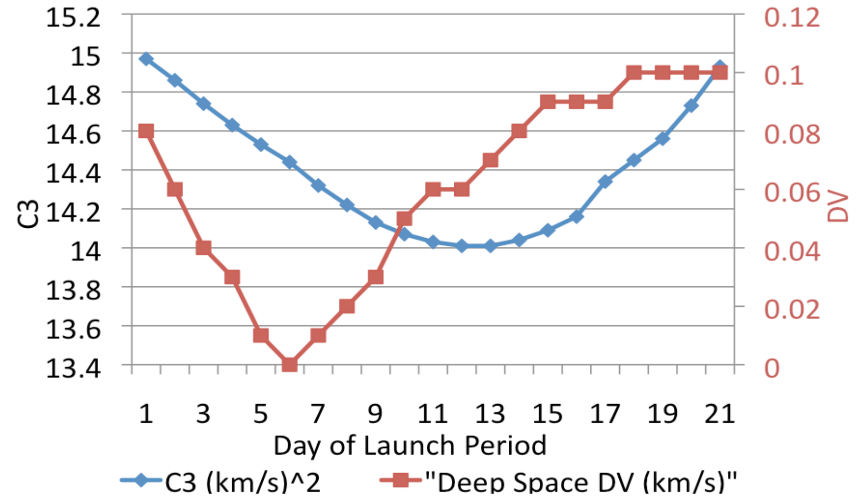
Field of View - SWIRS

Field of View - TI

Interplanetary Trajectory

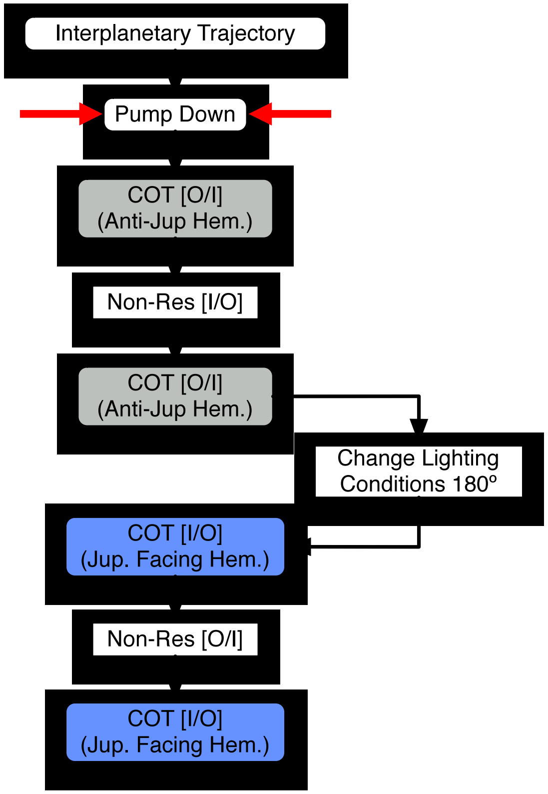
	Date	Flyby Alt. (km)
Launch	21-Nov-2021	
Venus	14-May-2022	3184
Earth	24-Oct-2023	11764
Earth	20-Oct-2025	3336
G0	03-Apr-2028 15:00	500
JOI	04-Apr-2028 03:32	12.8 Rj
PJR	20-Aug-2028	238 Rj
G1	21-Oct-2028	





IPR Coverage

Panels:
0 of 14


Interplanetary Trajectory

Pump Down

COT [O/I]
(Anti-Jup Hem.)

Non-Res [I/O]

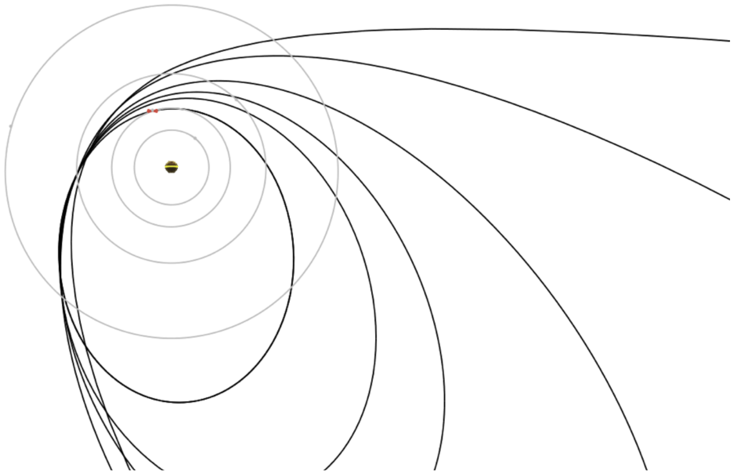
COT [O/I]
(Anti-Jup Hem.)

Change Lighting
Conditions 180°

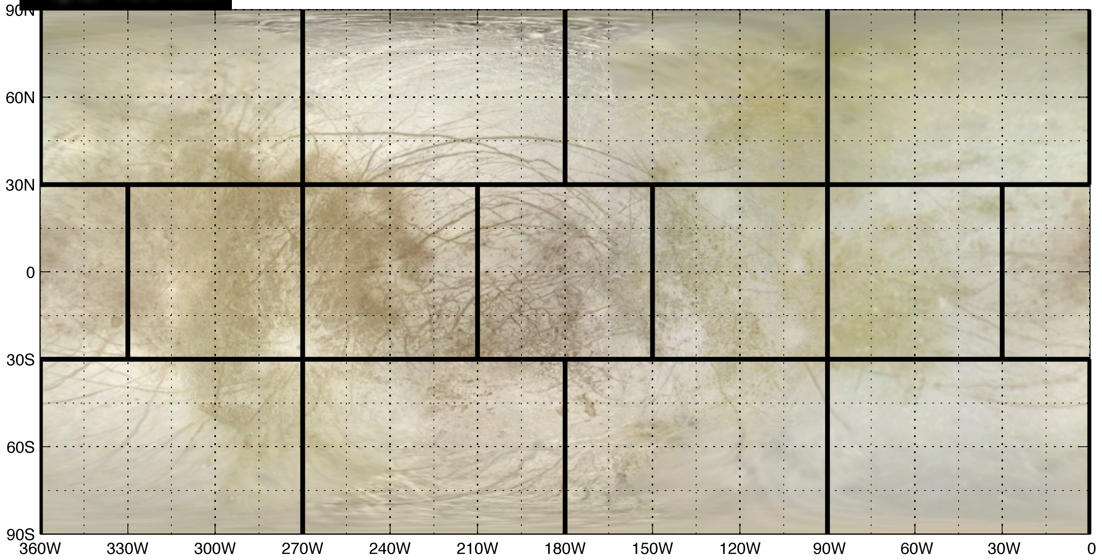
COT [I/O]
(Jup. Facing Hem.)

