Appendix C: Additional Details

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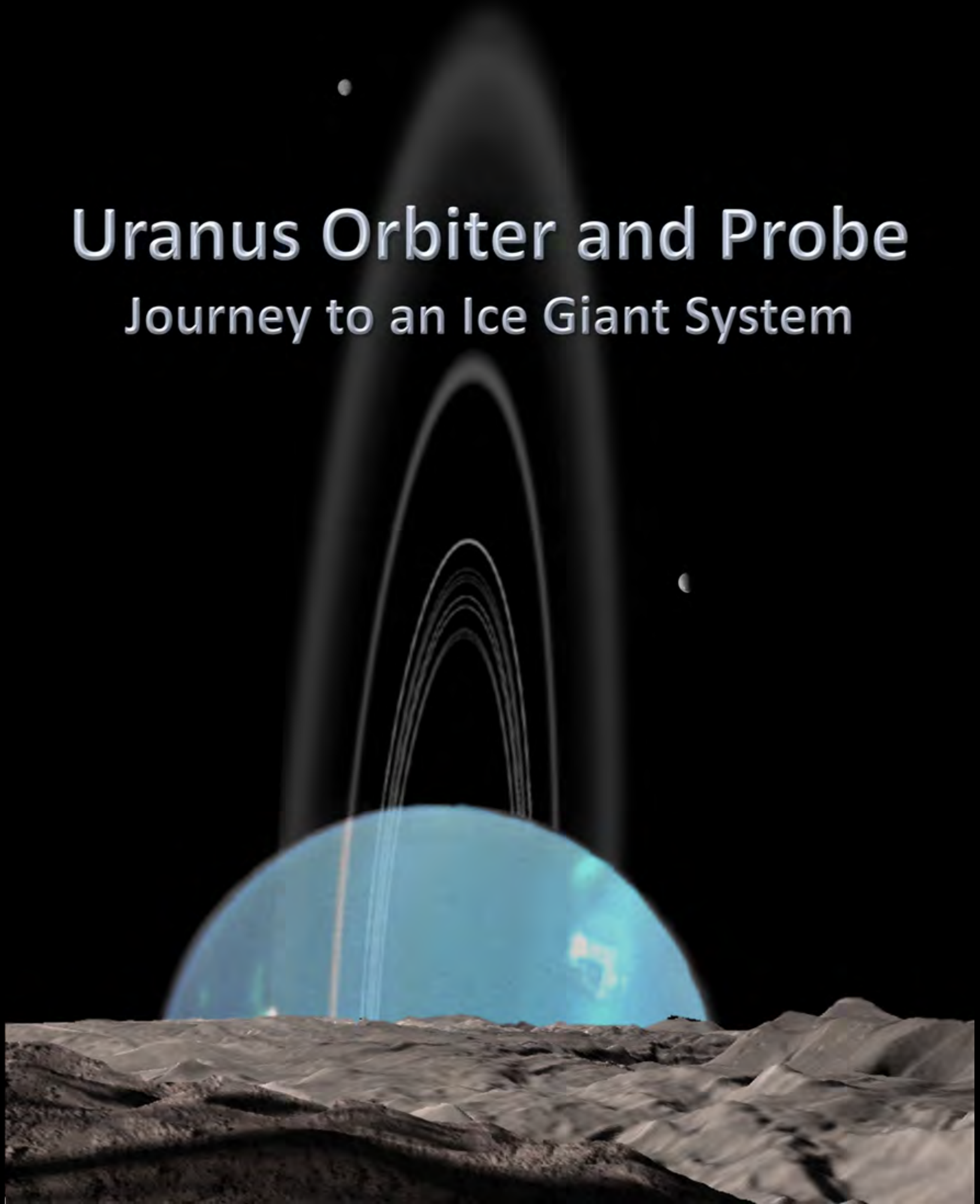
APPLIED PHYSICS LABORATORY

Uranus Orbiter and Probe 2023-2032 Planetary Mission Concept Study

Content for Appendix C: Additional Details

Uranus Orbiter and Probe

Journey to an Ice Giant System



Uranus Orbiter and Probe is a Flagship-class mission to explore all aspects of the Uranian system: the atmosphere, interior, magnetosphere, satellites, and rings

Science Champions:

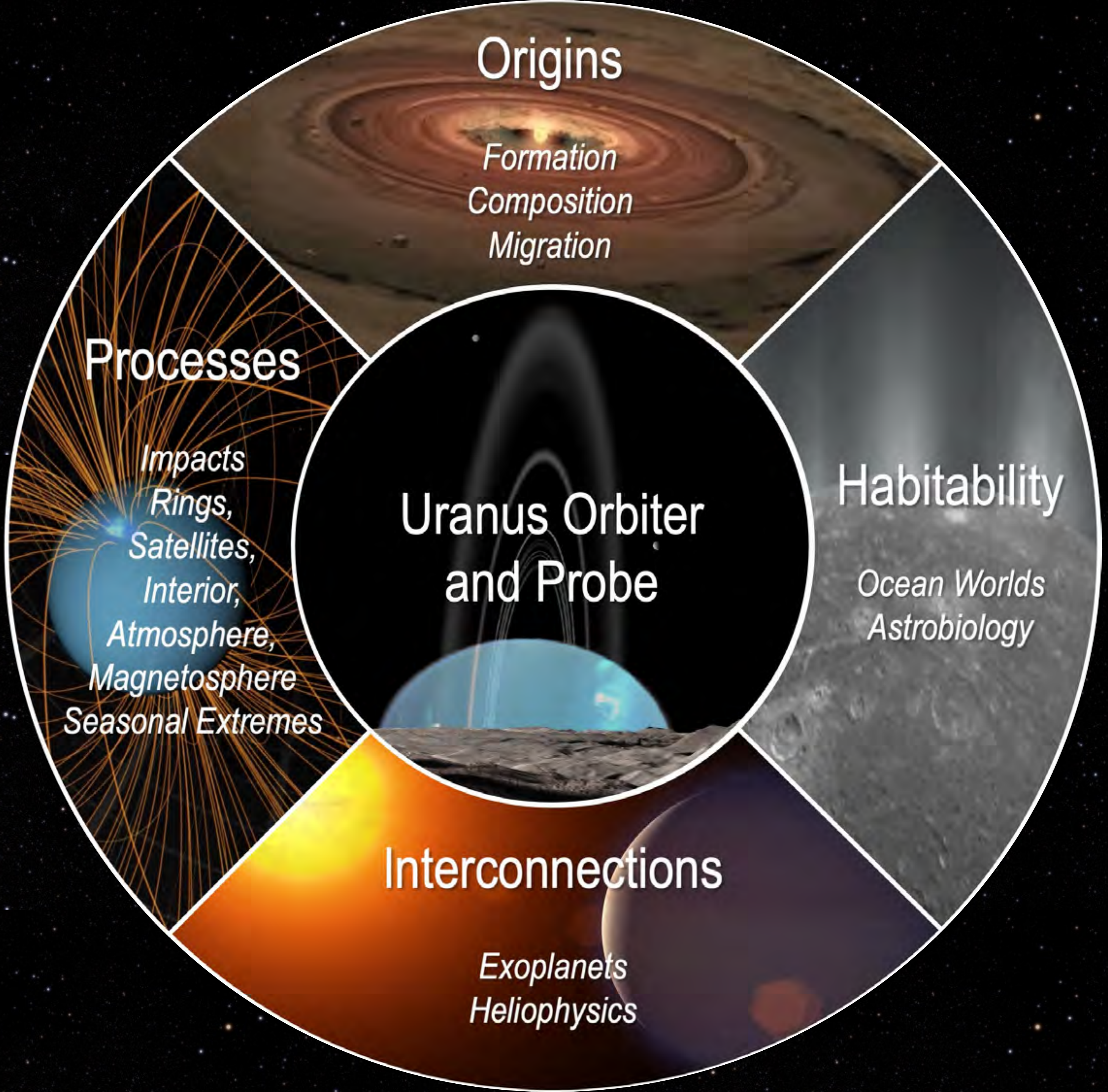
A. Simon (NASA GSFC), F. Nimmo (UCSC)

Study Design Team*:

Study Systems Lead: R. Anderson (APL)
Flight Dynamics: M. Ozimek (APL), J. Arrieta (Nabla Zero)
Systems: D. Chattopadhyay (APL)
Mission Operations: A. Calloway (APL)
Payload Performance: H. Nair (APL)
Mechanical: E. Schulze (APL)
Propulsion: J. John (APL)
Probe Entry/Descent: H. Hwang (NASA Ames), S. Dutta (NASA Langley)
Schedule: F. Kahler (APL)
Cost: K. Kha (APL)

* Full list in backup

The Uranus Orbiter and Probe mission enables broad multi- and cross-disciplinary science across nearly all Decadal thematic questions.



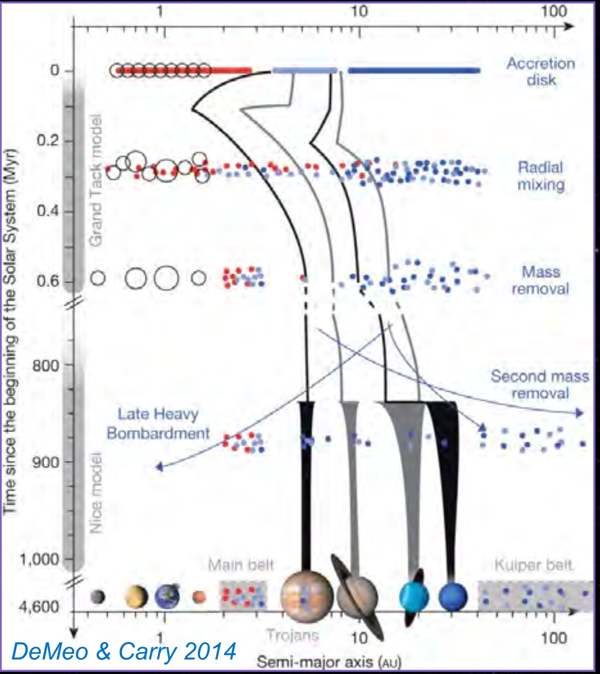
Thematic Question	Mission Element
Q1	UO+P
Q2	UO+P
Q3	UO+P
Q4	UO+P
Q5	UO
Q6	UO
Q7	UO+P
Q8	UO
Q9	--
Q10	UO
Q11	UO
Q12	UO+P

Overarching Science Goals (and example questions)

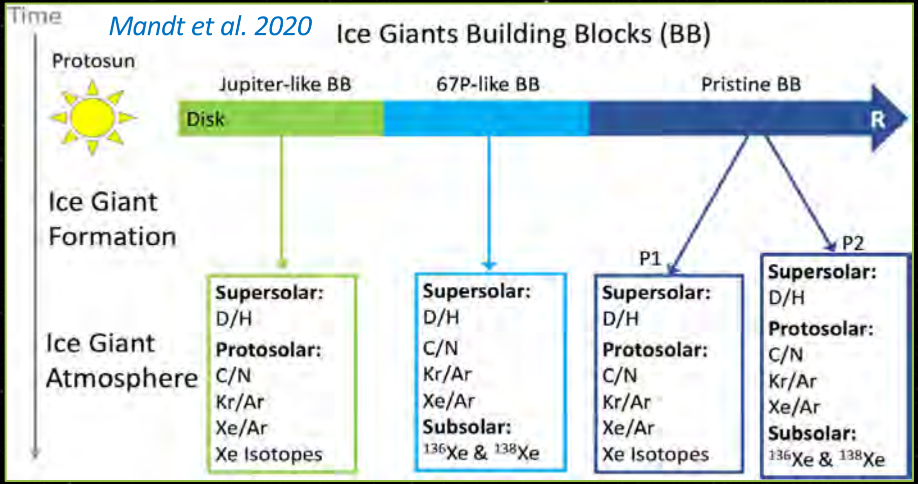
- Understanding Solar System Origins: Addresses Thematic Q1-Q3, Q12
  - When and where did Uranus form in the protosolar nebula?
  - Did Uranus and Neptune migrate or swap positions?
  - Did a catastrophic giant impact tilt Uranus, rearrange its interior, and form satellites?
- Studying Processes: Addresses Thematic Q4-Q8, Q12
  - What mechanisms are transporting heat / energy in the planet and satellites today?
  - How do all the components in the Uranian system interact with each other?
  - What external factors are altering the planet, satellites, and ring compositions?
  - What interior structure produces Uranus's complex magnetosphere?
- Exploring Habitability: Addresses Thematic Q10, Q11
  - Did any of Uranus's moons have oceans in the past?
  - Are any of the moons presently ocean worlds?
- Informing Interconnections:
  - How do ice giant-mass planets form and evolve in exoplanetary systems?
  - How does solar wind couple to a magnetosphere with a rapidly changing orientation?

Science Traceability Matrix available in back-up

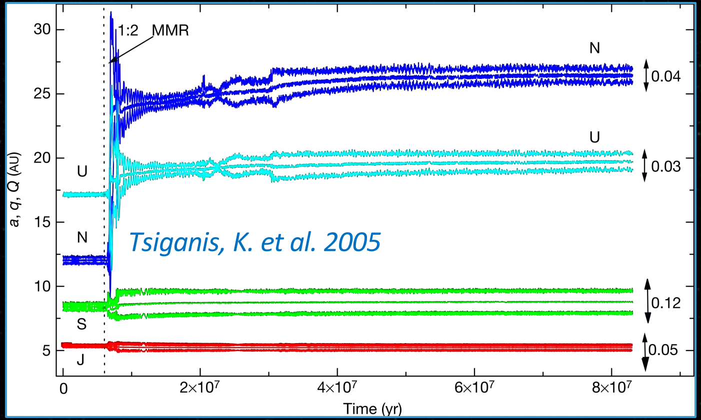
Origins

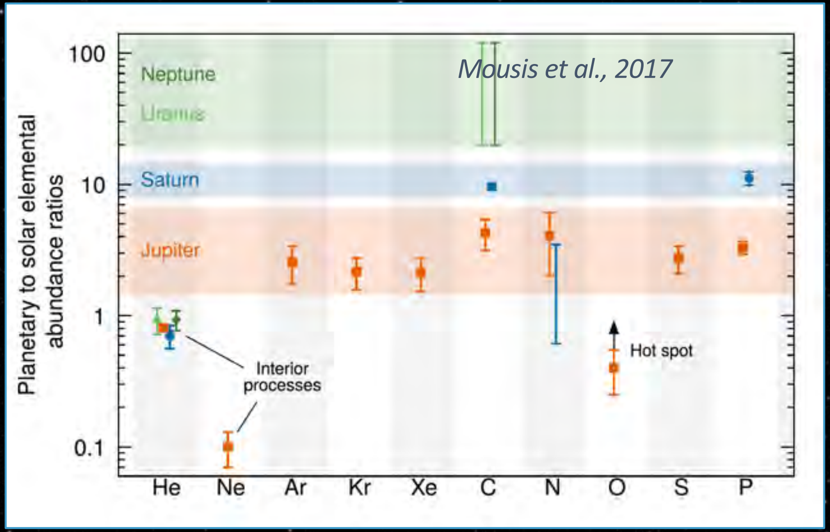


Uranus & Neptune swap positions in ~50% of Grand Tack simulations; isotope and noble gas measurements can tell us when & where they formed



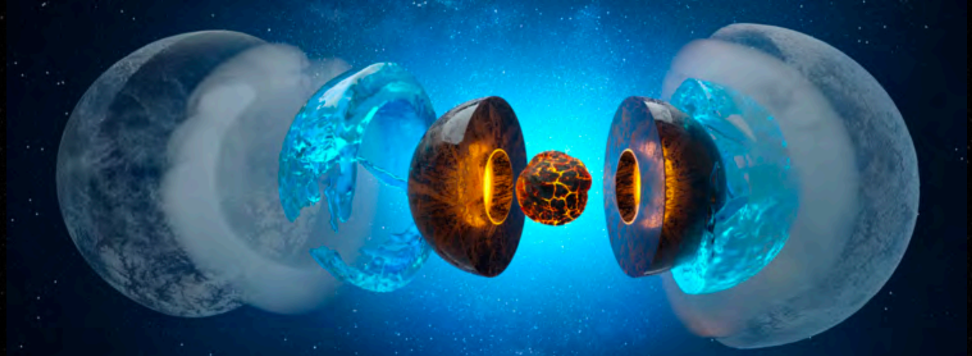
Uranus composition measurements help constrain protosolar nebula and accretion models



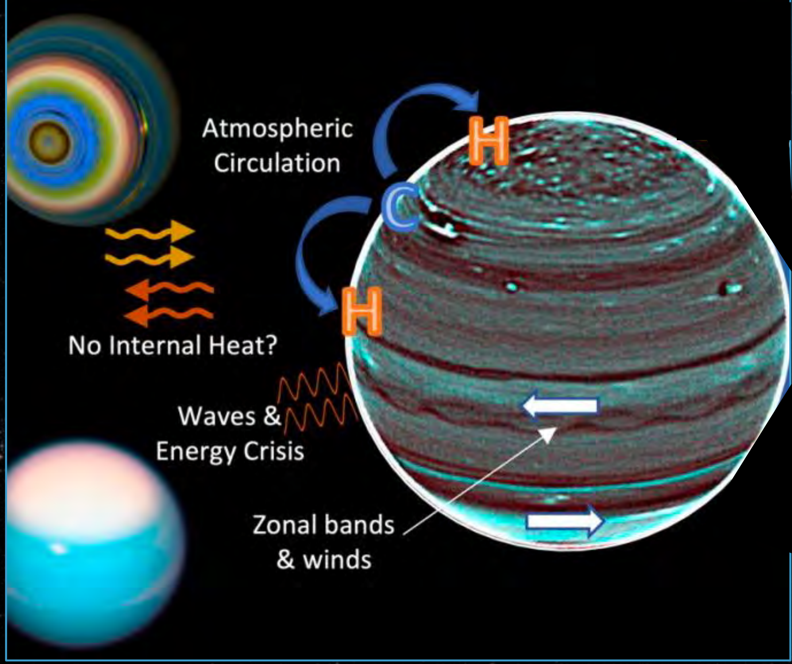


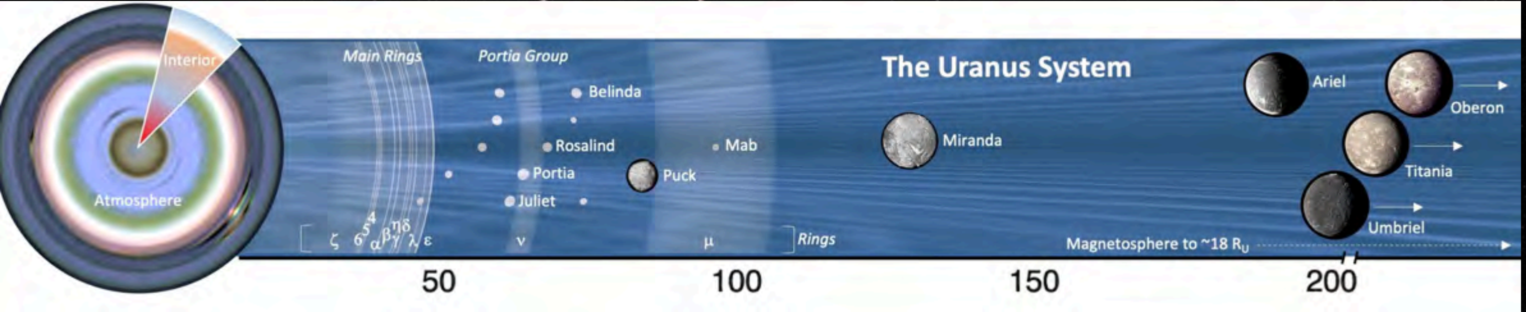
In situ composition and gravity measurements also answer questions about Uranus's formation and evolution, the role of giant impacts in its obliquity, interior structure, and internal heat

Processes

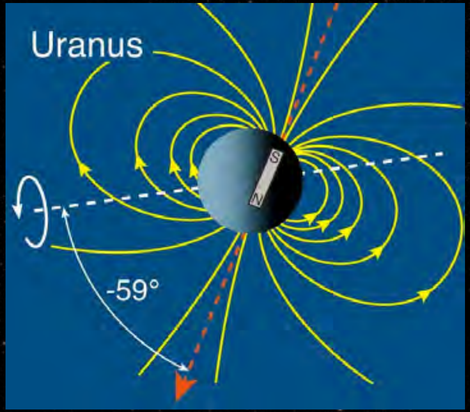


What is Uranus's interior structure?





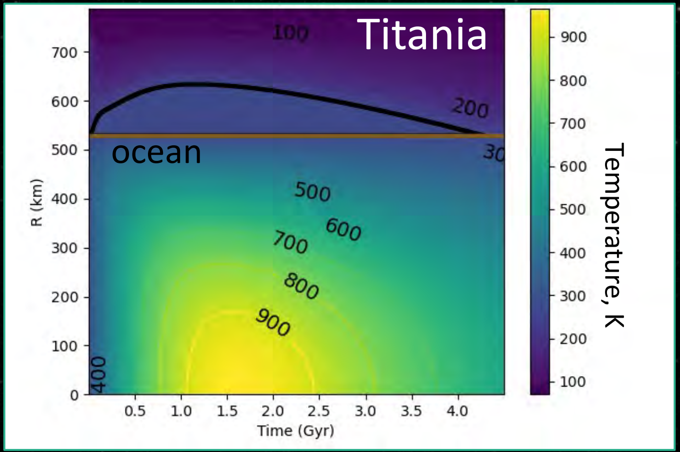
Regular satellite and ring system, young surfaces

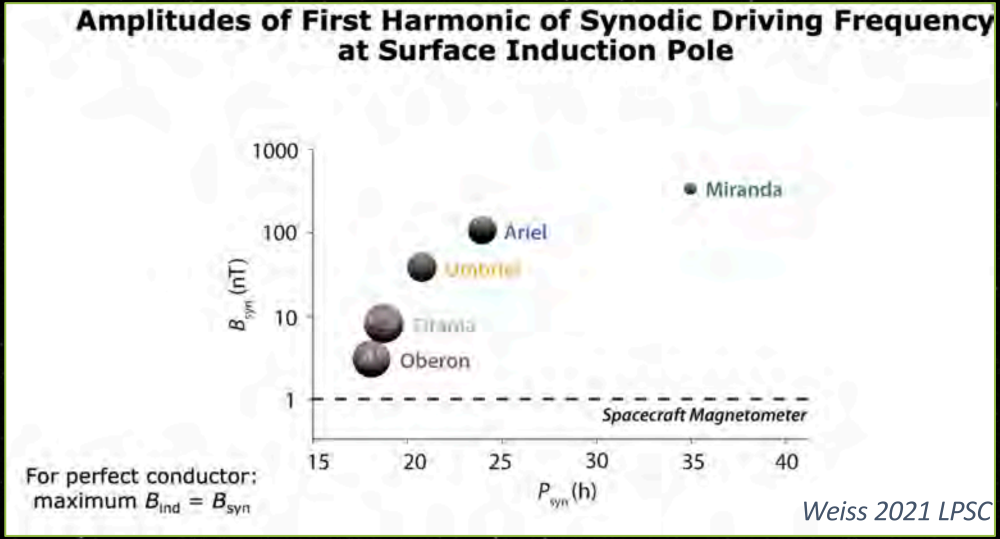


How/where is the dynamo generated?
Magnetosphere is offset and tilted, interacts with rings and satellites, atmosphere (aurorae), solar wind

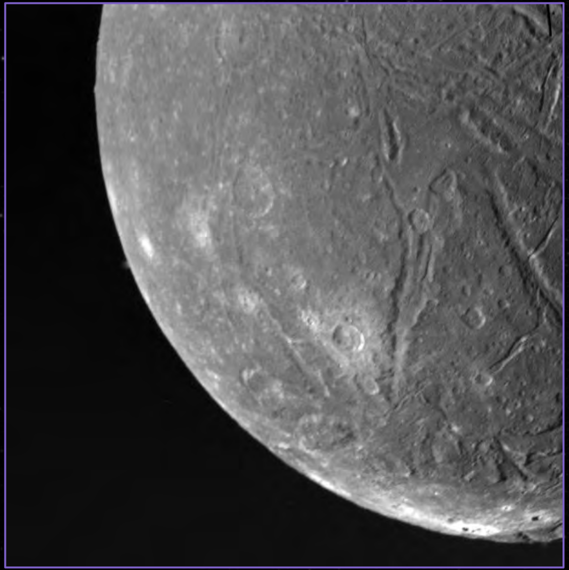
Extreme seasons, dynamic weather

Habitability



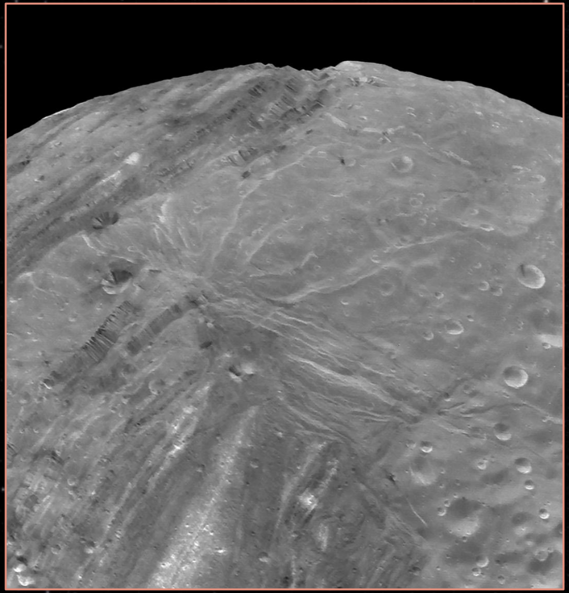


Are there active plumes or substantial internal heat and oceans now?



Spectral data will investigate surface composition including organics

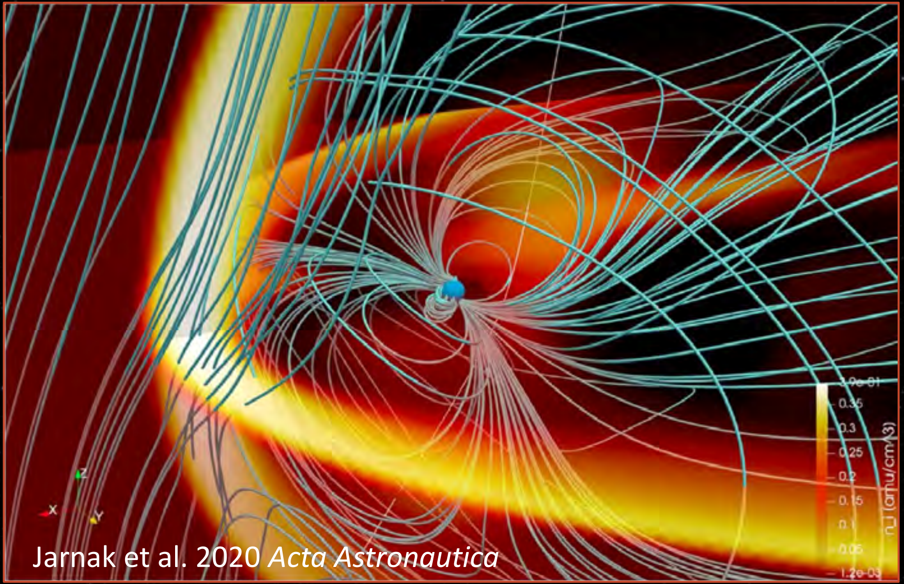
Possible subsurface oceans on several moons, plus evidence of past resurfacing.



Implications of habitable worlds so far from the sun?

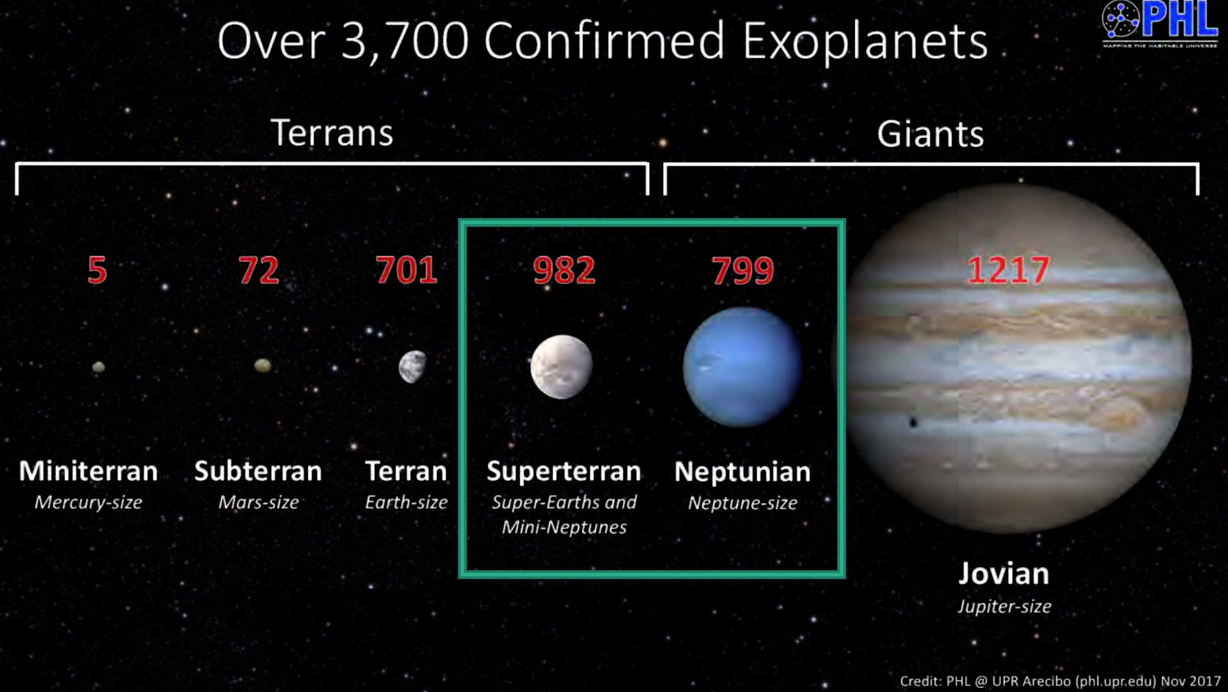
Interconnections

"… the Solar Wind-Magnetosphere Interactions panel's highest priority in planetary magnetospheres is a mission to orbit Uranus," 2013 Solar and Space Physics Decadal

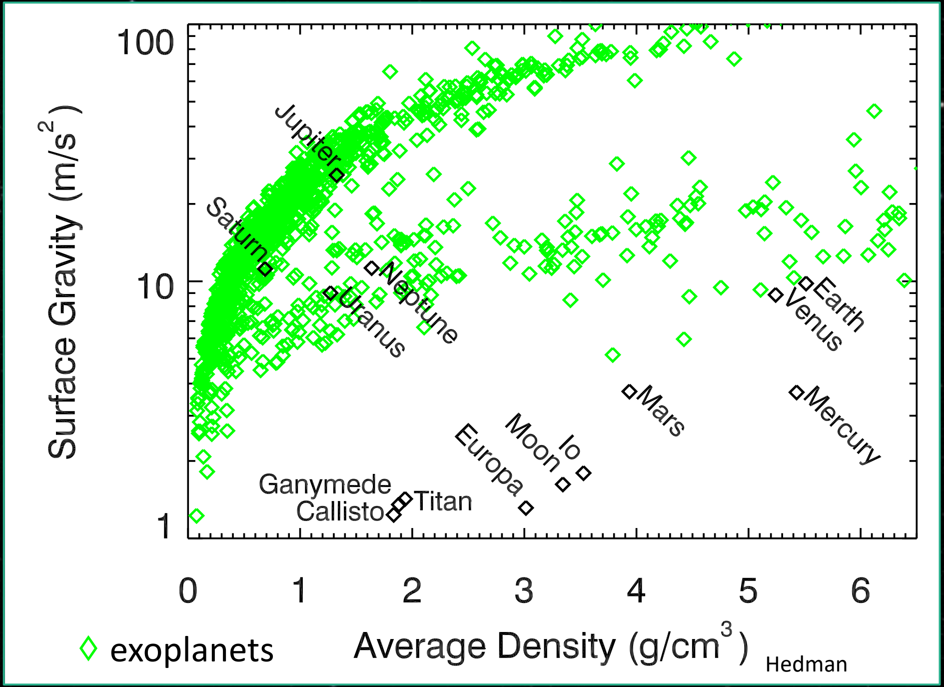


Jarnak et al. 2020 *Acta Astronautica*

Complex, tilted magnetosphere interacts with the solar wind in intriguing ways



Uranus and Neptune are in a different class than Jupiter & Saturn, and relevant to a different set of exoplanets (based on mass and radius)



Data from exoplanetarchive, filtered to remove high uncertainty data points

Mission Synergies

- Only mission to Uranus was Voyager 2 flyby in 1986
  - Synergy with Cassini, Galileo, etc. for comparative planetology
- Strong international interest
  - Many reports, ESA/NASA studies, workshops since 2013
- Strong NASA cross-divisional interest
  - Recommended in both the Planetary and Solar and Space Physics 2013 Decadal Reports

Mission Design Summary

- UOP is feasible and flexible
  - No new technology required
  - Lots of launch window and tour options
- Notional science payload:
  - Orbiter: Magnetometer, Narrow Angle Camera, Wide Angle Camera, Thermal IR Camera, Visible-Near IR Imaging Spectrometer, Comprehensive Fields and Particle Suite, Radio Science with USO
  - Probe: Atmospheric Structure, Mass Spectrometer, USO, Ortho-para hydrogen Sensor
- Flight time: 11+ years, depending on trajectory chosen
  - Falcon 9 Heavy Expendable
  - Delivers ~4200 kg into orbit (including probe and margins)
    - Stacked dry mass = 2756 kg (MPV), wet mass = 7235 kg
    - Leaves ~1100-kg margin on LV
  - Cruise trajectory to orbit insertion to probe release and orbital tour closes
    - First end-to-end trajectory design
- Cost ~$2.8B FY25, $2.6B without LV

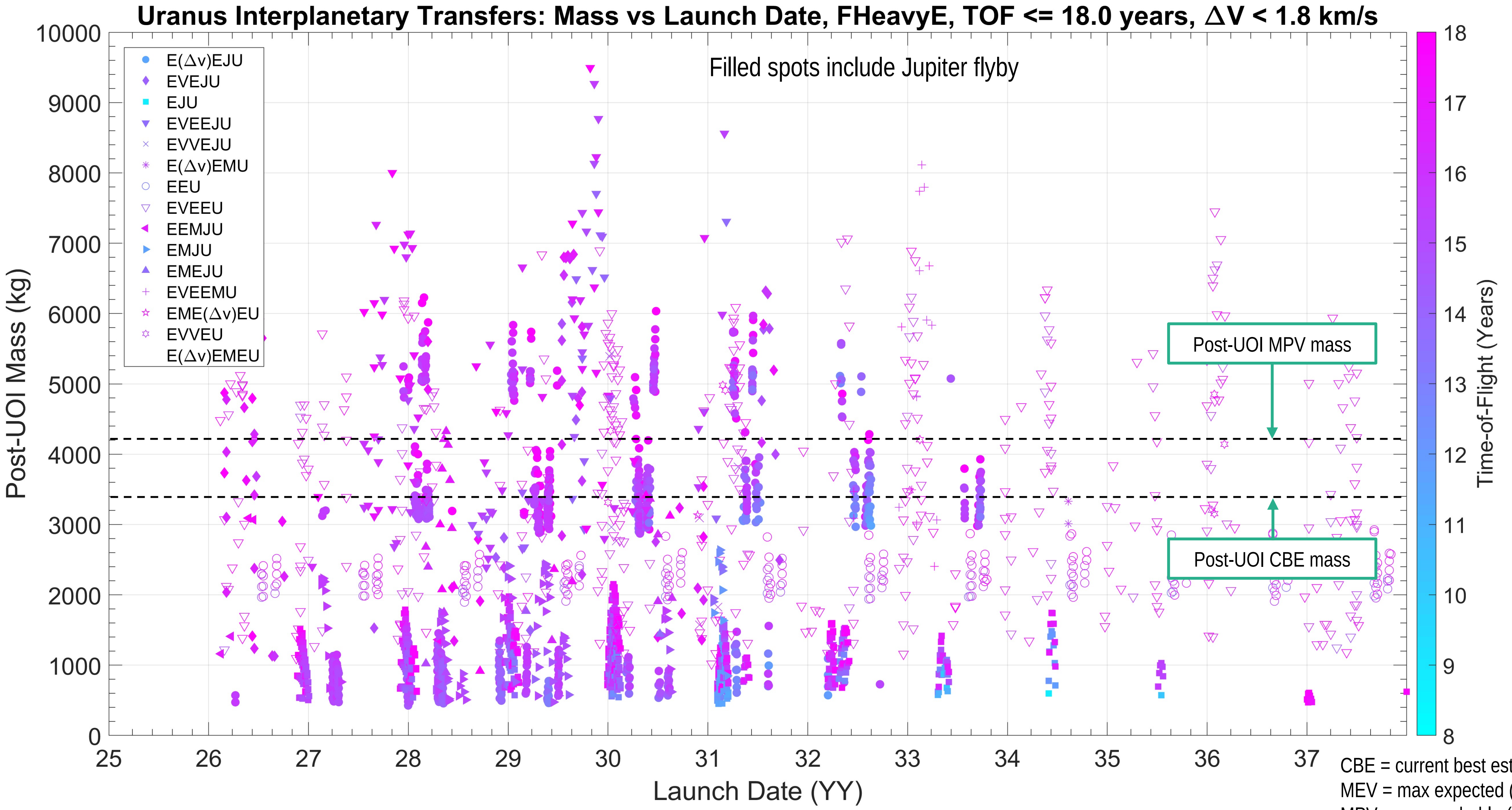
Trajectories and Launch Windows

- Optimal launch dates include a Jupiter gravity assist
  - Most cost-efficient approach, but THIS IS NOT A SHOWSTOPPER.
  - Have identified good opportunities with Venus flybys and/or SEP
  - Lower mass/margins also open up trade space

- Final mission formulation in Phase A will need to optimize based on overall budget profile and launch date.

Launch Date	C3 (km2/s2)	Path	DSM (km/s)	UOI (km/s)	PLΔV (km/s)	Post-UOI Mass (kg)	TOF (yrs)
6/13/2031	27.1	E(DV)EJU	0.773	1.011	1.783	4919	13.4
6/15/2031	27	E(DV)EJU	0.717	1.251	1.968	4643.5	12.7
4/29/2032	28.8	E(DV)EJU	0.602	0.956	1.558	5111.5	12.8

Nominal Trajectories: many options over the decade



CBE = current best estimate
MEV = max expected (CBE + ~15%)
MPV = max probable (MEV + 30%)

Other Example Chemical Trajectory Solutions

	Launch Date	C3 (km^2/s^2)	Path	DSM (km/s)	UOI (km/s)	PL∆V (km/s)	Post-UOI Mass (kg)	TOF (yrs)
	9/30/2029	13.7	EVEEJU	0.00	1.221	1.221	7865.2	14.5
	10/31/2029	11.3	EVEEJU	0.00	1.901	1.901	6665.4	13.1
	3/7/2031	17.5	EVEEJU	0.05	1.722	1.771	6068.7	12.5
	4/3/2031	28.6	E(∆V)EJU	0.65	1.033	1.68	4934.7	13.5
ACE Run baseline	6/13/2031	27.1	E(∆V)EJU	0.77	1.011	1.783	4919	13.4
	6/15/2031	27	E(∆V)EJU	0.72	1.251	1.968	4643.5	12.7
	7/18/2031	19.8	EVEJU	1.07	1.763	2.834	4089.3	11.6
	8/1/2031	18	EVEJU	1.05	1.374	2.426	4855	12.3
	8/9/2031	20.2	EVEJU	1.06	1.504	2.561	4433.5	12
ACE Run backup	4/29/2032	28.8	E(∆V)EJU	0.60	0.956	1.558	5111.5	12.8
	5/3/2032	29.2	E(∆V)EJU	0.76	1.147	1.904	4527.2	12.2
	8/15/2032	49.5	E(∆V)EJU	0.42	1.302	1.726	3056.3	11.8
Example windows w/o Jupiter flyby	1/8/2033	23.6	EVEEU	0.42	1.012	1.434	5933.3	15.3
	5/27/2034	23.1	EVEEU	0.68	0.946	1.629	5626.4	15.2
	2/28/2036	28.2	EVEEU	0.54	0.974	1.519	5240.5	15.3
	1/8/2038	35.5	EVEEU	0.00	1.307	1.307	4812.3	14.2

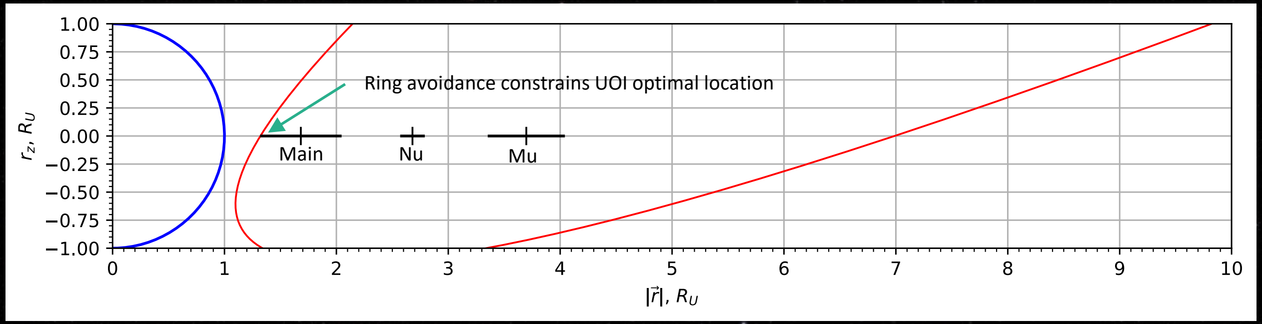
Lighter colors = best solutions

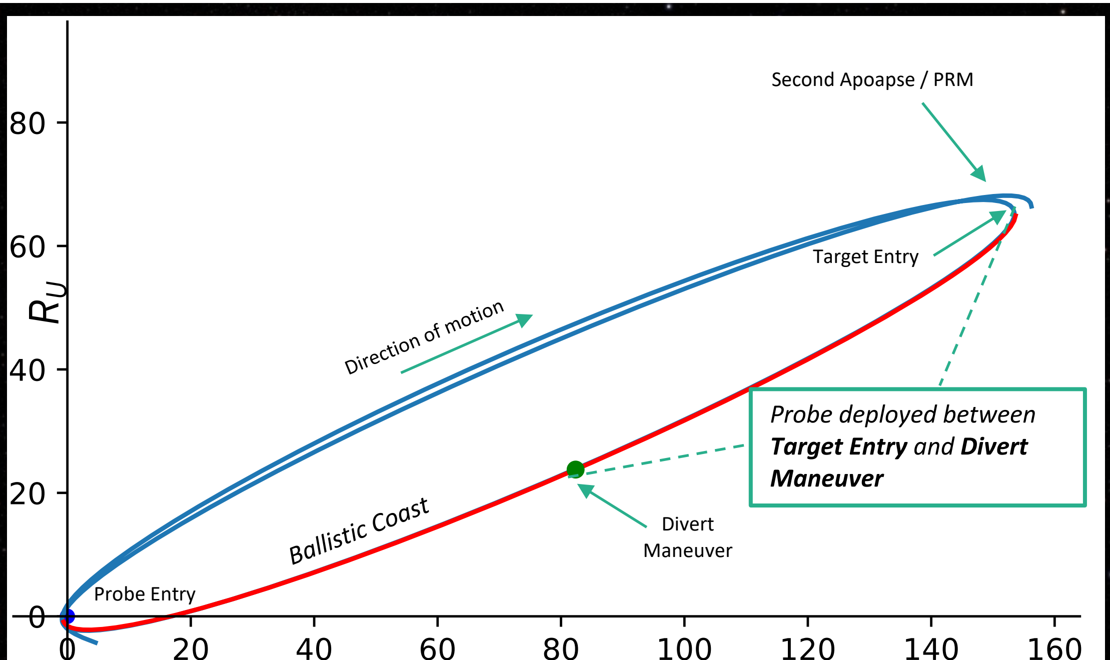
High-level Mission Phases for Trajectory Design

Cruise Phase	*Science Phase*	
Interplanetary Cruise	Capture/Probe Deploy	Science Focused Tour

20 June 2031 Launch — 5 Dec 2044 UOI — 6 Apr 2045 Probe Entry — 6 July 2045 Tour starts — EOM

Parameter	Value
Earth Departure	20-Jun-2031
Departure C_3	26.81 km^2/s^2
DSM	27-Jun-2032
DSM Δv	659.320 m/s
Earth Flyby	27-Apr-2033
Flyby Altitude	450 km
Jupiter Flyby	21-Dec-2035
Flyby Altitude	369550 km
Uranus Approach	05-Nov-2044
Inbound v_∞	6.267 km/s
TOF	13.462 yr



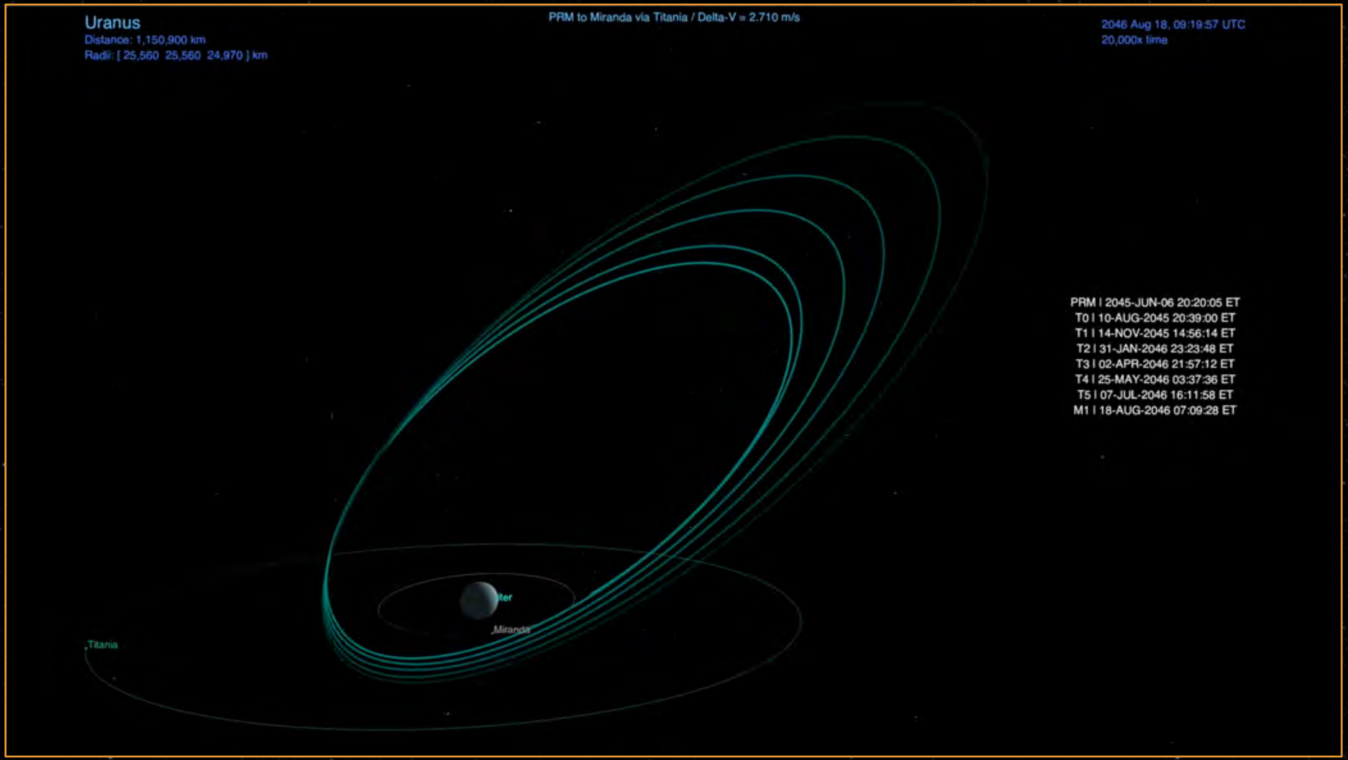


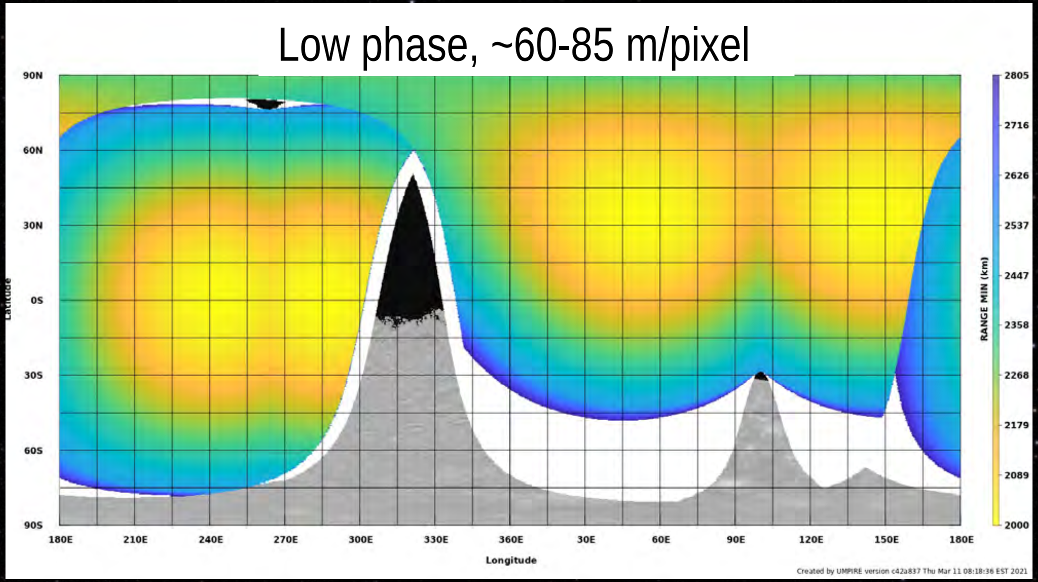
Concept of Operations

- Orbital period during tour ~34 days
  - Start in polar orbit, use Titania to pump down to equatorial
- General data strategy
  - Tour - Ka-band science downlink, one 8-hr pass /day
  - Possible additional passes for critical events and nav purposes
  - Compression assumption – average, assuming 2:1
- Onboard Storage of all science data and housekeeping
  - Some instruments also have their own storage
- Solar conjunction not a problem during any of the critical events
- Considered 4 orbit types, all have sufficient downlink to achieve science goals
  - Uranus/Rings Remote sensing focused
  - F&P and Mag focused
  - Satellite flyby w/ remote sensing focused
  - Multiple satellite flyby focused (equatorial phase)