Non-Res [O/I]

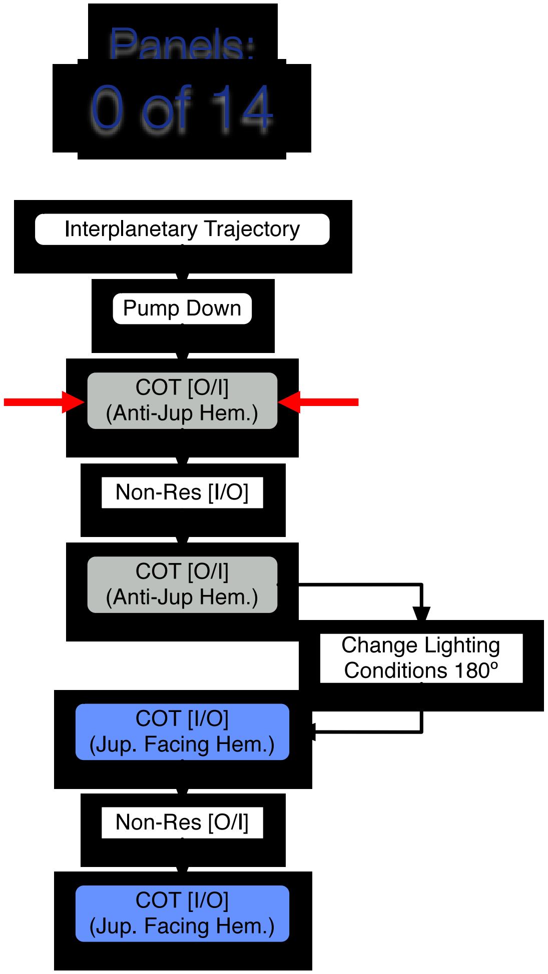
COT [I/O]
(Jup. Facing Hem.)



*r_p ! 400 km



IPR Coverage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Interplanetary Trajectory

Pump Down

COT [O/I]
(Anti-Jup Hem.)

Non-Res [I/O]

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Change Lighting
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(Jup. Facing Hem.)

Non-Res [O/I]

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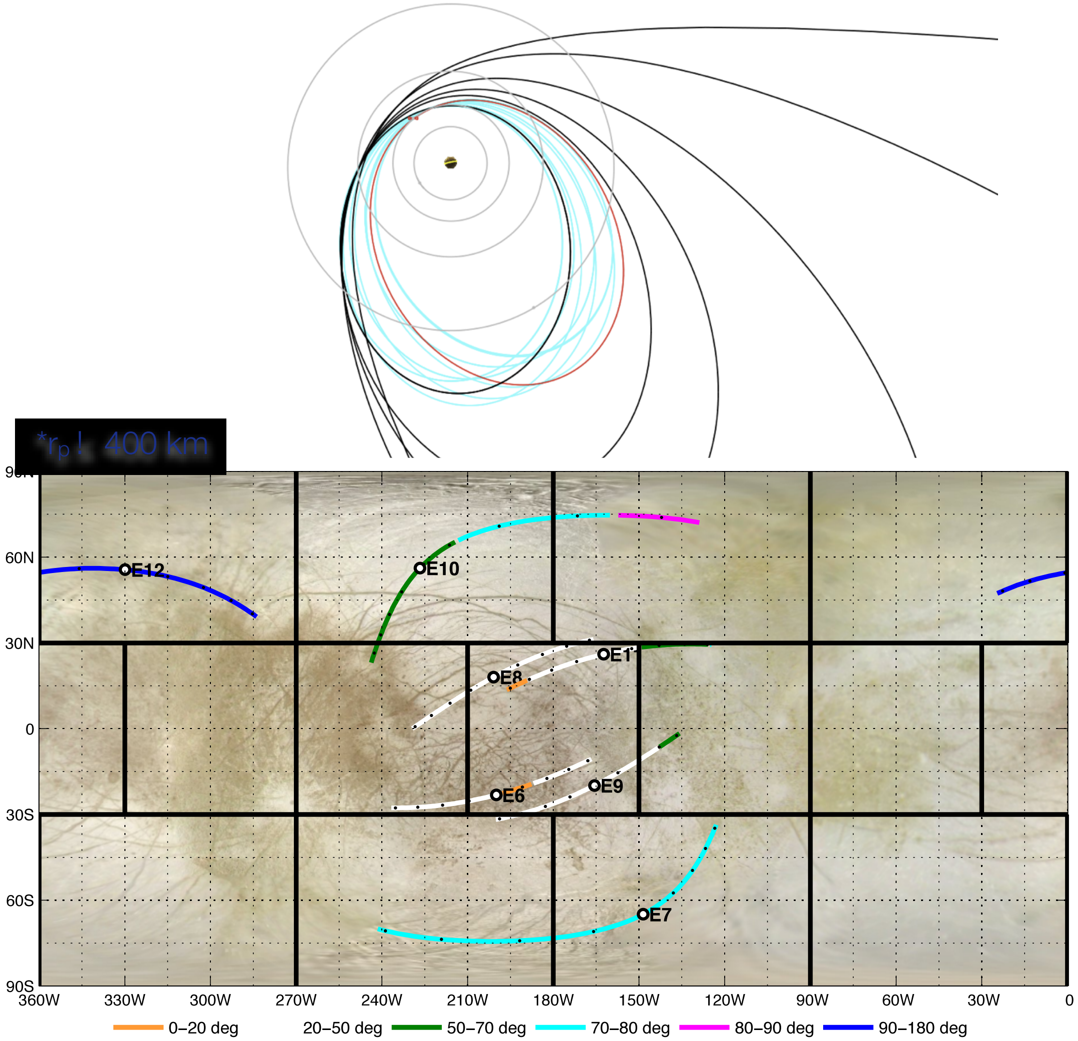
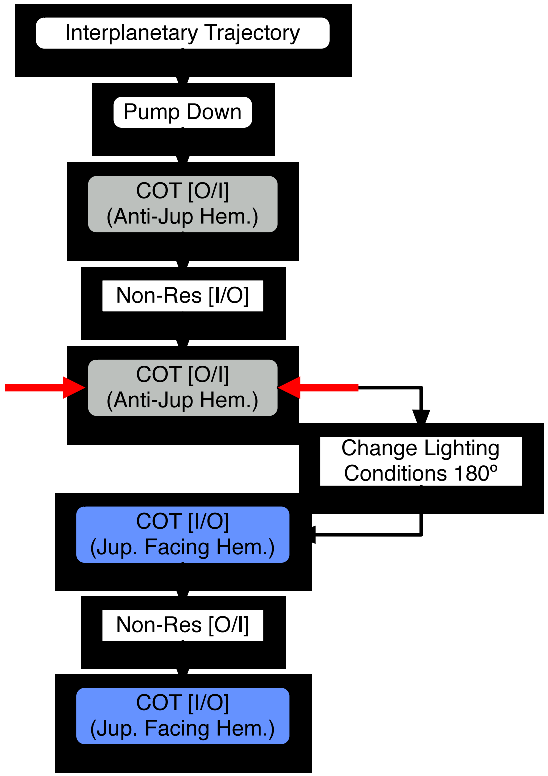
(Jup. Facing Hem.)


*r_p ! 400 km

IPR Coverage

Panels:
7 of 14



Interplanetary Trajectory

Pump Down

COT [O/I] (Anti-Jup Hem.)

Non-Res [I/O]

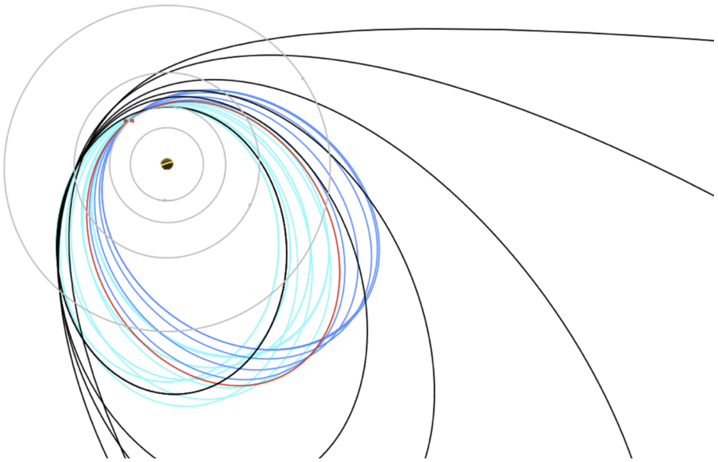
COT [O/I] (Anti-Jup Hem.)

Change Lighting Conditions 180°

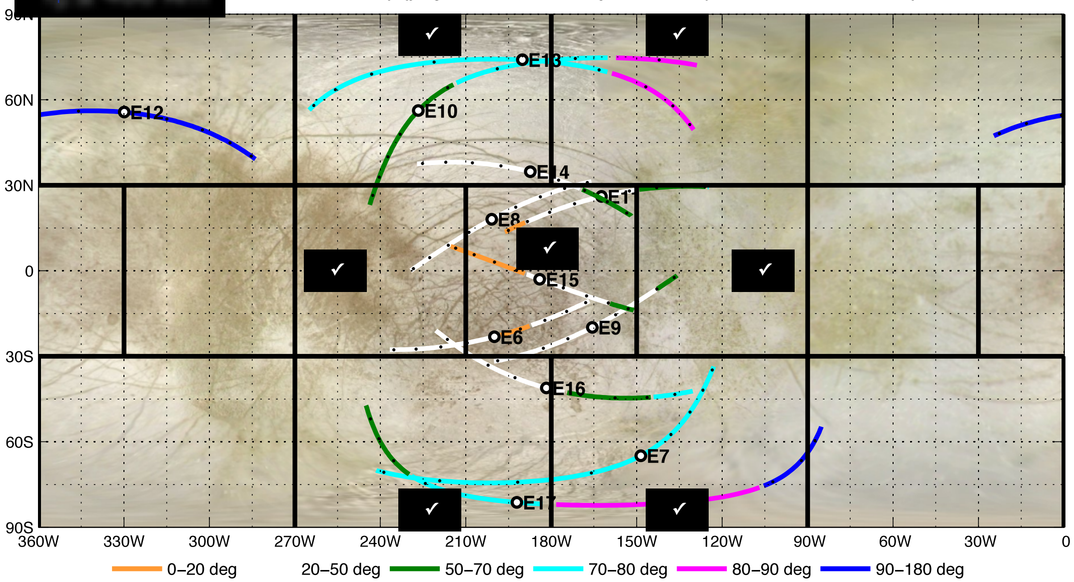
COT [I/O] (Jup. Facing Hem.)

Non-Res [O/I]

COT [I/O] (Jup. Facing Hem.)

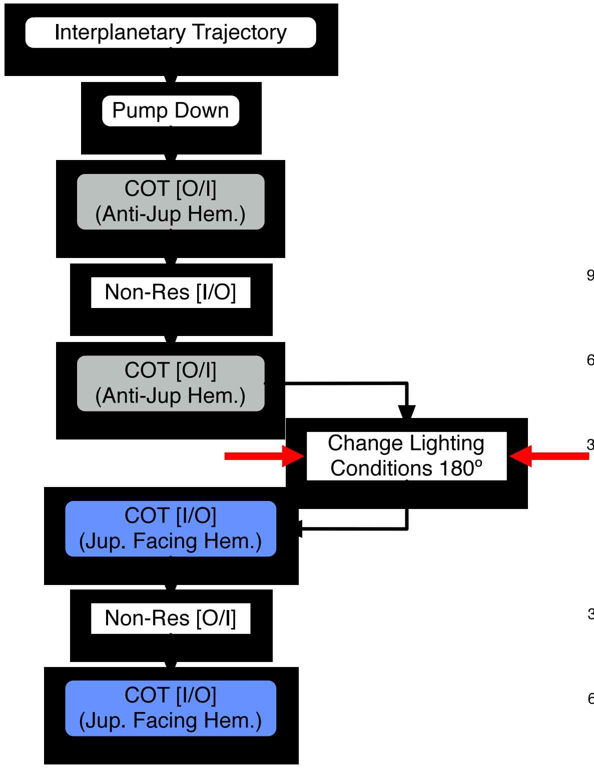


$*r_p \leq 400$ km



IPR Coverage

Panels:
7 of 14


Interplanetary Trajectory

Pump Down

COT [O/I]
(Anti-Jup Hem.)

Non-Res [I/O]

COT [O/I]
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Change Lighting
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COT [I/O]
(Jup. Facing Hem.)

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COT [I/O]
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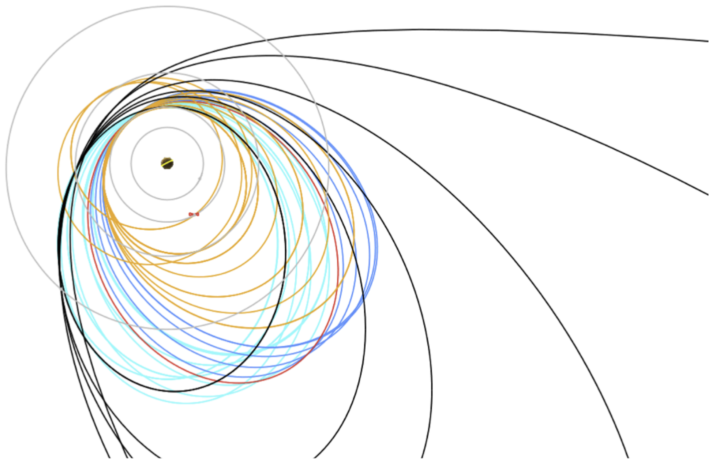
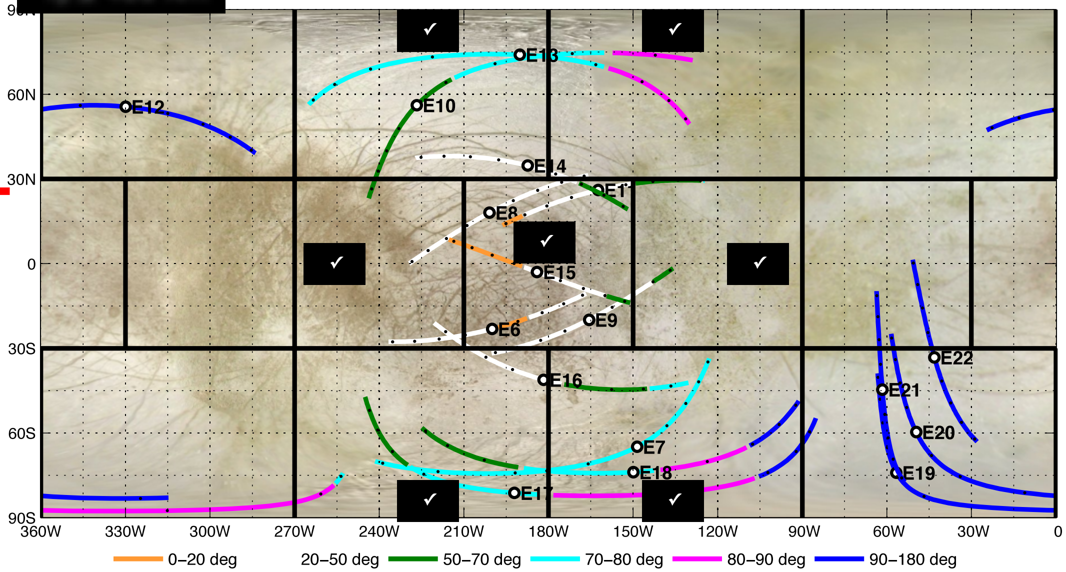
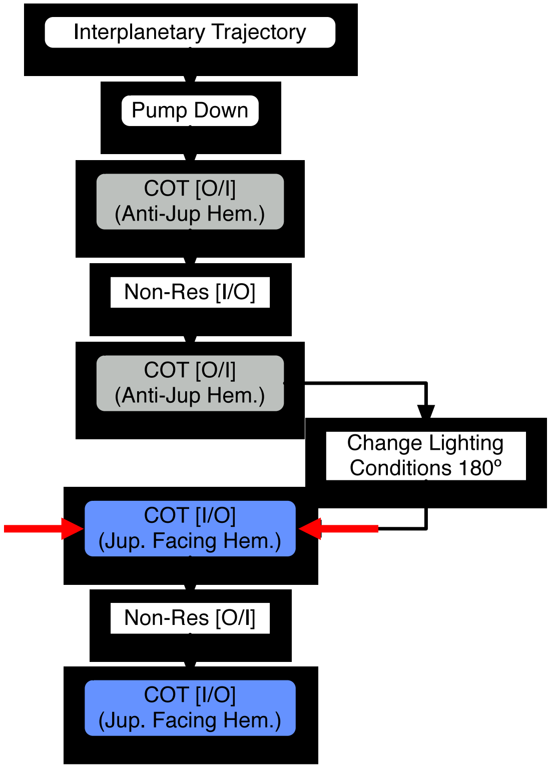