Tour Science Coverage

- Orbits start polar and are pumped down, using Titania, to equatorial for a satellite tour
- Most science objectives met in the high inclination phase
  - Additional satellites objectives fulfilled in satellite tour phase
  - Satellite flybys ≲ 4 km/s
- Tour has lots of flexibility, this example closes
  - Slight tweaks may be desired for highest spatial resolution rings and small moons imaging





Example Ariel imaging coverage

Cost

WBS		Ph A-D	Ph E-F	Total	Notes
		Uranus Orbiter & Probe Cost Estimate			
		Cost in FY25$K			
WBS		Ph A-D	Ph E-F	Total	Notes
	Phase A	$ 7,628	$ -	$ 7,628	Assumption based on previous studies
1	PM	$ 162,077	$ -	$ 162,077	A-D: Wrap factor based recent NFs and APL missions E-F: Bookkept with WBS 7
2	SE				
3	MA				
4	Science	$ 27,192	$ 223,668	$ 250,860	Average $13.3M per year during Phase E
5	Payload	$ 180,247	$ -	$ 180,247	Hardware estimated via parametric models (NICM, SEER Space)
6	SC	$ 724,234	$ -	$ 724,234	Estimated via parametric models
7	MOps	$ 41,121	$ 299,053	$ 340,174	Ph E: DSN $21.3M, Average Ph E MOps based on APL historical costs
8	LV	$ 236,000	$ -	$ 236,000	Falcon Heavy Expendable ($210M) + $26M NEPA
9	Ground	$ 18,573	$ 19,313	$ 37,886	BOE
10	I&T	$ 114,869	$ -	$ 114,869	Based on APL historical I&T %, includes testbeds
	Reserves	$ 634,157	$ 135,508	$ 769,665	Per Decadal guidelines: 50% A-D, 25% E-F. LV excluded
	Total	$ 2,146,097	$ 677,542	$ 2,823,640	
	Total w/o LV	$ 1,910,097	$ 677,542	$ 2,587,640	

- Cost estimates are reported in Fiscal Year 2025 (FY25) dollars
- The NASA New Start inflation index was used to adjust to FY25 dollars
- Major cost drivers: spacecraft complexity, long mission duration, RTGs (3)

Mission descopes

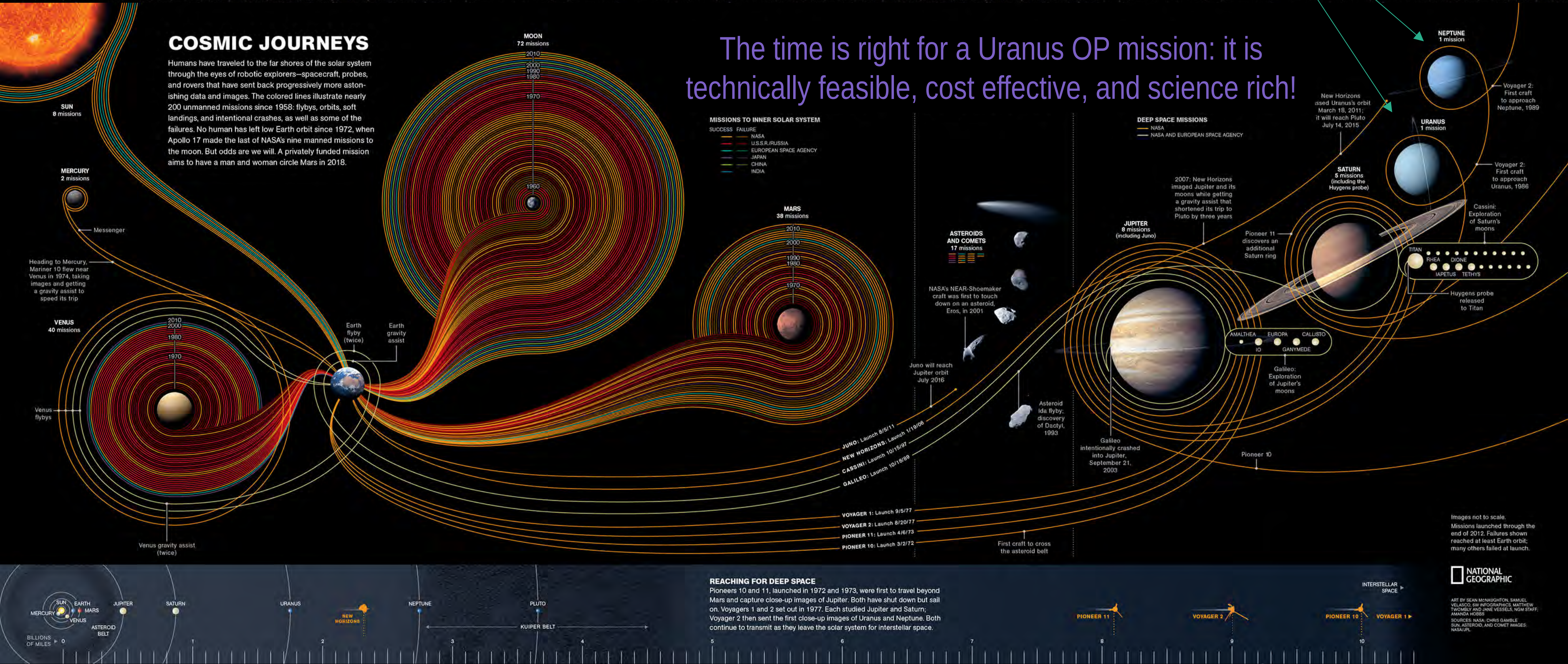
Category	Baseline Requirement	Threshold Requirement
Orbital tour	4 Years	2 Years
	Polar phase, followed by low inclination phase	Polar only
Satellite flybys	3 targeted, 2 non-targeted, flybys of each of the major moons @ <10 km/s	2 targeted,1 non-targeted, flybys of each of the major moons @ <10 km/s
	Targeted and non-targeted flybys of small moons	Non-targeted flybys only
	Polar and low inclination passes	Polar only
Uranus orbits	Close (1.1 R_u) polar & low inclination dayside passes	Polar only
Probe depth range	From 0.1 to 5 bars (10 bars preferred, but not a driver)	From 0.1 to > 1 bar
Payload	Full complement	Remove WAC from orbiter and ortho-para sensor from probe

Special Considerations

- No new technology is required for this mission
- Optimal launch windows are before ~2033 to include a Jupiter gravity assist
  - This is the most cost-efficient approach, but a JGA is NOT required
  - Mission Phase A formulation can update trajectory to include Venus flybys or SEP, as needed for launch window, but there may be cost, mass, or cruise duration penalties
- This concept study assumed the use of the Falcon 9 Heavy Expendable
  - Lower performance launch vehicles may also be feasible, with optimization
- Assumes 3 Next-Gen mod 1 RTGs are available

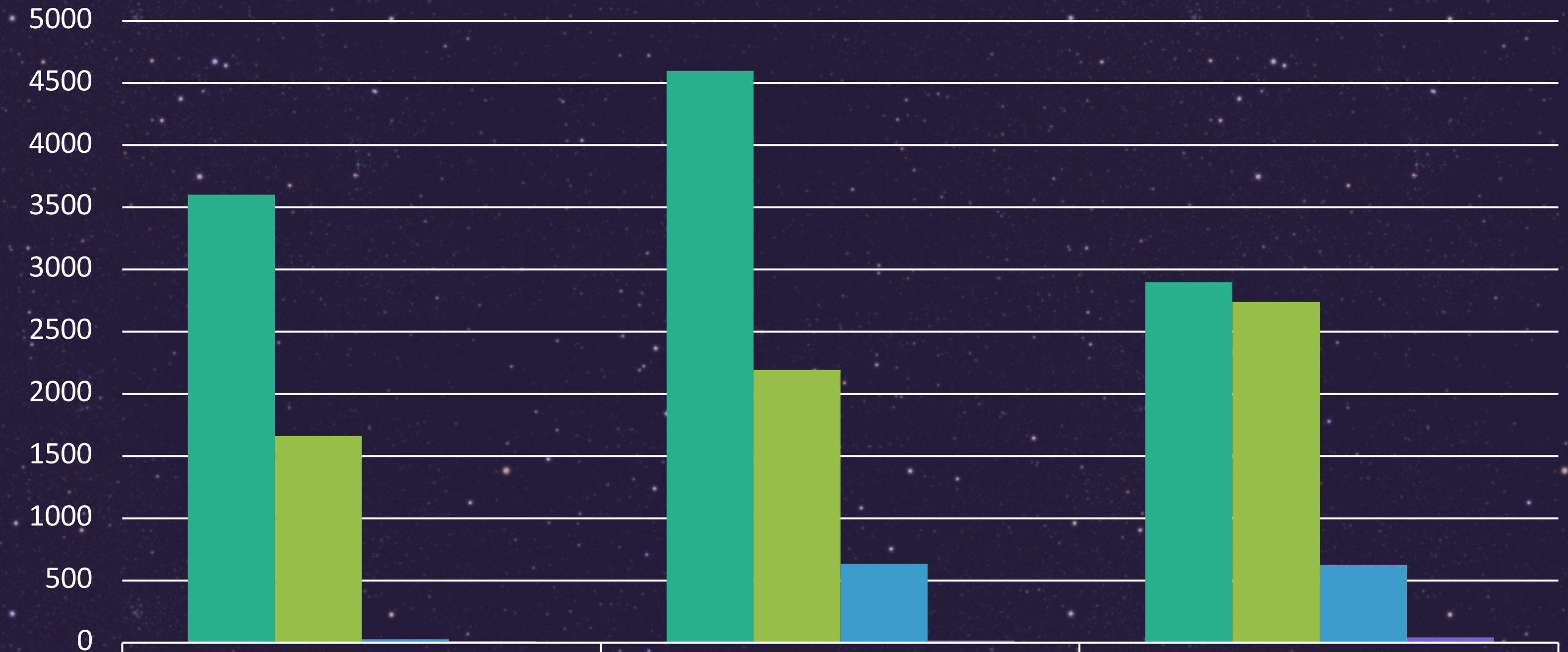
Many keys to understanding solar system origins, processes, and habitability lie in the least explored planets

The time is right for a Uranus OP mission: it is technically feasible, cost effective, and science rich!



Back-up Material

Scientific Value of Outer Planet Flagship Science Missions



	Galileo	Cassini	Voyager*
Cost FY20 ($M)	3600	4600	2900
Refereed Publications	1663	2192	2738
Data volume (GB)	30	635	625
Phase E (years)	14	20	42

Flagships provide the most bang for the buck:

- Comprehensive payload
- Critical system science
- Value grows over time, as they connect to other missions and provide comparative planetology

Galileo & Cassini Mission Cost data:
https://www.planetary.org/articles/cost-of-perseverance-in-context
*Voyager estimate inflates FY89 LCC + interstellar mission ops

Publications # are rough estimates found using ADS and same search terms for each mission, official Cassini project-tracked # is >4000 publications (L. Spilker)

Science Traceability (by discipline)

Discipline	Science Objective	Measurement	Nominal Instrument	Mission Functional Requirement
Atmospheres	A1. How does atmospheric circulation function, from interior to thermosphere, in an Ice Giant?	A. Cloud top zonal and 2D winds, waves to ~10 m/s resolution	NAC, imaging at 50 km/pixel	Repeated views of same features over timescales of minutes to hours
		B. *In situ* vertical wind profile to 10-20 m/s resolution	USO (probe), 10 measurements per scale height	Probe to 5 bars
		C. Resolved composition, disequilibrium species mapping (to P < 3 bars): CH_4, H_2S, H_3^+, C_2H_2, C_2H_6, etc., hydrogen ortho/para fraction to mixing ratio ±20%	Vis/NIR, 1000 km/pixel	
			TIR, ~1000 km horizontal spatial resolution	
			MS (probe)	Probe to 5 bars, 10 bars preferred
			Ortho/para sensor (probe)	Probe to 5 bars
		D. Depth of atmospheric winds (gravity moments)	RS, gravity passes	Polar and equatorial passes, distances of 1.1 R_u
	A2. What is the 3D atmospheric structure in the weather layer?	A. Cloud tomography and aerosols	Vis/NIR imaging spectra at 500-1000 km/pixel	Repeated views of same features over timescales of hours
			WAC or NAC imaging at 500-1000 km/pixel	Repeated views of same features over minutes to hours
		B. Vertical temperature profile to ±1K	ASI (probe), 4 measurements per scale height	Probe to 5 bars
			Ortho/para sensor (probe)	Probe to 5 bars
			RS+USO, occultations	Atmospheric occultations
		C. Global temperature variations in troposphere, stratosphere, thermosphere	TIR, 500-1000 km/px mapping	Global coverage, repeated views
			Vis/NIR spectra at 500-1000 km/pixel	
Atmospheres / Interiors	A3./I1. When, where, and how did Uranus form, and how did it evolve both thermally and spatially, including migration?	A. Noble gas (& isotopes of He, Xe) abundances to ± 5%	MS (probe)	Probe to 5 bars
		B. Elemental (& isotopes of H, C, S, N & O (stretch goal)) abundances, lower bounds on CH_4, H_2S, NH_3, H_2O, and the variation with depth	MS (probe)	Probe to 5 bars, 10 bars preferred
		C. Global distribution of atmospheric composition	*Same as A1.C above*	
		D. Global energy balance (Bond albedo and thermal emission) to 1%	TIR, 1000 km/pixel	Repeat orbiter ~yearly to determine variability
			Vis/NIR spectra at 500-1000 km/pixel	Repeat ~yearly to determine variability
Interiors	I2. What is the bulk composition and its depth dependence?	A. Gravity field to at least J_8, uncertainties on J_2-J_6	RS+USO, gravity passes	
	I3. Does Uranus have discrete layers or fuzzy core, and can this be tied to its formation and tilt?	A. Gravity field to at least J_8, uncertainties on J_2-J_6	*Same as I2.A above*	Polar passes, distances of 1.1 R_u require validation of safe passage inward of rings
		B. Ring oscillations	NAC imaging of rings (<1 km/pix)	
			RS+USO, occultations	
	I4. What is the true rotation rate of Uranus, does it rotate uniformly, and how deep are the winds?	A. Internal magnetic field structure	MAG, 0.1 to 20,000 nT, 1-second cadence	Many close passes
		B. Planet shape	RS+USO, occultations	

STM, continued...

Discipline	Science Objective	Measurement	Nominal Instrument	Mission Functional Requirement
Magnetospheres	M1. What dynamo process produces Uranus's complex magnetic field?	A. Internal magnetic field structure	MAG, 0.1 to 20,000 nT, 1-second cadence	Close passes
	M2. What are the plasma sources & dynamics of Uranus's magnetosphere and how does it interact with the solar wind?	A. Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)	F&P package	Multiple passes
	M3. How does the magnetosphere interact with Uranus's upper atmosphere and satellite surfaces?	A. Energetic particle fluxes at satellite orbital ranges	F&P package	
		B. Plasma/energetic particle fluxes over Uranus polar regions	F&P package	Polar passes
Rings and Small Satellites	R1. What processes sculpted the ice giant rings and small moons into their current configuration?	A. Fine-scale structures in the dense rings at multiple times and longitudes	WAC or NAC imaging (100 m/pixel)	Repeat views of rings
			RS+USO, occultations	
			WAC or NAC stellar occultations	
		B. Measure longitudinal variations in the ring structure (including normal modes and arcs)	WAC or NAC imaging (1 km/pixel)	Image all co-rotating longitudes in the main ring system multiple times
		C. Inventory and shape of small moons > 0.5 km in radius within 500,000 km of the planet's center	WAC or NAC imaging (100 m/pixel)	Large area coverage
	R2. What are the compositions, origins and history of the Uranian rings and inner small moons?	A. Ring (color) imaging at a wide range of phase angles	WAC multi-band imaging	Phase angle > 160
		B. Ring and small moon spectra (Cordelia to Mab), 1-5 μm	Vis/NIR imaging and spectroscopy	
Large Satellites and Ocean Worlds	S1. What are the internal structures and rock-to-ice ratios of the large Uranian moons? Which ones possess substantial internal heat sources or possible oceans?	A. Magnetic field intensity and direction	MAG, 0.1-20,000 nT, 1s cadence	Sample variable magnetic lat & long, altitude <0.5 satellite radii
		B. Static gravity coefficients	RS, 0.1 mm/s at 60s integration	Earth-pointing HGA +/- 30 mins of C/A; flyby velocities < 10 km/s at each satellite
		C. Global shape	NAC, global images, < 1 km/pix	Include limb
		D. Energy distribution of bulk plasma flow, 10eV-10 keV	F&P package	Point in plasma flow (ram) direction, <300 km baseline
		E. Plume/activity searches	NAC, <1 km/pix; thermal anomalies TIR	High phase
		F. Satellite orbital positions	NAC	Distant imaging
	S2. How do the compositions and properties of the Uranian moons and ring system constrain their formation and evolution?	A. Reflectance spectra from 0.8-5 μm, detect features 1% of continuum from 0.8-2.6 μm and 2% of continuum from 2.6-5.0 μm	Vis/NIR, < 3km/pix	
		B. Static gravity coefficients	See S1B above	
		C. Global shape	See S1C above	
	S3. What geological history and processes do the surfaces record and how can they inform outer solar system impactor populations?	A. Distribution and topography of surface features	NAC, global images & stereo, <0.5 km/pix	Non-targeted flybys of each satellite for global mapping and stereo
		B. Variations in surface composition	Vis/NIR, < 3 km/pix	Non-targeted flybys of each satellite for global mapping
		C. Energy distribution of bulk plasma flow, 1eV-1 keV	F&P package	
		D. High-phase plume-search images	NAC, <1 km/pix	Phase angle > 150
	S4. What evidence of exogenic interactions do the surfaces contain?	A. Energy distribution of bulk plasma flow, 10keV-10 MeV	F&P package	Point in plasma flow (ram) direction, <300 km baseline
		B. Variations in surface composition in reflectance spectra	*Same as S2.A above*	
		C. Evidence of radiation processing of surface ices	Vis/NIR, < 3 km/pix	

Notional Science Coverage

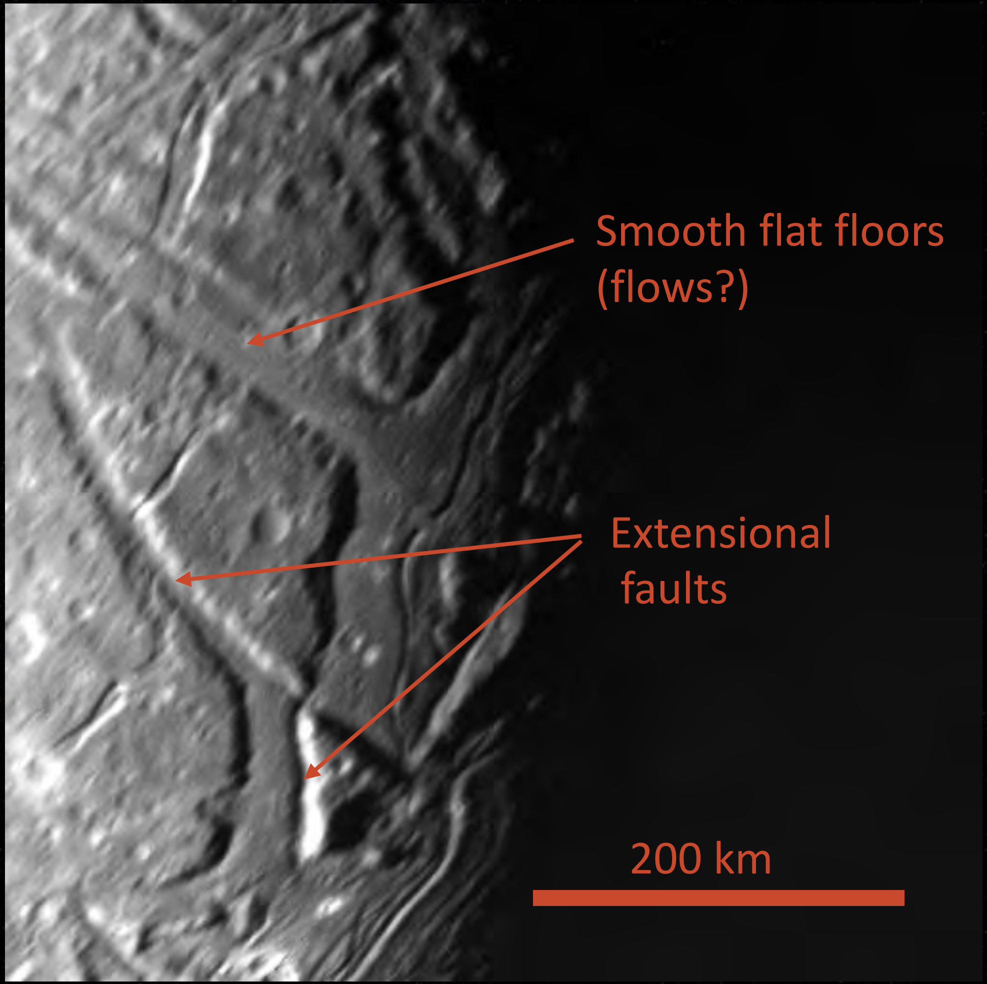
Measurement	Instrument	Concept of Operations (Notional Payload)	Coverage (Notional Tour)
A1A. Cloud top zonal and 2D winds, waves to ~10 m/s resolution	NAC, imaging at 50 km/pixel	Scan across planet from ~5x10^9 km range or lower, phase angle < 45°	Many opportunities
A1C. Resolved composition, disequilibrium species mapping	Vis/NIR, 1000 km/pixel	Scan across planet from ~4x10^6 km range, phase angle < 45°	Many opportunities
	TIR, ~1000 km horizontal spatial resolution	3 strip scans across planet from ~3x10^5 km range, any phase angle	Many opportunities
A2A. Cloud tomography and aerosols	Vis/NIR imaging spectra at 500-1000 km/pixel	Scans across planet from ~2 to <4x10^6 km range, phase angle < 45°	Many opportunities
	WAC or NAC imaging at 500-1000 km/pixel	Scans across planet from ~1 to 2 x10^7 km range, phase angle < 45°	Many opportunities
A2C. Global temperature variations in troposphere, stratosphere, thermosphere	TIR, 500-1000 km/px mapping	6 strip scans across planet from ~1.5 to 3x10^5 km range, phase angle > 90°	Many opportunities
	Vis/NIR spectra at 500-1000 km/pixel	Covered in A2A observations	Many opportunities
A3D. Global energy balance (Bond albedo and thermal emission) to 1%	TIR, 1000 km/pixel	Covered in A1C observations	Many opportunities
	Vis/NIR spectra at 500-1000 km/pixel	Covered in A2A observations	Many opportunities
I3B. Ring Oscillations	WAC or NAC imaging (1 km/pixel)	Same as R1B below	Many opportunities
I4A/M1. Internal magnetic field structure	MAG, 0.1 to 20,000 nT, 1-second cadence	Many close passes, sample field	Opportunities near periapse
M2A. Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)	F&P package	Multiple passes	Many opportunities
M3A. Energetic particle fluxes at satellite orbital ranges	F&P package		Opportunities during satellite tour phase
M3B. Plasma/energetic particle fluxes over Uranus polar regions	F&P package	Polar passes	Opportunities during polar phase
S4A. Bulk plasma flow	F&P package	Point in ram direction, <300 km altitude	Many opportunities
R1A. Fine-scale structures in the dense rings at multiple times and longitudes	WAC or NAC imaging (100 m/pixel)	Ring mosaics from ~1x10^7 km range or lower, phase angle < 90°	Rare opportunities, tour needs to be optimized
R1B. Measure longitudinal variations in the ring structure (including normal modes and arcs)	WAC or NAC imaging (1 km/pixel)	Ring mosaics from ~1x10^8 km range or lower, phase angle < 90°	Many opportunities
R1C. Inventory and shape of small moons > 0.5 km in radius within 500,000 km of the planet's center	WAC or NAC imaging (100 m/pixel)	Non targeted observations (range varies)	Rare opportunities, tour needs to be optimized
R2A. Ring (color) imaging at a wide range of phase angles	WAC multi-band imaging	Best effort resolution, scan across ring plane, Phase angle > 160°	Many opportunities
R3B. Ring and small moon spectra (Cordelia to Mab)	Vis/NIR imaging and spectroscopy	Best effort resolution, scan across rings, Phase angle < 90°	Many opportunities
S1B. Static gravity coefficients	Radio Science	Earth-pointing HGA +/- 30 mins of C/A	Several opportunities, more possible during satellite tour phase
S1C. Global Shape	NAC, global images < 1km/pix	Framing at ~300,000 km and ~200,000 km range, terminator should be visible	Many opportunities
S1E. Plume activity searches	NAC, < 1km/pix	Framing at ~200,000km, phase angle > 150^o	Many opportunities
	TIR	Scan across satellite range ~25,000 km, any phase angle	Many opportunities
S1F. Satellite positions	NAC, global images, < 10 km/pix	Framing other satellites at ~2,000,000 km range	Many opportunities
S2A. Satellite composition	Vis/NIR, < 3km/pix	Scan across disk, range ~35,000 km	Several opportunities, more possible during satellite tour phase
S3A. Geology & Topography	NAC, <0.5 km/pix	Framing at ~100,000 km range, (stereo pairs, parallax angle <30^o)	Rare opportunities, more possible during satellite tour phase
		Framing at ~15,000 km range	2 images inbound, 2 images outbound
S3B. Surface composition.	Vis/NIR, < 3 km/pix	Covered in S2A observations	Many opportunities
S3D. Plume search	NAC, < 1km/pix	Covered in S1E observations	Many opportunities
S4A. Bulk plasma flow	F&P package	Point in ram direction, <300 km altitude	Several opportunities, more possible during satellite tour phase

Uranian Moons: Present Knowledge

- Evidence for tectonics and ?cryovolcanism
- Dark surfaces (organics?) and CO_2 frost
- Evidence for past high heat fluxes (Ariel, Miranda)
- Some surfaces are "young" (Ariel, Miranda)
- Analogous moon Dione has hints of a subsurface ocean (gravity & topo.)
- Do the Uranian moons have subsurface oceans?

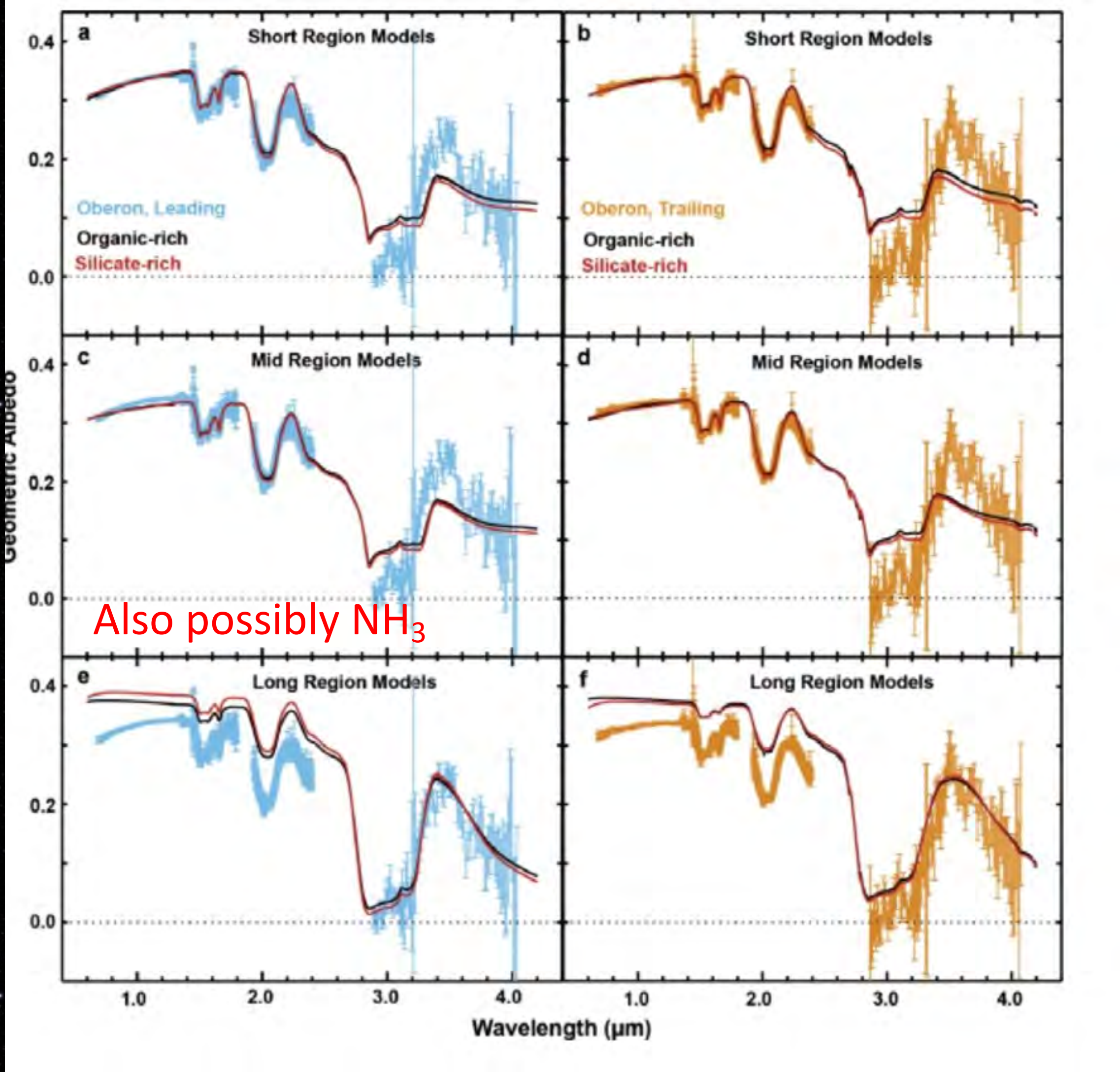
Tectonics & Cryovolcanism?

Ariel (2.4 km/pix)



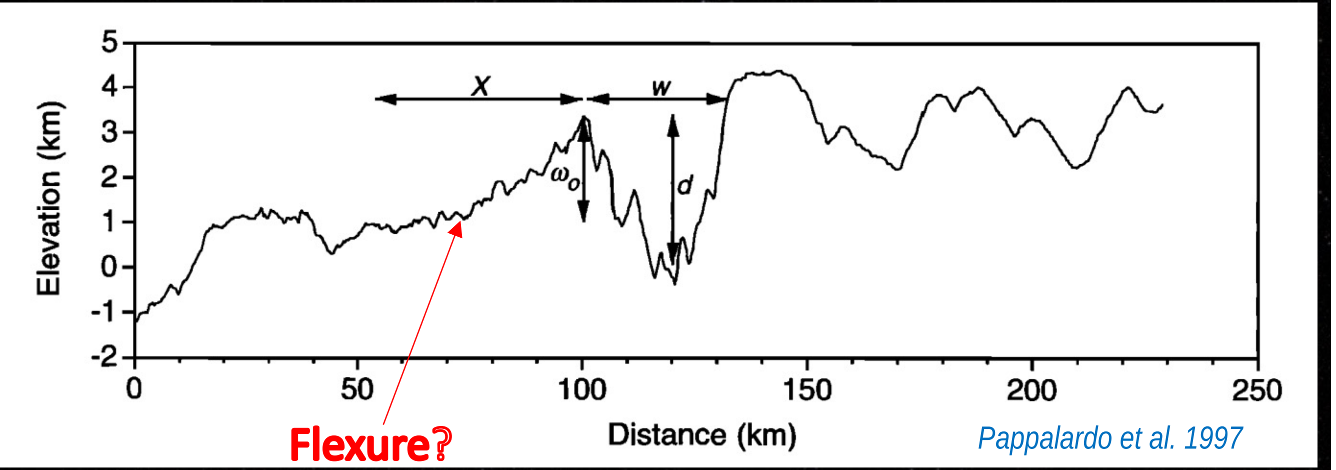
Dark (organic?) Material

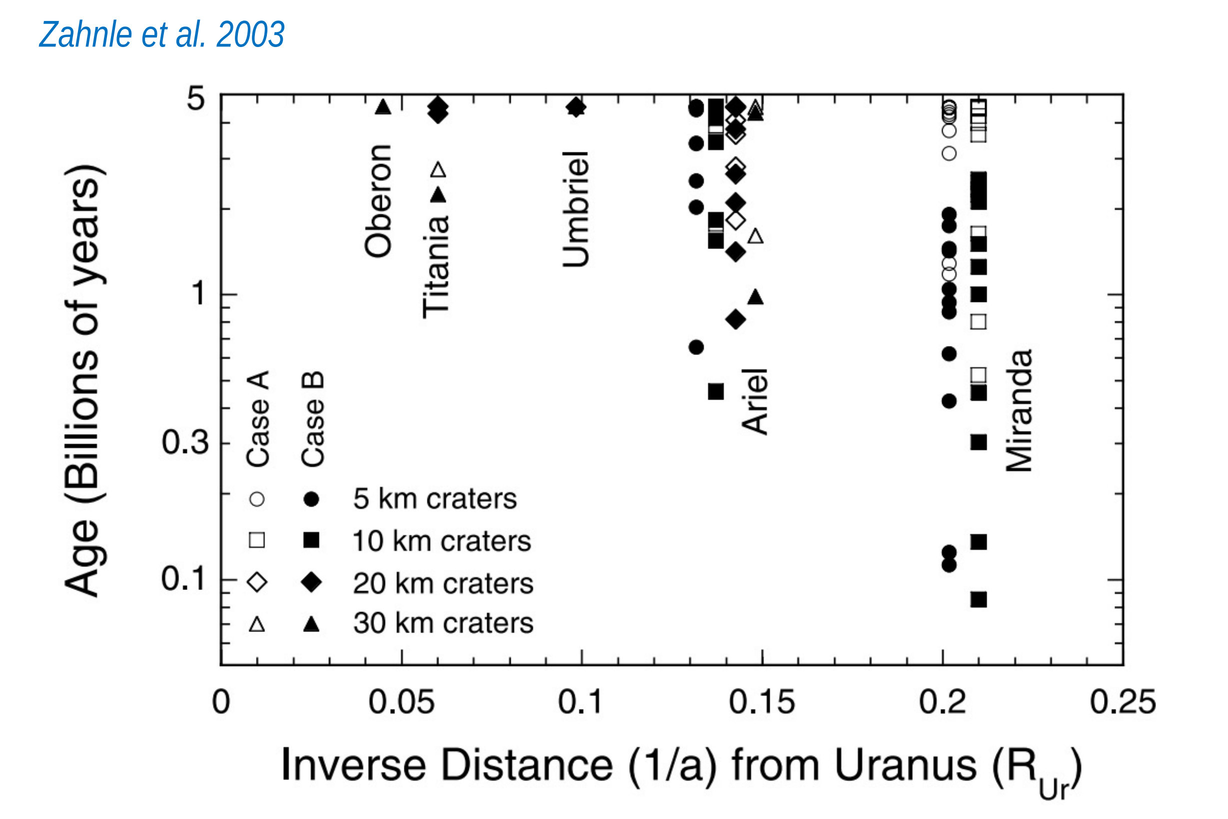
SpeX/LXD Cartwright et al. 2018



High Heat Fluxes

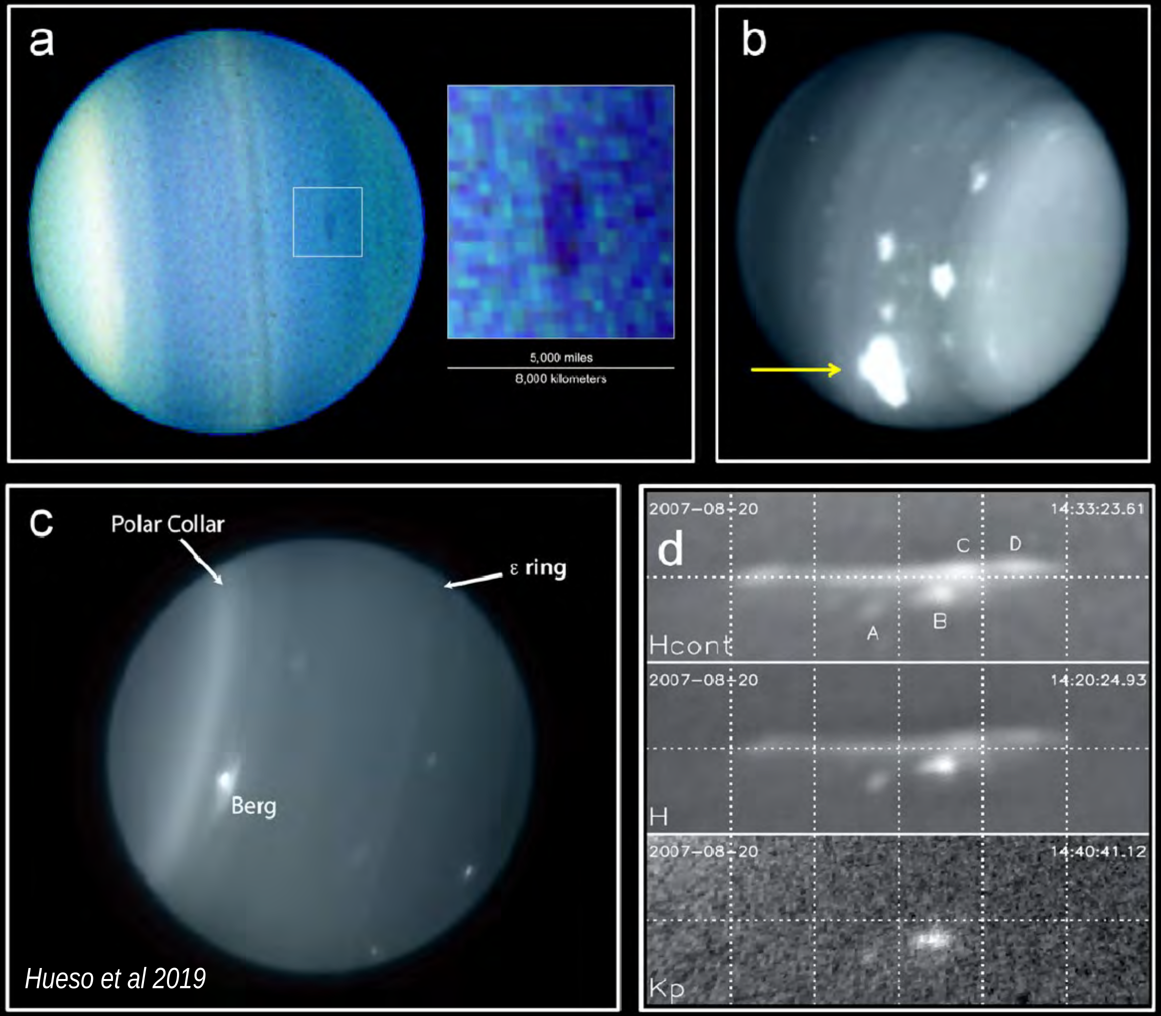
“Young” Surfaces

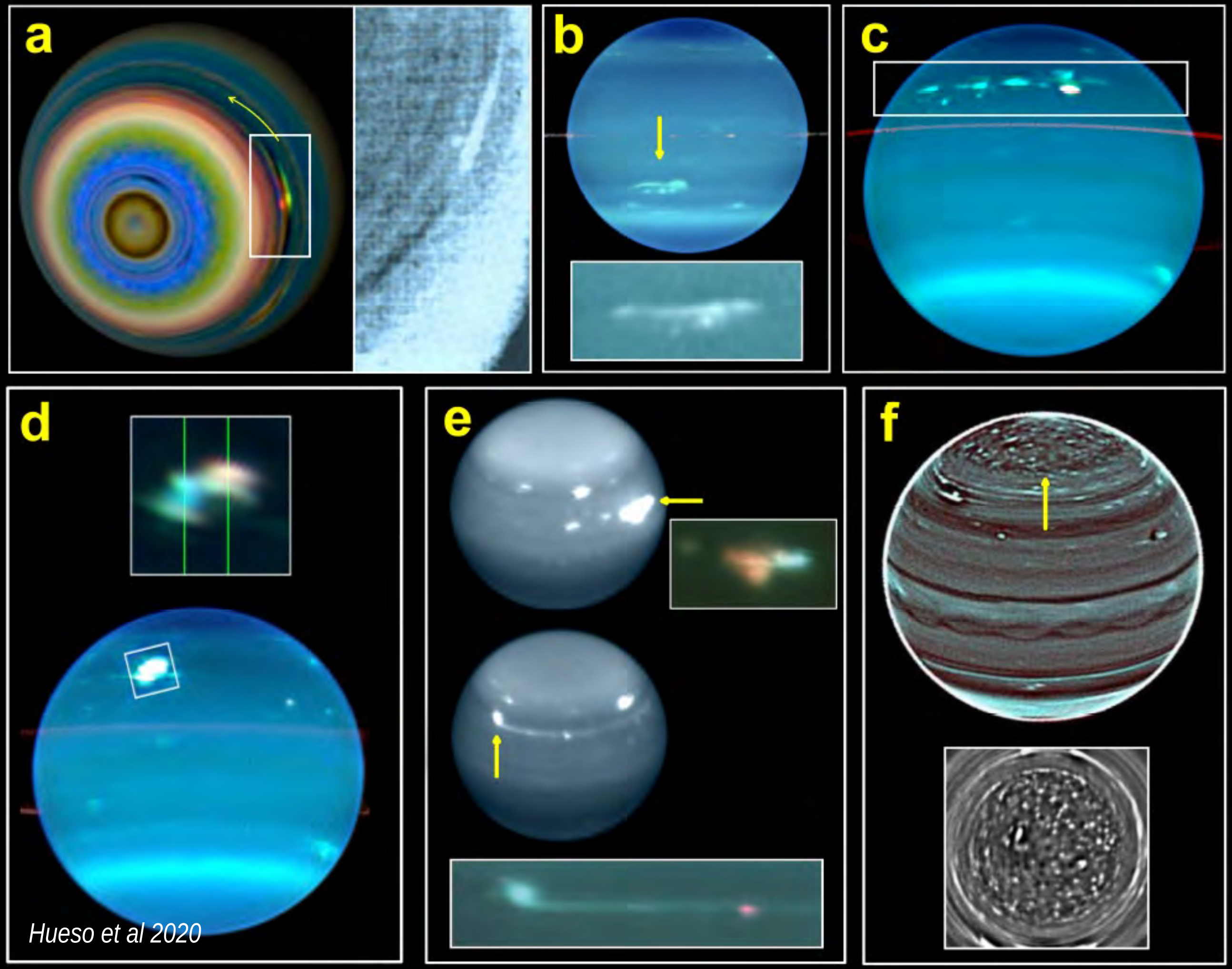




Elastic thickness ~ 2 km, heat flux ~60-200 mW/m^2
(similar results for Ariel)

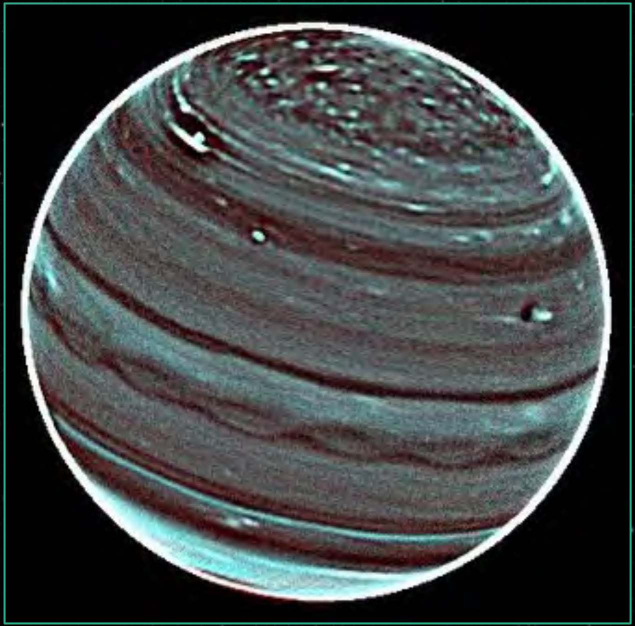
Uranus's Dynamic Atmosphere

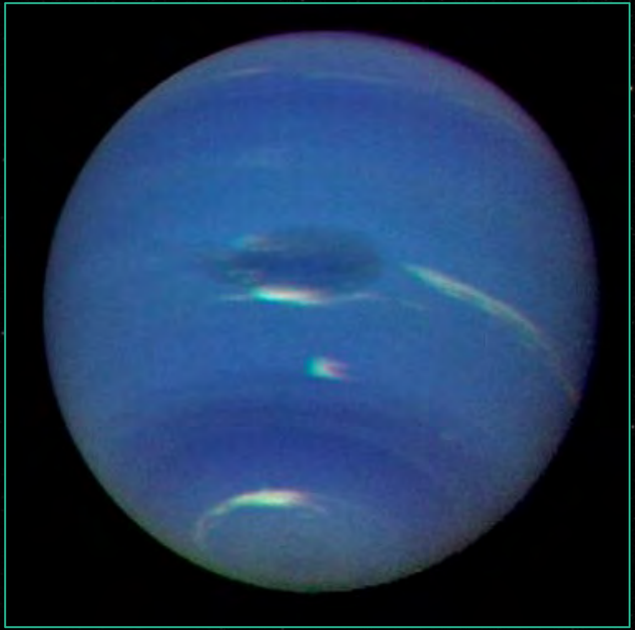




Wave and storm activity despite low solar insolation *and* low internal heat

Gas Giants vs. Ice Giants: Comparative Planetology

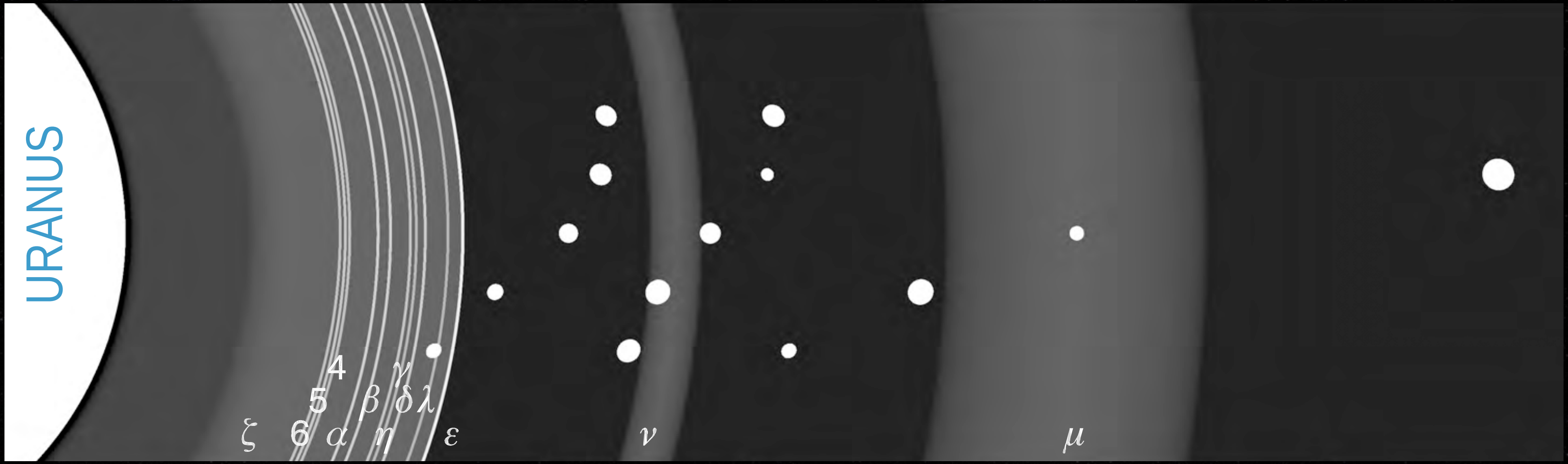




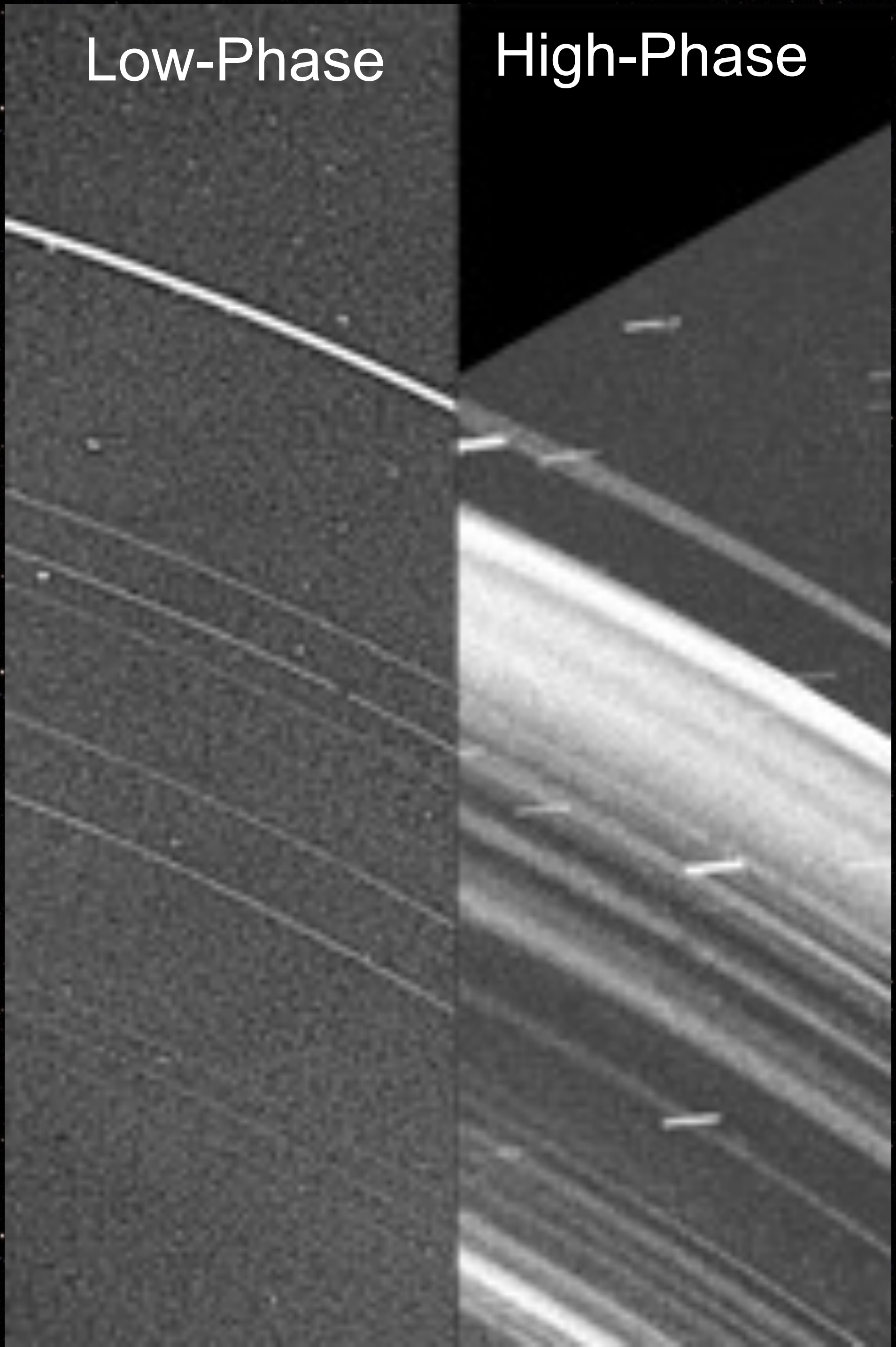
- 95-318x Earth Mass
- Mostly H_2 and He.
- NH_3 and NH_4SH clouds.
- Formed quickly.
- Metallic H_2 at great depth.