*r_p ! 400 km



IPR Coverage

Panels:
7 of 14



Interplanetary Trajectory

Pump Down

COT [O/I]
(Anti-Jup Hem.)

Non-Res [I/O]

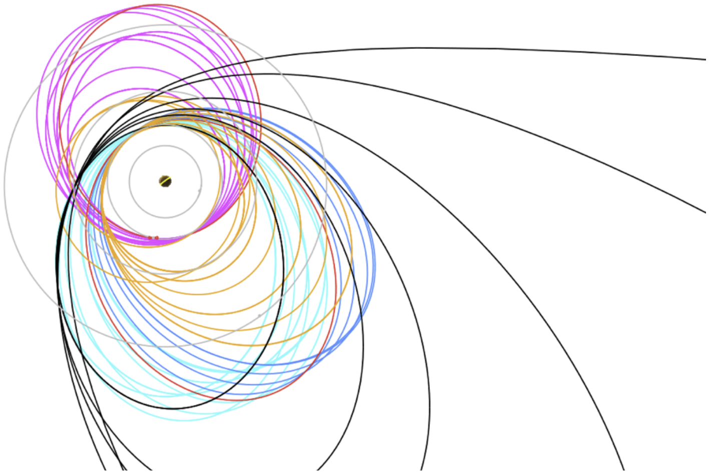
COT [O/I]
(Anti-Jup Hem.)

Change Lighting
Conditions 180°

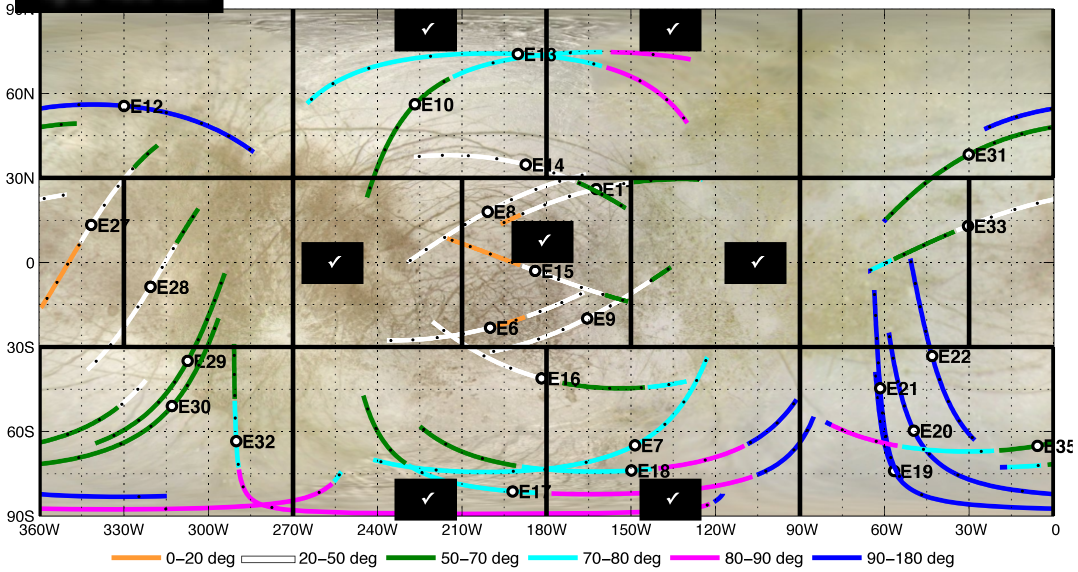
COT [I/O]
(Jup. Facing Hem.)

Non-Res [O/I]

COT [I/O]
(Jup. Facing Hem.)



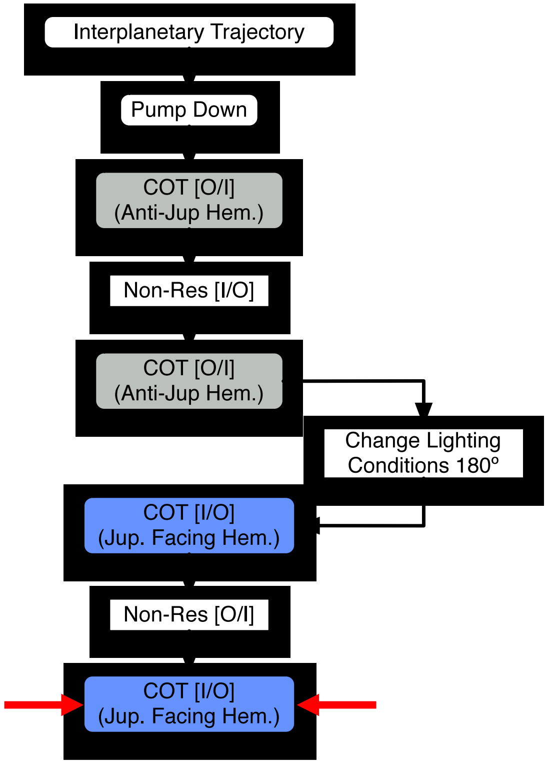
*r_p ! 400 km



IPR Coverage

Panels:

12 of 14



Interplanetary Trajectory

Pump Down

COT [O/I] (Anti-Jup Hem.)