- 14-17x Earth Mass
- Mostly CH_4, H_2O, NH_3, H_2S + rocks
- CH_4 and H_2S clouds.
- Formed slowly.
- Superionic H_2O ice mantle at great depth.

Uranian rings and small moons



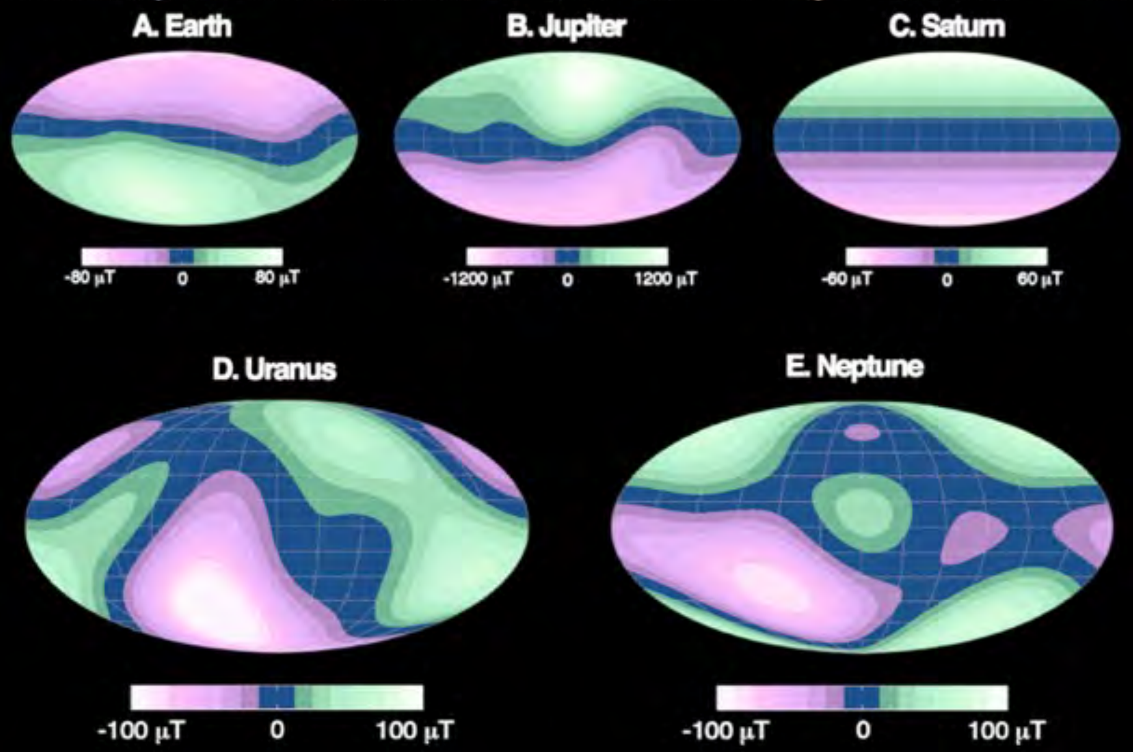
Complex system, co-orbital dynamics and resonances, possible connection between Mab and rings

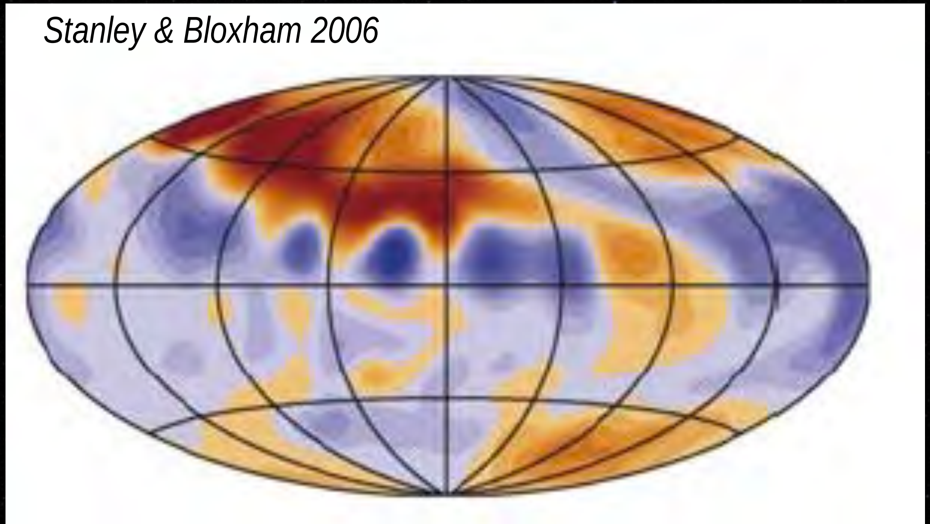


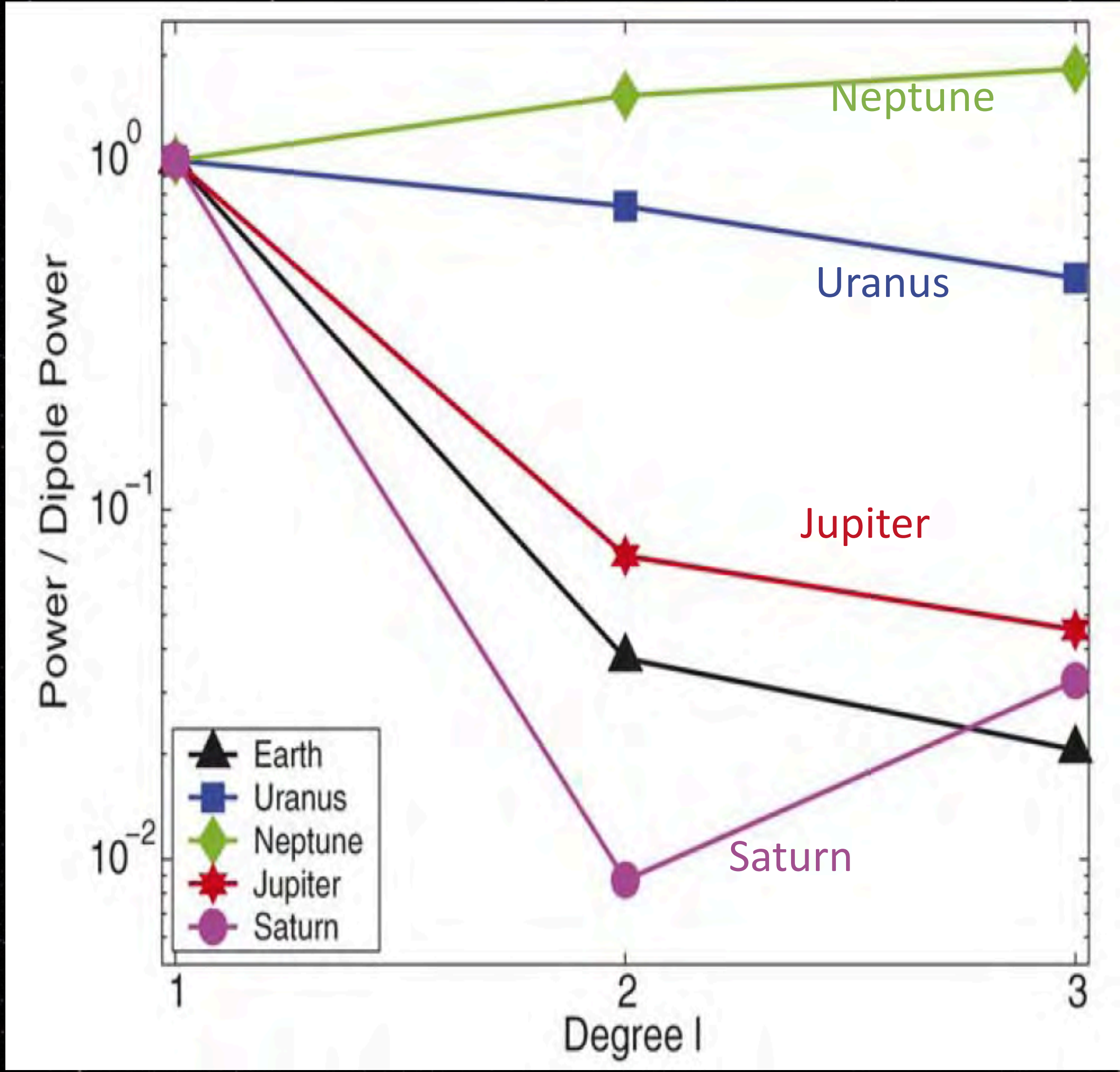
Uranian Ring Seismology

Dense ringlets and inter-ring dust sheets could be influenced by resonances with planetary oscillations.

Weird Dynamos of Uranus & Neptune



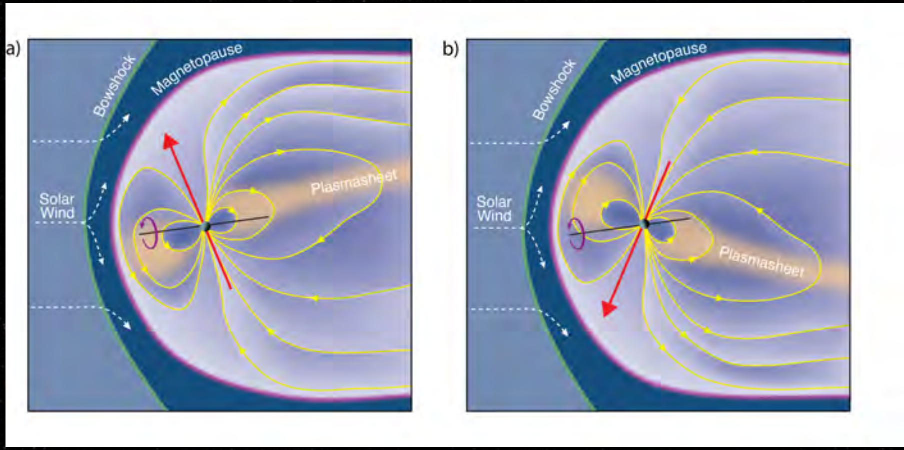




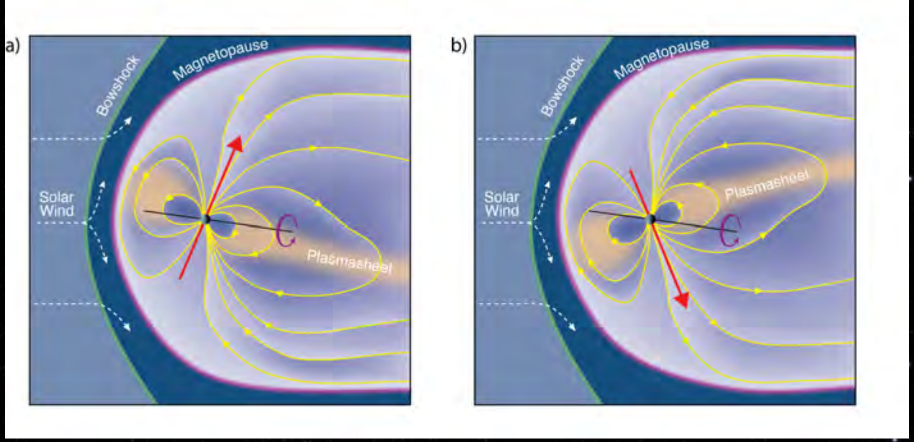
Modeling Uranus & Neptune non-dipolar fields: thin-shell dynamo over a stratified core

Solstice Orientation

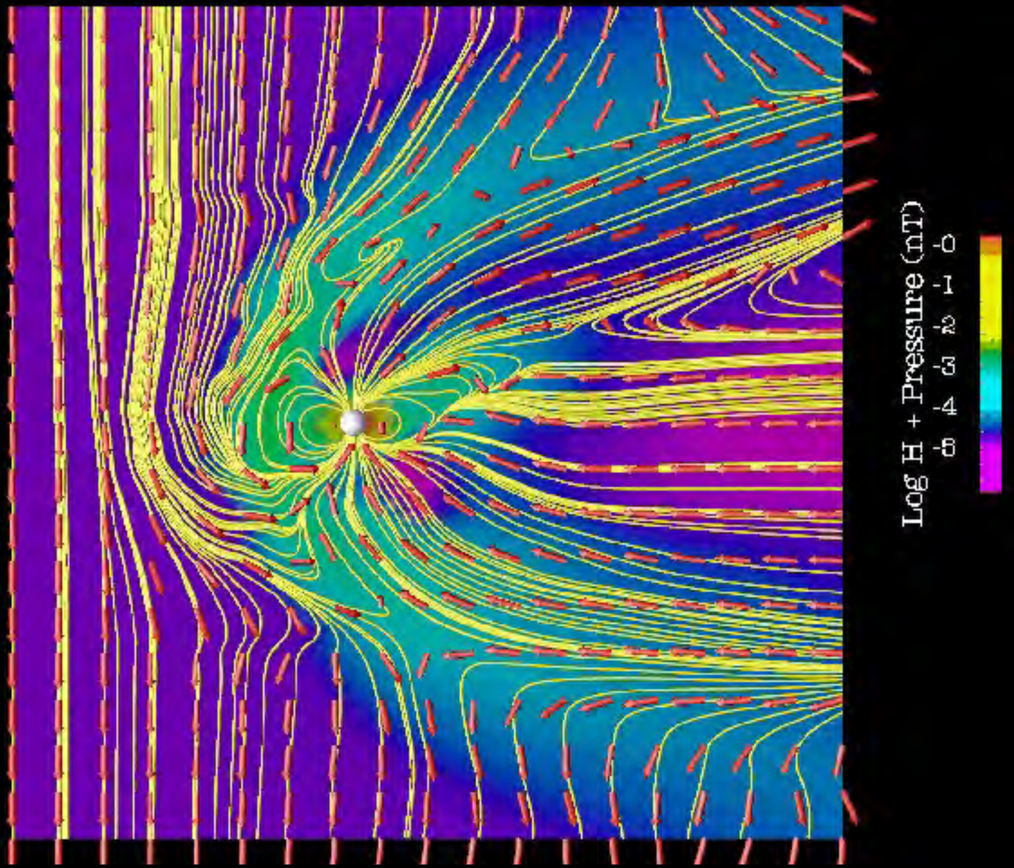
1986 - Voyager



2028-2030: Similar to Voyager era, but opposite polarity



Equinox = Complicated!



Diurnal variation of plasma pressure & magnetic field

Either orientation is instructive for solar wind interactions!

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Uranus Orbiter and Probe 2023-2032 Planetary Mission Concept Study

Mission Study Design Team Supplemental Material:

APL Advanced Concepts Engineering (ACE) Lab

2021 Uranus Orbiter Probe Flagship Decadal Study Team

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Uranus Orbiter and Probe Mission Design

Juan Arrieta and Martin Ozimek

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Summary of Key Cruise Phase Findings

I. Cruise trajectories for a Uranus Orbiter & Probe flagship concept are favorable in the upcoming decade
   1. Modern launch vehicle offerings in the next decade (Vulcan Falcon Heavy) offer significant performance advantages compared to the previous decade
   2. Jupiter flyby geometry is enabled in the 2031-2032 launch timeframe
   - I.1&I.2 allow **elimination of solar electric propulsion** (cost/complexity) and **Venus gravity assists** (thermal challenge)
   - I.2&I.2 additionally provide **40-90% more launch** mass capability than prior studies

II. By our adjusted calculations our UOP concept reduces ΔV by 100-450 m/s over prior studies while reducing probe deployment risk (see Science Phase Presentation)

III. Elimination of Jupiter gravity assist extends launch availability throughout mid/late 2030's with similar point design capability assuming the following penalties are tolerable:
   I. Mission duration can be extended 2- or more years
   II. Spacecraft can endure thermal environment of 1- or more Venus gravity assists

High-level Mission Phases for Trajectory Design

Cruise Phase	*Science Phase*	
Interplanetary (10-14 years)	Capture/Probe Deploy (0.5-1 years)	Science Focused Tour (2-3 years)

Interplanetary Trajectory Drivers: Time of flight launch Energy/mass Uranus arrival velocity

Capture/Probe Deploy Trajectory Drivers: Feasible probe ConOps Δv Time of flight ring hazard avoidance science tour IC radiation

Science Tour Drivers: Time of flight Δv flyby science disposal radiation

Overall Goal:

Update the 2010 Visions & Voyages Uranus Orbiter & Probe study for current launch dates refined science goals and payload increase maturity/fidelity.

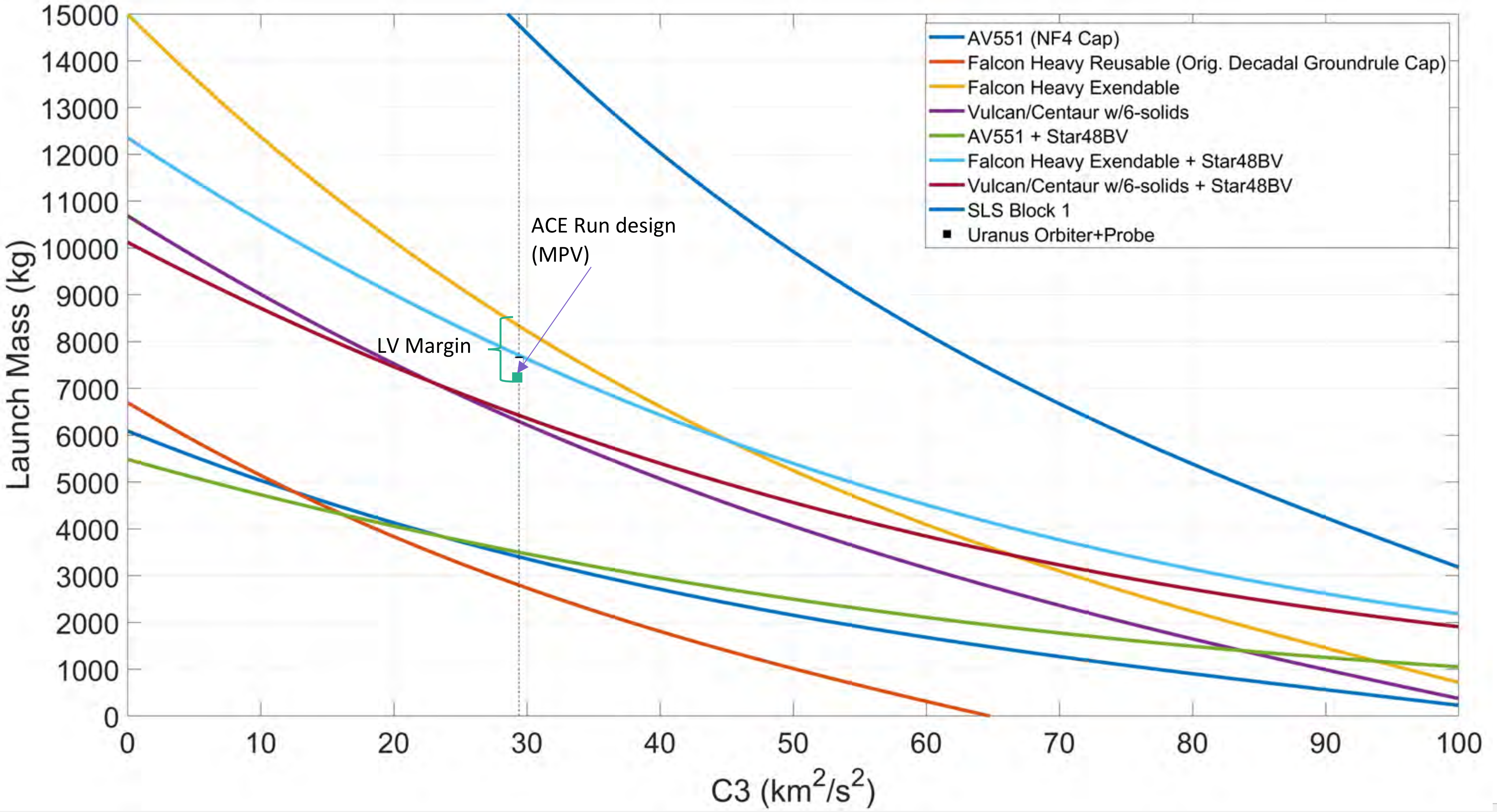
*Per science champions/decadal questionnaire - attempt to remove SEP stage from mission design.

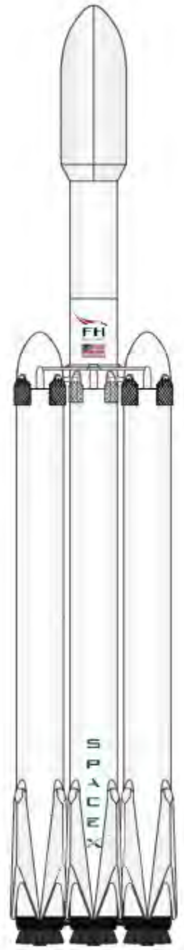
Mission Design Deliverables:

Cruise Phase: Optimal chemical cruise trajectory for next decade without SEP*.

Science Phase: Refined preliminary probe design and CONOPS (a design that fully closes); preliminary Tour (2 year threshold 4 year baseline).

Launch Vehicle Performance

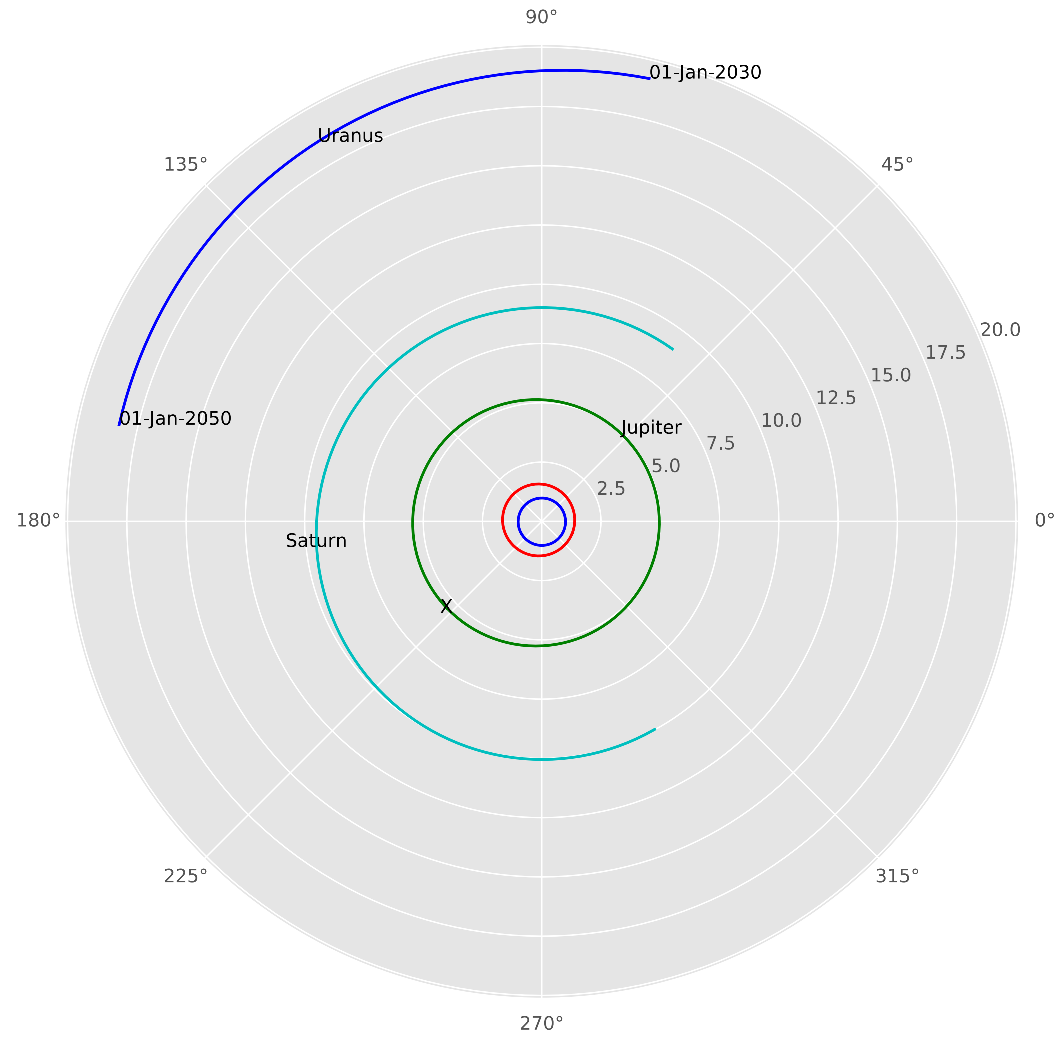




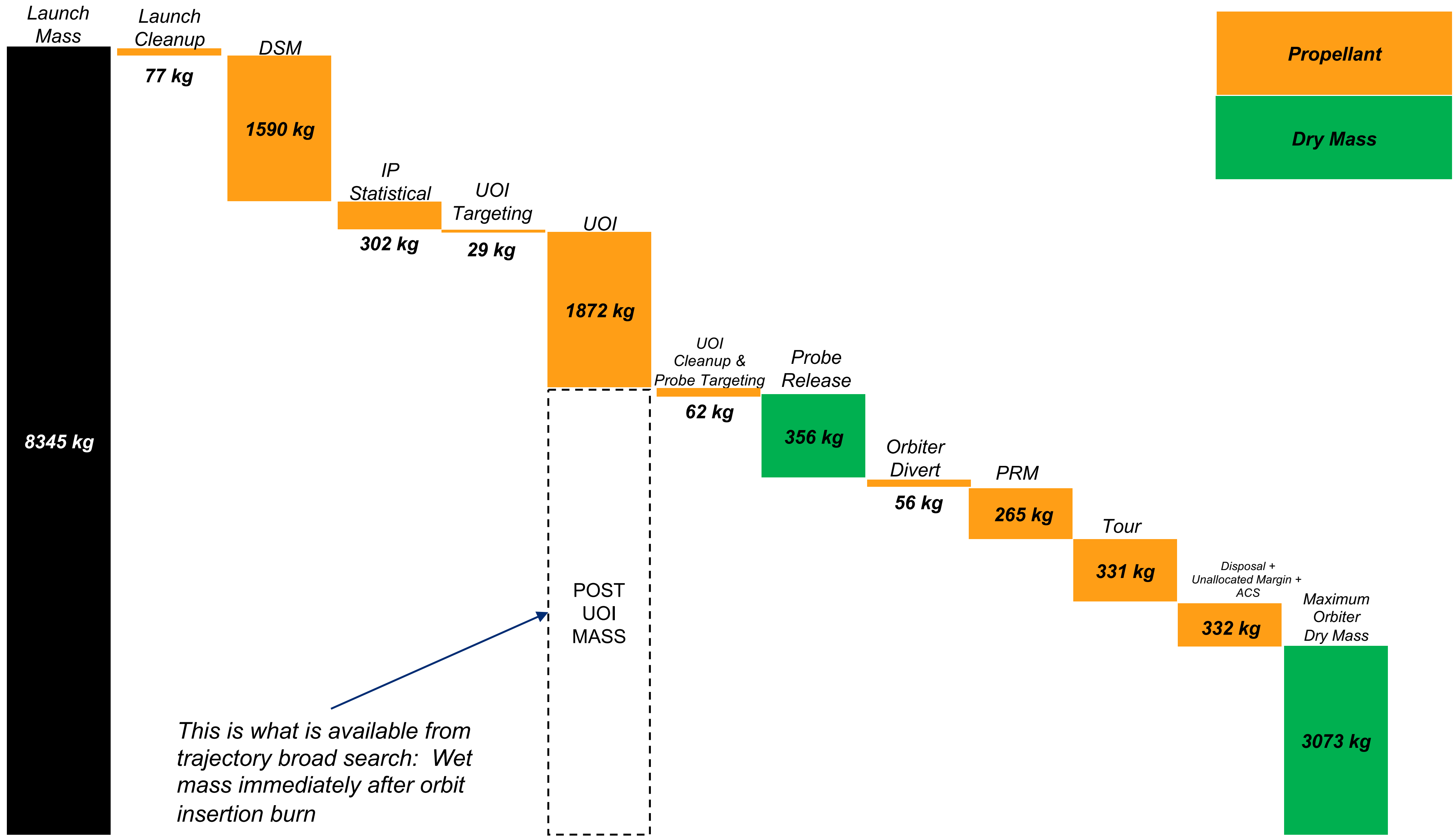
Falcon Heavy

Trajectory Broad Search Overview

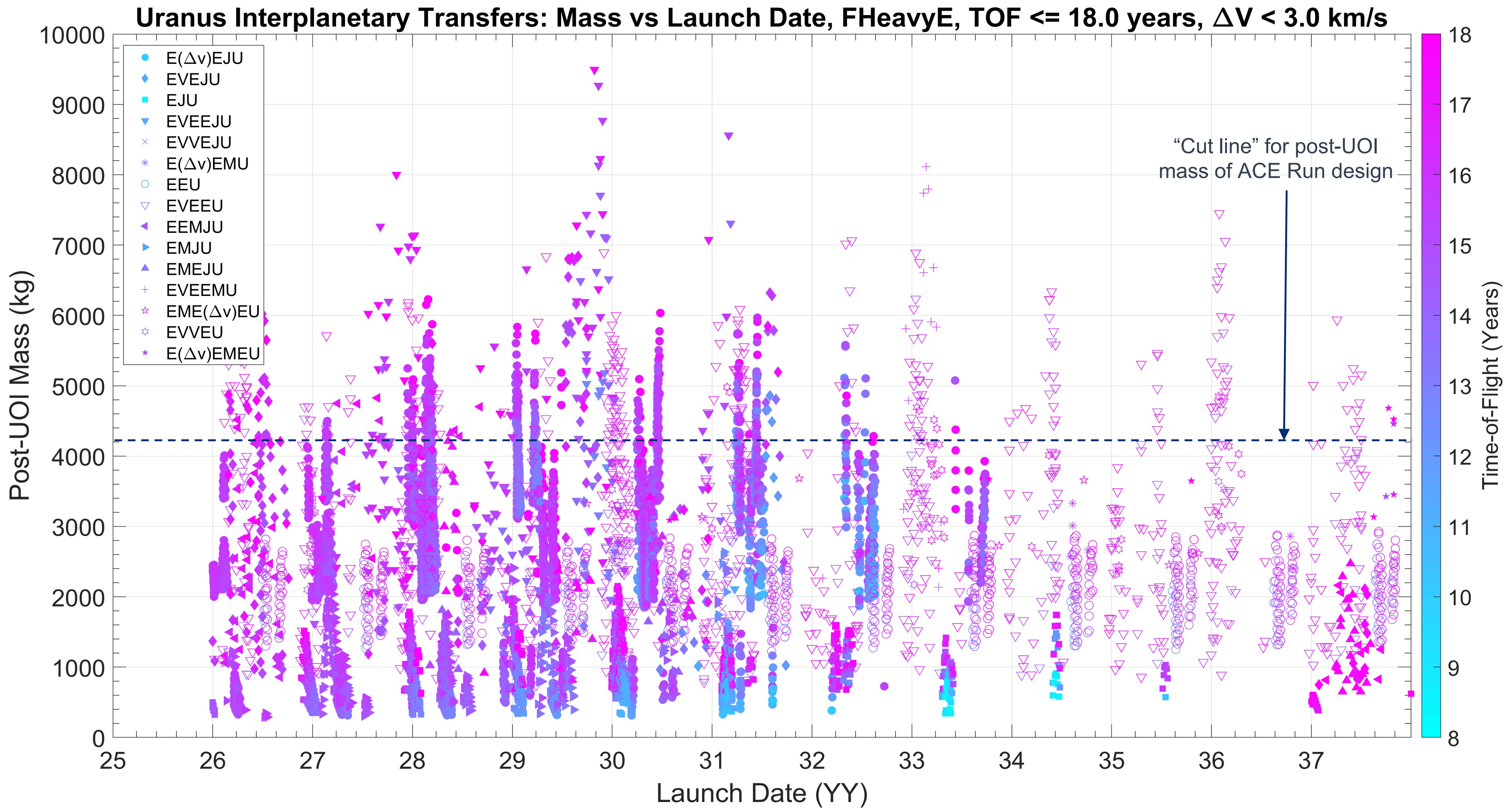
- Launch in 2030 to 2035
- Methodology: Patched conics with APL software packages EXPLORE and MINX
- Main Engine I_{sp} 315 sec (~Leros 1B)
- Uranus capture orbit condition:
  - Periapsis range: ~1.05 R_U
  - Period: ~140 days
- Most favorable gravity assist paths derived from 2017 Ice Giants Pre-decadal
  - New broad search rerun around these paths
  - Search continues to run interim results shown below
- Focus is on an investigation of Falcon Heavy Expendable LV
  - Highest performing LV currently on NASA NLS-II contract aside from SLS
- Goal: Present the mass to Uranus time-of-flight and propulsive (ΔV) trade space in order to select an interplanetary trajectory



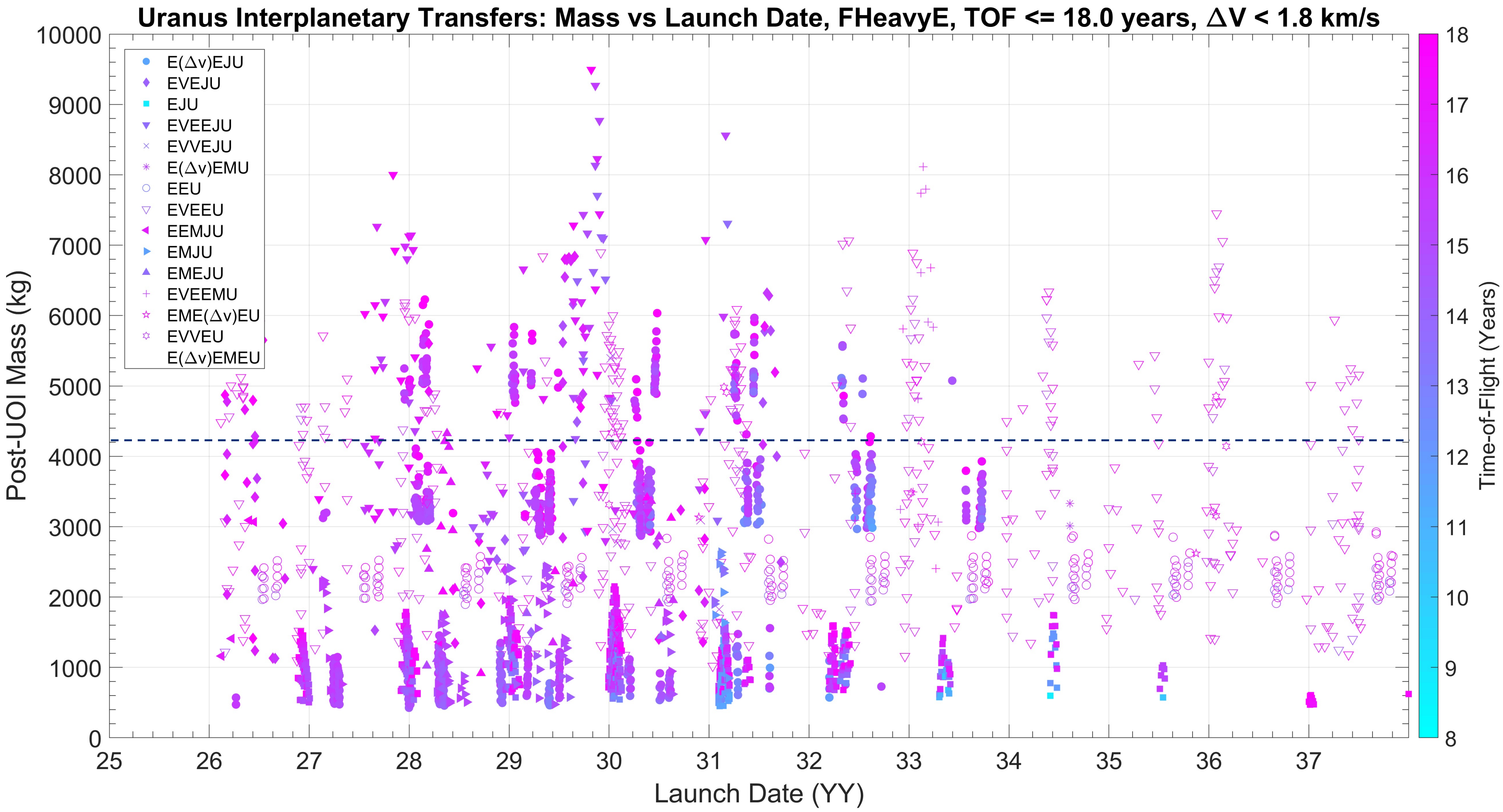
Estimation of Dry Mass Capability



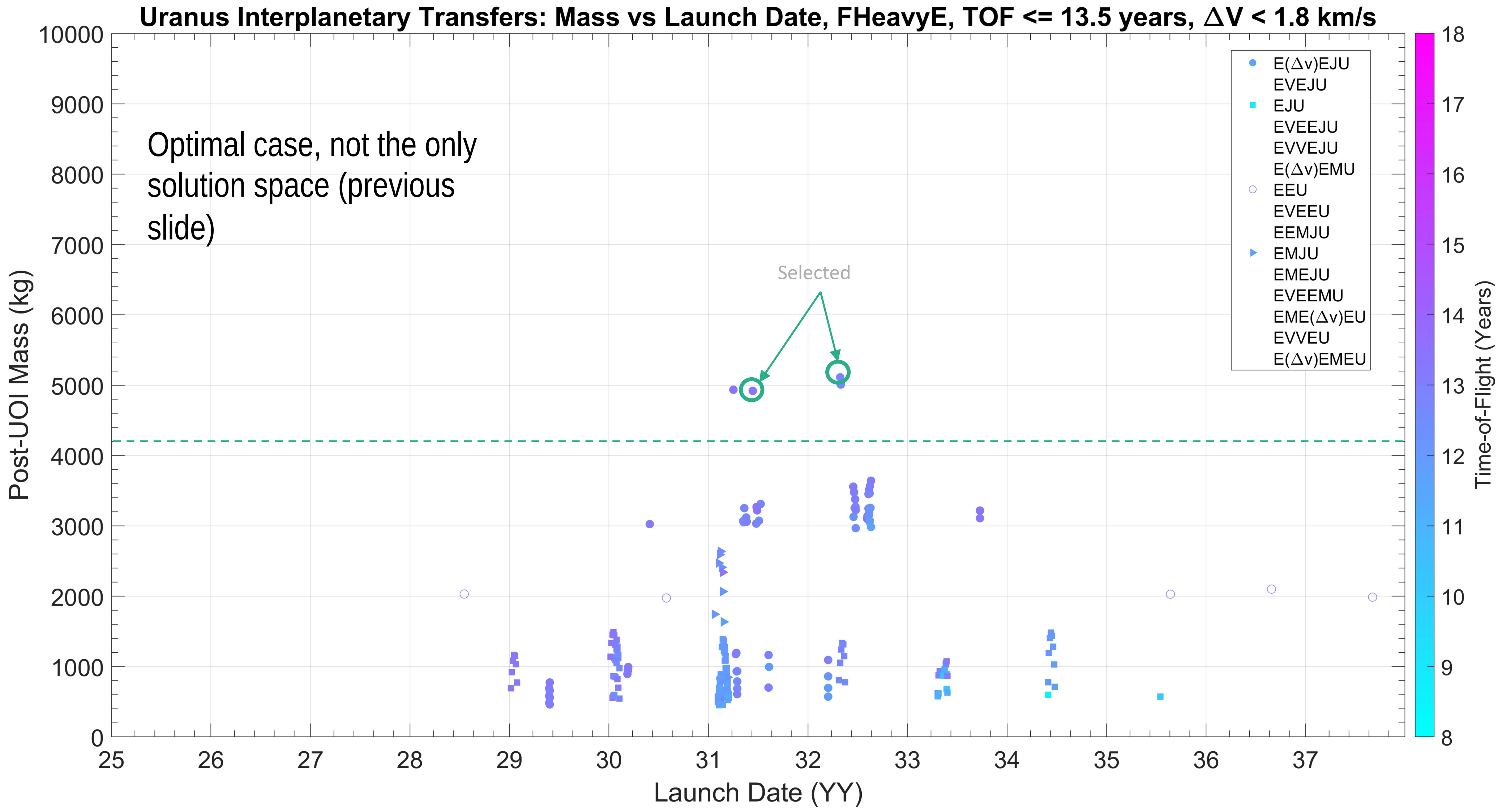
Initial Results: *Filter Settings: TOF ≤ 18.0 yrs ΔV ≤ 3.0 km/s*

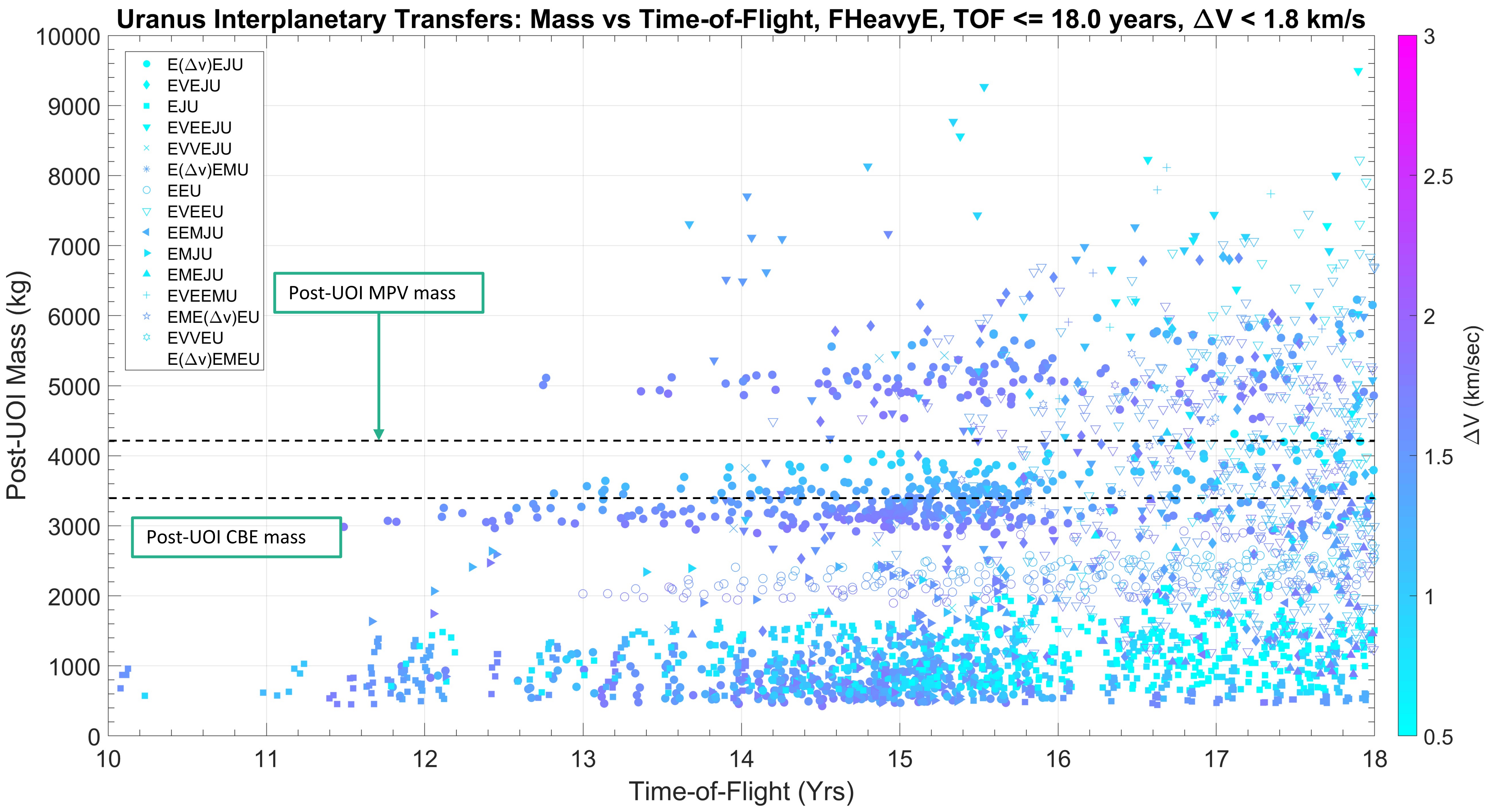


Initial Results: *Filter Settings: TOF ≤ 18.0 yrs ΔV ≤ 1.8 km/s*



Trajectory selection for this study: no Venus flybys, TOF< 13.5 yrs




Uranus Interplanetary Transfers: Mass vs Time-of-Flight, FHeavyE, TOF <= 18.0 years, ΔV < 1.8 km/s
Post-UOI Mass (kg)
Time-of-Flight (Yrs)
ΔV (km/sec)
E(Δv)EJU
EVEJU
EJU
EVEEJU
EVVEJU
E(Δv)EMU
EEU
EVEEU
EEMJU
EMJU
EMEJU
EVEEMU
EME(Δv)EU
EVVEU
E(Δv)EMEU
Post-UOI MPV mass
Post-UOI CBE mass
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
10
11
12
13
14
15
16
17
18
3
2.5
2
1.5
1
0.5

Interesting Solutions

Launch Date	C3 (km^2/s^2)	Path	DSM (km/s)	UOI (km/s)	PLΔV (km/s)	Post-UOI Mass (kg)	TOF (yrs)
9/30/2029	13.7	EVEEJU	0.00	1.221	1.221	7865.2	14.5
10/31/2029	11.3	EVEEJU	0.00	1.901	1.901	6665.4	13.1
2/21/2031	80.2	EJU	0.00	1.457	1.457	1360.9	11.6
3/1/2031	82.1	EJU	0.00	1.324	1.324	1317.3	12
3/7/2031	17.5	EVEEJU	0.05	1.722	1.771	6068.7	12.5
4/3/2031	28.6	E(ΔV)EJU	0.65	1.033	1.68	4934.7	13.5
5/16/2031	49.9	E(ΔV)EJU	0.25	1.693	1.938	2827.7	12
6/13/2031 (ACE Run baseline)	27.1	E(ΔV)EJU	0.77	1.011	1.783	4919	13.4
6/15/2031	27	E(ΔV)EJU	0.72	1.251	1.968	4643.5	12.7
7/10/2031	49.5	E(ΔV)EJU	0.23	1.64	1.869	2918.1	11.9
7/18/2031	19.8	EVEJU	1.07	1.763	2.834	4089.3	11.6
8/1/2031	18	EVEJU	1.05	1.374	2.426	4855	12.3
8/9/2031	20.2	EVEJU	1.06	1.504	2.561	4433.5	12
4/29/2032 (ACE Run backup)	28.8	E(ΔV)EJU	0.60	0.956	1.558	5111.5	12.8
5/3/2032	29.2	E(ΔV)EJU	0.76	1.147	1.904	4527.2	12.2
6/23/2032	51	E(ΔV)EJU	0.43	1.383	1.816	2861.4	11.8
8/13/2032	49.5	E(ΔV)EJU	0.50	1.405	1.908	2878.5	11.6
8/15/2032	49.5	E(ΔV)EJU	0.42	1.302	1.726	3056.3	11.8
1/8/2033 (Backups w/o Jupiter flyby)	23.6	EVEEU	0.42	1.012	1.434	5933.3	15.3
5/27/2034 (Backups w/o Jupiter flyby)	23.1	EVEEU	0.68	0.946	1.629	5626.4	15.2
2/28/2036 (Backups w/o Jupiter flyby)	28.2	EVEEU	0.54	0.974	1.519	5240.5	15.3
1/8/2038 (Backups w/o Jupiter flyby)	35.5	EVEEU	0.00	1.307	1.307	4812.3	14.2

Observations

- EΔVEJU is a balanced choice
  - No Venus flyby
  - Δv manageable around 12.8-13.5 year cruise timeframe
  - Opportunities in 2031-2032
  - Low UOI (arrival speed) can help probe deployment
  - Likely can find a baseline/backup pair (see recommendation)
- Best performance from VEEJU but
  - Requires Venus flyby and slightly longer duration
  - Requires low Earth-altitude flyby can reduce with Δv
  - Clustered around 2029-2031 (earlier)
  - Difficult to find a baseline/backup pair – 3/7/2031 solution doesn't have a similar backup
- VEEU can eliminate Jupiter requirement and extend launch opportunities (see next slide)
  - Costs ~2 year time penalty for same arrival velocity conditions 1- or more Venus flybys (thermal complexity) and possibly a powered Earth flyby
  - However extends launch availability past 2032 and into mid/late 2030's
- For time-of-flight ≤ 12 years
  - Ceiling of 4000 kg but Δv is very high
  - Alternatively reasonable Δv (1.8-2.0 km/s) can deliver 2800-3000 kg
  - Direct-to-Jupiter (EJU) likely infeasible without Falcon Heavy kickstsage
- ACE Run recommendation (solutions to optimize further)

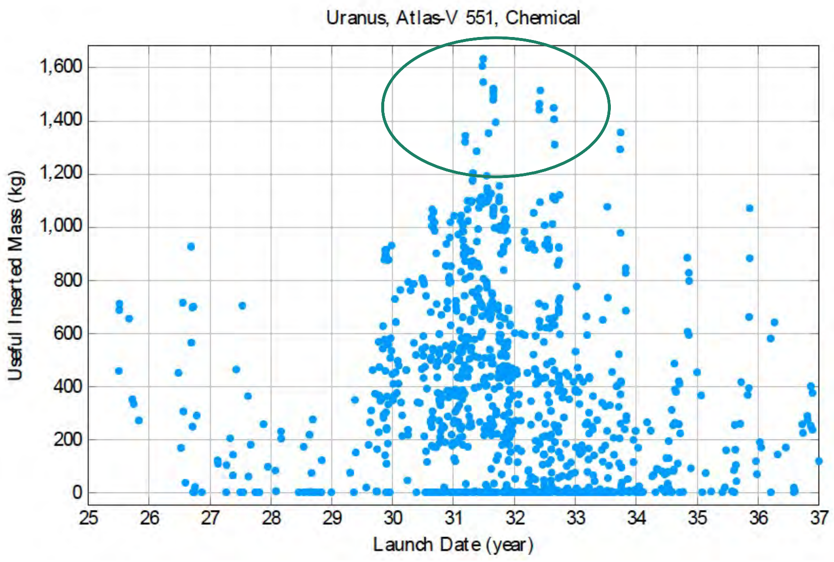
Launch Date	C3 (km2/s2)	Path	DSM (km/s)	UOI (km/s)	PLΔV (km/s)	Post-UOI Mass (kg)	TOF (yrs)
6/13/2031	27.1	E(DV)EJU	0.773	1.011	1.783	4919	13.4
6/15/2031	27	E(DV)EJU	0.717	1.251	1.968	4643.5	12.7
4/29/2032	28.8	E(DV)EJU	0.602	0.956	1.558	5111.5	12.8

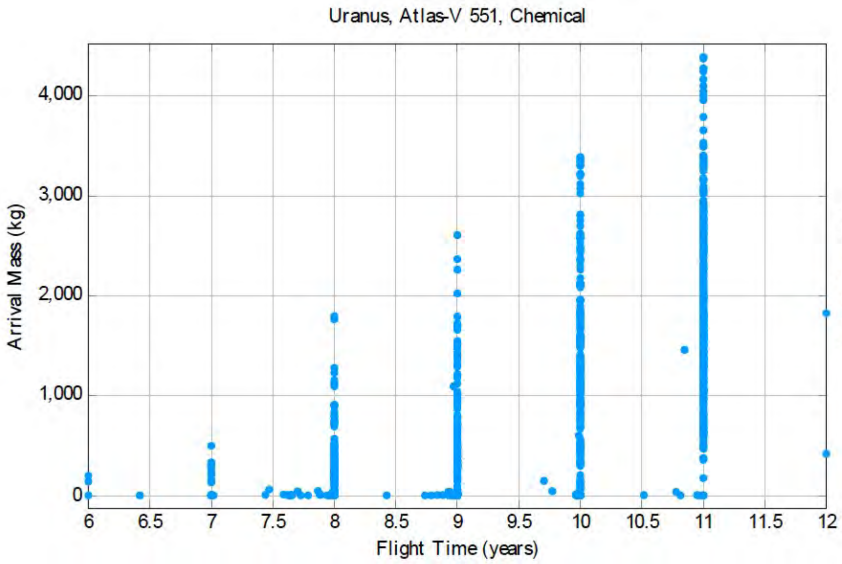
Other Trajectories (JPL 2017)

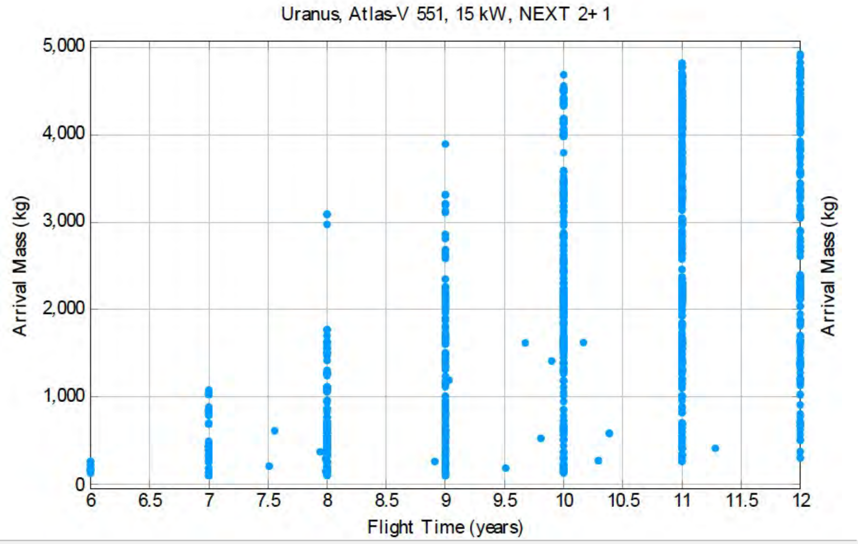
2017 study found many opportunities that close with a launch on an Atlas V551 with chemical-only propulsion or with SEP, reasonable cruise durations, and mass into orbit

Main difference is in the post-UOI mass assumptions:

- Probe release before UOI
- Gravity losses not included
- Tour Delta V not defined

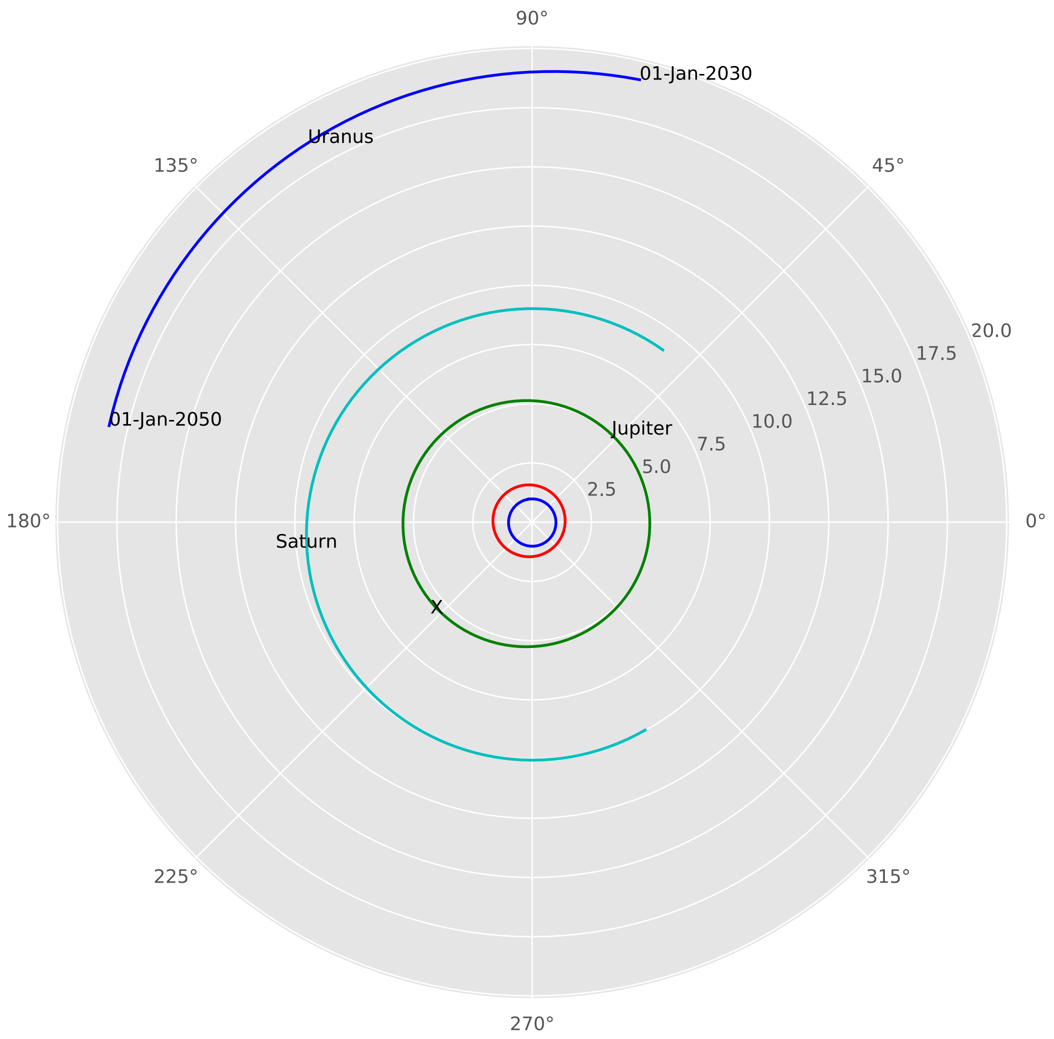




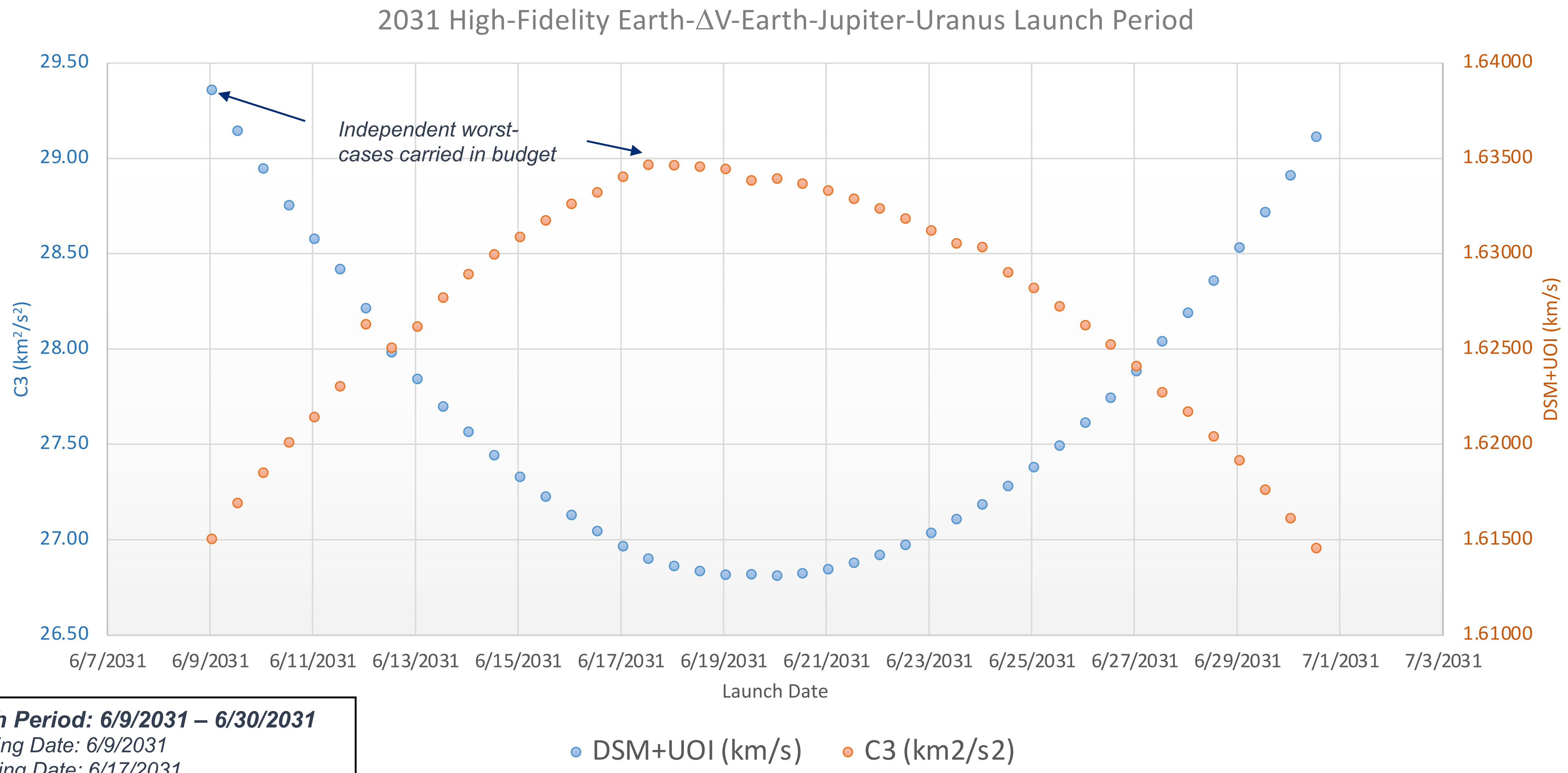


Transition to High-Fidelity

- Methodology: Fully optimized & integrated trajectories for 2031 launch period (2032 is superior and will close around 2031)
  - This design-fidelity is beyond that of a preliminary study. Typical of Phase A – Phase B NASA mission.
- Finite-burn UOI & PRM Main Engine 2x635 N Isp 318 sec (~Leros 1B)
- Uranus capture orbit condition:
  - Periapsis: 3000 km altitude
  - Period: 122 days
- Ephemeris
  - Planets: DE430 (Sun Earth Moon and planet barycenters)
  - Jupiter: JUP320 (Jovian System)
  - Uranus: URA111 (Uranian System)

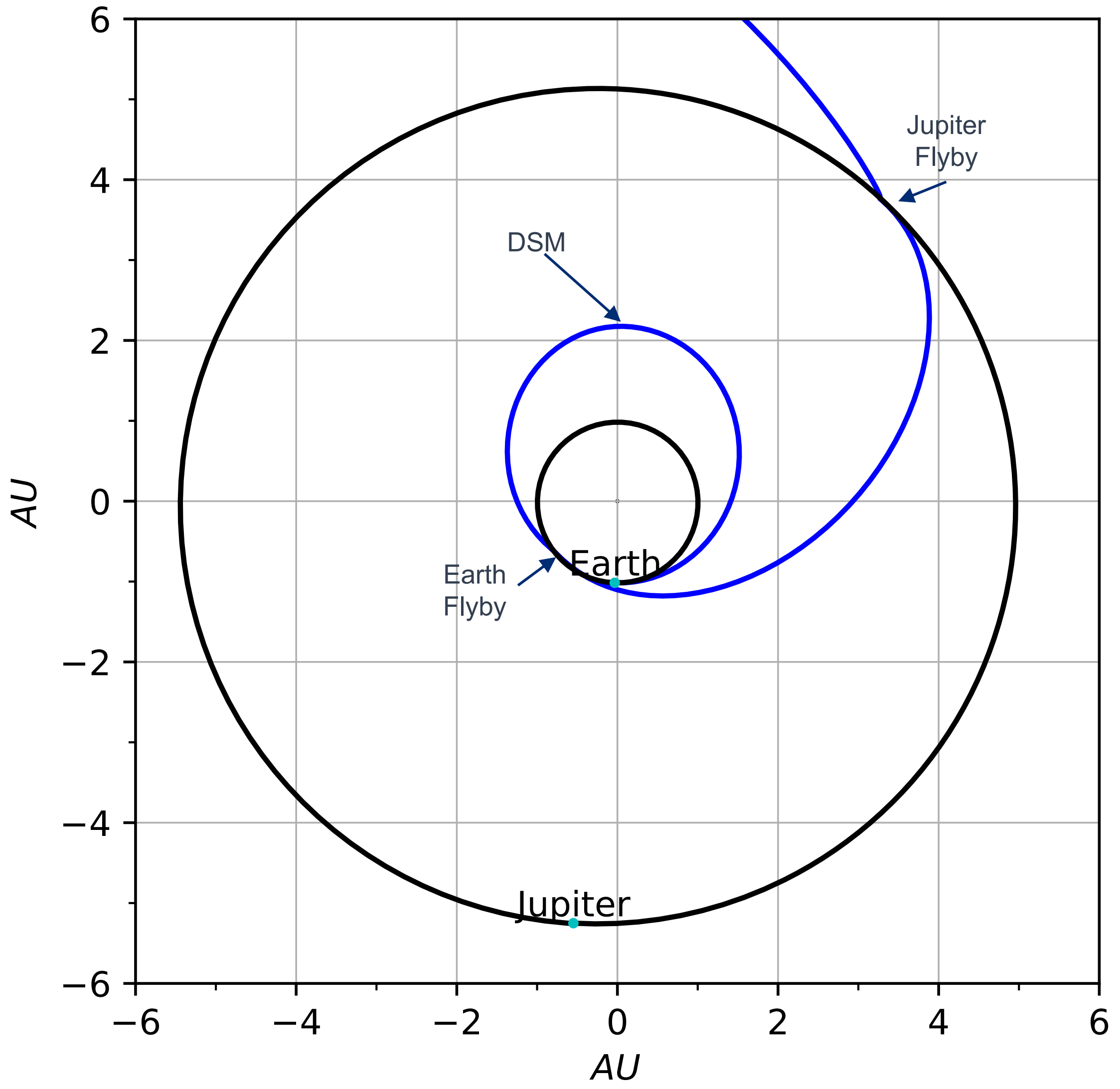


2031 Launch Period Analysis



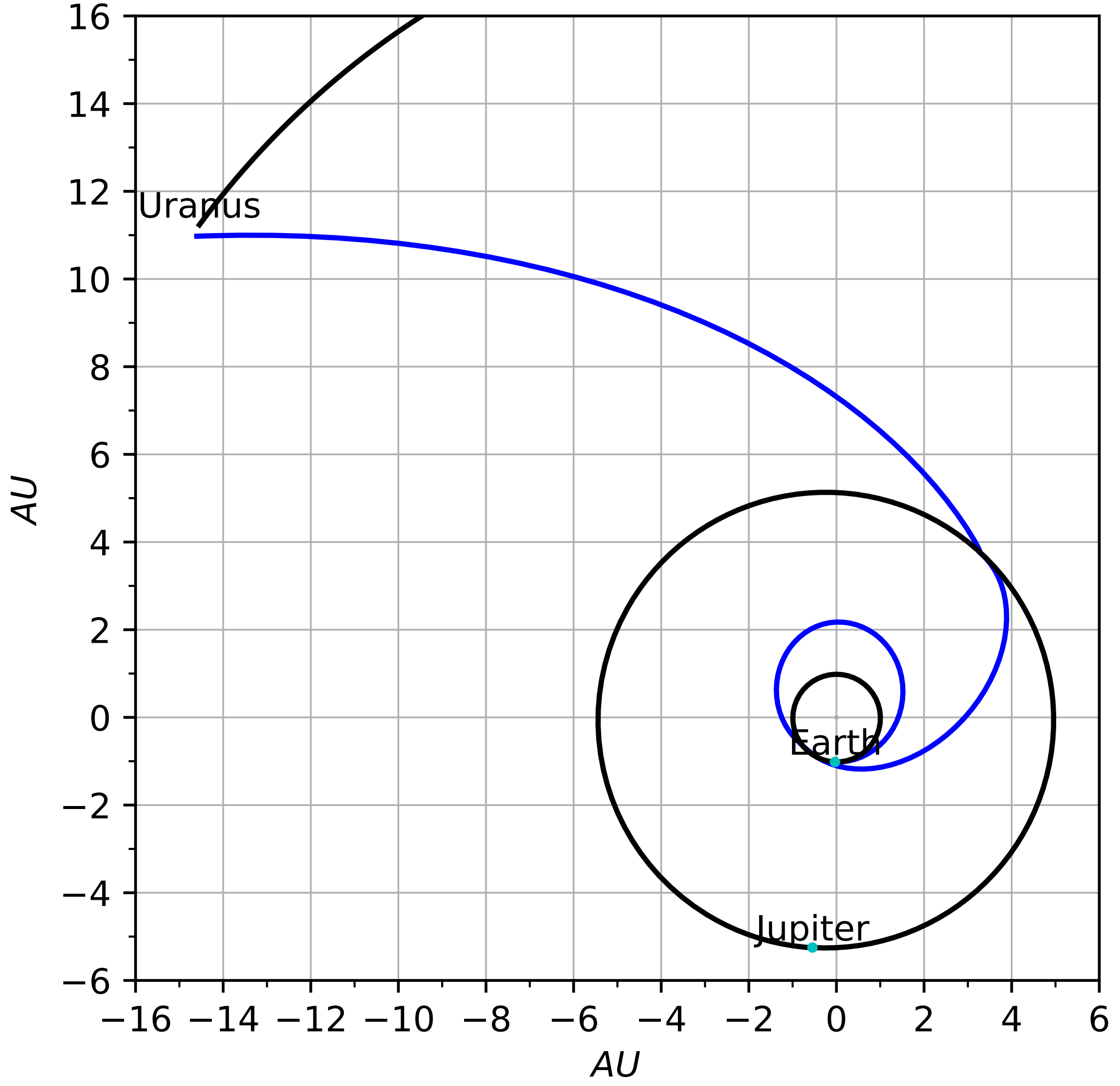
Launch Period: 6/9/2031 – 6/30/2031
C3 Driving Date: 6/9/2031
DV Driving Date: 6/17/2031

High-Fidelity Baseline Cruise Trajectory



Parameter	Value	Units
Earth Departure	20-Jun-2031	ET
Departure C_3	26.81	km^2/s^2
DSM	27-Jun-2032	ET
DSM Dv	659.320	m/s
Earth Flyby	27-Apr-2033	ET
Flyby Altitude	450	km
Jupiter Flyby	21-Dec-2035	ET
Flyby Altitude	369550	km
Uranus Approach	05-Nov-2044	ET
Inbound v_∞	6.267	km/sec
TOF	13.462	year

High-Fidelity Baseline Cruise Trajectory



Parameter	Value	Units
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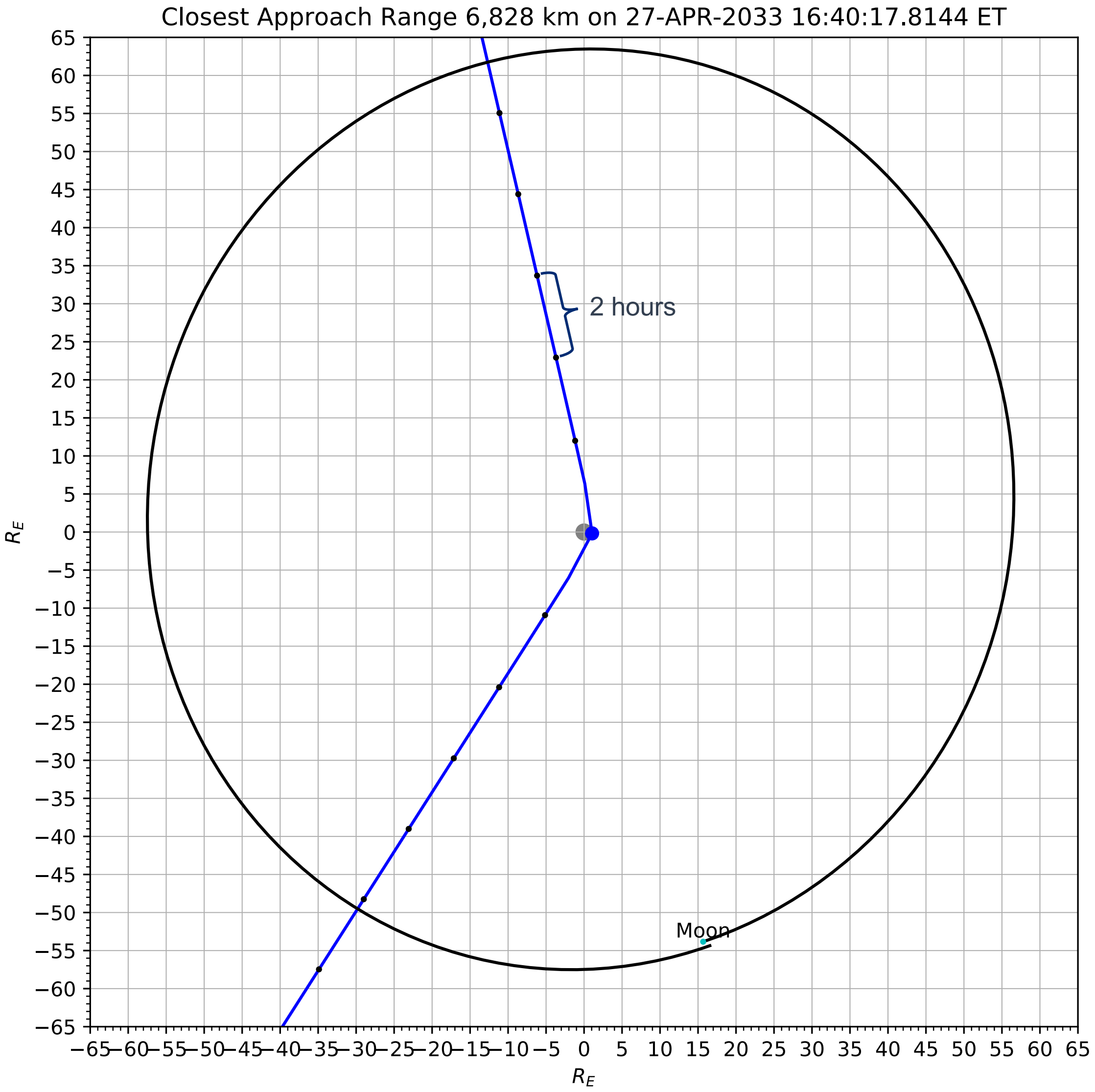
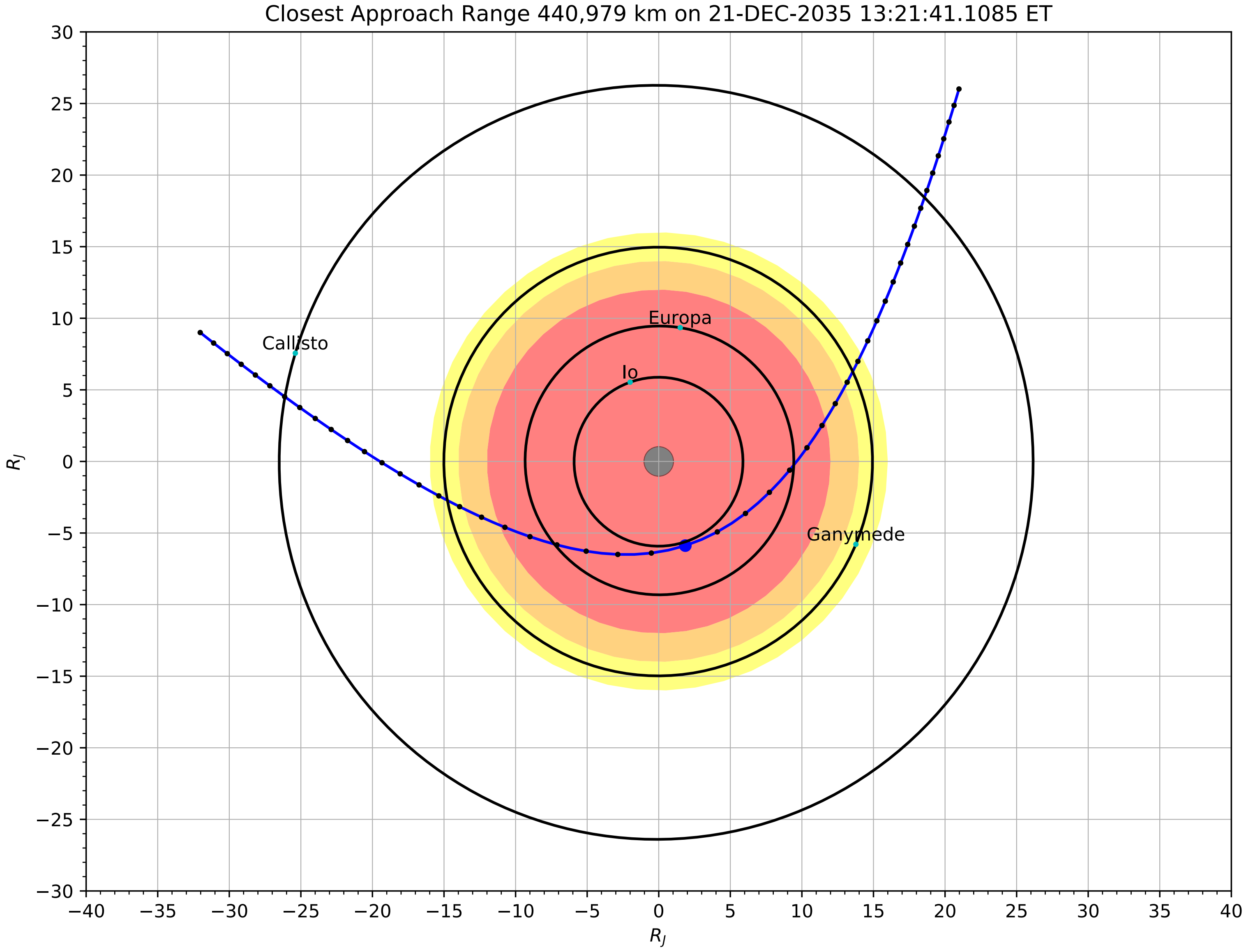
Flyby Altitude	369550	km
Uranus Approach	05-Nov-2044	ET
Inbound v_∞	6.267	km/sec
TOF	13.462	year

Earth Flyby Detail



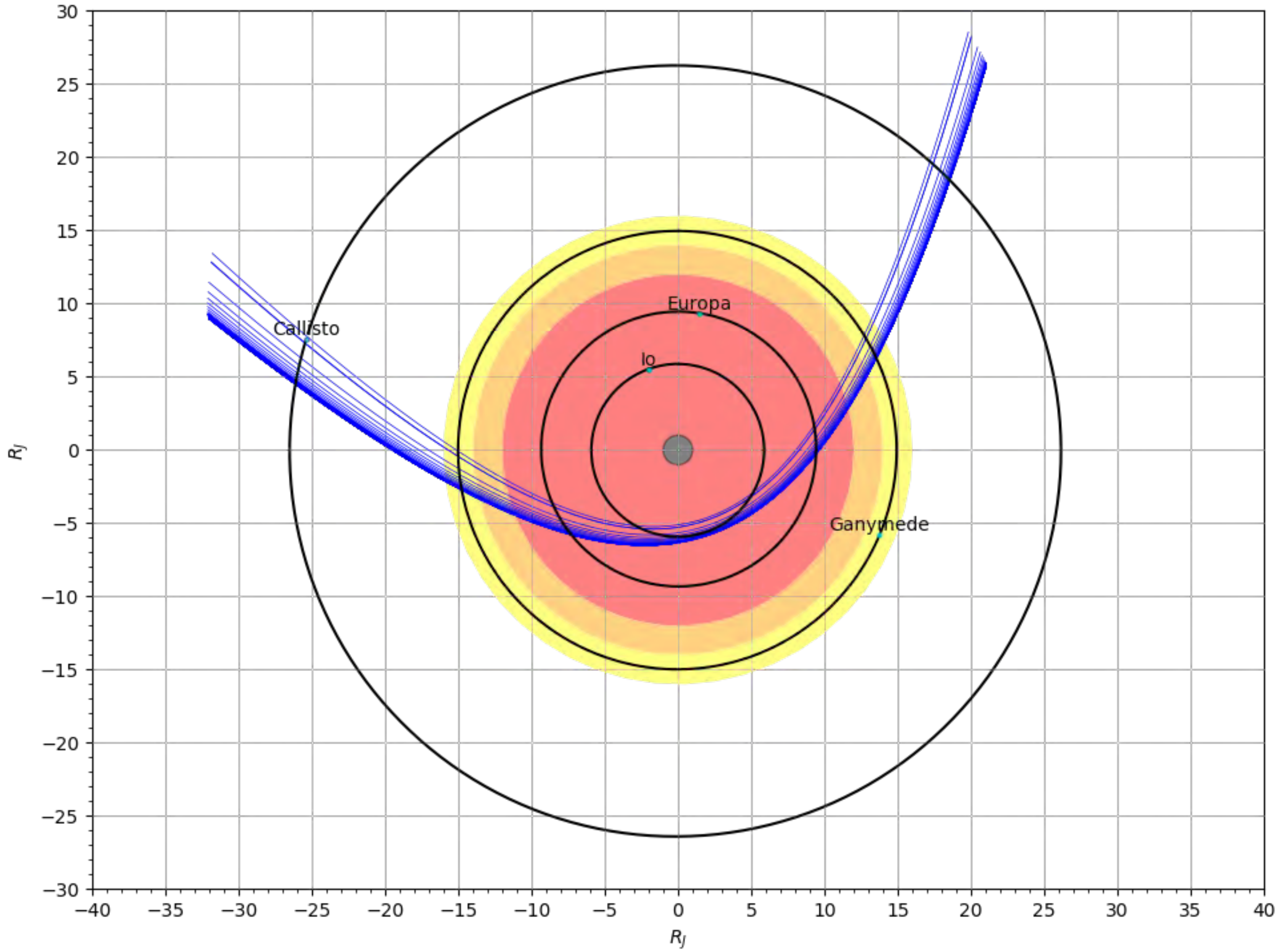
- Encounter altitude (450 km) compatible with *Dragonfly* (also nuclear-powered)

Jupiter Flyby Detail



- During Jupiter gravity assist spacecraft dwells for ~24h inside Jupiter radiation zone

Jupiter Flyby Detail



- During Jupiter gravity assist spacecraft dwells for ~24h inside Jupiter radiation zone
- All alternatives in the launch period exhibit this behavior

Summary of Key Science Phase Findings

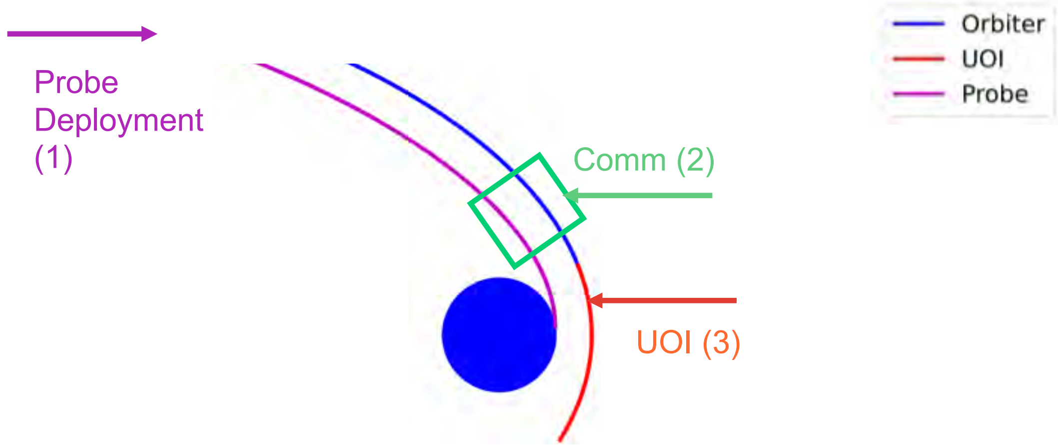
I. UOP is first study to investigate in detail Uranus Orbit Injection probe deployment and tour design relying on **consolidated high-fidelity models**
   1. Fully investigated ring avoidance during Uranus Orbit Injection
   2. Gravity losses (which accounted for 175 m/s) brought down to 50 m/s via higher thrust level and velocity-tracking burn implementation
   3. Tour design validated in high-fidelity

II. Post-capture probe release is essential for concept feasibility

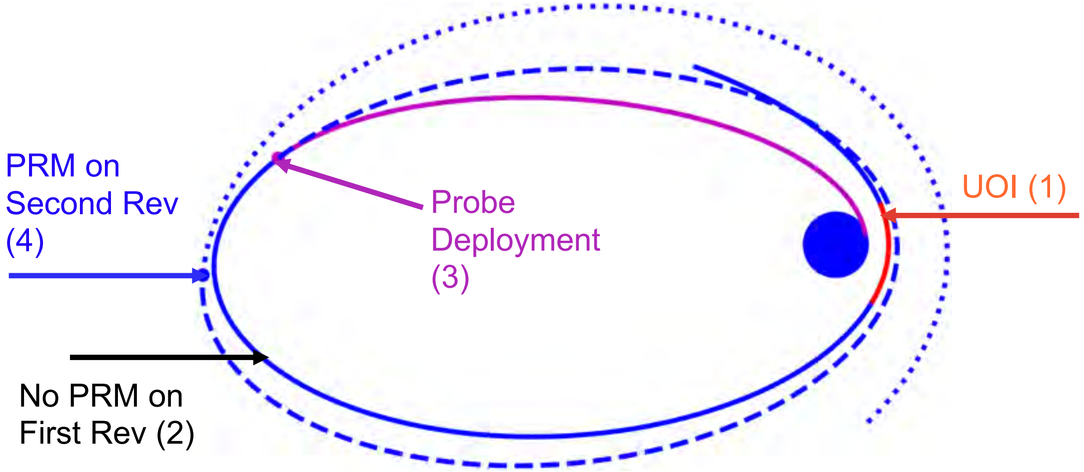
III. UOP capture conditions enable a variety of tour architectures (8 studies analyzed so far)
   1. Currently, equatorial tour of major satellites with robust science return is designed
   2. Design methodology largely independent of cruise trajectory type
   3. End-of-life architecture currently under investigation
      1. Based on orbiter disposal via Uranus atmospheric entry
   4. Planetary protection considerations currently under investigation
      1. Approach validated by well-accepted concepts like Cassini and Europa Clipper