Non-Res [I/O]

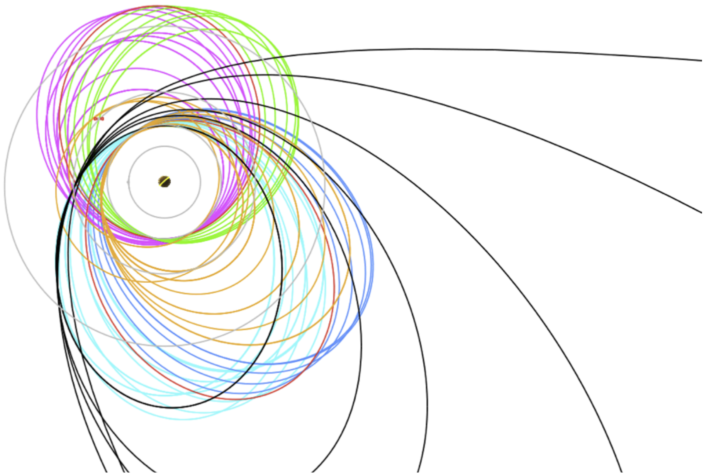
COT [O/I] (Anti-Jup Hem.)

Change Lighting Conditions 180°

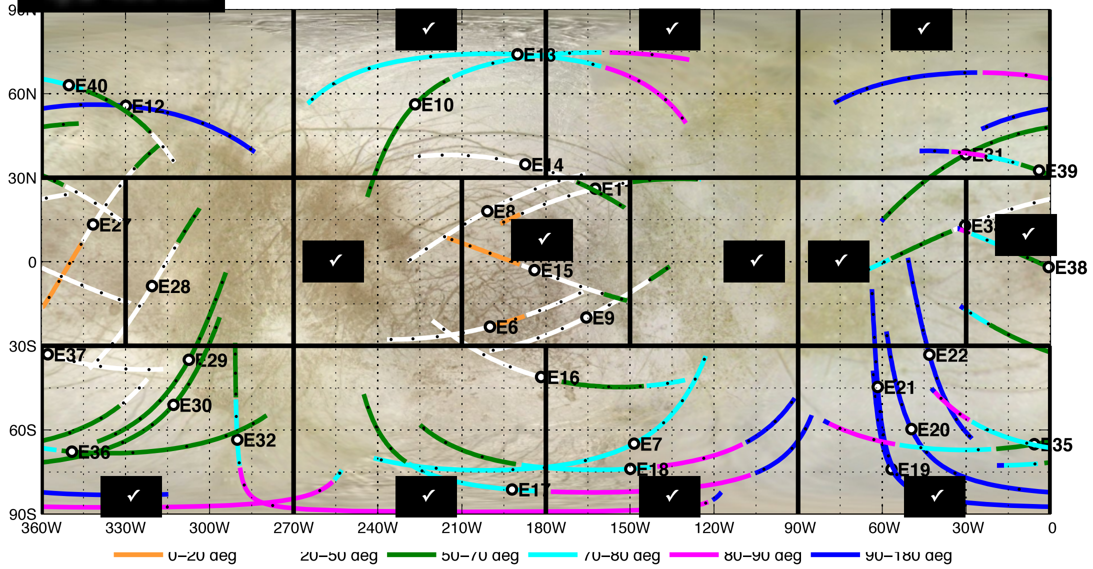
COT [I/O] (Jup. Facing Hem.)

Non-Res [O/I]

COT [I/O] (Jup. Facing Hem.)