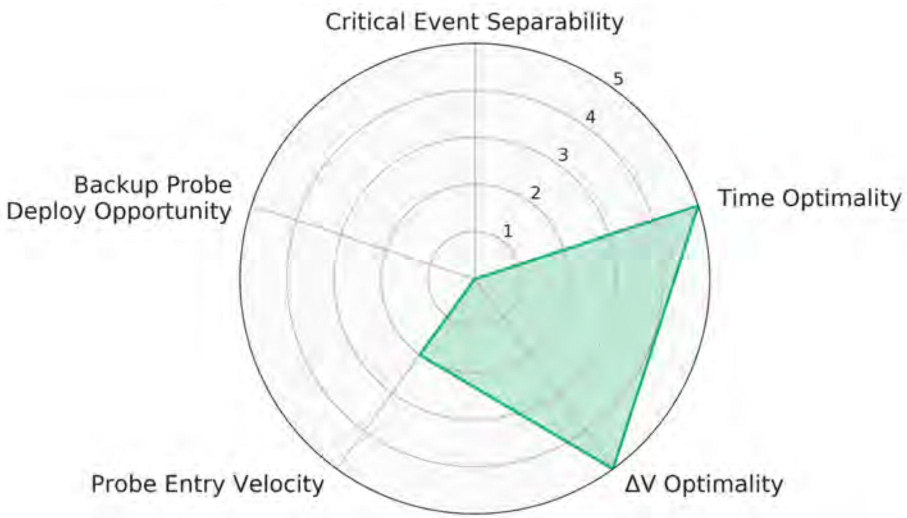
Probe/Orbiter Architectures to Consider

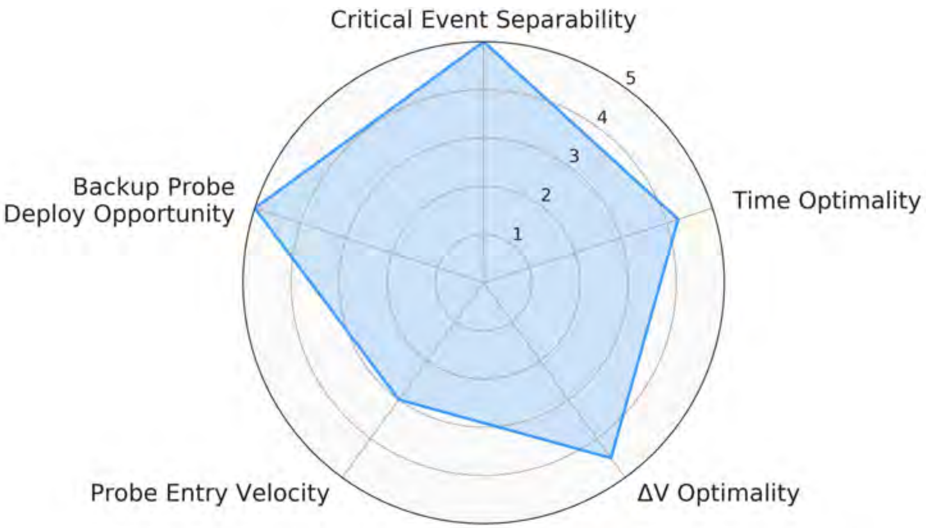
Deployment on Hyperbolic Approach



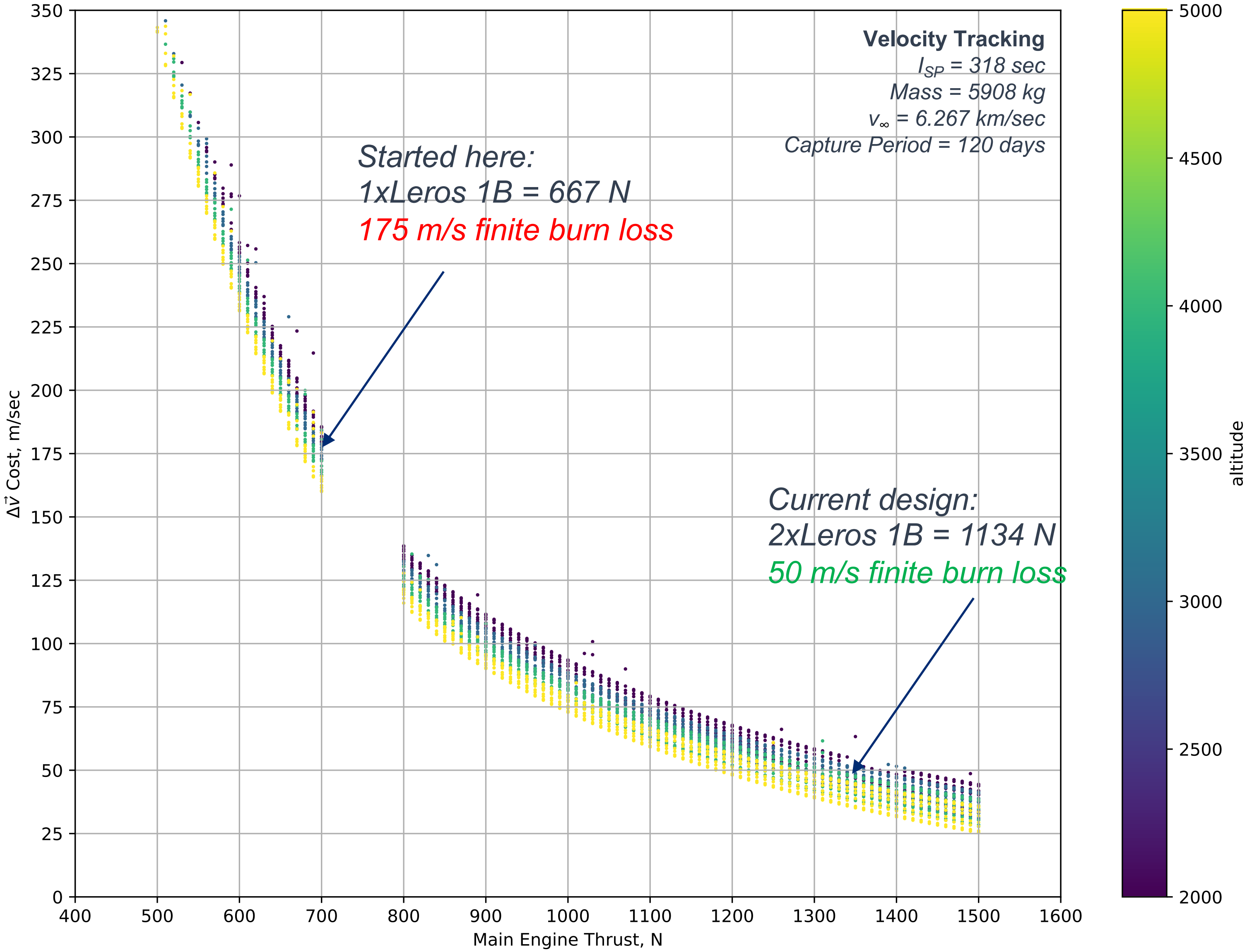
Deployment on Elliptic Post-Capture

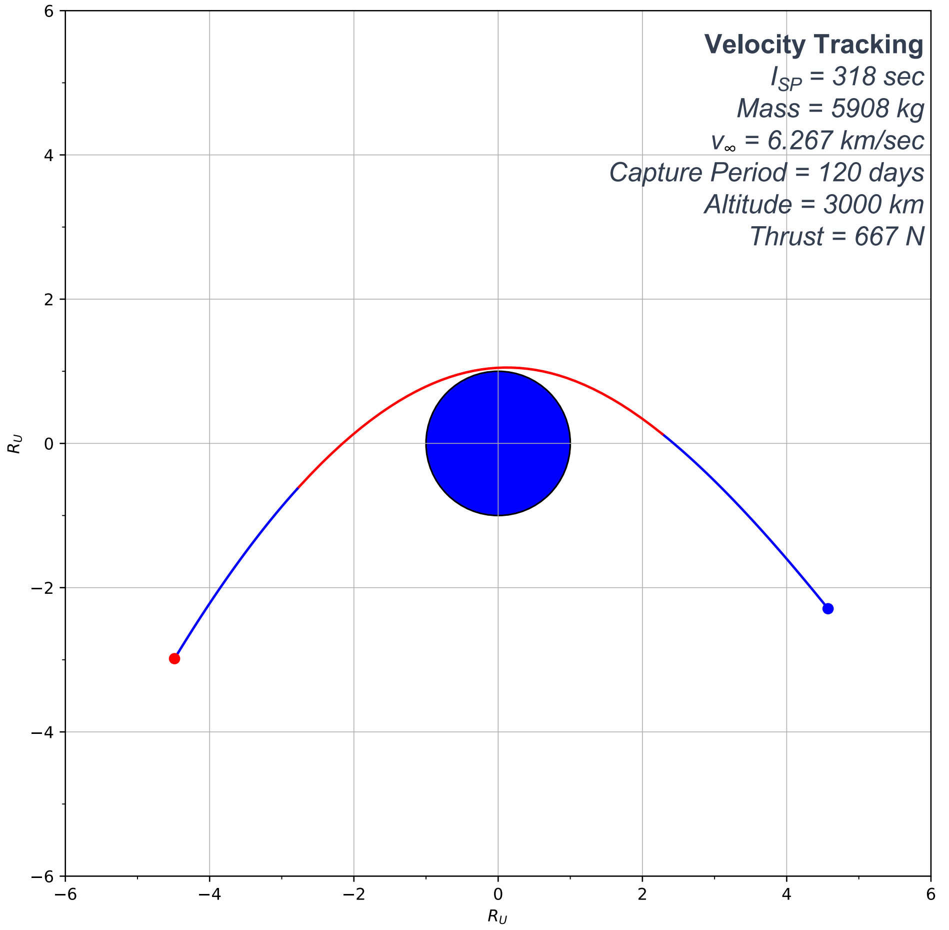




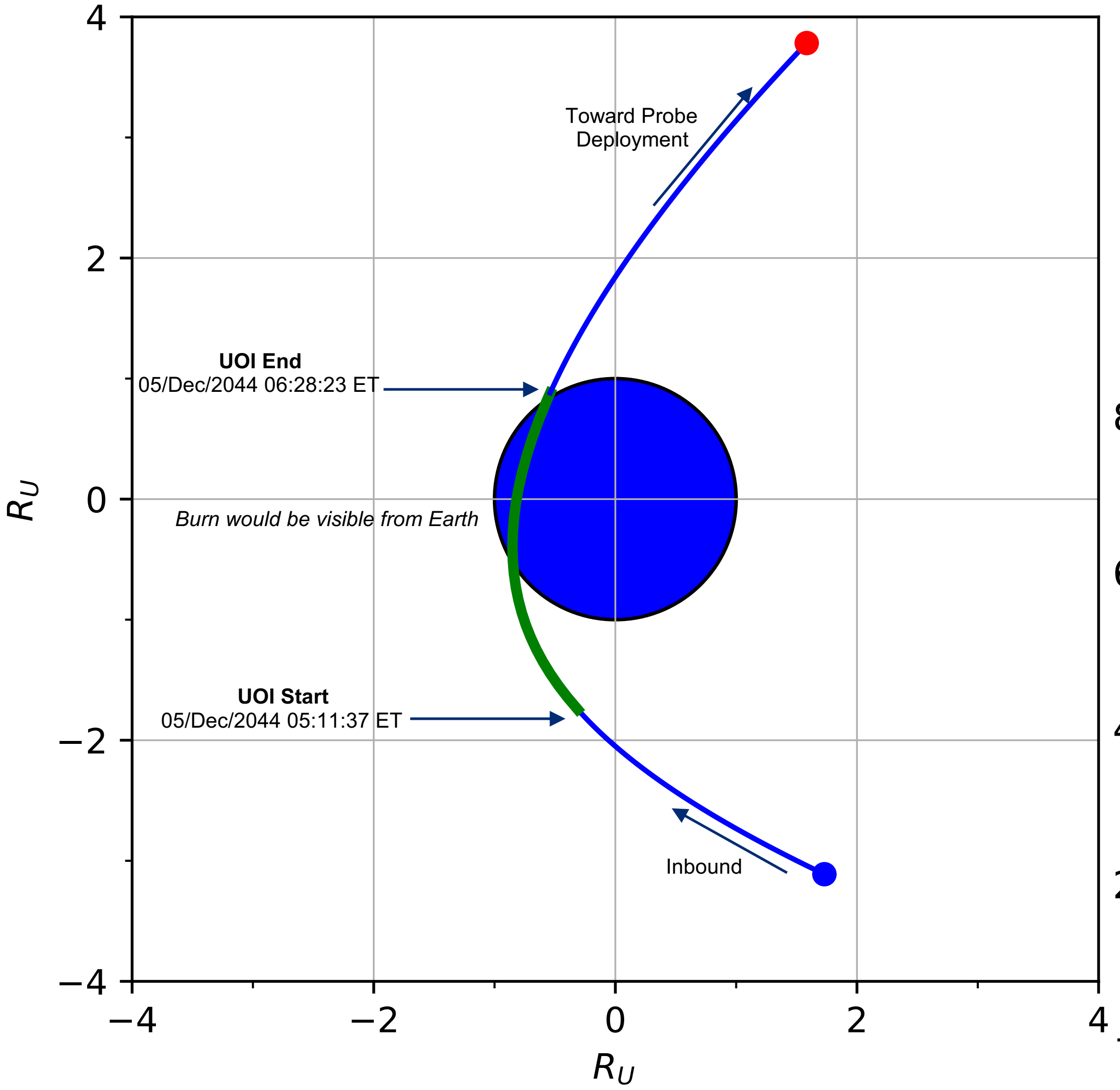


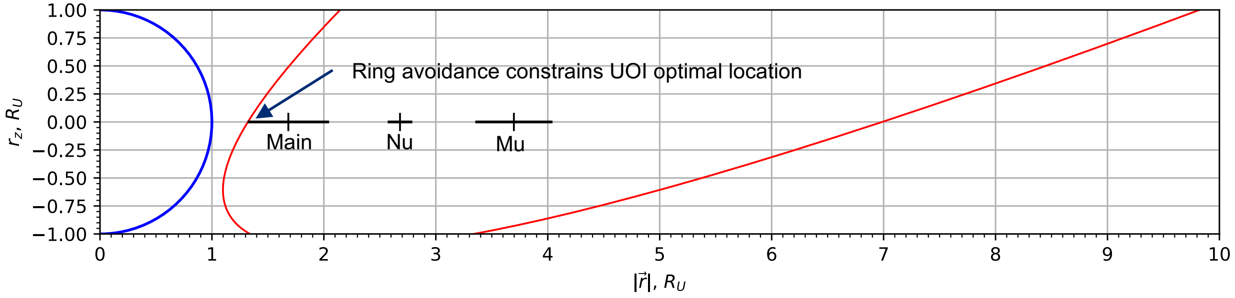
Finite Burns Entail High Gravity Losses

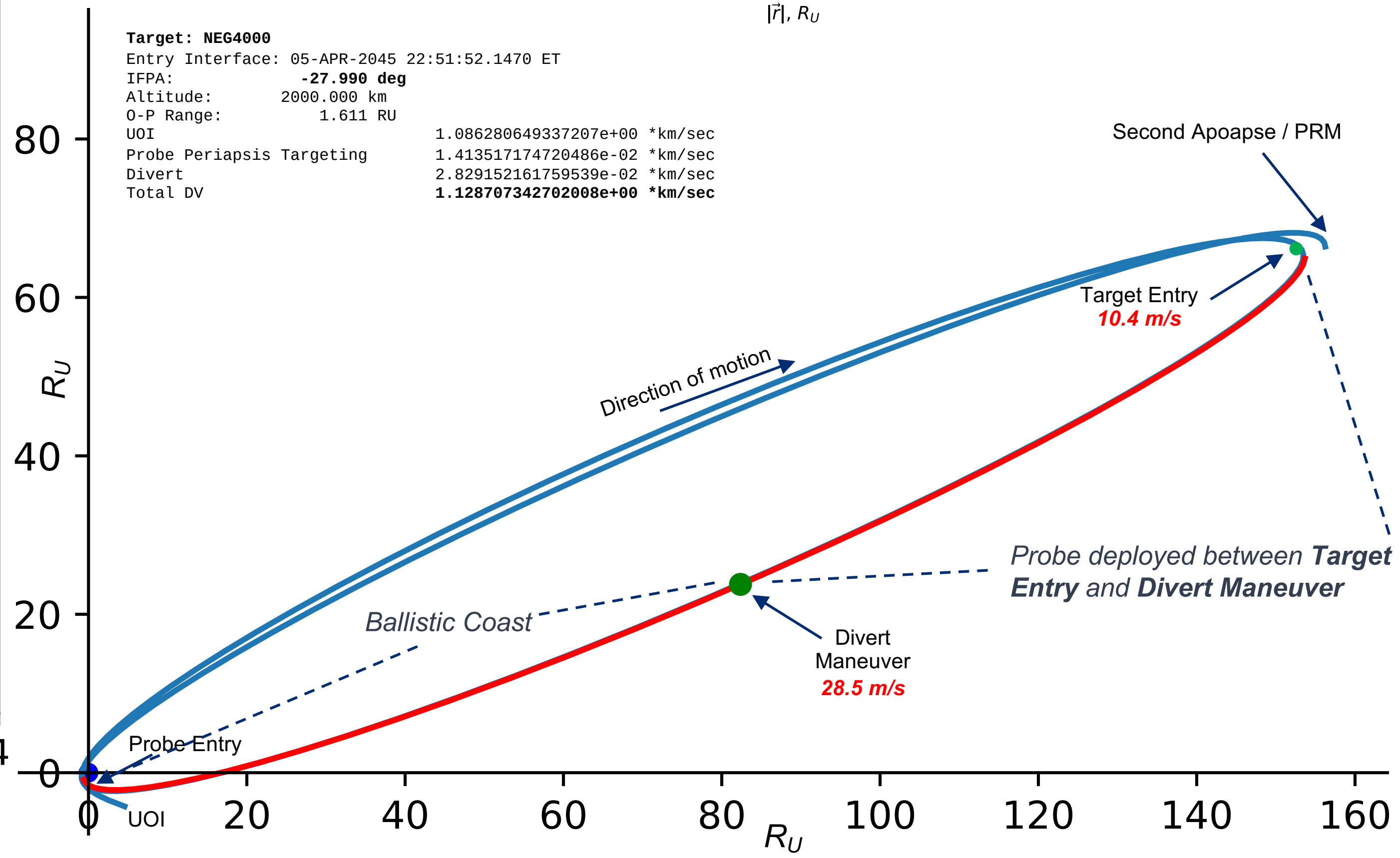




Detailed Capture and Probe Deployment ConOps







Sequence of Events

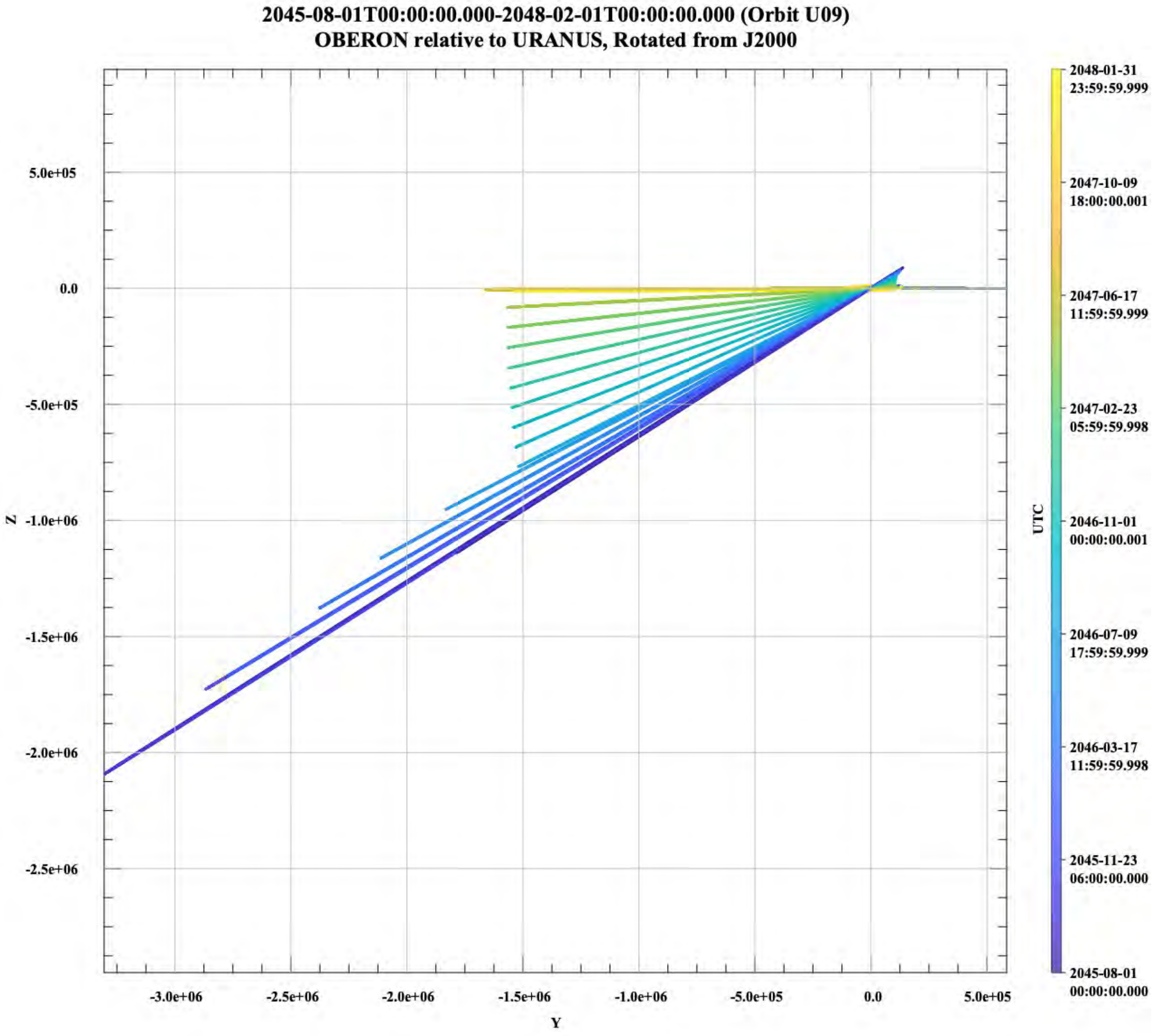
Event	Date (ET)
Launch	20-Jun-2031
Deep Space Maneuver	27-Jun-2032
Earth Flyby	27-Apr-2033
Jupiter Flyby	20-Dec-2035
Uranus Arrival / UOI	05-Dec-2044
Capture Apoapsis / Entry Targeting	05-Feb-2045 (E-60.8 days)
Probe Release	E-60.8 days and E-12.9 days [TBD]
Divert Maneuver	24-Mar-2045 (E-12.9 days)
Probe Entry	06-Apr-2045 19:28:40 (E-0 sec)
Orbiter Periapsis	06-Apr-2045 20:11:41 (E+43 min)
Orbiter Apoapsis / PRM	06-Jun-2045 (E+61 days)
Tour Start	~06-Jul-2045

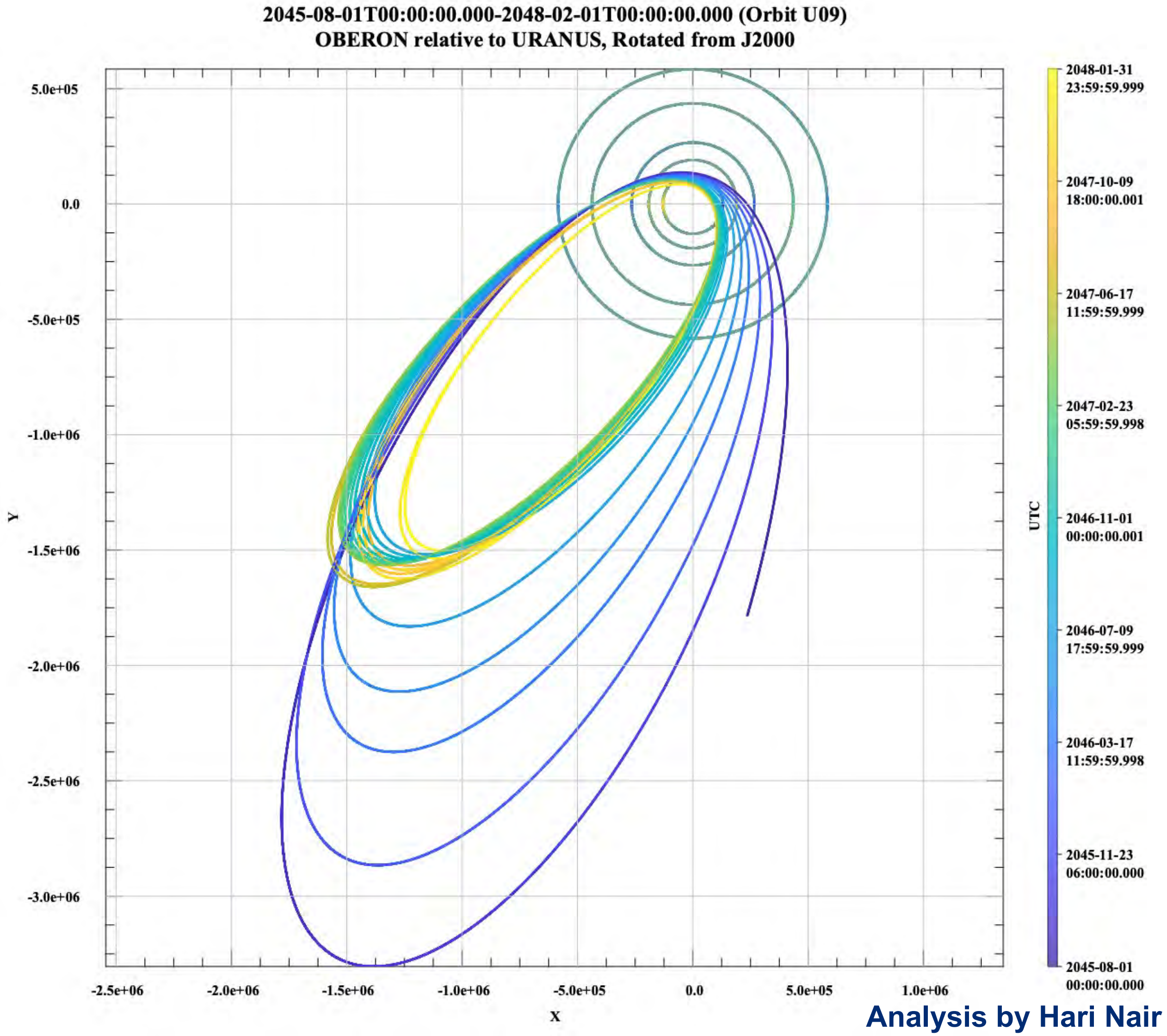
Case Study – Nearly Ballistic Equatorial Tour

ORBIT	BODY	TIME (UTC)	PHASE (deg)	RANGE (km)	ALTITUDE (km)	GROUND SPEED (km)	LAT	LON	SUBSOLAR LAT	SUBSOLAR LON
U01	TITANIA	2045-08-11T00:46:27.584	13.77	1173.59	384.69	2.97	34.11N	91.07E	20.70N	87.58E
U02	TITANIA	2045-11-14T19:05:12.272	44.58	861.27	72.37	4.05	60.94N	64.46E	19.49N	87.71E
U03	TITANIA	2046-02-01T03:32:54.217	33.62	851.66	62.76	4.10	51.78N	81.93E	18.49N	87.86E
U04	TITANIA	2046-04-03T02:06:54.944	43.21	931.66	142.76	3.74	59.92N	75.09E	17.72N	87.95E
U05	TITANIA	2046-05-25T07:47:54.361	38.73	815.59	26.69	4.28	55.68N	84.30E	17.06N	88.11E
U06	TITANIA	2046-07-07T20:22:05.547	24.37	814.65	25.75	4.28	39.17N	98.21E	16.51N	87.97E
U07	TITANIA	2046-08-11T16:08:54.669	73.16	814.67	25.77	4.28	75.42N	3.27E	16.06N	88.06E
U08	TITANIA	2046-09-15T12:01:06.741	73.68	827.26	38.36	4.22	77.21N	3.27E	15.62N	88.32E
U09	TITANIA	2046-10-20T07:46:29.321	74.12	842.32	53.42	4.15	78.98N	3.56E	15.18N	88.37E
U10	TITANIA	2046-11-24T03:27:42.357	75.26	882.17	93.27	3.95	80.43N	359.60E	14.74N	88.31E
U11	TITANIA	2046-12-28T23:11:50.916	74.96	860.55	71.65	4.05	82.40N	4.92E	14.29N	88.33E
U12	TITANIA	2047-02-01T18:59:10.052	75.53	865.09	76.19	4.03	84.10N	5.20E	13.85N	88.44E
U13	TITANIA	2047-03-08T14:46:21.575	75.73	875.19	86.29	3.99	85.86N	11.02E	13.41N	88.54E
U14	TITANIA	2047-04-12T10:29:02.705	76.42	885.69	96.79	3.94	87.48N	12.85E	12.96N	88.52E
U15	TITANIA	2047-05-17T06:14:11.162	93.12	964.45	175.55	3.61	72.71N	294.23E	12.52N	88.57E
U16	UMBRIEL	2047-06-22T04:14:56.556	118.51	5939.16	5354.46	0.52	1.79S	77.31E	12.12N	196.11E
U17	OBERON	2047-07-28T01:01:16.109	106.02	1799.96	1038.56	1.62	4.16S	66.71E	11.89N	172.23E
U17	ARIEL	2047-07-29T02:01:59.826	126.31	4364.67	3786.72	0.76	0.18S	82.60E	11.56N	209.74E
U18	ARIEL	2047-08-30T20:41:55.111	53.31	2399.50	1821.57	1.39	0.19N	264.17E	11.15N	211.63E
U19	UMBRIEL	2047-10-03T18:37:22.110	118.14	4237.63	3652.93	0.73	2.61N	76.52E	10.80N	195.82E
U20	TITANIA	2047-11-07T11:48:26.141	159.86	7294.53	6505.63	0.47	1.88S	292.06E	10.30N	93.64E
U21	OBERON	2047-12-09T16:53:44.176	105.44	1223.55	462.15	2.40	8.53N	65.78E	10.17N	173.26E
U22	ARIEL	2048-01-10T10:35:28.468	44.24	2056.50	1478.66	1.66	45.15N	99.27E	9.46N	68.86E

Analysis by Hari Nair

Orbit view – “side” and “top”

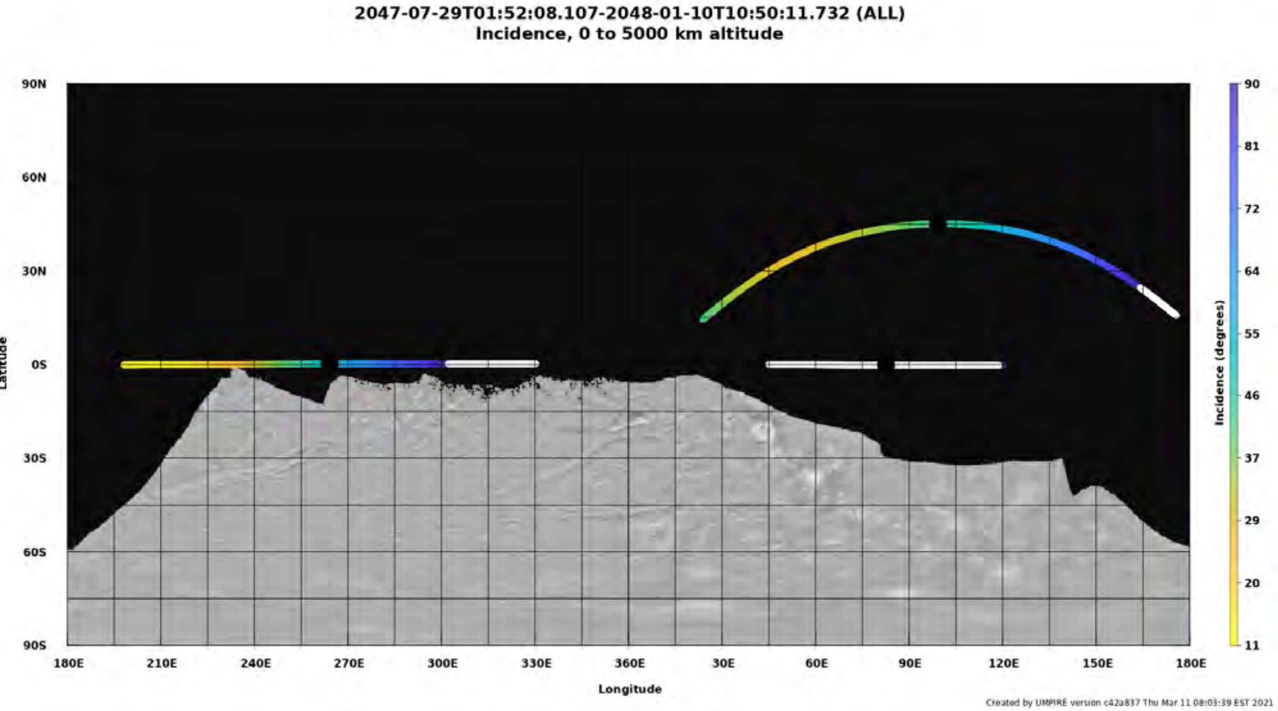


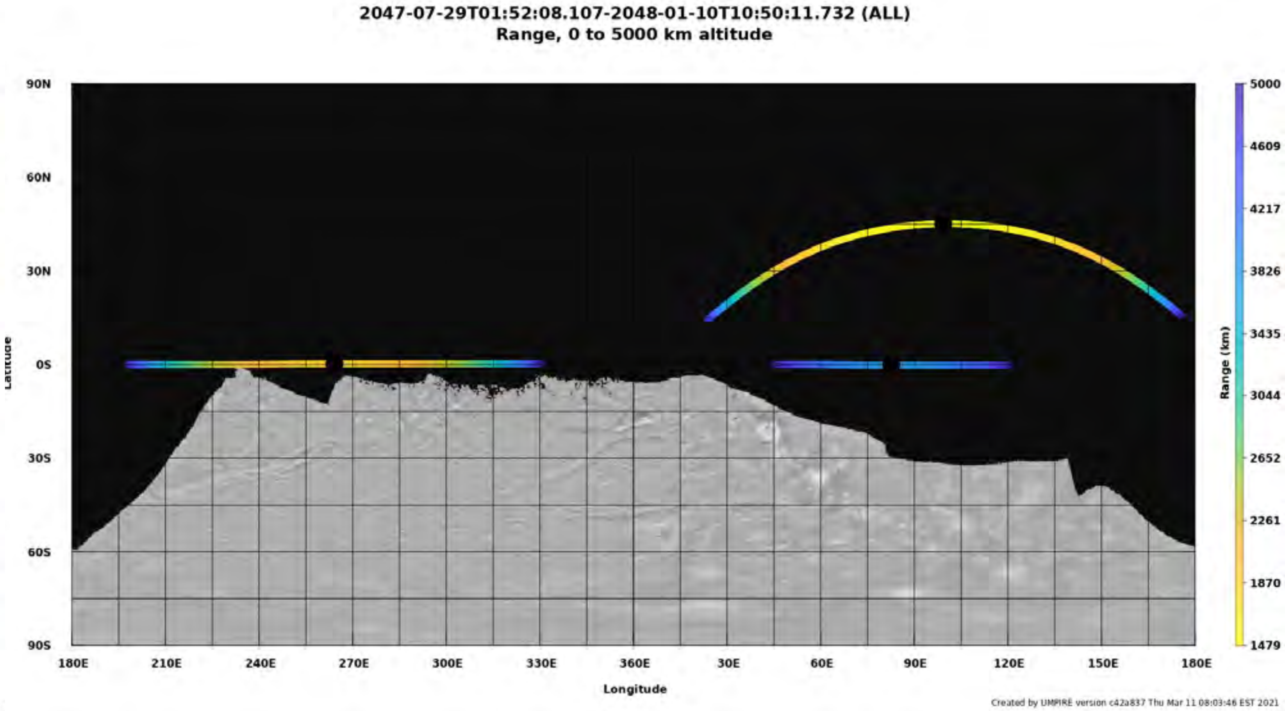


Analysis by Hari Nair

3 Ariel flybys

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U17	ARIEL	2047-07-29T02:01:59.826	126.31	4364.67	3786.72	0.76	0.18S	82.60E	11.56N	209.74E
U18	ARIEL	2047-08-30T20:41:55.111	53.31	2399.50	1821.57	1.39	0.19N	264.17E	11.15N	211.63E
U22	ARIEL	2048-01-10T10:35:28.468	44.24	2056.50	1478.66	1.66	45.15N	99.27E	9.46N	68.86E

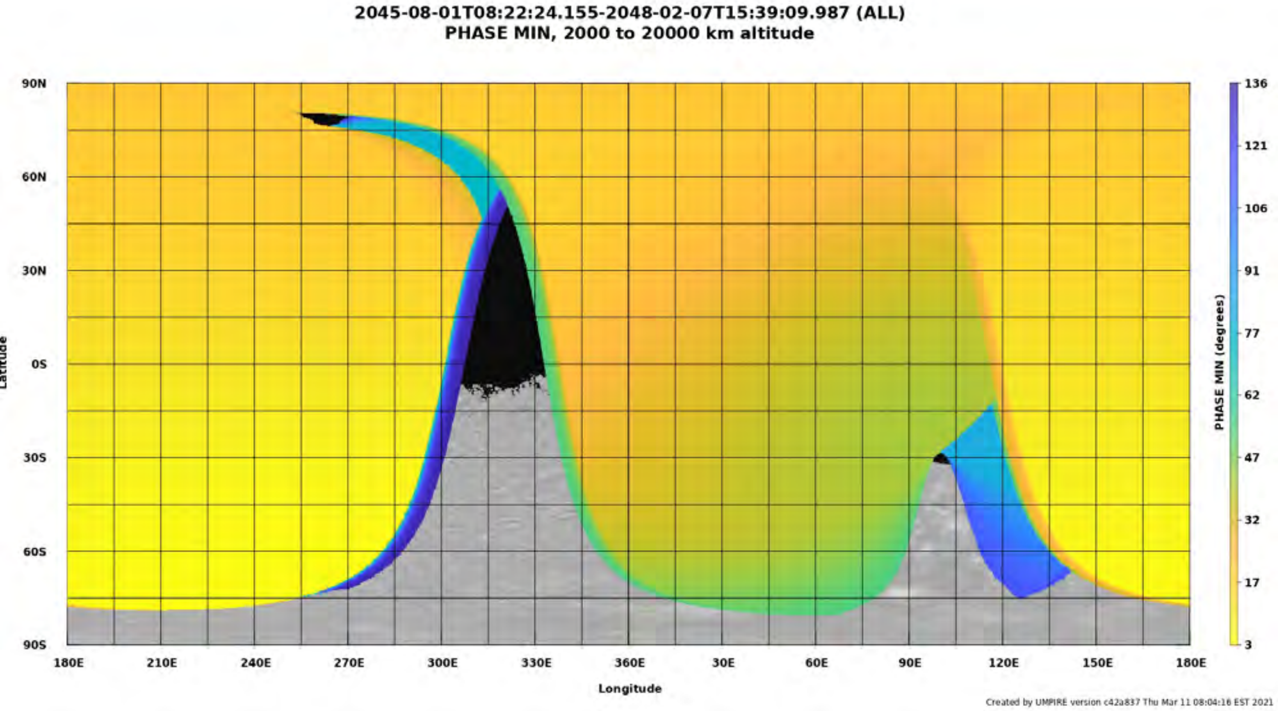


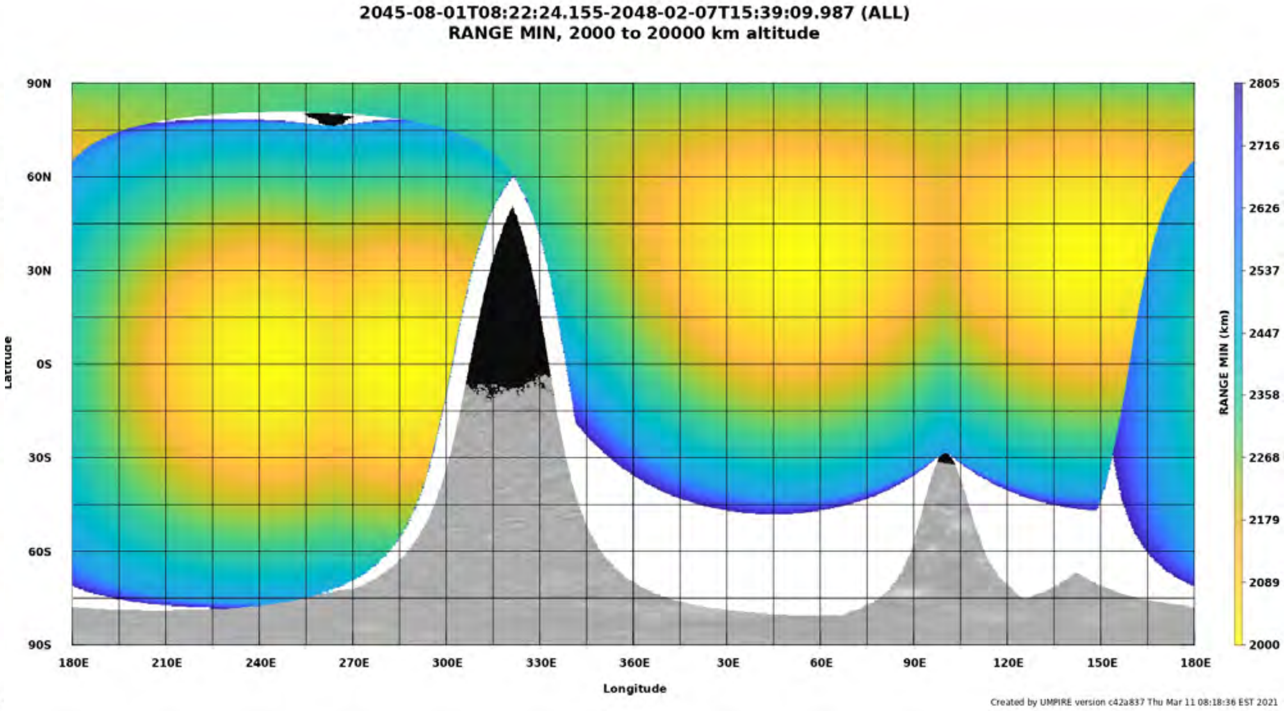


Analysis by Hari Nair

Ariel flyby imaging opportunities

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U17	ARIEL	2047-07-29T02:01:59.826	126.31	4364.67	3786.72	0.76	0.18S	82.60E	11.56N	209.74E
U18	ARIEL	2047-08-30T20:41:55.111	53.31	2399.50	1821.57	1.39	0.19N	264.17E	11.15N	211.63E
U22	ARIEL	2048-01-10T10:35:28.468	44.24	2056.50	1478.66	1.66	45.15N	99.27E	9.46N	68.86E

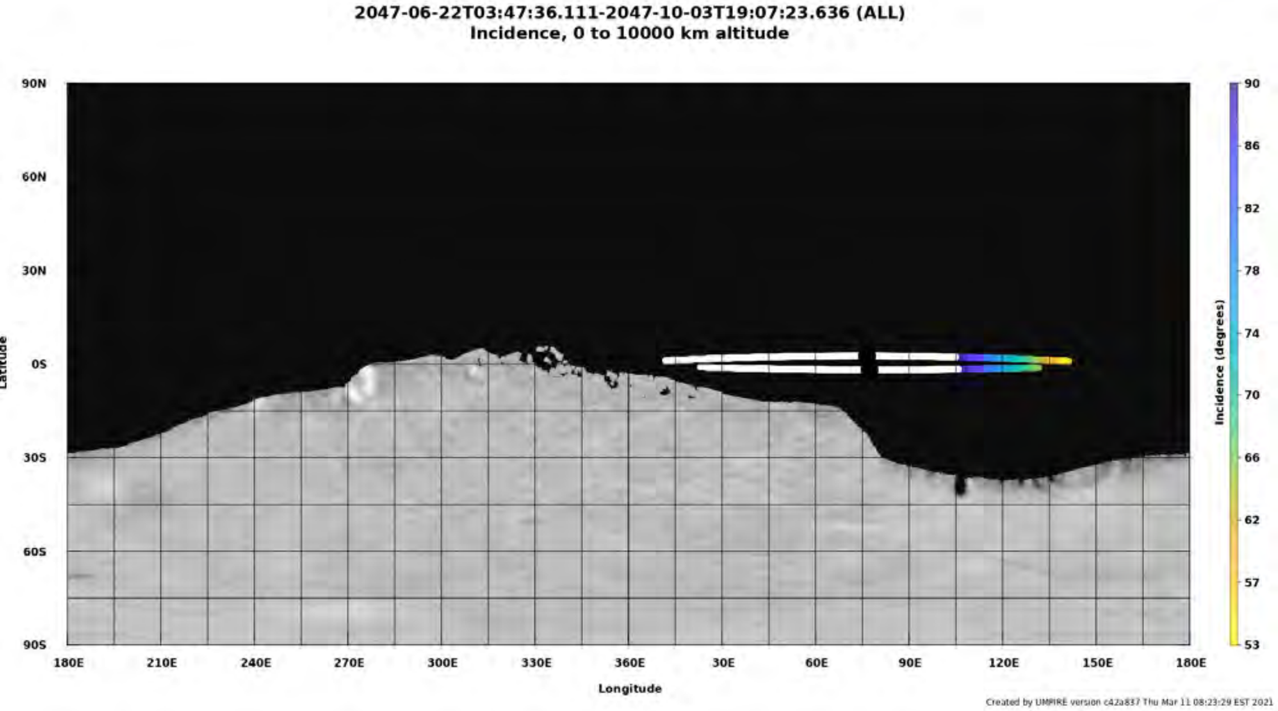


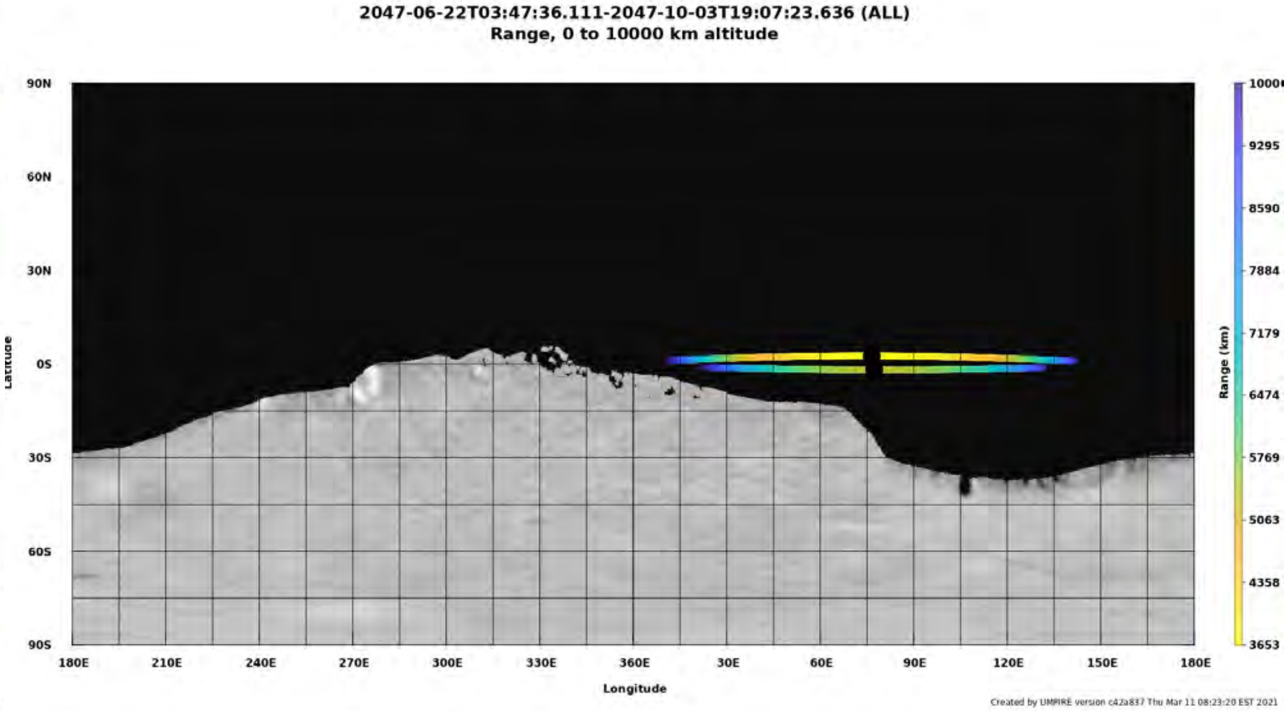


Analysis by Hari Nair

2 Umbriel flybys

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U16	UMBRIEL	2047-06-22T04:14:56.556	118.51	5939.16	5354.46	0.52	1.79S	77.31E	12.12N	196.11E
U19	UMBRIEL	2047-10-03T18:37:22.110	118.14	4237.63	3652.93	0.73	2.61N	76.52E	10.80N	195.82E

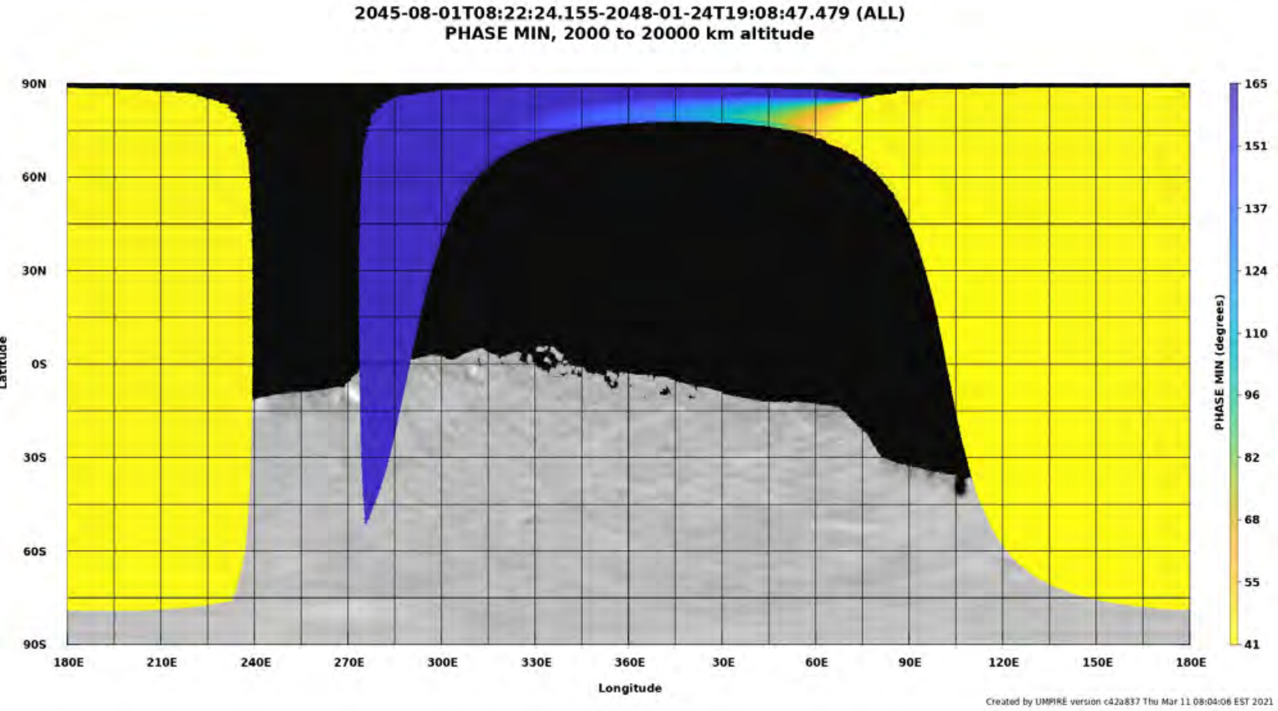


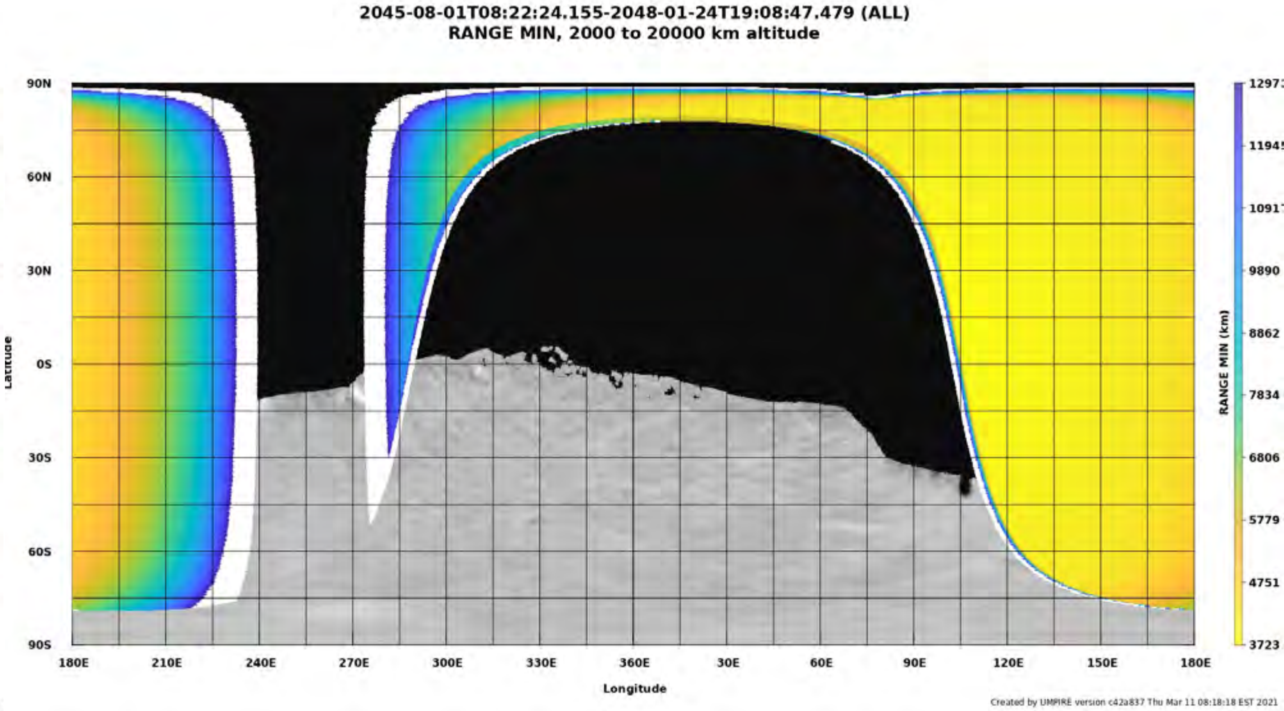


Analysis by Hari Nair

Umbriel flyby imaging opportunities

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U16	UMBRIEL	2047-06-22T04:14:56.556	118.51	5939.16	5354.46	0.52	1.79S	77.31E	12.12N	196.11E
U19	UMBRIEL	2047-10-03T18:37:22.110	118.14	4237.63	3652.93	0.73	2.61N	76.52E	10.80N	195.82E



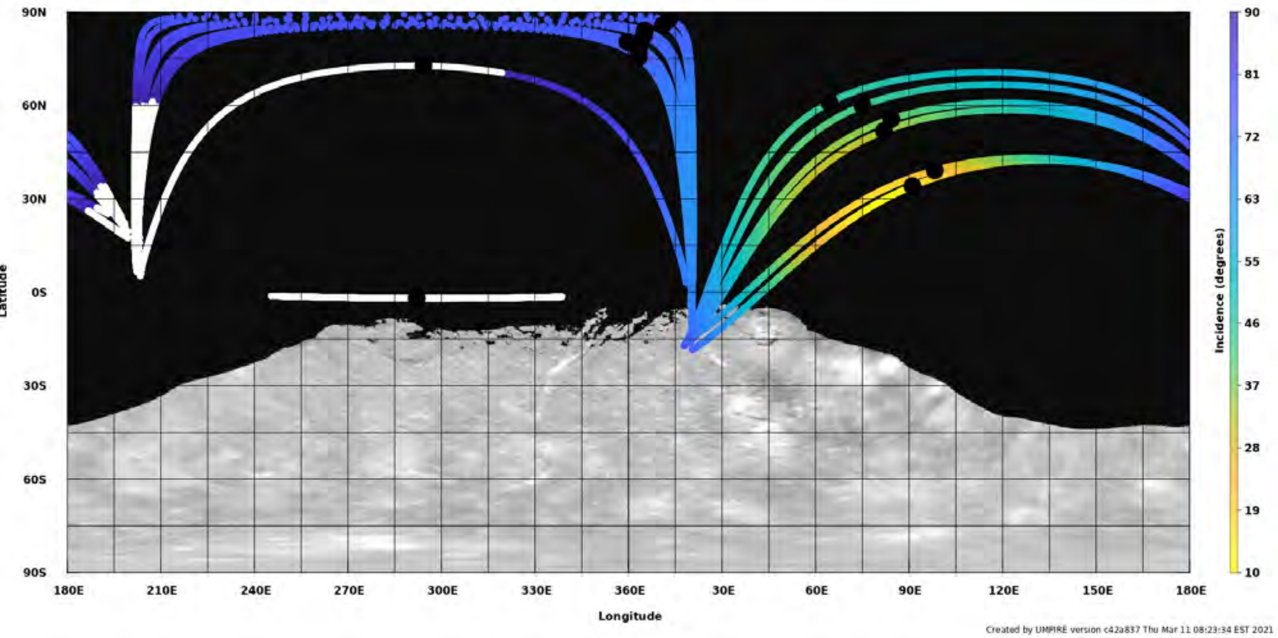


Analysis by Hari Nair

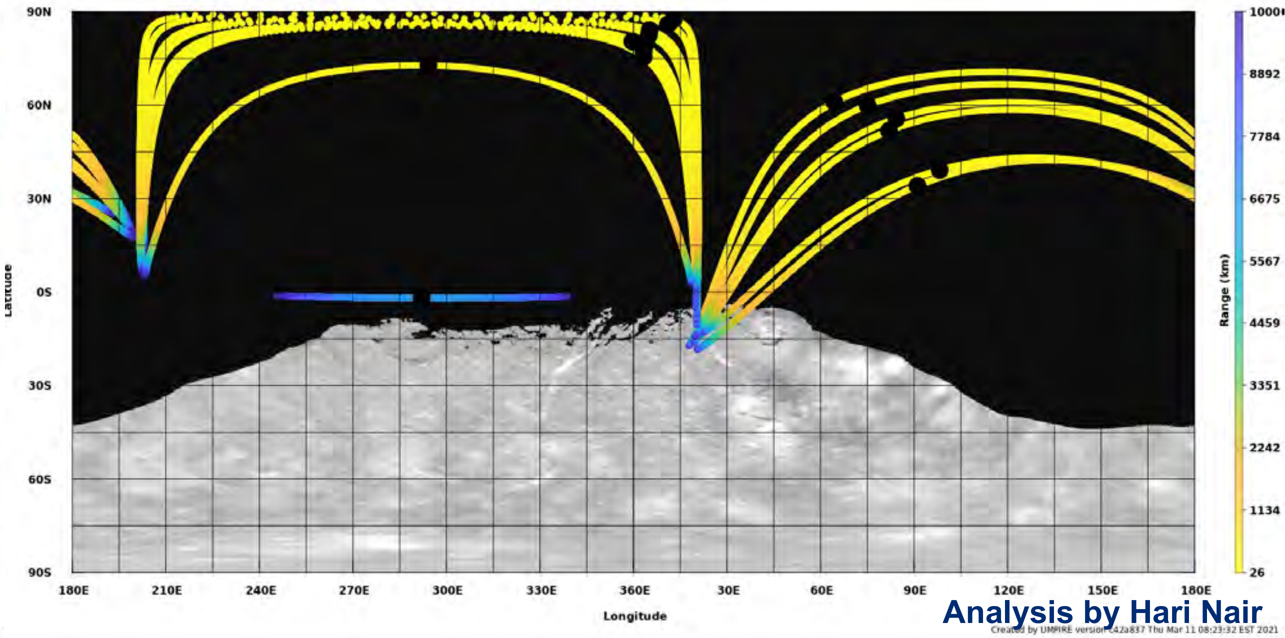
15 Titania flybys

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U01	TITANIA	2045-08-11T00:46:27.584	13.77	1173.59	384.69	2.97	34.11N	91.07E	20.70N	87.58E
U02	TITANIA	2045-11-14T19:05:12.272	44.58	861.27	72.37	4.05	60.94N	64.46E	19.49N	87.71E
U03	TITANIA	2046-02-01T03:32:54.217	33.62	851.66	62.76	4.10	51.78N	81.93E	18.49N	87.86E
U04	TITANIA	2046-04-03T02:06:54.944	43.21	931.66	142.76	3.74	59.92N	75.09E	17.72N	87.95E
U05	TITANIA	2046-05-25T07:47:54.361	38.73	815.59	26.69	4.28	55.68N	84.30E	17.06N	88.11E
U06	TITANIA	2046-07-07T20:22:05.547	24.37	814.65	25.75	4.28	39.17N	98.21E	16.51N	87.97E
U07	TITANIA	2046-08-11T16:08:54.669	73.16	814.67	25.77	4.28	75.42N	3.27E	16.06N	88.06E
U08	TITANIA	2046-09-15T12:01:06.741	73.68	827.26	38.36	4.22	77.21N	3.27E	15.62N	88.32E
U09	TITANIA	2046-10-20T07:46:29.321	74.12	842.32	53.42	4.15	78.98N	3.56E	15.18N	88.37E
U10	TITANIA	2046-11-24T03:27:42.357	75.26	882.17	93.27	3.95	80.43N	359.60E	14.74N	88.31E
U11	TITANIA	2046-12-28T23:11:50.916	74.96	860.55	71.65	4.05	82.40N	4.92E	14.29N	88.33E
U12	TITANIA	2047-02-01T18:59:10.052	75.53	865.09	76.19	4.03	84.10N	5.20E	13.85N	88.44E
U13	TITANIA	2047-03-08T14:46:21.575	75.73	875.19	86.29	3.99	85.86N	11.02E	13.41N	88.54E
U14	TITANIA	2047-04-12T10:29:02.705	76.42	885.69	96.79	3.94	87.48N	12.85E	12.96N	88.52E
U15	TITANIA	2047-05-17T06:14:11.162	93.12	964.45	175.55	3.61	72.71N	294.23E	12.52N	88.57E

2045-08-11T00:05:32.945-2047-11-07T12:18:15.373 (ALL)
Incidence, 0 to 10000 km altitude



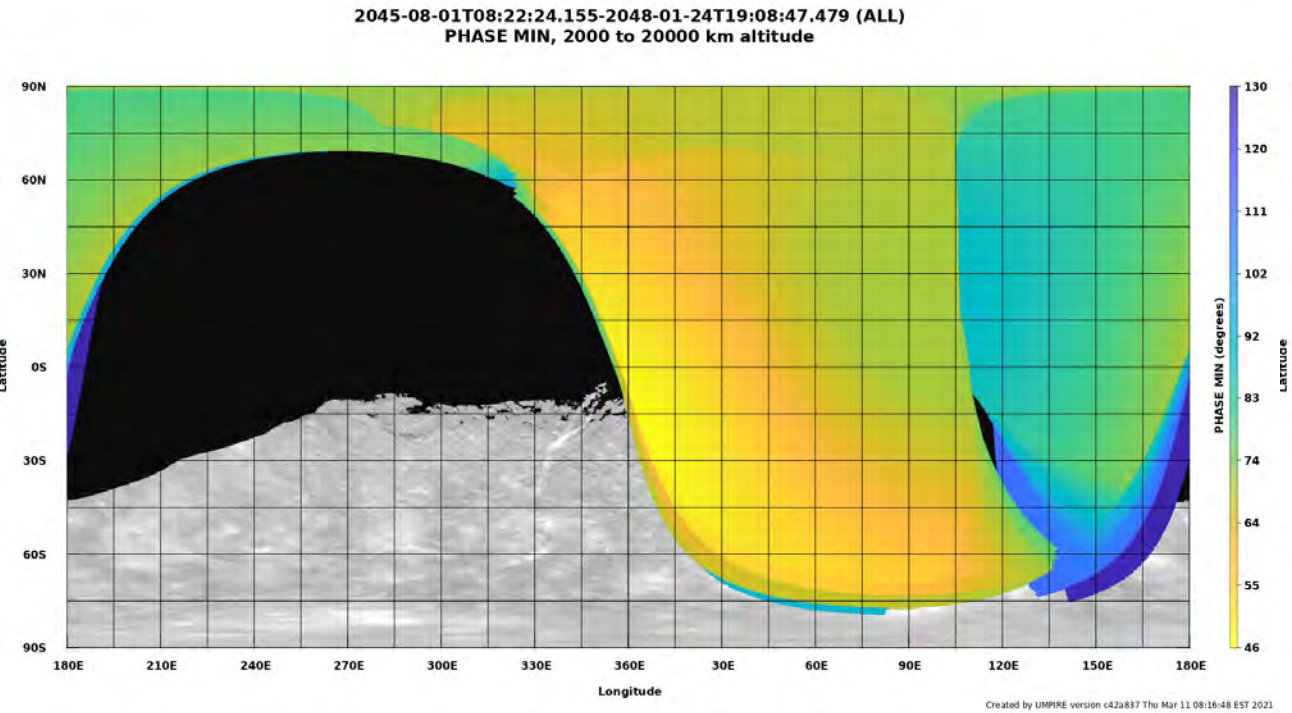
2045-08-11T00:05:32.945-2047-11-07T12:18:15.373 (ALL)
Range, 0 to 10000 km altitude

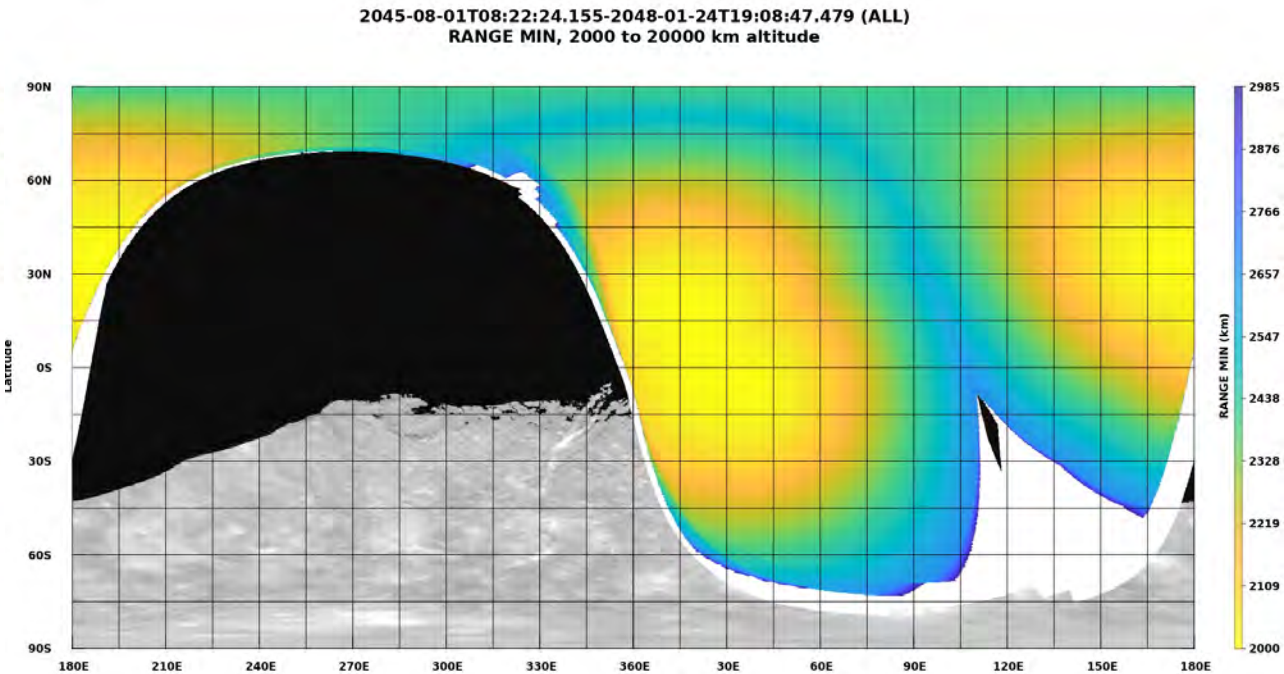


Analysis by Hari Nair

Titania flyby imaging opportunities

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U01	TITANIA	2045-08-11T00:46:27.584	13.77	1173.59	384.69	2.97	34.11N	91.07E	20.70N	87.58E
U02	TITANIA	2045-11-14T19:05:12.272	44.58	861.27	72.37	4.05	60.94N	64.46E	19.49N	87.71E
U03	TITANIA	2046-02-01T03:32:54.217	33.62	851.66	62.76	4.10	51.78N	81.93E	18.49N	87.86E
U04	TITANIA	2046-04-03T02:06:54.944	43.21	931.66	142.76	3.74	59.92N	75.09E	17.72N	87.95E
U05	TITANIA	2046-05-25T07:47:54.361	38.73	815.59	26.69	4.28	55.68N	84.30E	17.06N	88.11E
U06	TITANIA	2046-07-07T20:22:05.547	24.37	814.65	25.75	4.28	39.17N	98.21E	16.51N	87.97E
U07	TITANIA	2046-08-11T16:08:54.669	73.16	814.67	25.77	4.28	75.42N	3.27E	16.06N	88.06E
U08	TITANIA	2046-09-15T12:01:06.741	73.68	827.26	38.36	4.22	77.21N	3.27E	15.62N	88.32E
U09	TITANIA	2046-10-20T07:46:29.321	74.12	842.32	53.42	4.15	78.98N	3.56E	15.18N	88.37E
U10	TITANIA	2046-11-24T03:27:42.357	75.26	882.17	93.27	3.95	80.43N	359.60E	14.74N	88.31E
U11	TITANIA	2046-12-28T23:11:50.916	74.96	860.55	71.65	4.05	82.40N	4.92E	14.29N	88.33E
U12	TITANIA	2047-02-01T18:59:10.052	75.53	865.09	76.19	4.03	84.10N	5.20E	13.85N	88.44E
U13	TITANIA	2047-03-08T14:46:21.575	75.73	875.19	86.29	3.99	85.86N	11.02E	13.41N	88.54E
U14	TITANIA	2047-04-12T10:29:02.705	76.42	885.69	96.79	3.94	87.48N	12.85E	12.96N	88.52E
U15	TITANIA	2047-05-17T06:14:11.162	93.12	964.45	175.55	3.61	72.71N	294.23E	12.52N	88.57E

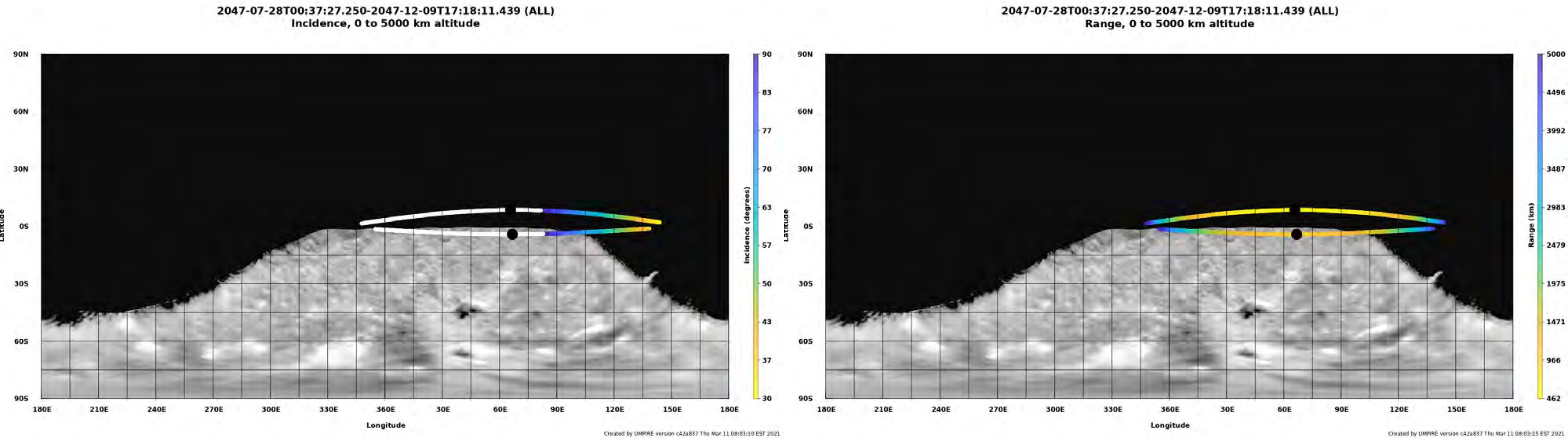




Analysis by Hari Nair

2 Oberon flybys

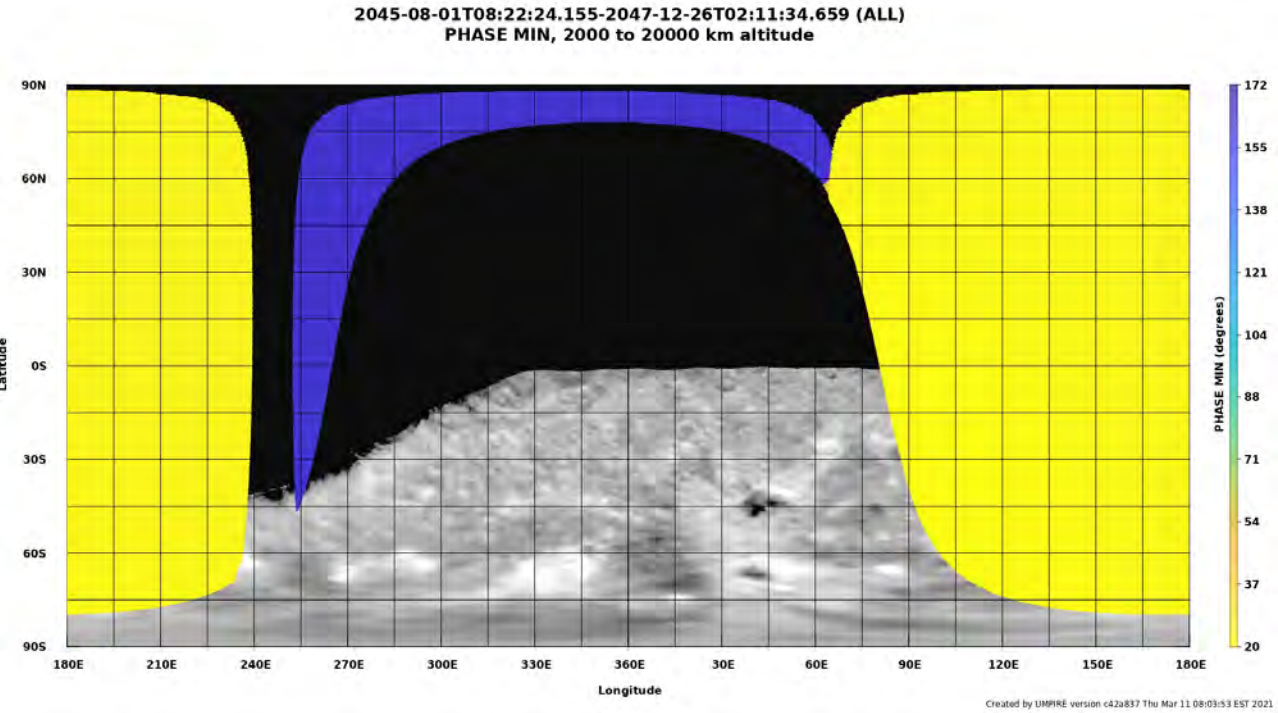
orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U17	OBERON	2047-07-28T01:01:16.109	106.02	1799.96	1038.56	1.62	4.16S	66.71E	11.89N	172.23E
U21	OBERON	2047-12-09T16:53:44.176	105.44	1223.55	462.15	2.40	8.53N	65.78E	10.17N	173.26E

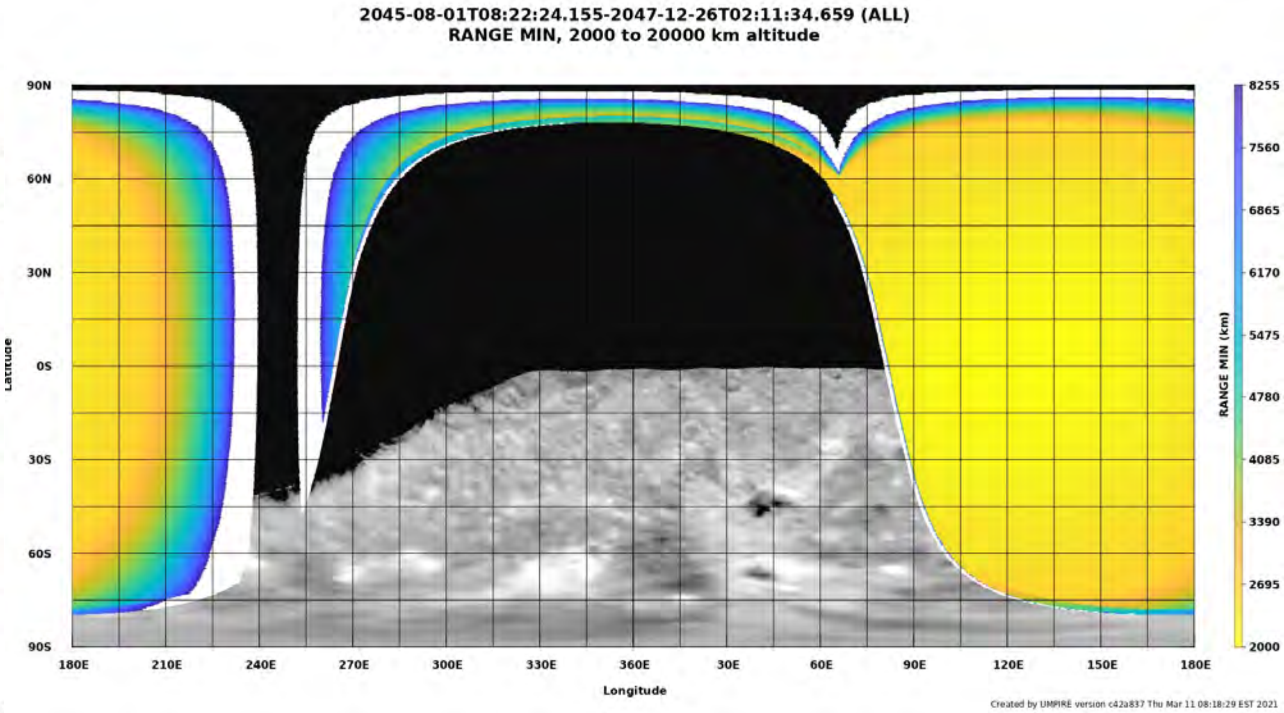


Analysis by Hari Nair

Oberon flyby imaging opportunities

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U17	OBERON	2047-07-28T01:01:16.109	106.02	1799.96	1038.56	1.62	4.16S	66.71E	11.89N	172.23E
U21	OBERON	2047-12-09T16:53:44.176	105.44	1223.55	462.15	2.40	8.53N	65.78E	10.17N	173.26E





Analysis by Hari Nair

23 Uranus flybys

All satellite flybys closer than 10,000 km are listed here.

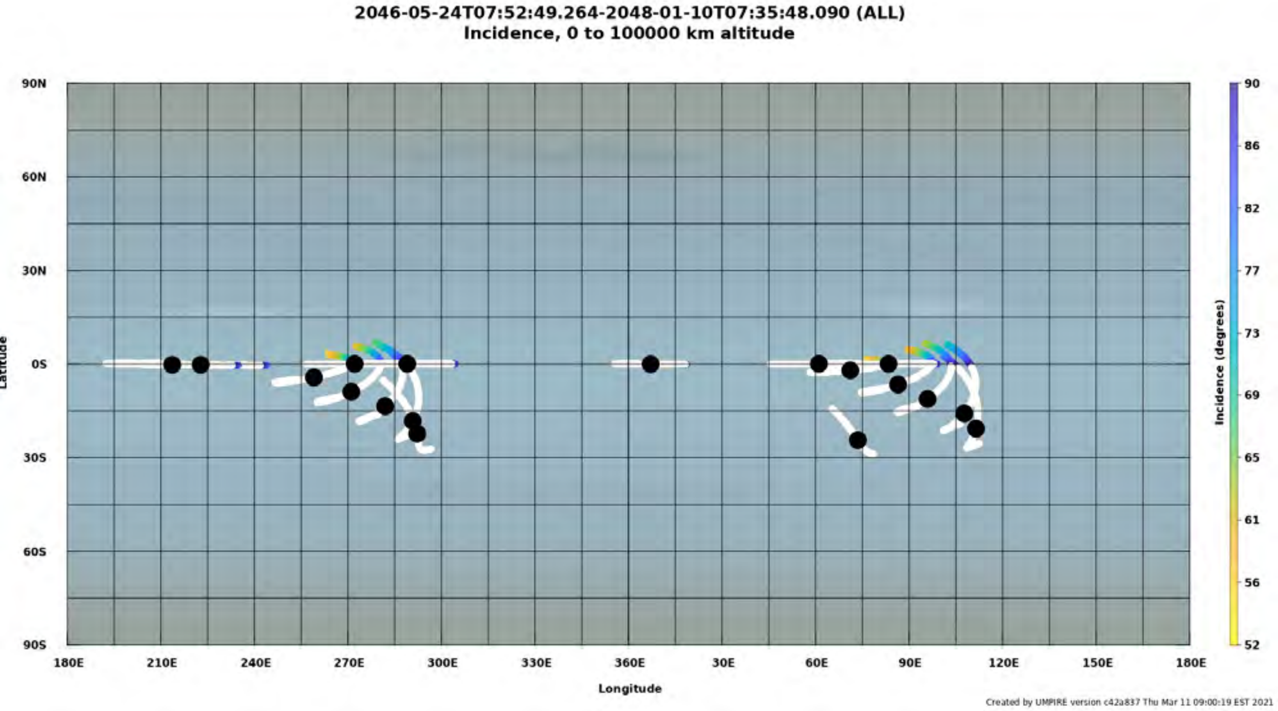
orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U01	URANUS	2045-08-10T02:16:35.990	155.13	155591.33	130187.58	0.90	30.54S	75.07E	20.86N	229.56E
U02	URANUS	2045-11-13T20:31:56.628	152.20	147396.32	121986.33	0.84	29.85S	189.76E	19.64N	341.17E
U03	URANUS	2046-01-31T05:07:07.453	149.65	137751.93	112325.42	0.78	27.98S	222.68E	18.65N	11.11E
U04	URANUS	2046-04-02T03:44:13.143	146.48	127203.59	101762.15	0.72	26.21S	168.29E	17.88N	313.13E
U05	URANUS	2046-05-24T09:35:19.838	144.04	118586.72	93130.39	0.68	24.37S	73.57E	17.22N	215.76E
U06	URANUS	2046-07-06T22:18:13.676	141.06	108786.67	83314.66	0.69	22.31S	292.22E	16.66N	71.23E
U07	URANUS	2046-08-10T18:13:26.842	137.43	98272.89	72789.19	0.86	20.67S	111.47E	16.22N	246.71E
U08	URANUS	2046-09-14T14:17:51.442	136.60	93615.60	68115.88	0.91	18.25S	290.81E	15.78N	65.39E
U09	URANUS	2046-10-19T10:15:34.230	135.82	89572.79	64058.96	0.98	15.85S	107.69E	15.34N	241.73E
U10	URANUS	2046-11-23T06:06:03.339	135.10	86180.61	60654.60	1.06	13.50S	281.94E	14.89N	55.56E
U11	URANUS	2046-12-28T01:56:04.717	134.43	83463.78	57927.73	1.14	11.22S	95.93E	14.45N	229.23E
U12	URANUS	2047-01-31T21:49:36.683	133.77	81173.74	55629.24	1.22	8.89S	271.08E	14.01N	44.12E
U13	URANUS	2047-03-07T17:44:03.255	133.13	79439.77	53888.74	1.29	6.58S	86.48E	13.56N	219.33E
U14	URANUS	2047-04-11T13:30:44.342	132.53	78169.29	52613.67	1.35	4.28S	259.10E	13.12N	31.84E
U15	URANUS	2047-05-16T09:15:56.045	131.97	77508.55	51950.30	1.38	2.01S	71.14E	12.68N	203.82E
U16	URANUS	2047-06-22T14:43:35.794	132.53	79333.99	53774.99	1.24	0.01S	7.09E	12.20N	140.85E
U17	URANUS	2047-07-29T08:38:24.391	134.44	74097.37	48538.37	1.65	0.08N	61.07E	11.74N	196.74E
U18	URANUS	2047-08-31T03:20:36.048	134.31	74478.14	48919.14	1.62	0.07N	289.03E	11.32N	64.48E
U19	URANUS	2047-10-04T05:01:31.101	134.63	74138.77	48579.77	1.65	0.07N	83.41E	10.88N	219.11E
U20	URANUS	2047-11-06T15:06:15.680	134.77	74144.58	48585.58	1.65	0.07N	272.17E	10.46N	47.92E
U21	URANUS	2047-12-11T00:23:45.075	137.73	67939.37	42380.38	2.24	0.22S	222.78E	10.02N	1.45E
U22	URANUS	2048-01-10T04:02:17.408	137.87	67842.02	42283.03	2.25	0.22S	213.63E	9.63N	352.36E
U23	URANUS	2048-02-07T15:39:09.987	9.65	404611.94	379052.95	2.45	0.20S	225.55E	9.27N	227.43E

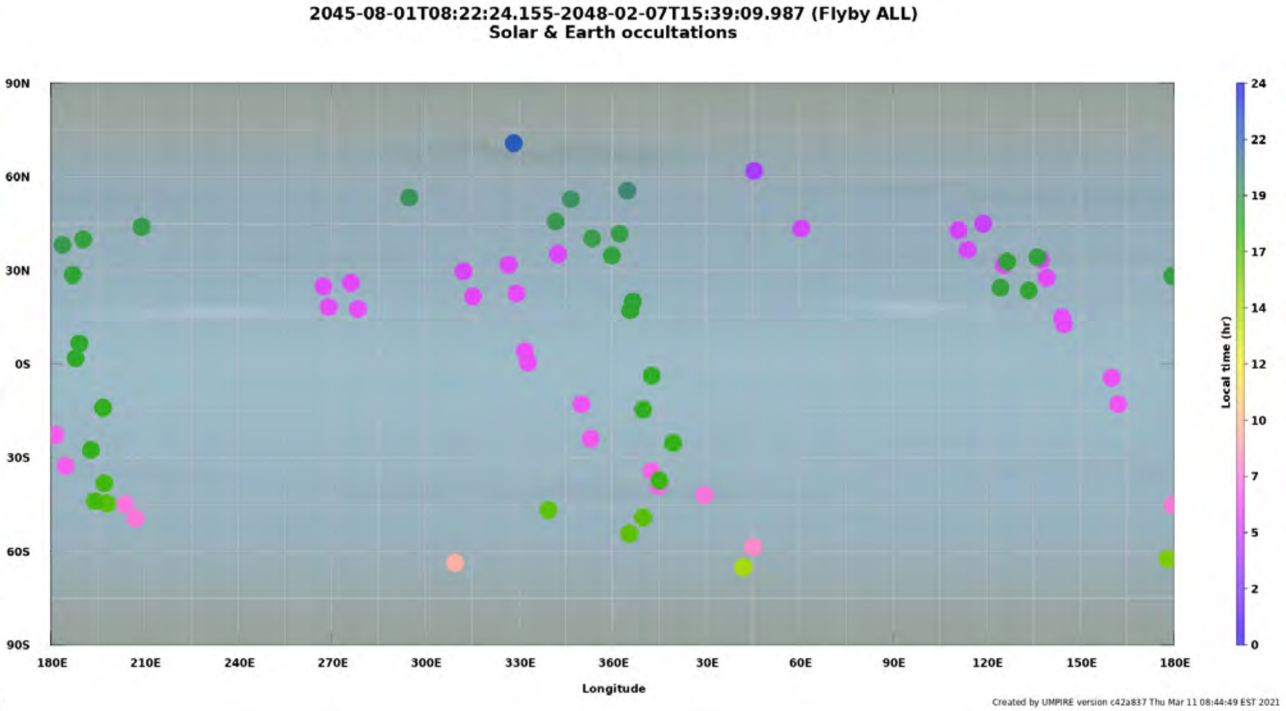
More available with optimized satellite tour phase – this is very flexible

Analysis by Hari Nair

Uranus imaging opportunities

All nightside passes but many opportunities for solar occultations



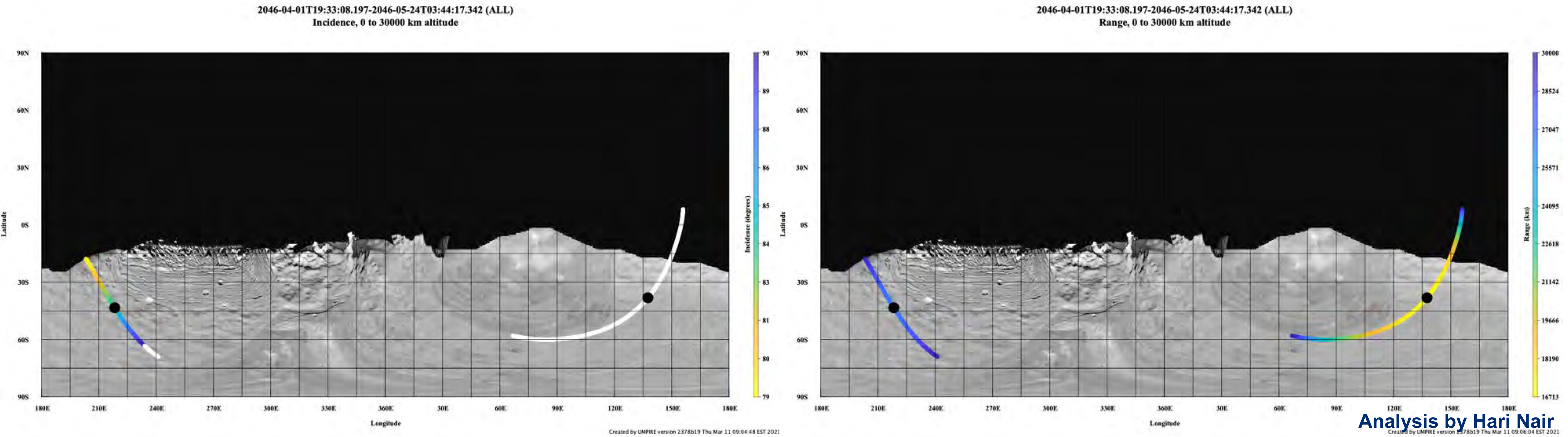


Analysis by Hari Nair

Miranda flybys

Alternate trajectory after probe release; not integrated with equatorialization

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U2	TITANIA	2045-08-10T20:37:51.629	21.35	1288.92	500.02	2.67	41.41N	86.54E	20.70N	80.44E
U3	TITANIA	2045-11-14T14:55:05.725	33.33	1188.92	400.02	2.89	52.77N	78.22E	19.49N	80.53E
U4	TITANIA	2046-01-31T23:22:39.554	27.06	988.92	200.02	3.49	44.90N	87.77E	18.49N	80.67E
U5	MIRANDA	2046-04-01T20:25:41.329	84.31	27027.24	26791.71	0.04	43.38S	218.34E	14.38N	285.81E
U5	TITANIA	2046-04-02T21:56:03.065	42.83	922.00	133.10	3.74	60.32N	74.55E	17.72N	80.74E
U6	MIRANDA	2046-05-24T02:17:49.996	133.07	16948.98	16713.25	0.06	38.13S	137.54E	13.83N	272.04E
U6	TITANIA	2046-05-25T03:36:27.246	38.03	840.91	52.01	4.11	54.97N	84.92E	17.06N	80.89E
U7	TITANIA	2046-07-07T16:10:49.469	65.24	1345.75	556.85	2.55	74.88N	26.06E	16.51N	80.75E

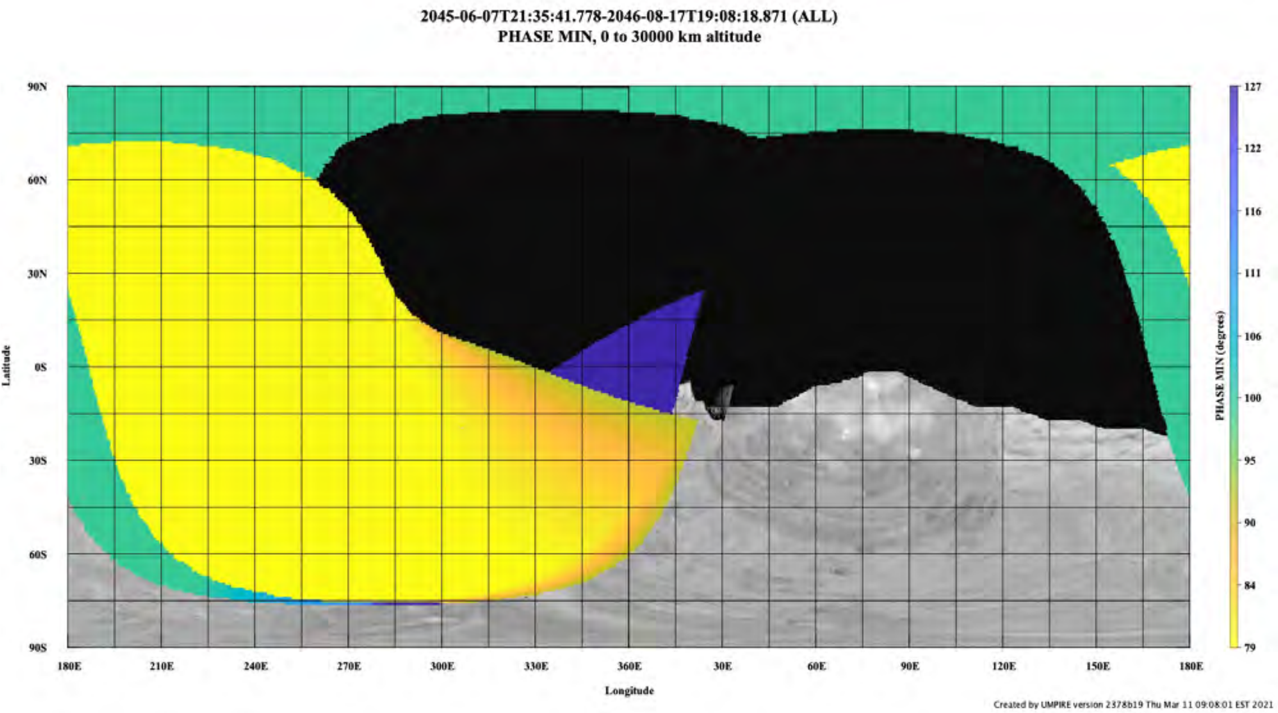


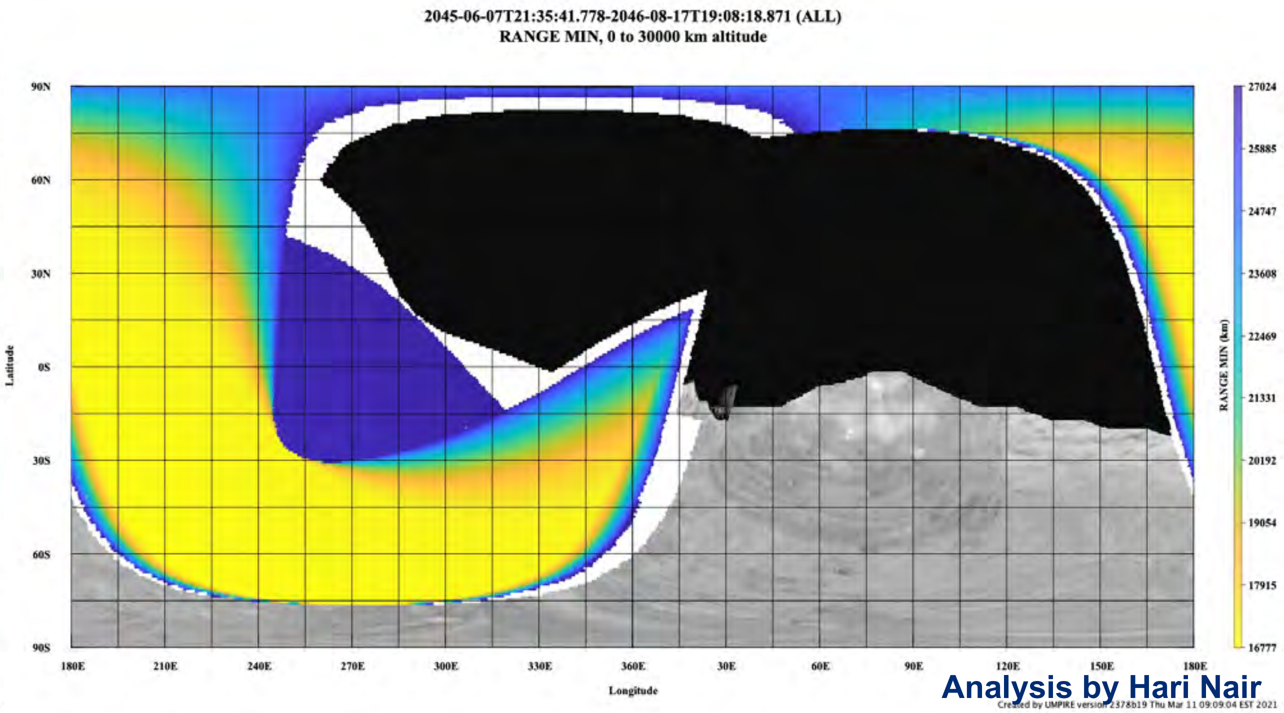
Analysis by Hari Nair

Miranda flybys

Alternate trajectory after probe release; not integrated with equatorialization

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U2	TITANIA	2045-08-10T20:37:51.629	21.35	1288.92	500.02	2.67	41.41N	86.54E	20.70N	80.44E
U3	TITANIA	2045-11-14T14:55:05.725	33.33	1188.92	400.02	2.89	52.77N	78.22E	19.49N	80.53E
U4	TITANIA	2046-01-31T23:22:39.554	27.06	988.92	200.02	3.49	44.90N	87.77E	18.49N	80.67E
U5	MIRANDA	2046-04-01T20:25:41.329	84.31	27027.24	26791.71	0.04	43.38S	218.34E	14.38N	285.81E
U5	TITANIA	2046-04-02T21:56:03.065	42.83	922.00	133.10	3.74	60.32N	74.55E	17.72N	80.74E
U6	MIRANDA	2046-05-24T02:17:49.996	133.07	16948.98	16713.25	0.06	38.13S	137.54E	13.83N	272.04E
U6	TITANIA	2046-05-25T03:36:27.246	38.03	840.91	52.01	4.11	54.97N	84.92E	17.06N	80.89E
U7	TITANIA	2046-07-07T16:10:49.469	65.24	1345.75	556.85	2.55	74.88N	26.06E	16.51N	80.75E





Analysis by Hari Nair

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Uranus Orbiter Imager Coverage

Hari Nair
Lillian Nguyen

Summary

- This trajectory is focused on lowering the orbiter inclination to allow a proper tour once the orbiter is in the plane of Uranus equator/satellite orbits.
- Even so, many opportunities for Uranus, satellite, and ring science exist.
- Difficulties are:
  - Proper illumination for satellite stereo at desired resolutions
  - Desired resolution for rings/small satellites. When we are close to the rings we are in the ring plane and Uranus may be in the background. It would be desirable to have closer Uranus flybys early in the tour when we are at high inclinations.
- This slide set shows examples of images which meet the science objectives. Detailed coverage plots can be created with a proper tour trajectory.