*r_p ≤ 400 km



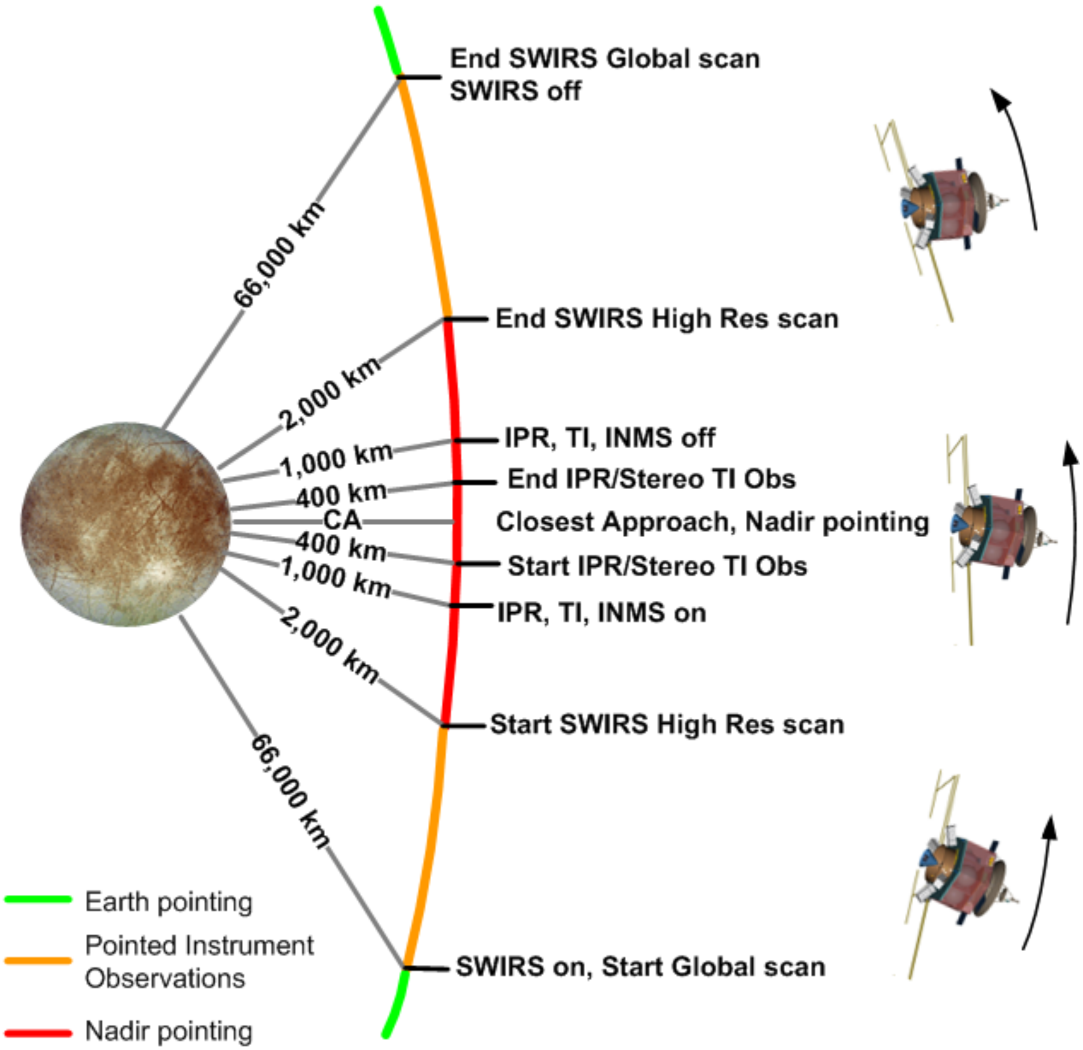
Satellite Flybys

	Phase	Flyby	In/Out	Altitude [km]	V-Infinity [km/s]	Inc [deg]	Peri (RJ)	Apo (RJ)	m	n	Period (days)	tof (days)	
Anti-Jupiter Hemisphere Coverage	Pump Down	Ganymede0	I	500	7.382	5.14	11.74	264.88	N	R	202.75	202.08	11 months
		Ganymede1	O	100	6.341	4.6	11.99	97.73	7	1	50.09	50.09	
		Ganymede2	O	100	6.415	1.54	11.16	64.37	4	1	28.61	28.61	
		Ganymede3	O	3496.3	6.366	1.37	10.63	51.74	3	1	21.46	21.46	
		Ganymede4	O	172.9	6.396	0.45	9.33	36.18	N	R	13.37	25.88	
	COT-1	Europa5	O	724.3	3.841	2.32	9.27	34.04	7	2	12.43	24.88	4.7 months
		Europa6	O	100	3.92	3.33	9.42	37.93	4	1	14.20	14.19	
		Europa7	O	100	3.916	5.98	9.45	33.89	7	2	12.43	24.87	
		Europa8	O	100	3.935	5.01	9.5	37.86	4	1	14.20	14.19	
		Europa9	I	100	3.934	6.03	9.48	33.86	7	2	12.43	24.87	
		Europa10	I	**25**	3.916	3.27	9.42	37.92	4	1	14.20	14.19	
		Europa11	I	100	3.929	2.05	9.29	33.94	7	2	12.43	24.86	
	Non-Res	Europa12	I	100	3.898	0.34	9.34	38.12	N	R	14.25	14.43	
	COT-2	Europa13	O	100	3.814	3.11	9.39	37.98	4	1	14.20	14.21	3.2 months
		Europa14	O	100	3.823	4.72	9.42	37.96	4	1	14.20	14.21	
		Europa15	I	100	3.823	4.55	9.37	38	4	1	14.20	14.21	
		Europa16	I	**25**	3.814	2.58	9.31	38.07	4	1	14.20	14.21	
		Europa17	I	**25**	3.8	0.72	9.27	38.09	4	1	14.20	14.19	
		Europa18	I	100	3.817	3.36	9.22	34.12	7	2	12.43	24.85	
	Pump Down, Crank Up	Europa19	I	100	3.849	6.17	9.17	29.92	3	1	10.65	10.64	2.7 months
		Europa20	I	100	3.853	8.73	9.22	25.39	5	2	8.88	17.75	
		Europa21	I	100	3.872	11.09	9.23	20.6	2	1	7.10	7.10	
		Europa22	I	100	3.877	12.87	9.28	17.15	5	3	5.92	17.74	
		Europa23	I	805.1	3.889	13.87	8.27	14.03	N	R	5.22	28.71	
	Pi-tran	Ganymede24	O	1346.7	2.784	14.86	13.91	13.99	pi-tran		7.15	3.53	0.6 months
		Ganymede25	O	123.1	2.79	11.93	12.64	17.3	1	1	7.11	7.11	
		Ganymede26	O	1584.7	2.754	10.2	9.06	15.75	N	R	5.39	8.51	
Jupiter-facing Hem. Coverage	COT3 Pump Up, Crank Down	Europa27 (e)	I	100	3.506	10.81	9.35	17.07	5	3	5.92	17.75	3.7 months
		Europa28 (e)	I	100	3.501	9.63	9.43	20.41	2	1	7.10	7.10	
		Europa29 (e)	I	100	3.497	7.26	9.45	25.18	5	2	8.88	17.75	
		Europa30 (e)	I	100	3.496	4.52	9.42	29.67	3	1	10.65	10.62	
		Europa31	O	100	3.476	6.56	9.39	25.25	5	2	8.88	17.77	
		Europa32	O	100	3.499	3.51	9.38	29.71	3	1	10.65	10.62	
		Europa33	O	**25**	3.444	4.4	9.28	25.36	5	2	8.88	17.77	
		Europa34	O	601.8	3.474	2.52	9.34	29.78	3	1	10.65	10.64	
	Non-Res	Europa35	O	100	3.489	0.47	9.32	29.66	N	R	10.58	10.35	
	COT-4	Europa36	I	100	3.475	3.47	9.31	29.79	3	1	10.65	10.65	2.4 months
		Europa37	I	100	3.463	5.2	9.37	29.74	3	1	10.65	10.63	
		Europa38	I	100	3.485	5.26	9.36	29.75	3	1	10.65	10.66	
		Europa39	O	100	3.488	3.52	9.33	29.76	3	1	10.65	10.63	
		Europa40	O	**25**	3.416	0.43	9.29	29.77	3	1	10.65	10.58	
		Europa41	O	2661.5	3.306	0.19	9.12	28.08	N	R	9.89	18.58	
	Impact	Ganymede42	I	100	5.766	-	-	-	-	-	-	-	

e: Flyby in eclipse

Representative Europa Science Encounter

Altitude Range (km)	Time at Altitude (minutes)	Instrument On Time (minutes)			
		IPR	TI	SWIRS	INMS
66,000 to 2,000	265			265	
2,000 to 1,000	5			5	
1,000 to 400	4	4	4	4	4
400 to CA	4	4	4	4	4
CA to 400	4	4	4	4	4
400 to 1,000	4	4	4	4	4
1,000 to 2,000	5			5	
2,000 to 66,000	265			265	
Total Minutes	554	15	15	554	15