Assumptions

Spacecraft Axes:

- HGA points along +X
- Optical instruments along +Z

Scan Platform - instrument boresights move in spacecraft X-Z plane

- Spacecraft will not have a scan platform but we've simulated one for simplicity (easier than independent instrument scan mirrors)

Nominal spacecraft attitude:

- Primary: +X to Earth
- Secondary: +Z to Uranus – use instrument scan mirrors to point to Uranus

Encounter attitude (+/- 60 minutes of closest approach)

- Primary: +X to Earth (gravity science) or +X to ram (imaging flyby)
- Secondary: +Z to nadir – use instrument scan mirrors to point nadir

Instruments:

- NAC: LORRI analog, 1024x1024, 10 μrad IFOV
- VNIR:
  - LEISA analog, 1024 pixel line scanner, 1472 channels, 250 μrad IFOV
  - MVIC analog, 5024x64, 5 channels, 50 μrad IFOV
- TIR: LRO DIVINER analog, 9x20 array, 3.4 mrad across track IFOV, 6.7 mrad along track

Satellite flybys

All satellite flybys closer than 10000 km are listed here.

orbit	body	time (UTC)	phase (deg)	range (km)	altitude (km)	ground speed (km)	sub s/c lat	sub s/c lon	subsolar lat	subsolar lon
U01,	TITANIA,	2045-08-11T00:46:27.584,	13.77,	1173.59,	384.69,	2.97,	34.11N,	91.07E,	20.70N,	87.58E
U02,	TITANIA,	2045-11-14T19:05:12.272,	44.58,	861.27,	72.37,	4.05,	60.94N,	64.46E,	19.49N,	87.71E
U03,	TITANIA,	2046-02-01T03:32:54.217,	33.62,	851.66,	62.76,	4.10,	51.78N,	81.93E,	18.49N,	87.86E
U04,	TITANIA,	2046-04-03T02:06:54.944,	43.21,	931.66,	142.76,	3.74,	59.92N,	75.09E,	17.72N,	87.95E
U05,	TITANIA,	2046-05-25T07:47:54.361,	38.73,	815.59,	26.69,	4.28,	55.68N,	84.30E,	17.06N,	88.11E
U06,	TITANIA,	2046-07-07T20:22:05.547,	24.37,	814.65,	25.75,	4.28,	39.17N,	98.21E,	16.51N,	87.97E
U07,	TITANIA,	2046-08-11T16:08:54.669,	73.16,	814.67,	25.77,	4.28,	75.42N,	3.27E,	16.06N,	88.06E
U08,	TITANIA,	2046-09-15T12:01:06.741,	73.68,	827.26,	38.36,	4.22,	77.21N,	3.27E,	15.62N,	88.32E
U09,	TITANIA,	2046-10-20T07:46:29.321,	74.12,	842.32,	53.42,	4.15,	78.98N,	3.56E,	15.18N,	88.37E
U10,	TITANIA,	2046-11-24T03:27:42.357,	75.26,	882.17,	93.27,	3.95,	80.43N,	359.60E,	14.74N,	88.31E
U11,	TITANIA,	2046-12-28T23:11:50.916,	74.96,	860.55,	71.65,	4.05,	82.40N,	4.92E,	14.29N,	88.33E
U12,	TITANIA,	2047-02-01T18:59:10.052,	75.53,	865.09,	76.19,	4.03,	84.10N,	5.20E,	13.85N,	88.44E
U13,	TITANIA,	2047-03-08T14:46:21.575,	75.73,	875.19,	86.29,	3.99,	85.86N,	11.02E,	13.41N,	88.54E
U14,	TITANIA,	2047-04-12T10:29:02.705,	76.42,	885.69,	96.79,	3.94,	87.48N,	12.85E,	12.96N,	88.52E
U15,	TITANIA,	2047-05-17T06:14:11.162,	93.12,	964.45,	175.55,	3.61,	72.71N,	294.23E,	12.52N,	88.57E
U16,	UMBRIEL,	2047-06-22T04:14:56.556,	118.51,	5939.16,	5354.46,	0.52,	1.79S,	77.31E,	12.12N,	196.11E
U17,	OBERON,	2047-07-28T01:01:16.109,	106.02,	1799.96,	1038.56,	1.62,	4.16S,	66.71E,	11.89N,	172.23E
U17,	ARIEL,	2047-07-29T02:01:59.826,	126.31,	4364.67,	3786.72,	0.76,	0.18S,	82.60E,	11.56N,	209.74E
U18,	ARIEL,	2047-08-30T20:41:55.111,	53.31,	2399.50,	1821.57,	1.39,	0.19N,	264.17E,	11.15N,	211.63E
U19,	UMBRIEL,	2047-10-03T18:37:22.110,	118.14,	4237.63,	3652.93,	0.73,	2.61N,	76.52E,	10.80N,	195.82E
U20,	TITANIA,	2047-11-07T11:48:26.141,	159.86,	7294.53,	6505.63,	0.47,	1.88S,	292.06E,	10.30N,	93.64E
U21,	OBERON,	2047-12-09T16:53:44.176,	105.44,	1223.55,	462.15,	2.40,	8.53N,	65.78E,	10.17N,	173.26E
U22,	ARIEL,	2048-01-10T10:35:28.468,	44.24,	2056.50,	1478.66,	1.66,	45.15N,	99.27E,	9.46N,	68.86E

Satellite imaging

Measurement	Instrument	ConOps	Data Volume	Notes
S1C. Global Shape	NAC, global images < 1km/pix	Framing at ~300,000 km and ~200,000 km range, terminator should be visible	2 images inbound, 2 images outbound, 6 Mbytes per flyby	Many opportunities
S1E. Plume activity searches	NAC, < 1km/pix	Framing at ~200,000km, phase angle > 150º	2 images per flyby, 3 Mbytes per flyby (can be combined with S1C)	Many opportunities
	TIR	Scan across satellite range ~25,000 km, any phase angle	1 image inbound, one image outbound, 10x20 pixel long strips x 2 = 0.005 Mbytes.	Many opportunities
S1F. Satellite positions	NAC, global images, < 10 km/pix	Framing other satellites at ~2,000,000 km range	Best-effort basis.	Many opportunities
S2A. Satellite composition	Vis/NIR, < 3km/pix	Scan across disk, range ~35,000 km,	1 image per flyby; 530 lines span satellite, 2.16*530/1024=1.1 Mbytes/line = 591 Mbytes	Several opportunities, will be easier during satellite tour.
S3A. Geology & Topography	NAC, <0.5 km/pix	Framing at ~100,000 km range	2 images (stereo pairs, with parallax angle <30º) inbound, 2 images outbound, 6 Mbytes/flyby	Opportunities for stereo imaging exist but are rare. Should be easier during satellite tour.
		Framing at ~15,000 km range	2 images inbound, 2 images outbound, 6 Mbytes/flyby	
S3B. Surface composition.	Vis/NIR, < 3km/pix	Covered in S2A observations		
S3D. Plume search	NAC, <1km/pix	Covered in S1E observations		
S4A. Bulk plasma flow	F&P package	Point in ram direction, <300 km altitude	See F&P separate	
S1B. Static gravity coefficients	Radio Science	Earth-pointing HGA +/- 30 mins of C/A	Minimal.	

S1C: Global Shape

- NAC global images < 1 km/pixel, terminator should be visible

Simulated Umbriel Image (fictitious map):

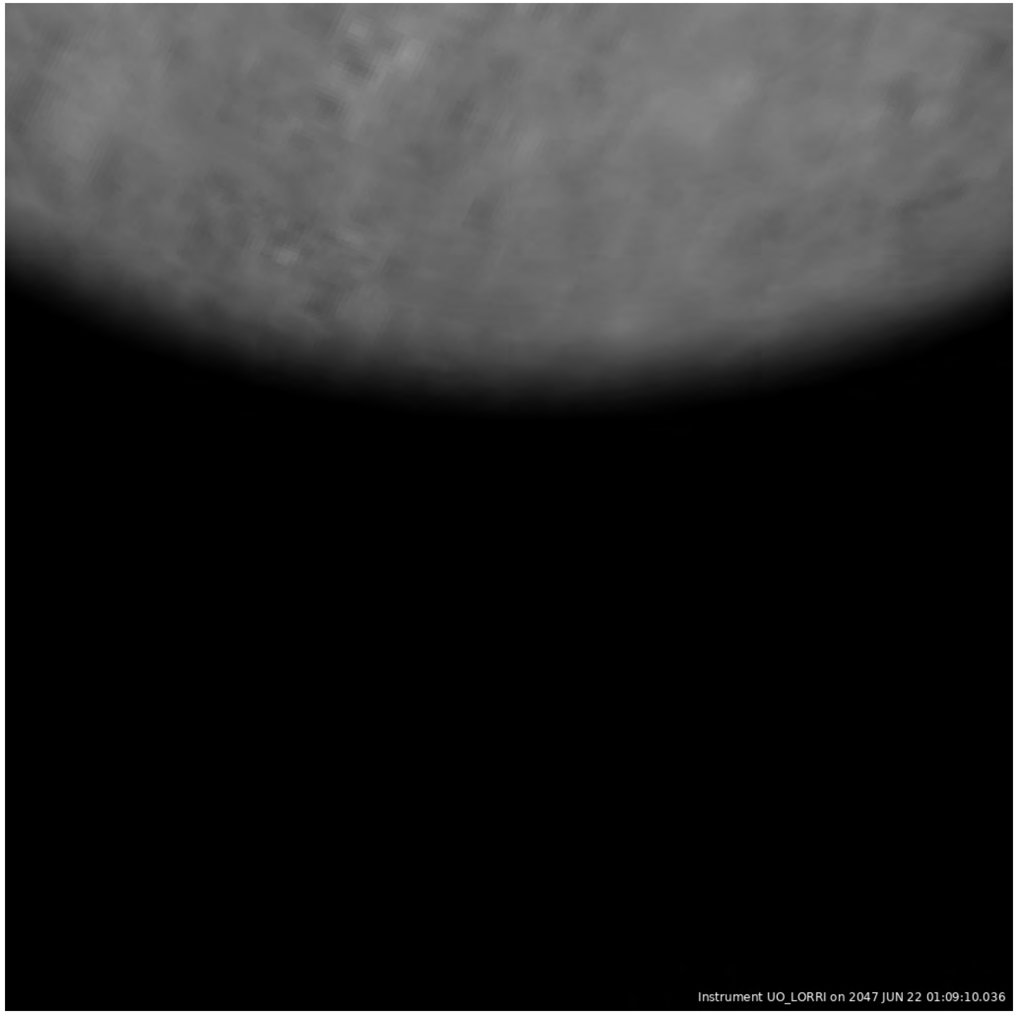
Orbit U16

2047-06-22T01:09:38

resolution 0.6 km/pixel

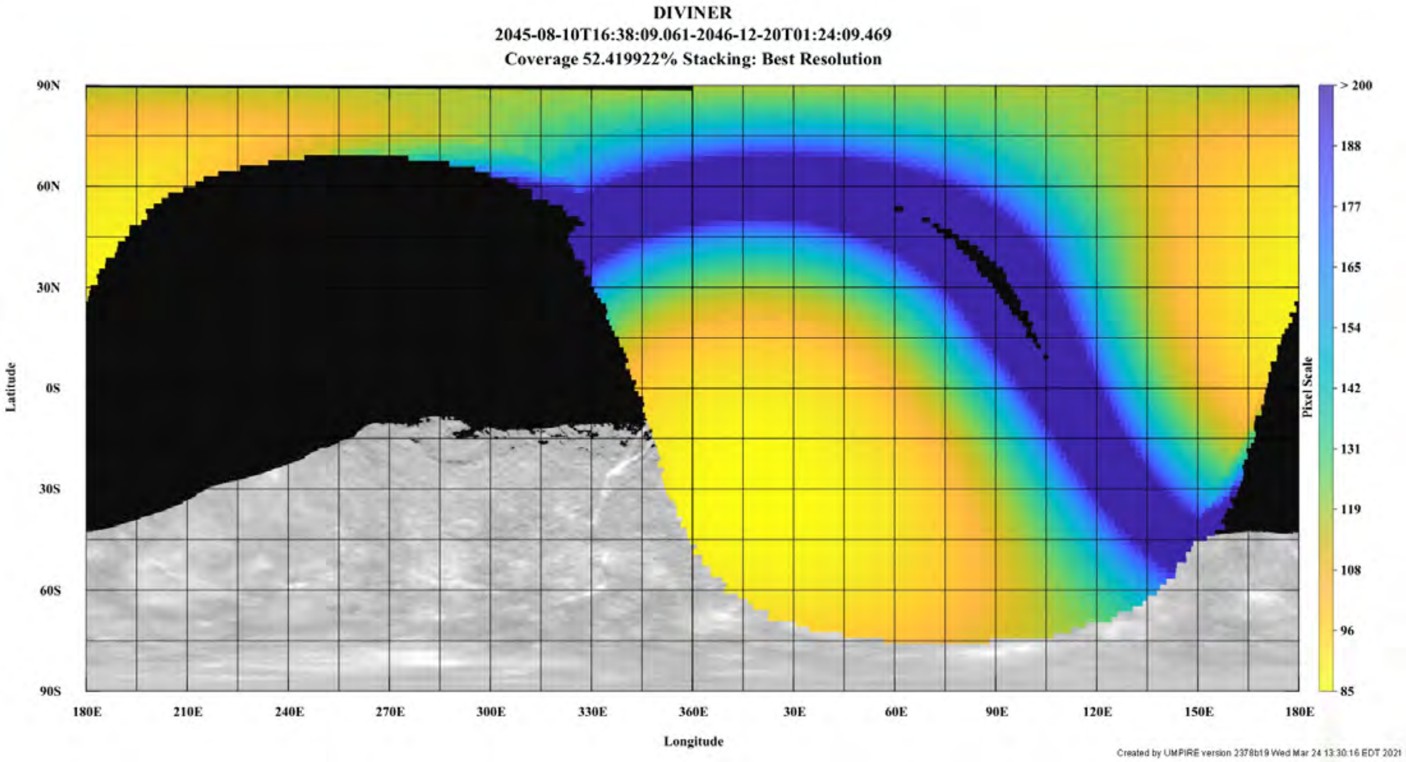
Distance 59949 km

Phase 36°



S1E: Plume Activity Searches/S3D: Plume Search

- NAC images < 1 km/pixel, phase > 150°
- TIR scans at 25000 km



S1F: Satellite Positions

- NAC, global images < 10 km/pixel

Simulated Oberon Image (fictitious map):

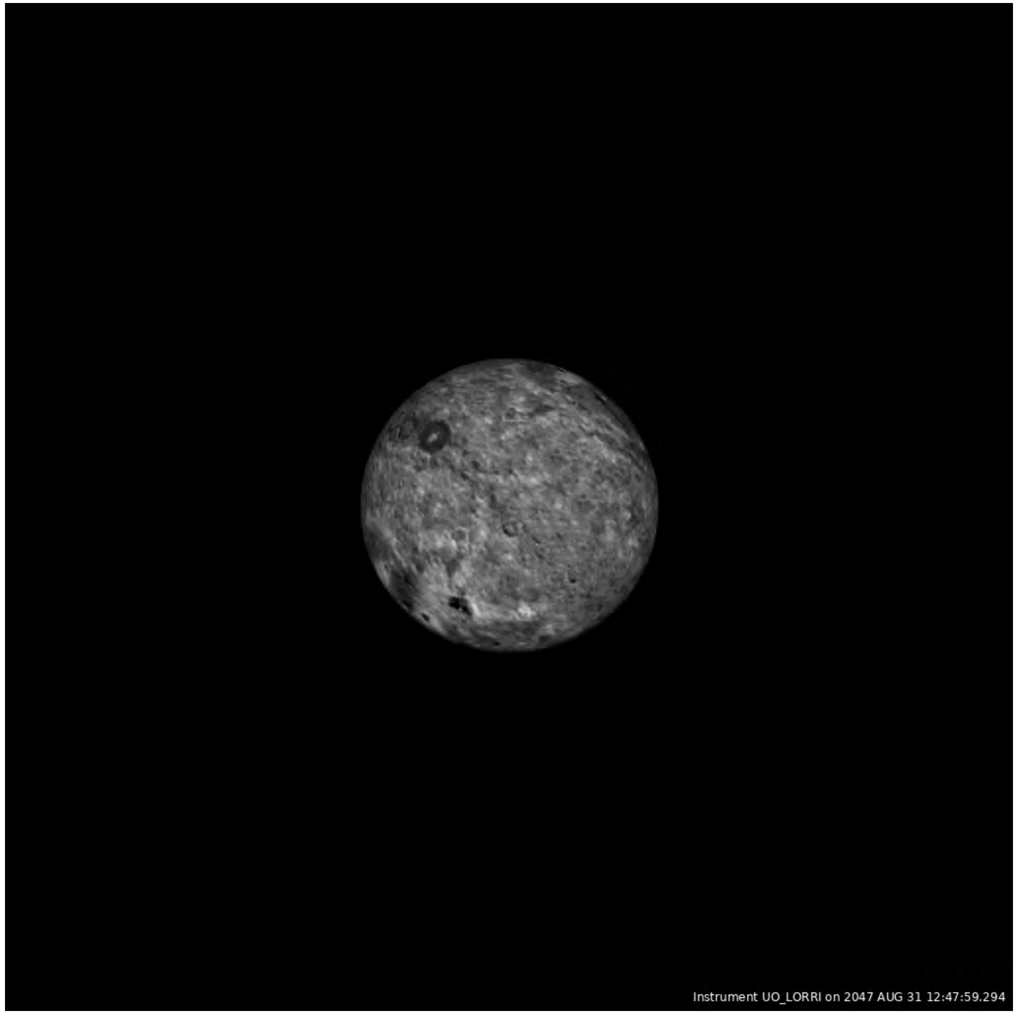
Orbit U18

2047-08-31T12:47:59

resolution 5 km/pixel

Distance 500051 km

Phase 16°



S2A: Satellite Composition/S3B Surface Composition

- Vis/NIR < 3 km/pixel, scan across disk

LEISA Scan of Titania:

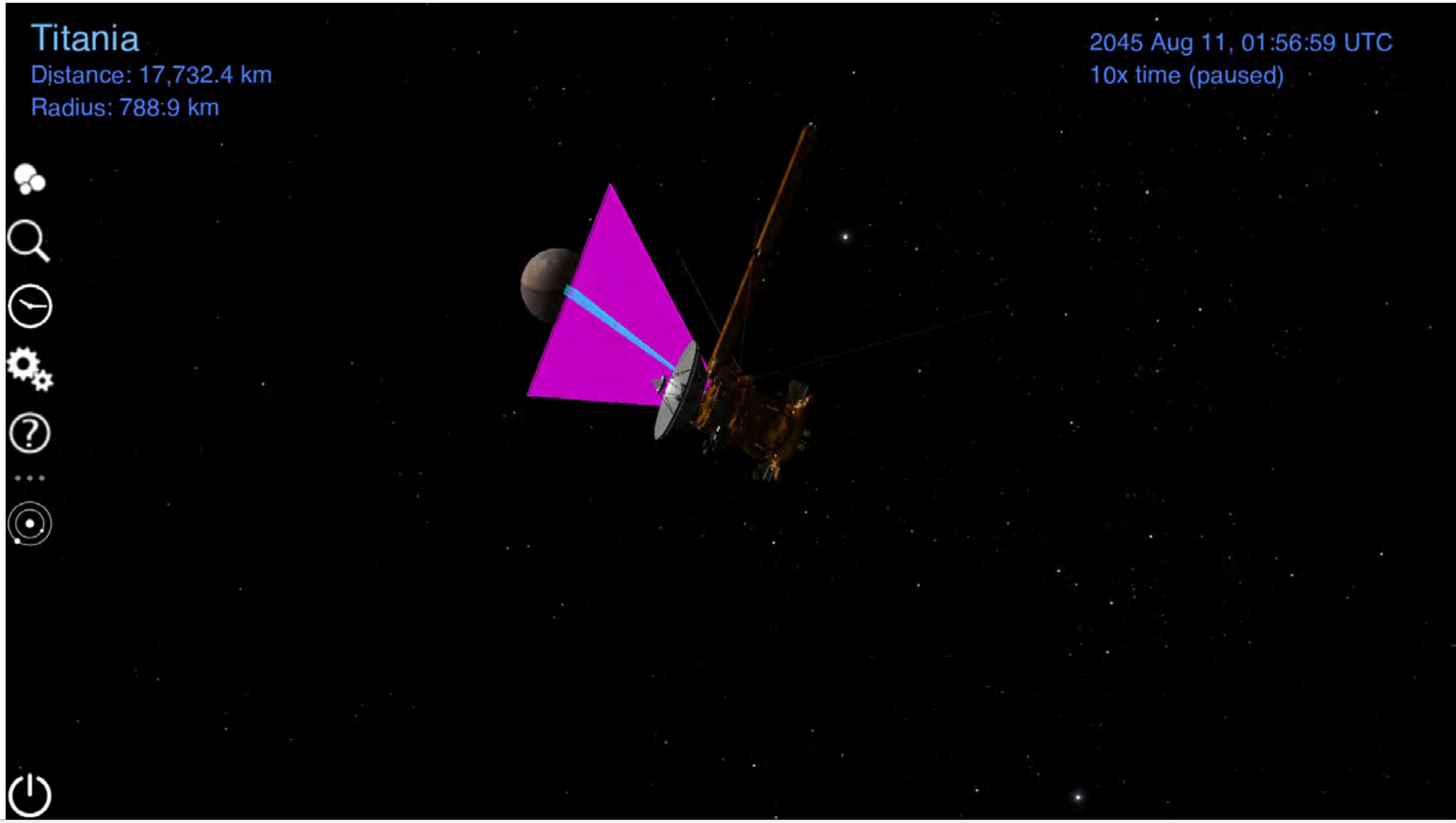
Orbit U01

2045-08-11T01:54:11

resolution 4.25 km/pixel

Distance 17000 km

Phase 96°



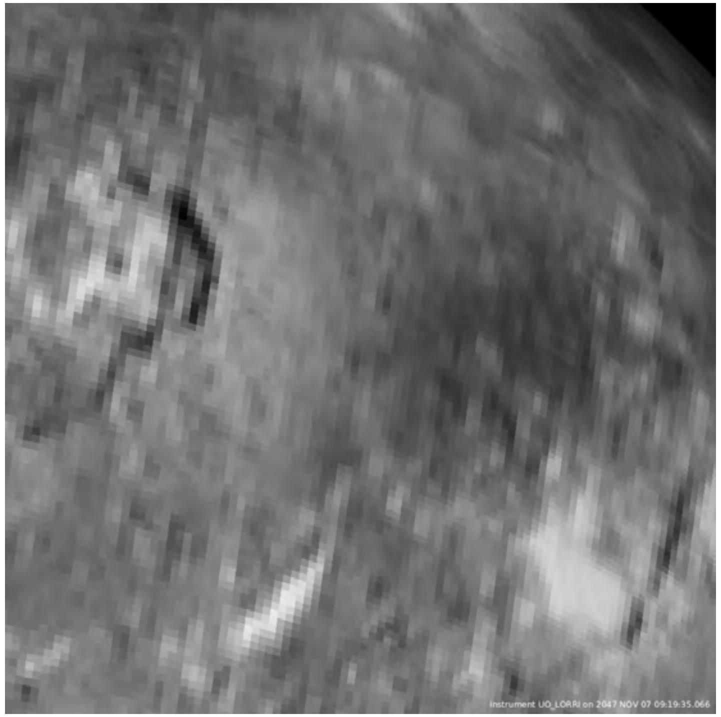
S3A: Geology & Topography

- NAC < 0.5 km/pixel, 1 stereo pair inbound, 1 stereo pair outbound

Flyby U20, Titania full disk (5 km/pixel) and mosaic (0.4 km/pixel) stereo complement (fictitious map)

2047-11-06T13:54:55
resolution 5 km/pixel
Distance 499728 km
Phase 62°

2047-11-07T09:19:35
resolution 400 m/pixel
Distance 39837 km
Phase 82°



23 Uranus flybys

Closest Uranus flybys are ~50000 km altitude, or 3 Uranus radii from the center.

orbit,	body,	time (UTC),	phase (deg),	range (km),	altitude (km),	ground speed (km),	sub s/c lat,	sub s/c lon,	subsolar lat,	subsolar lon
U01,	URANUS,	2045-08-10T02:16:35.990,	155.13,	155591.33,	130187.58,	0.90,	30.54S,	75.07E,	20.86N,	229.56E
U02,	URANUS,	2045-11-13T20:31:56.628,	152.20,	147396.32,	121986.33,	0.84,	29.85S,	189.76E,	19.64N,	341.17E
U03,	URANUS,	2046-01-31T05:07:07.453,	149.65,	137751.93,	112325.42,	0.78,	27.98S,	222.68E,	18.65N,	11.11E
U04,	URANUS,	2046-04-02T03:44:13.143,	146.48,	127203.59,	101762.15,	0.72,	26.21S,	168.29E,	17.88N,	313.13E
U05,	URANUS,	2046-05-24T09:35:19.838,	144.04,	118586.72,	93130.39,	0.68,	24.37S,	73.57E,	17.22N,	215.76E
U06,	URANUS,	2046-07-06T22:18:13.676,	141.06,	108786.67,	83314.66,	0.69,	22.31S,	292.22E,	16.66N,	71.23E
U07,	URANUS,	2046-08-10T18:13:26.842,	137.43,	98272.89,	72789.19,	0.86,	20.67S,	111.47E,	16.22N,	246.71E
U08,	URANUS,	2046-09-14T14:17:51.442,	136.60,	93615.60,	68115.88,	0.91,	18.25S,	290.81E,	15.78N,	65.39E
U09,	URANUS,	2046-10-19T10:15:34.230,	135.82,	89572.79,	64058.96,	0.98,	15.85S,	107.69E,	15.34N,	241.73E
U10,	URANUS,	2046-11-23T06:06:03.339,	135.10,	86180.61,	60654.60,	1.06,	13.50S,	281.94E,	14.89N,	55.56E
U11,	URANUS,	2046-12-28T01:56:04.717,	134.43,	83463.78,	57927.73,	1.14,	11.22S,	95.93E,	14.45N,	229.23E
U12,	URANUS,	2047-01-31T21:49:36.683,	133.77,	81173.74,	55629.24,	1.22,	8.89S,	271.08E,	14.01N,	44.12E
U13,	URANUS,	2047-03-07T17:44:03.255,	133.13,	79439.77,	53888.74,	1.29,	6.58S,	86.48E,	13.56N,	219.33E
U14,	URANUS,	2047-04-11T13:30:44.342,	132.53,	78169.29,	52613.67,	1.35,	4.28S,	259.10E,	13.12N,	31.84E
U15,	URANUS,	2047-05-16T09:15:56.045,	131.97,	77508.55,	51950.30,	1.38,	2.01S,	71.14E,	12.68N,	203.82E
U16,	URANUS,	2047-06-22T14:43:35.794,	132.53,	79333.99,	53774.99,	1.24,	0.01S,	7.09E,	12.20N,	140.85E
U17,	URANUS,	2047-07-29T08:38:24.391,	134.44,	74097.37,	48538.37,	1.65,	0.08N,	61.07E,	11.74N,	196.74E
U18,	URANUS,	2047-08-31T03:20:36.048,	134.31,	74478.14,	48919.14,	1.62,	0.07N,	289.03E,	11.32N,	64.48E
U19,	URANUS,	2047-10-04T05:01:31.101,	134.63,	74138.77,	48579.77,	1.65,	0.07N,	83.41E,	10.88N,	219.11E
U20,	URANUS,	2047-11-06T15:06:15.680,	134.77,	74144.58,	48585.58,	1.65,	0.07N,	272.17E,	10.46N,	47.92E
U21,	URANUS,	2047-12-11T00:23:45.075,	137.73,	67939.37,	42380.38,	2.24,	0.22S,	222.78E,	10.02N,	1.45E
U22,	URANUS,	2048-01-10T04:02:17.408,	137.87,	67842.02,	42283.03,	2.25,	0.22S,	213.63E,	9.63N,	352.36E
U23,	URANUS,	2048-02-07T15:39:09.987,	9.65,	404611.94,	379052.95,	2.45,	0.20S,	225.55E,	9.27N,	227.43E

Uranus imaging

Measurement	Instrument	ConOps	Data Volume*	Notes
A1A. Cloud top zonal and 2D winds, waves to ~10 m/s resolution	NAC, imaging at 50 km/pixel	Scan across planet from ~5x10^9 km range or lower, phase angle < 45°	4 images/feature track, 2 feature tracks/remote sensing* orbit = 12 Mbytes	Many opportunities
A1C. Resolved composition, disequilibrium species mapping	Vis/NIR, 1000 km/pixel	Scan across planet from ~4x10^6 km range, phase angle < 45°	Planet spans ~51 pixels, assume 60x60 = 7.6 Mbytes per image cube. Max is one per remote sensing orbit	Some opportunities from ~4x10^6 km, can also image from ~2x10^6 km and use binning
	TIR, ~1000 km horizontal spatial resolution	3 strip scans across planet from ~3x10^5 km range, any phase angle	60-pixel long strips = 0.05 Mbytes. Max is one per remote sensing orbit	Many opportunities
A2A. Cloud tomography and aerosols	Vis/NIR imaging spectra at 500-1000 km/pixel	Scans across planet from ~2 to <4x10^6 km range, phase angle < 45°	Planet spans ~102 pixels, assume 110x110 = 25.5 Mbytes per image cube. Max is two per remote sensing orbit	Many opportunities
	WAC or NAC imaging at 500-1000 km/pixel	Scans across planet from ~1 to 2 x10^7 km range, phase angle < 45°	WAC assumed, planet spans 100 pixels, rings can also be included in cross track, 2 to 4 scans = 7.2 to 14.4 Mbytes per observation, as fits	Many opportunities
A2C. Global temperature variations in troposphere, stratosphere, thermosphere	TIR, 500-1000 km/px mapping	6 strip scans across planet from ~1.5 to 3x10^5 km range, phase angle > 90°	120-pixel long strips = 0.2 Mbytes	Not modeled yet
	Vis/NIR spectra at 500-1000 km/pixel	Covered in A2A observations		
A3D. Global energy	TIR, 1000 km/pixel	Covered in A1C observations		

A1A: Cloud top zonal and 2D winds

- NAC images < 50 km/pixel, phase < 45°

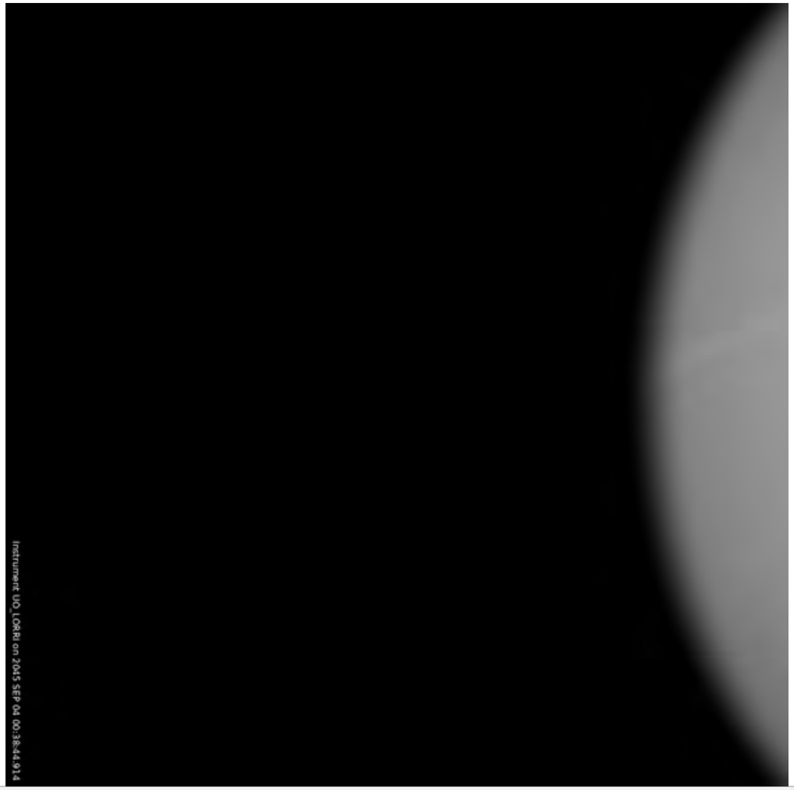
    Orbit U01

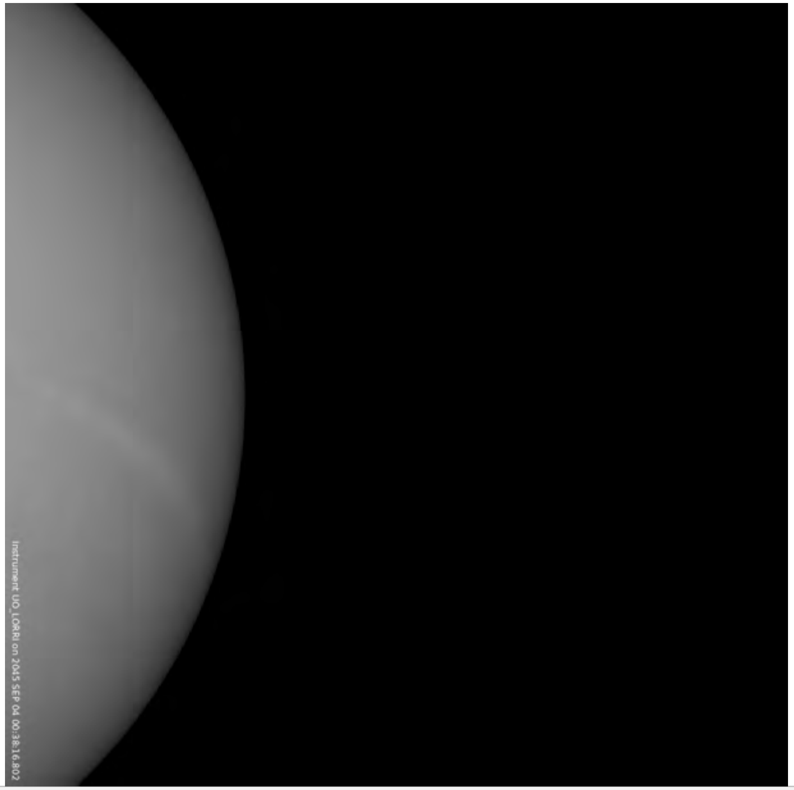
    2045-09-04T00:38:44

    resolution 35 km/pixel

    Distance 350000 km

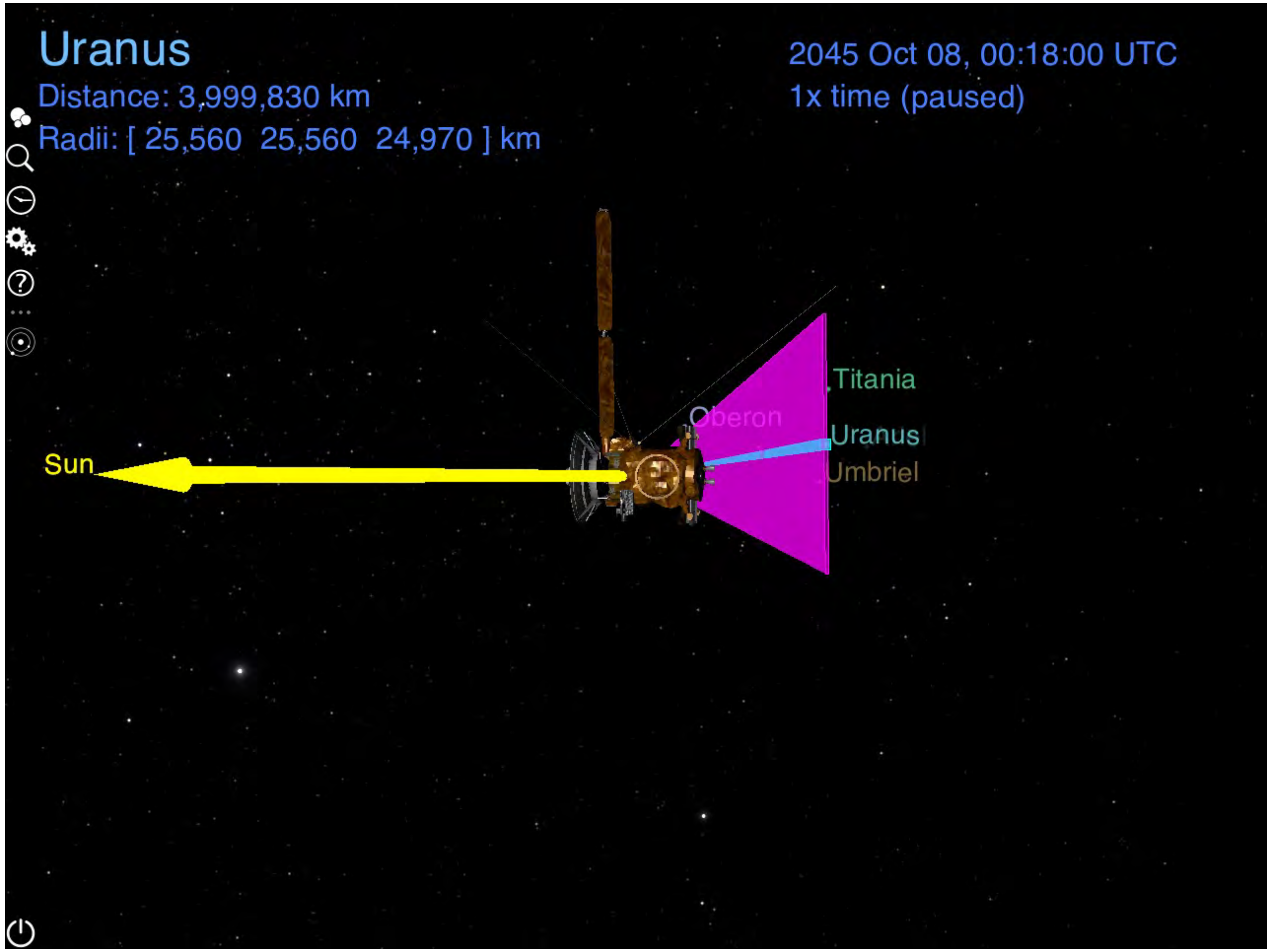
    Phase 34°





A1C: Resolved composition, disequilibrium species

- Vis/NIR 1000 km/pixel, phase < 45°



A2A: Cloud Tomography and Aerosols/A2C: Global Temperature/A3D: Global Energy Balance

- Vis/NIR imaging at 500-1000 km/pixel, phase < 45°

LEISA/MVIC Scan:

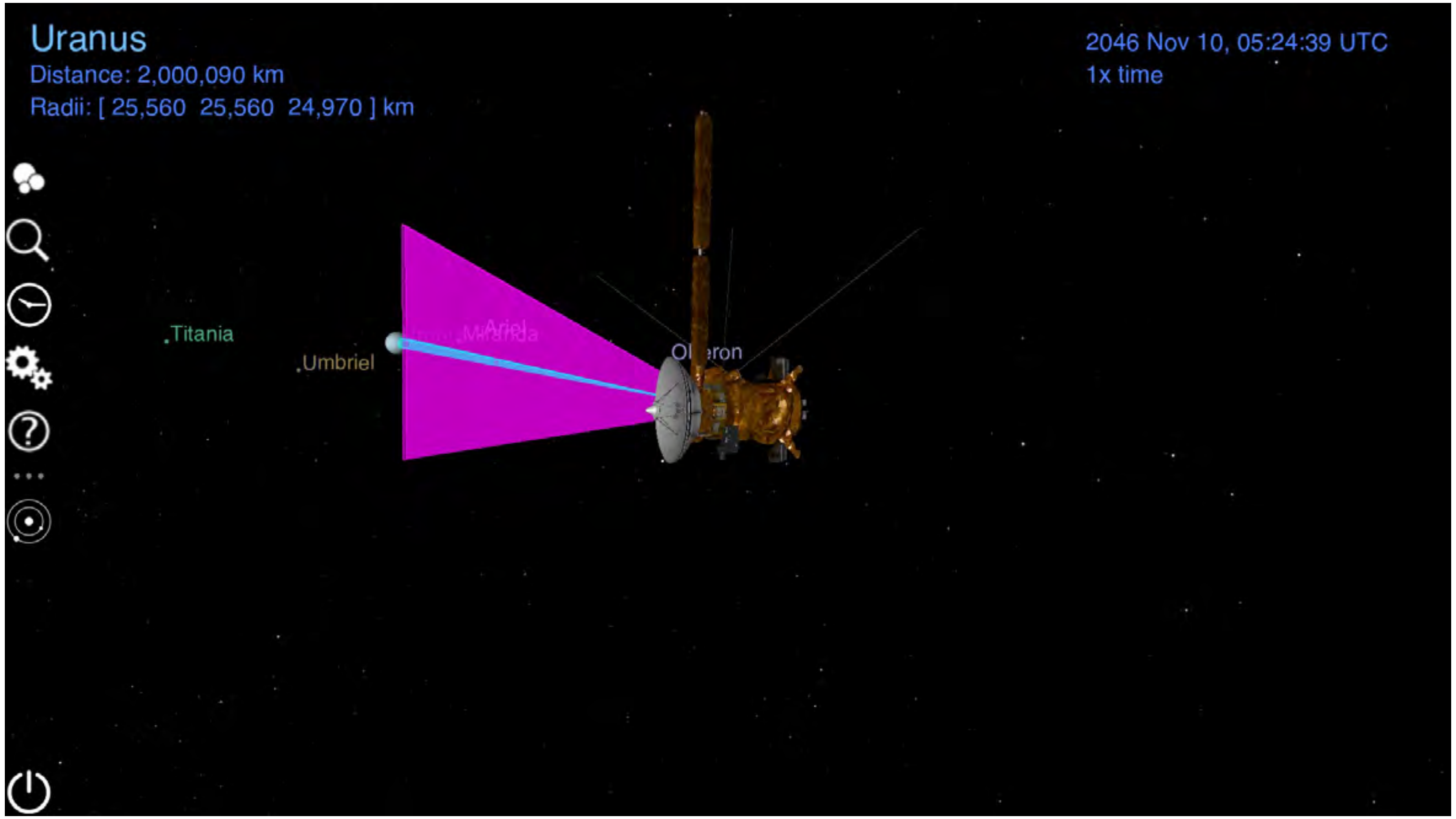
Orbit U10

2046-11-10T05:24:15

resolution 500 km/pixel

Distance 2000000 km

Phase 40°



Ring imaging

Measurement	Instrument	ConOps	Data Volume*	Notes
R1A. Fine-scale structures in the dense rings at multiple times and longitudes	WAC or NAC imaging (100 m/pixel)	Ring mosaics from ~1x10[7] km range or lower, phase angle < 90°	NAC assumed: 2 images across rings, 1 inbound, 1 outbound* orbit = 6 Mbytes	No opportunities
R1B. Measure longitudinal variations in the ring structure (including normal modes and arcs)	WAC or NAC imaging (1 km/pixel)	Ring mosaics from ~1x10[8] km range or lower, phase angle < 90°	NAC assumed: 4 images across rings, 1 inbound, 1 outbound* orbit = 12 Mbytes	Many opportunities
R1C. Inventory and shape of small moons > 0.5 km in radius within 500,000 km of the planet's center	WAC or NAC imaging (100 m/pixel)	Non targeted observations (range varies)	NAC assumed: 1 image per target = 1.5 Mbytes	No opportunities
R2A. Ring (color) imaging at a wide range of phase angles	WAC multi-band imaging	Best effort resolution, scan across ring plane, Phase angle > 160°	5-filter, assume 64 rows per filter = 2.3 Mbytes	Many opportunities for > 500 m/pixel
R3B. Ring and small moon spectra (Cordelia to Mab), 1-5 µm	Vis/NIR imaging and spectroscopy	Best effort resolution, scan across rings, Phase angle < 90°	Assume 60x60 = 7.6 Mbytes per image cube. Max is one per remote sensing orbit	Many opportunities for > 500 m/pixel
I4. Ring Oscillations	WAC or NAC imaging (1 km/pixel)	Same as R1B above		Many opportunities

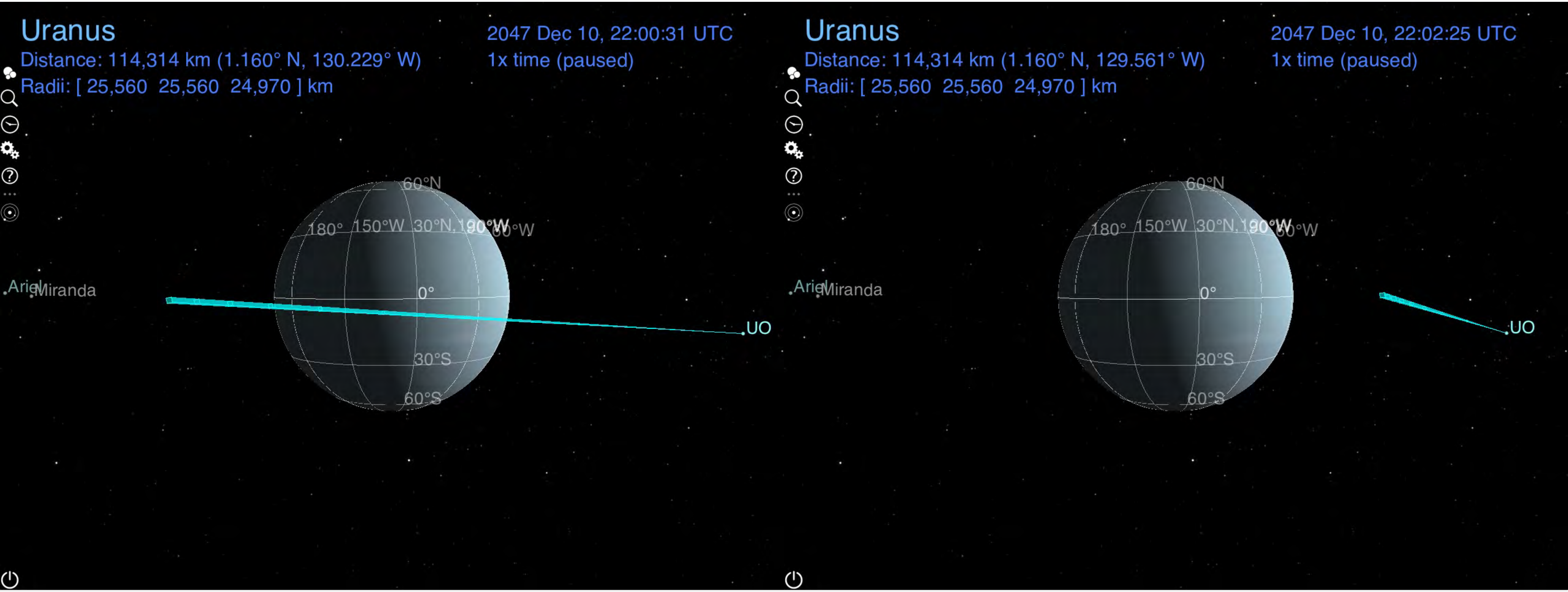
R1A: Fine scale structure

NAC imaging, 100 m/pixel, phase < 90°

No opportunities in this tour, should be done during high inclination passes but these are too far away.