End SWIRS Global scan
SWIRS off

End SWIRS High Res scan

IPR, TI, INMS off

End IPR/Stereo TI Obs

Closest Approach, Nadir pointing

Start IPR/Stereo TI Obs

IPR, TI, INMS on

Start SWIRS High Res scan

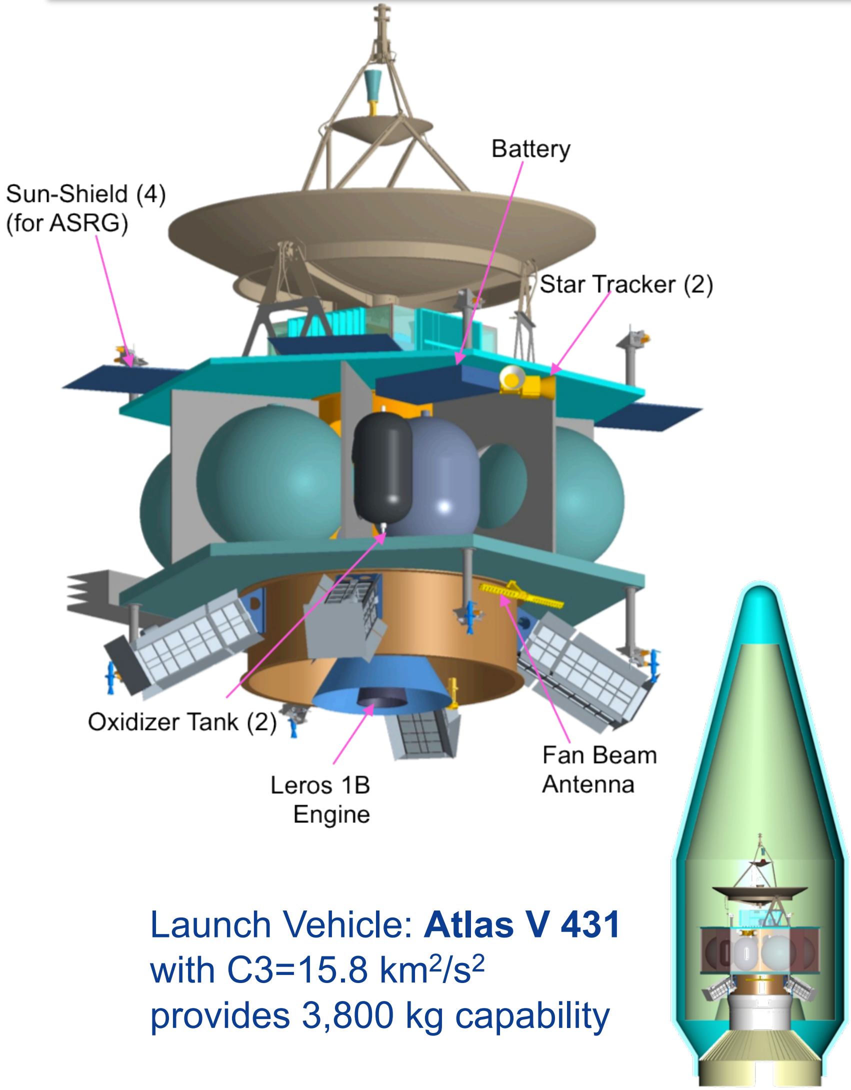
SWIRS on, Start Global scan

🟩 Earth pointing

🟧 Pointed Instrument Observations

🟥 Nadir pointing

Flyby Spacecraft Configuration



Launch Vehicle: **Atlas V 431** with C3=15.8 km^2/s^2 provides 3,800 kg capability

Power

- 4 ASRGs (including margin)
- Battery provides peak load capacity for transients

Propulsion

- Dual mode 1089 m/s Biprop and 620 m/s Monoprop system

G&C

- Spin-stabilized during cruise (supports hibernation)
- Three-axis control during science phase

Avionics

- Two single processor avionics chassis; SpaceWire interfaces
- Internally Redundant Power Distribution Unit
- Two Block Redundant SSRs (128 Gbit Storage)

Software

- Standard capability to support uploadable stored command sequences, autonomous fault protection

Communications

- X-band up and down, Ka-band science return
- LGA, MGA, Fan-beam antennas, 2.4 m HGA

Mechanical

- Panels are HoneyComb with Al core and Al facesheets

Thermal

- Thermos bottle with constant internal heat dissipation in vault

Radiation

- ~100 krad parts behind ~850 mils Al with RDM of 2; boxes individually shielded in 200 mil vault

Flyby Element
Mass, Delta-V, Power Summary

Flight System Mass

Atlas V 431 Capability	3779 kg
Propellant Mass (Max for LV Cap)	1531 kg
Dry Mass CBE	1242 kg
LV and Payload Adapter	79 kg
Total Wet Mass (CBE + Prop)	2852 kg
% Margin to CBE Dry Mass	41%

Flight System Delta-V Budget

Burn Type	Delta-V, m/s		
	Deterministic	Statistical	Total
Launch Injection Cleanup	20		20
Earth Bias DV	50		50
IP Statistical DV Cleanup		50	50
Deep Space Maneuver	150		150
JOI	900		900
Perijove Raise	80		80
Flyby Tour = 44 flybys	200	170	370
Total	1400	220	1620

Power Budget

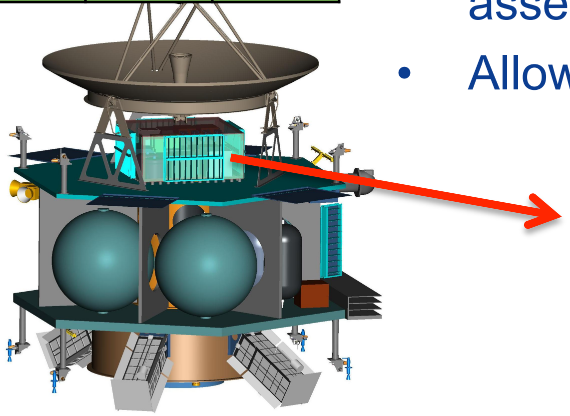
	Launch	Inner Cruise	Safe (Inner Cruise)	Outer Cruise (beacon)	Safe (Outer Cruise)	DSM/ JOI	Orbit Stand-By	3-axis Science	Ka Downlink	TCM
Spacecraft Total	129 W	193 W	246 W	189 W	246 W	353 W	193 W	180 W	293 W	292 W
Payloads Total	0 W	0 W	0 W	0 W	0 W	0 W	0 W	113 W	0 W	0 W
Harness Loss 1%	1.3 W	1.9 W	2.5 W	1.9 W	2.5 W	3.5 W	1.9 W	2.9 W	2.9 W	2.9 W
Flight System Demand	131 W	195 W	249 W	191 W	249 W	357 W	195 W	295 W	296 W	295 W
ASRG Power Available	434 W	413 W	413 W	400 W	400 W	400 W	391 W	391 W	391 W	391 W
Unallocated Available Power	303 W	218 W	164 W	209 W	151 W	43 W	195 W	96 W	95 W	96 W
POWER MARGIN	70%	53%	40%	52%	38%	40%	50%	40%		

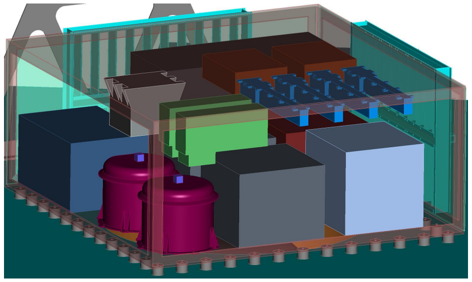
Radiation Mitigation Approach

Environment

Aluminum Thickness (mils)	Total Ionizing Dose (krad Si)			
	Electron	Photon	Proton	Total
100	1960	7.0	46.6	2010
200	893	7.9	10.9	912
400	341	8.9	1.9	352
600	178	9.5	0.9	188
800	107	9.9	0.5	117
1000	70.5	10.0	0.3	80.8
1200	48.9	10.0	0.3	59.1
1400	35.2	9.8	0.2	45.2
1600	25.9	9.6	0.2	35.7

- Followed a Juno-like vault approach
  - House most electronic assemblies within a vault to take advantage of neighbor shielding
  - Vault chassis provides 200 mils Al shielding
- Used NOVICE and FASTRAD along with CAD models of the spacecraft to determine dose levels within each electronic assembly
  - FASTRAD uses ray trace methodology
  - NOVICE performs radiation transport physics
  - Both methods yield similar results
- Adjusted the thickness for each electronic assembly housing for a 50 krad dose
- Allows use of 100 krad parts with RDF = 2





Planetary Protection

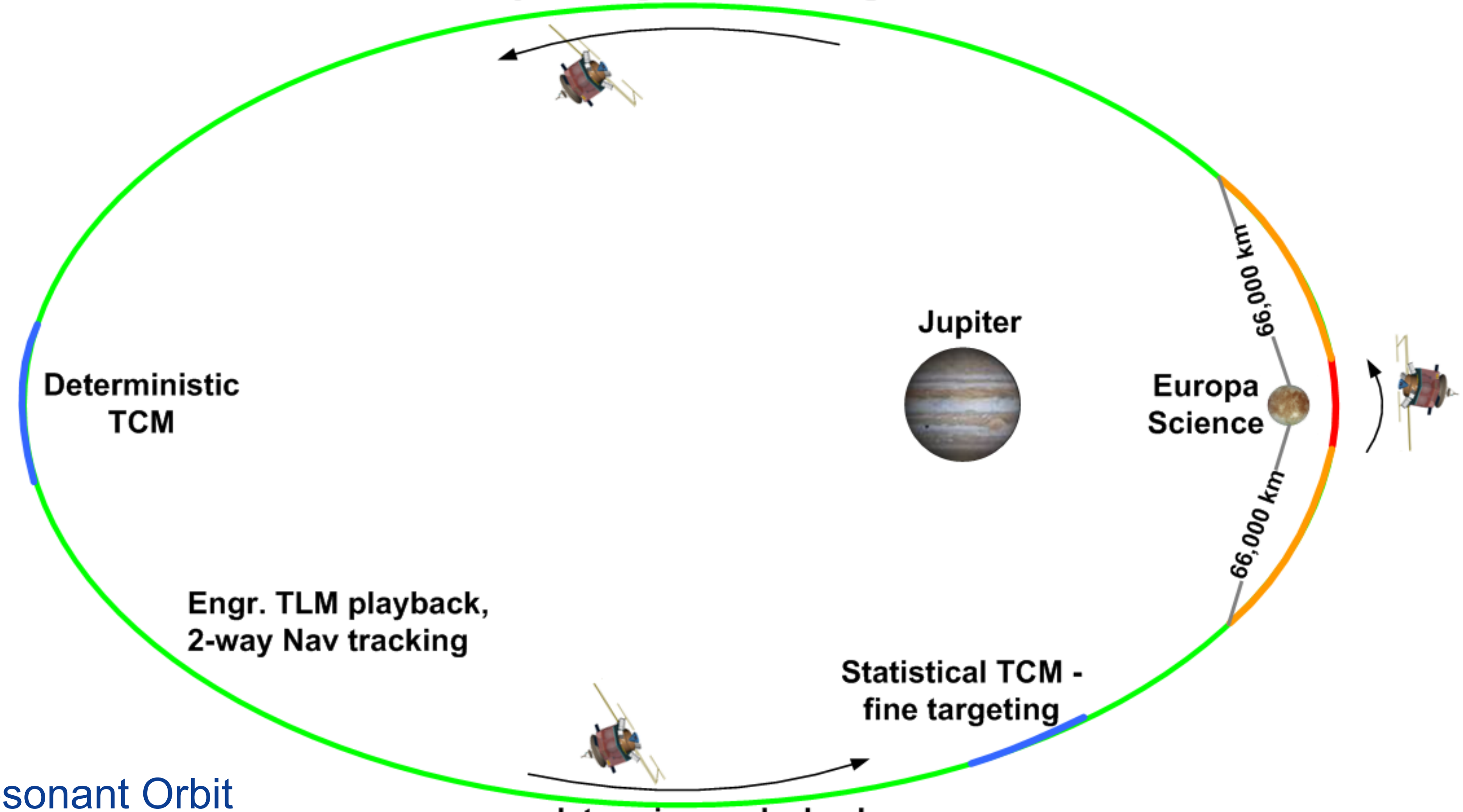
Article IX of the Outer Space Treaty of 1967 requires the prevention of “harmful contamination” of extraterrestrial solar system bodies. NASA’s compliance with this treaty is documented in NPR 8020.12C. Europa missions, in particular, are covered in section A. 3.1 stating:

> *“Requirements for Europa flyby, orbiter, or lander missions, including microbial reduction, shall be applied in order to reduce the probability of inadvertent contamination of an Europan ocean to less than 1x10^{-4} per mission.”*

- Flyby strategy is to impact Ganymede at the end of mission, reducing the element’s PP requirements
  - End of mission propellant has been budgeted
- Probability of contamination of a protected body is a function of:
  - Total bioburden at launch (DHMR)
  - Sterilization during cruise (yes)
  - Sterilization in the Jovian System (significant)
  - Sterilization during impact event (yes)
  - Probability of impact with a protected body (*calculate probability, minimized by trajectory design*)
  - Probability of survival and proliferation (minimal)

Would follow the Juno process, but to be conservative, have included system level sterilization in cost estimate

Science Operations Concept



science playback, 2-way Nav tracking, battery recharge, commanding

Deterministic TCM

Jupiter

Europa Science

Engr. TLM playback, 2-way Nav tracking

Statistical TCM - fine targeting

complete science playback, 2-way Nav tracking, commanding

Resonant Orbit

Science Data Return

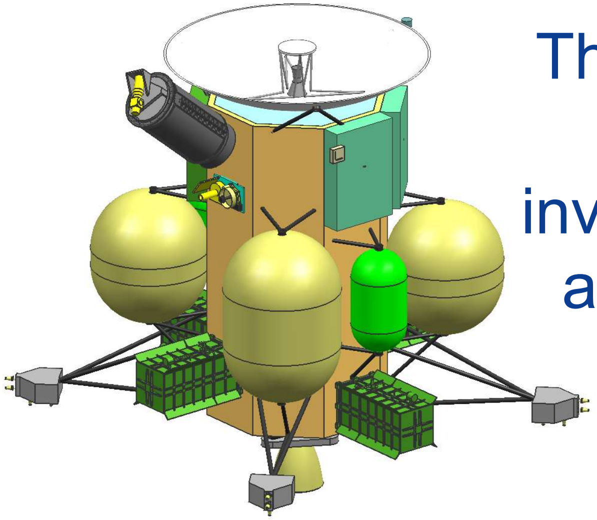
- 30 Gbits/flyby, two 64 Gbit block redundant SSRs provide up to 128 Gbits of storage
- Downlink Rate: ~79 Kbps (average), 57 Kbps (worst case)
- Time to downlink 30 Gbits @ 57 Kbps = 146 hrs (worst case)
- Time allotted to Science Playback = ~242 hrs (assume 10 hours for flyby, 2 hrs for 2 maneuvers)
- CCSDS File Delivery Protocol (CFDP) will be used to ensure timely and efficient data playback, and to ensure complete science return between encounters

Data Downlink Budget

	IPR	TI	SWIRS	INMS	Total/Flyby
Raw Data Rate (Kbps)	28,000	10,258	116	2	
On-time per flyby (Mins)	15	15	554	15	
Compression Factor	1	3	3	1	
Effective Output Rate (Kbps)	28,000	3,419	47	2	
Average Data Per Flyby (Gbit)	**25**	**3**	**2**	**0.002**	**30 Gbits**
Worst Case Downlink Rate (Kbps)					57 Kbps
Downlink Time Required (Hrs)					145 Hrs
Downlink Time Available (Hrs) (worst case)					187 Hrs
Downlink Margin					**22%**

Flyby Concept Summary

- Spacecraft concept specifically designed as a flyby element, utilizing proven approaches from Juno, New Horizons and other outer planets missions
- Significantly reduced mass to fit on mid-sized Atlas-V launch vehicle
- Significantly reduced amount of ^{238}Pu
- Simple technical system and mission implementation
- Simplified development and operations concepts
- Radiation challenges addressed through nested shielding to maximize use of existing, qualified components
- Planetary protection concerns addressed by sterilization, with the potential option to simplify mitigation
- Cost estimated at ~$1.5B (FY15)



The Flyby Element delivers a thorough science investigation of Europa, with a robust design that does not require technology advancements, at an affordable cost.