R1B: Longitudinal Variations/I4: Ring Oscillations

NAC imaging, 1 km/pixel, phase < 90°



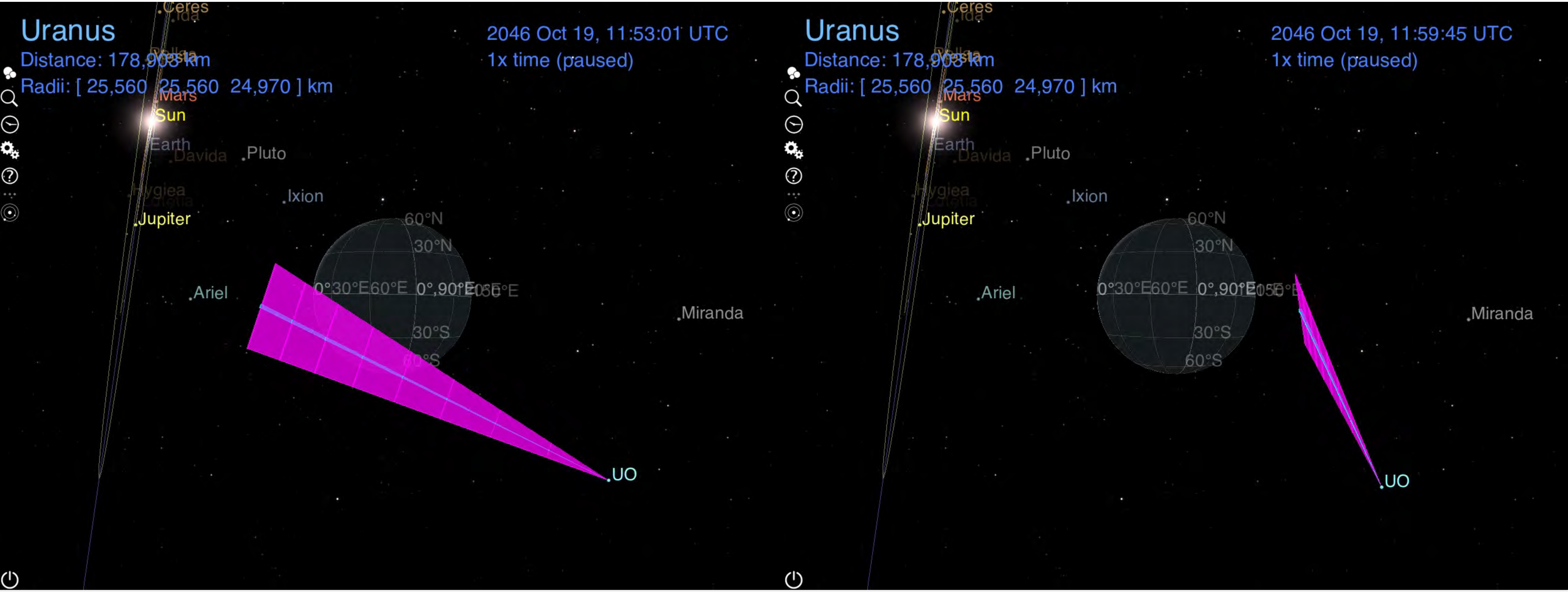
R1C: Inventory and Shape of Small Moons

NAC imaging, < 100 m/pixel

No opportunities in this tour, should be done during high inclination passes but these are too far away

R2A: Ring color imaging

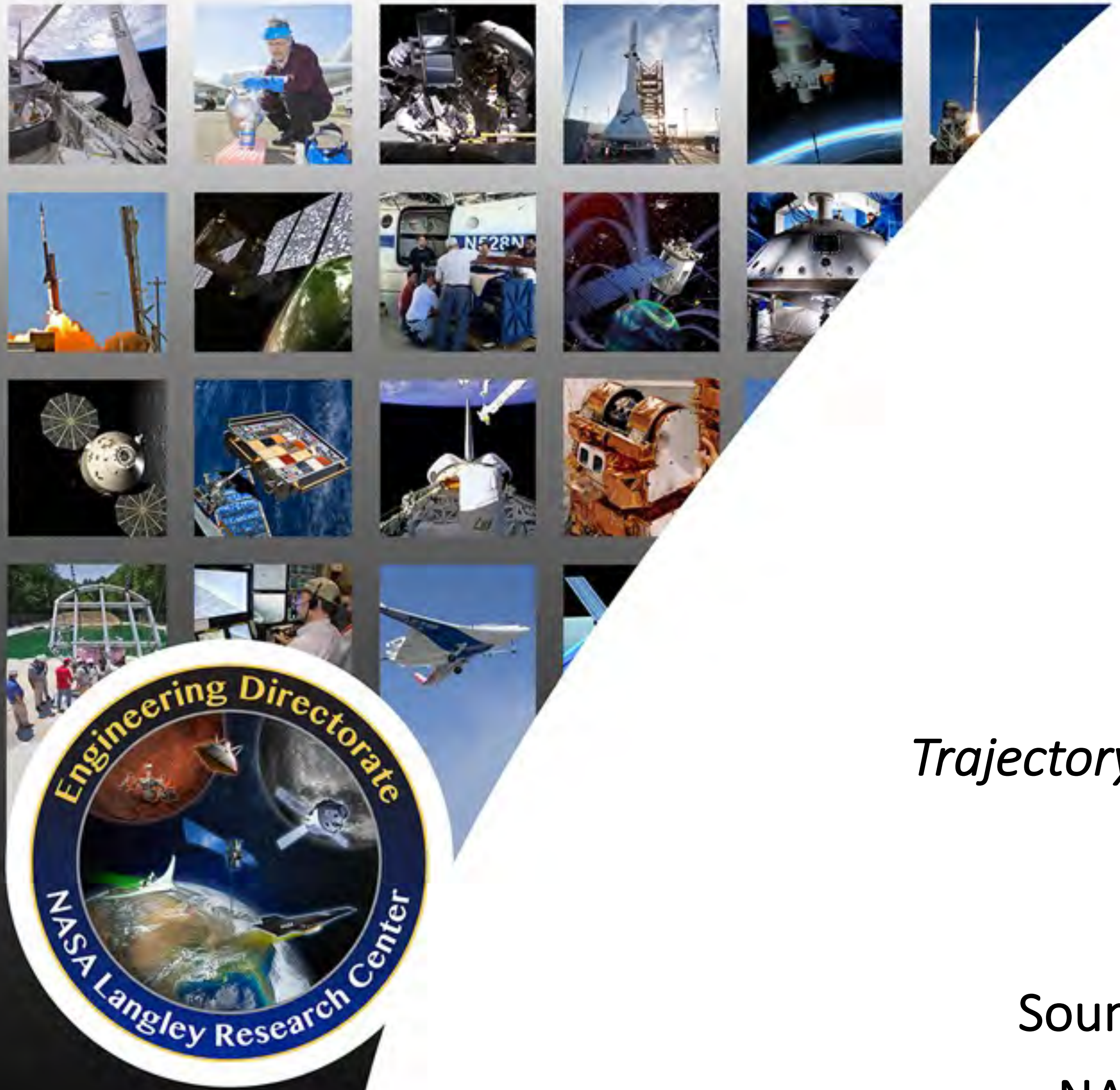
- WAC, scan across ring plane, phase > 160°



R3B: Ring and Small Moon Spectra

- Vis/NIR, scan across ring plane, phase < 90°

Can be done at the same time as R1B (NAC imaging < 1 km/pixel)



National Aeronautics and Space Administration

Uranus Study

Trajectory and Parachute System Discussion

Final Iteration

Soumyo Dutta, Alejandro Pensado
NASA Langley Research Center

May 29, 2021

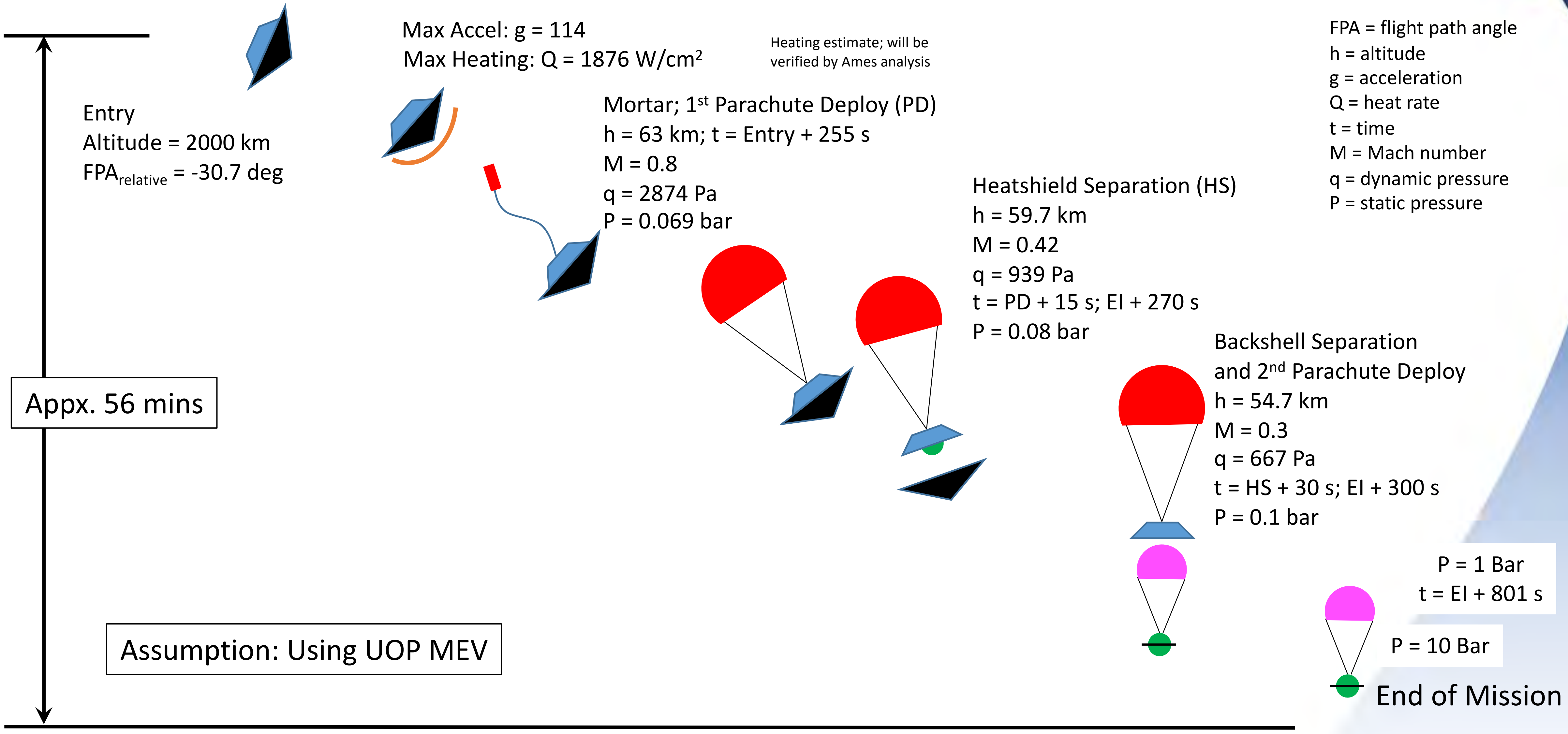
Assumptions for Final Iteration

- **3 Degree-of-Freedom Trajectory Analysis**
- **Entry Vehicle**
  - 45 deg. half-angle sphere-cone; heritage from Pioneer Venus and Galileo (Jupiter)
  - Entry Body Diameter: 1.26 m
  - Nose Radius: 0.4 m
  - Ballistic Coefficient: Approximately 220 kg/m^2
  - Assumed no shape change due to ablation; effect on trajectory of mass loss due to ablation will be quantified
- **Parachutes**
  - 1st parachute: Conical Ribbon, Diameter: 2.5 m
    - Deploy at Mach 0.8
    - Mortar deployed
    - Used for separation system – separate heatshield and then probe from backshell
    - Conical Ribbon Parachute – heritage from Pioneer Venus and Galileo (Jupiter)
  - 2nd parachute: Ringsail, Diameter: 1.8 m
    - Deploy at Mach 0.3
    - Increases descent time by 10 mins
    - Inflates as backshell separates (not mortar deployed)
    - Ringsail Parachute – heritage from Earth flights at low subsonic conditions
- **Atmosphere:** Uranus GRAM 2021 Atmosphere (Based on Lindal, Bishop, and Herbert)
  - Analysis includes Sromovsky's wind model to capture a notional impact on the trajectory
- **Descent Probe:** Diameter: 0.7 m

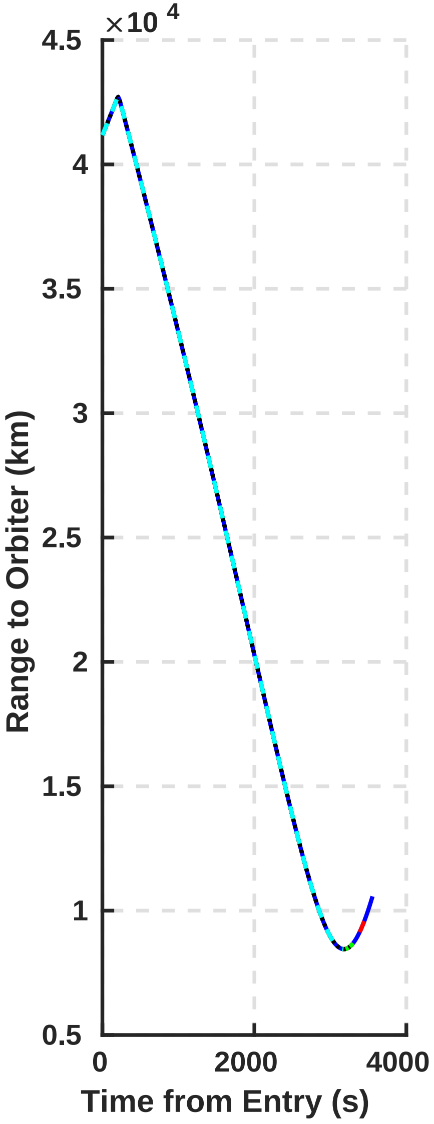
Conical Ribbon Parachute

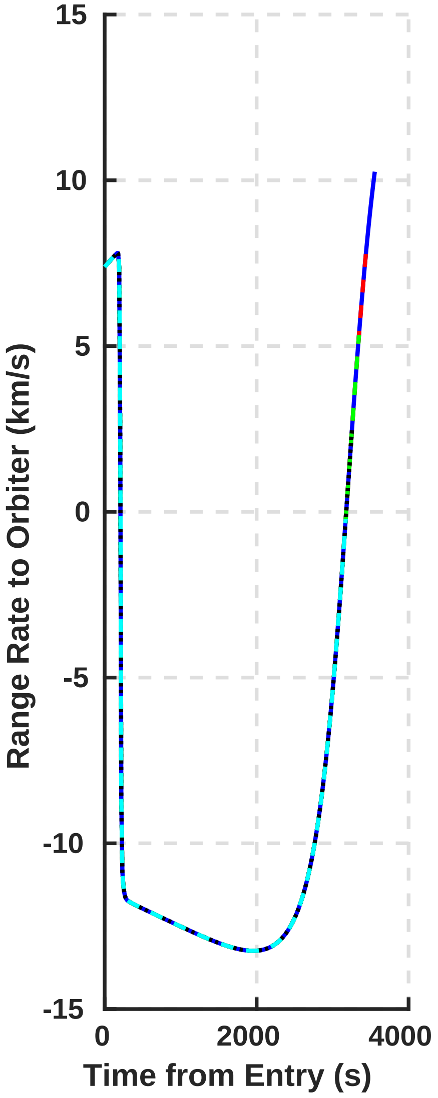
Ringsail Parachute

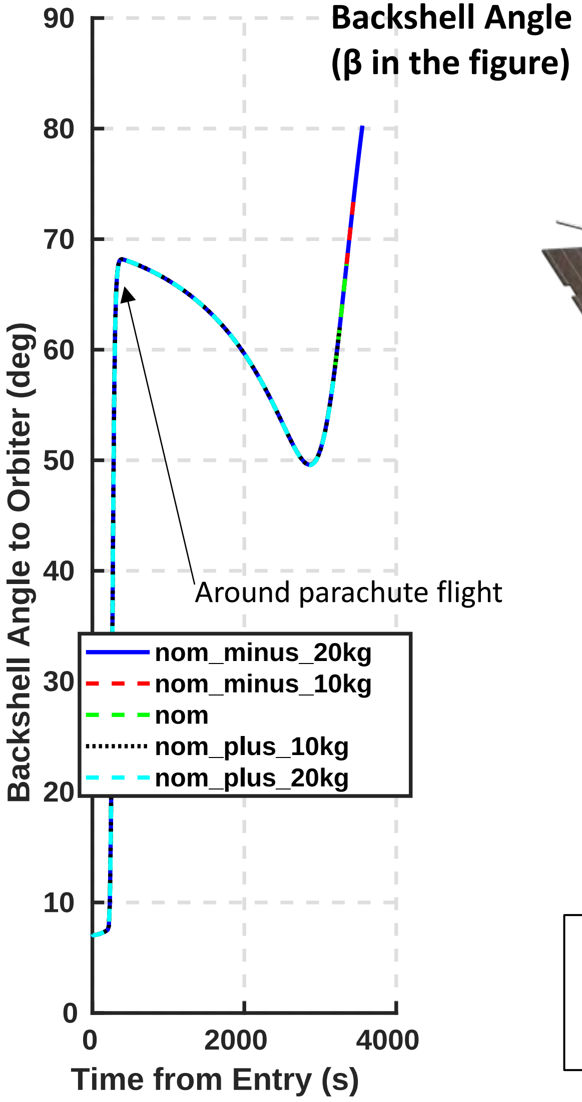
Trajectory Concept of Operations (Final Iteration)

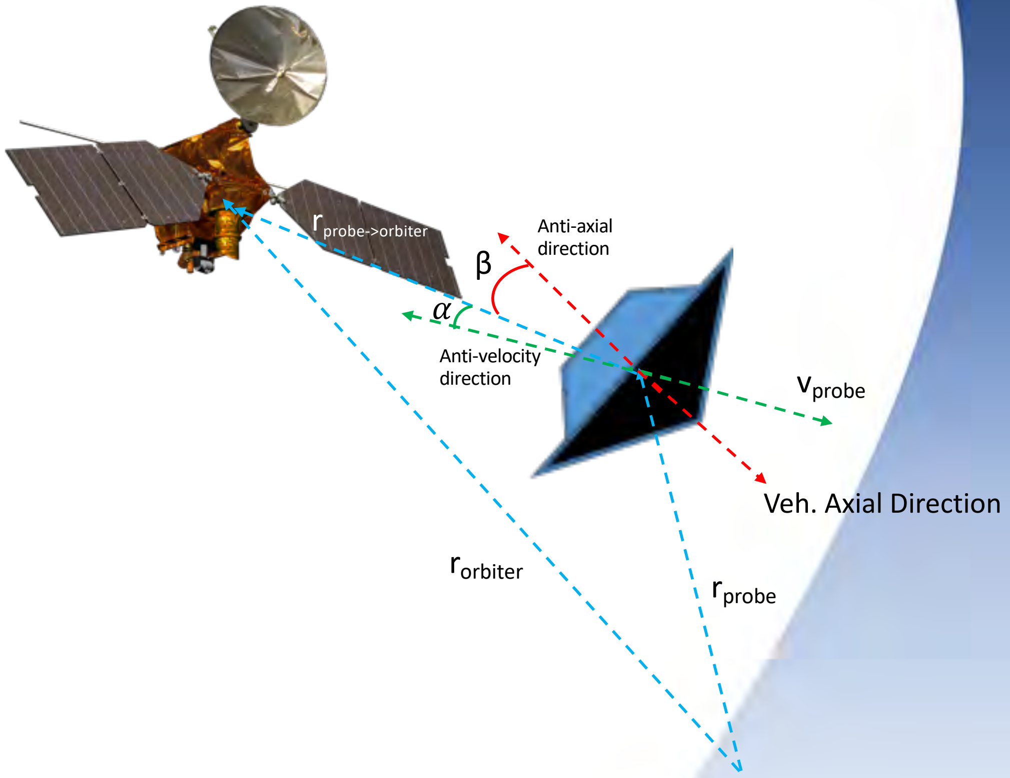


Communications to Orbiter (Final Iteration)









Note: Atmospheric effects and antenna pattern were not used for this analysis. This is purely geometric data

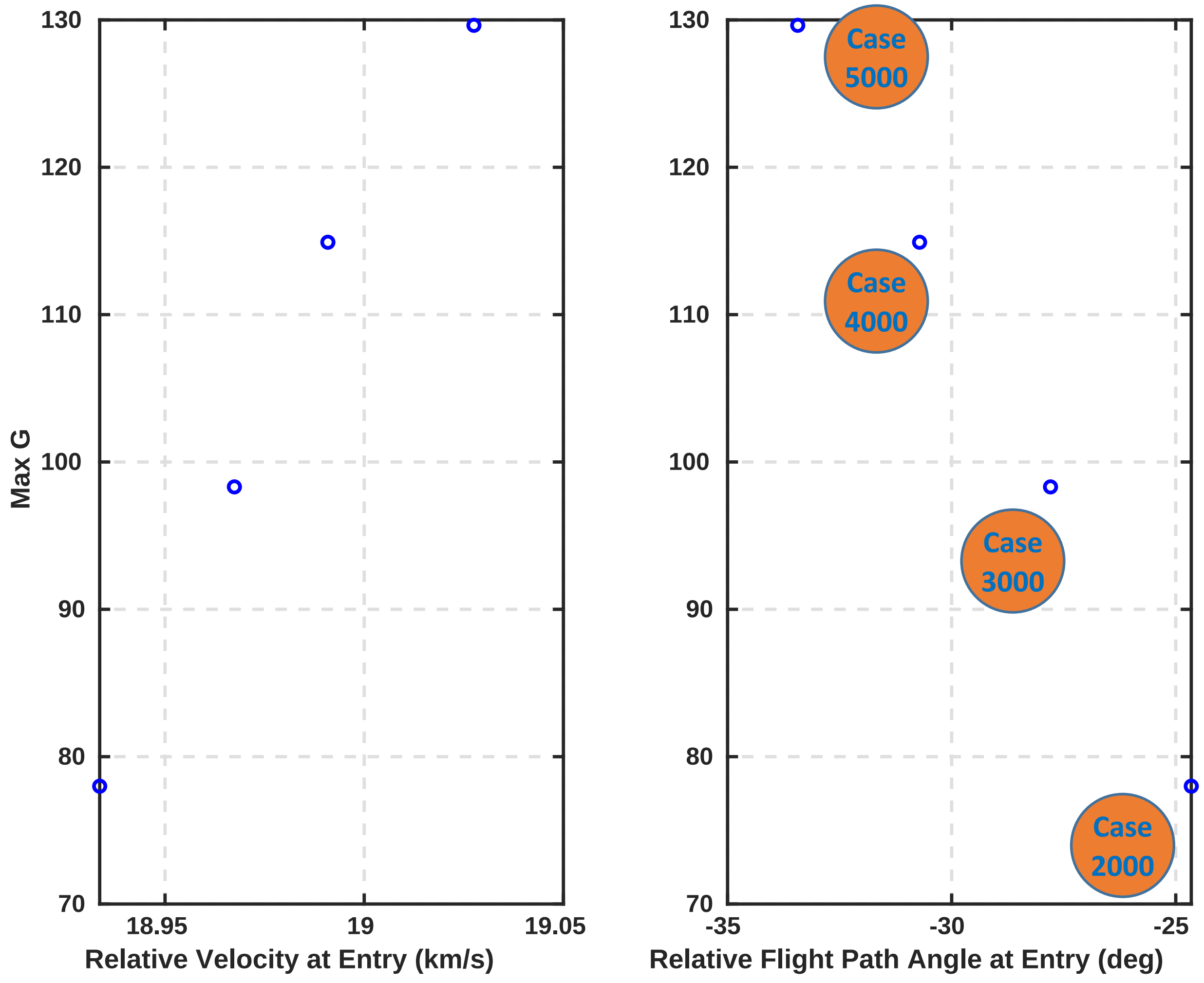
Update during ACE Run Outbrief

- Previous case4000 case resulted in lower timeline: Probe reached 10 bar at EI+48 mins
  - This was slightly faster than what the science team wanted
  - Led to reduction in amount of data that could be uplinked
- Descent parachute was sized at 1.5 m diameter
  - Inherited from Neptune Odyssey
  - There is room to increase the size to increase descent time without any recontact risk
- Descent parachute increased to 1.8 m diameter (no change in mass of the parachute deployable since the value in MEL already covers this size)
  - Recovers timeline to EI + 56 mins to get to 10 bar
  - MEV case seems to have similar backshell angle to orbiter
  - If mass decreases significantly from MEV, the backshell angle changes with respect to 10 bar time

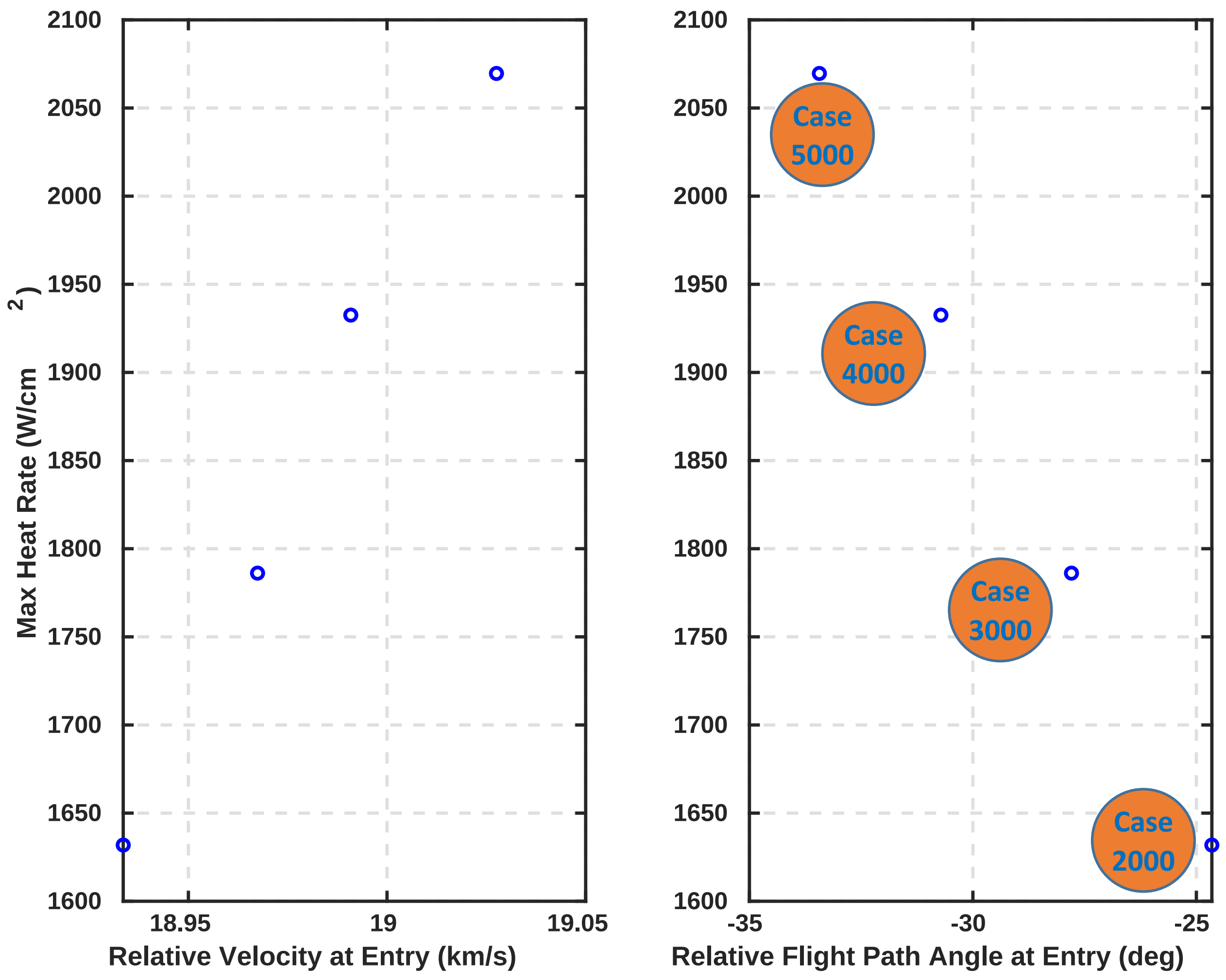
EDL Downselection Summary

- First iteration consisted of releasing the probe prior to the orbiter doing Uranus Orbit Insertion (UOI)
  - EDL was conducted from a hyperbolic entry trajectory
  - EDL parameters such as max acceleration, max heat flux, and max heat load were higher but not outside the capabilities of the heritage system
  - However, communication story between the probe and orbiter was poor and the orbiter trajectory post-probe separation potentially conflicted with ring avoidance constraints
- Second version of iteration consisted of releasing probe post UOI
  - EDL was conducted from an elliptical entry trajectory
  - EDL parameters were in general had lower max acceleration, max heat flux, and max heat load
  - Final point design was chosen trading EDL metrics and communication performance from four potential entry states that targeted various periapsis altitudes: -2000 km, -3000 km, -4000 km, and -5000 km. These were called case2000, case3000, case4000, case5000

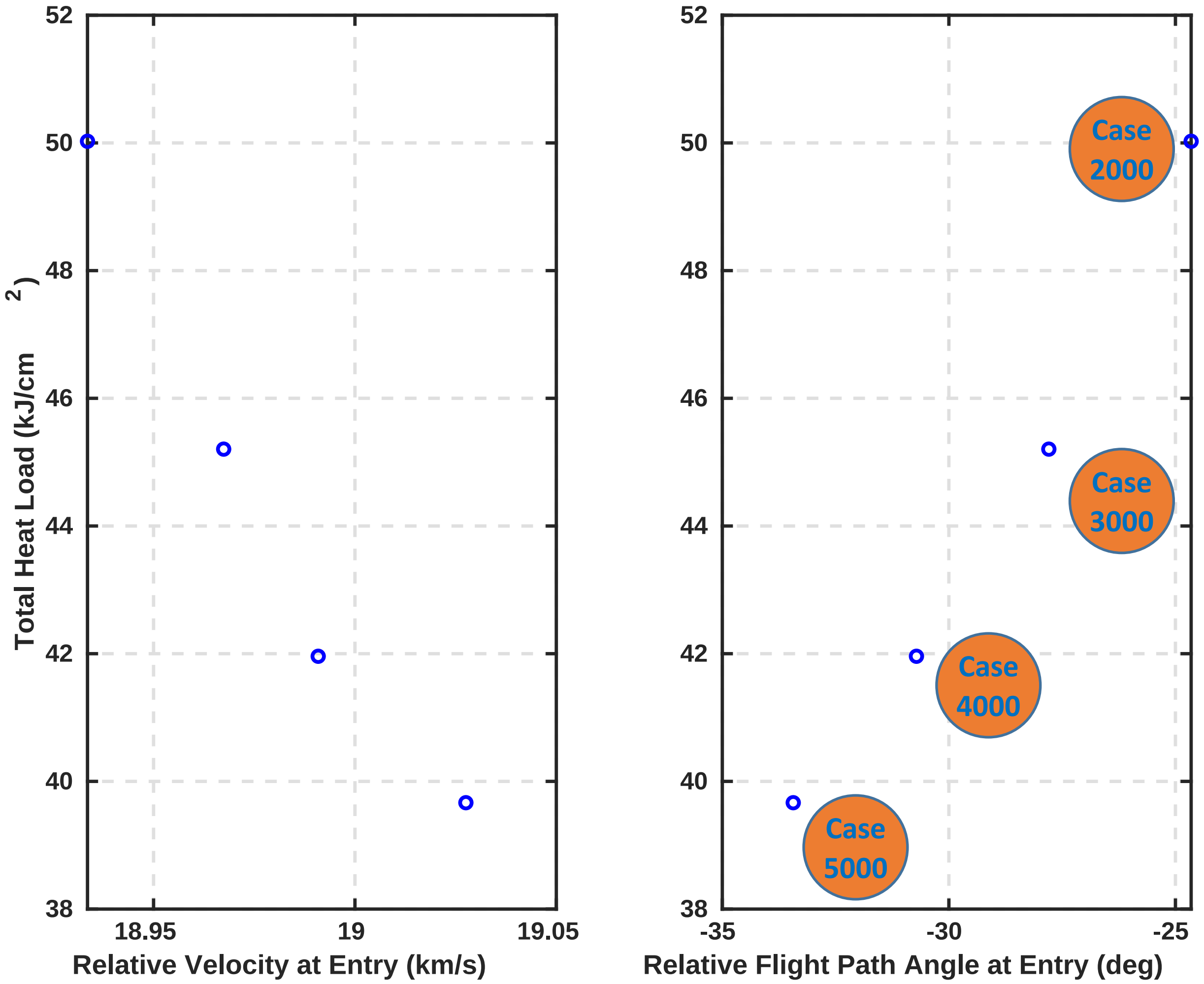
Max Sensed Acceleration



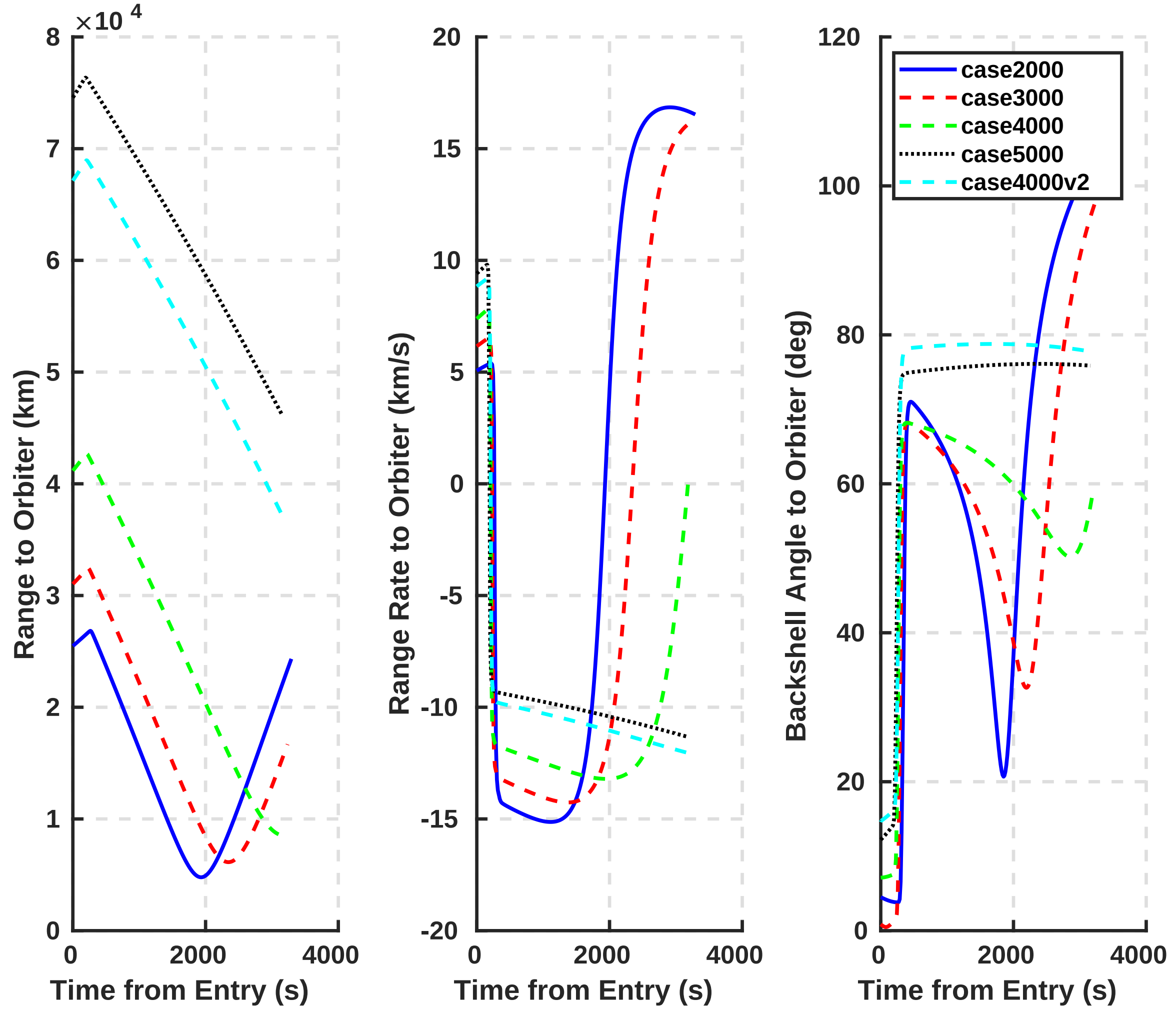
Max Heat Flux



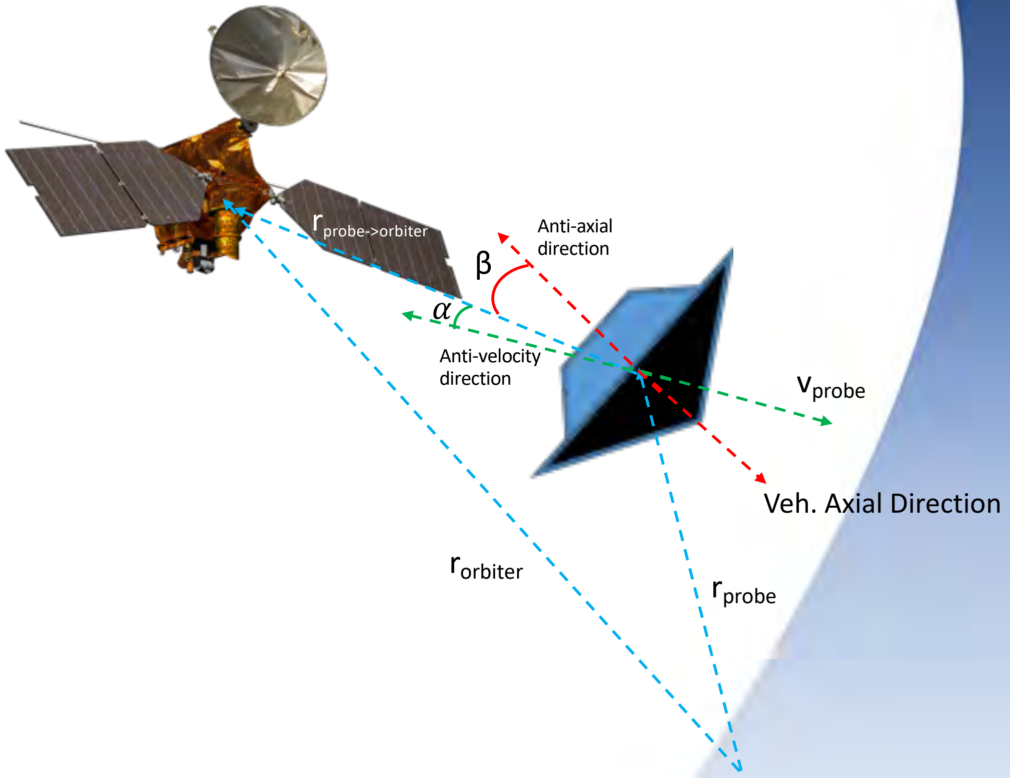
Total Heat Load at Parachute Deploy



Communications to Orbiter



Backshell Angle
(β in the figure)

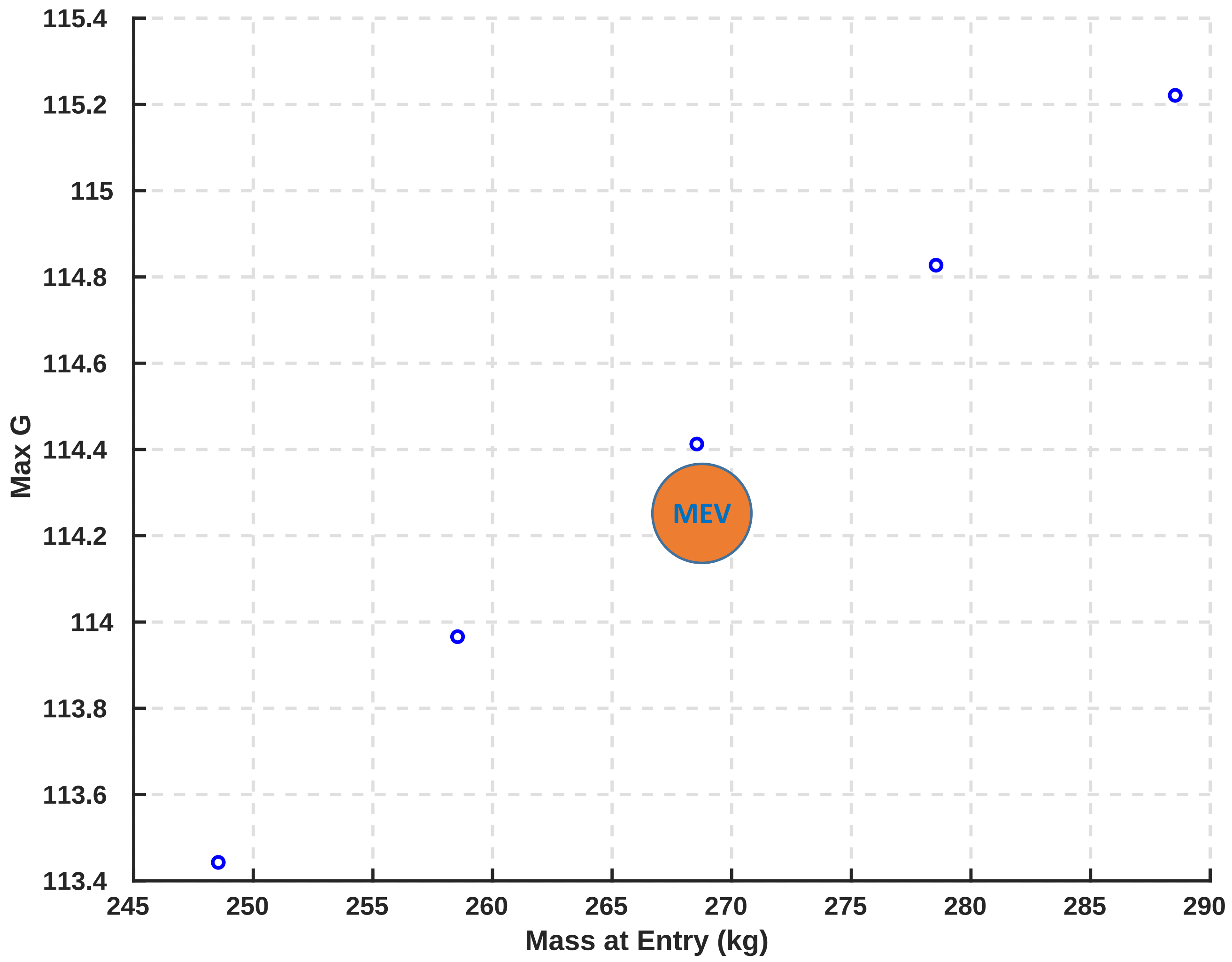


Note: Atmospheric effects and antenna pattern were not used for this analysis. This is purely geometric data

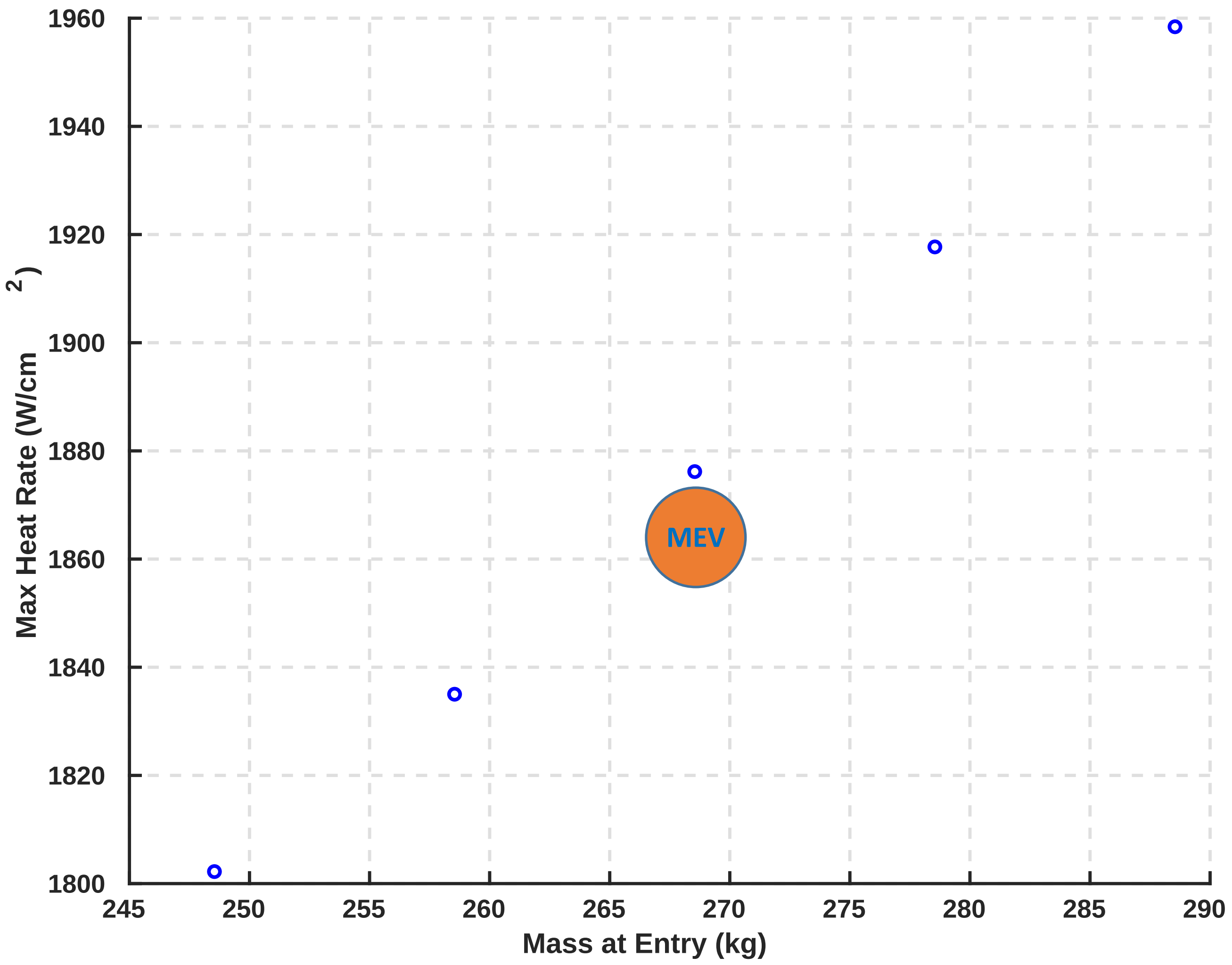
Summary

- One case has been downselected for EDL and comm purposes – case4000
  - Had the best communication and link budget story
  - Acceptable combination of max acceleration, max heat flux, and total heat load
- Mass properties have been updated to MEV for UOP: 268.5 kg
  - Also ran some cases that were +/- 10, 20 kg for sensitivity

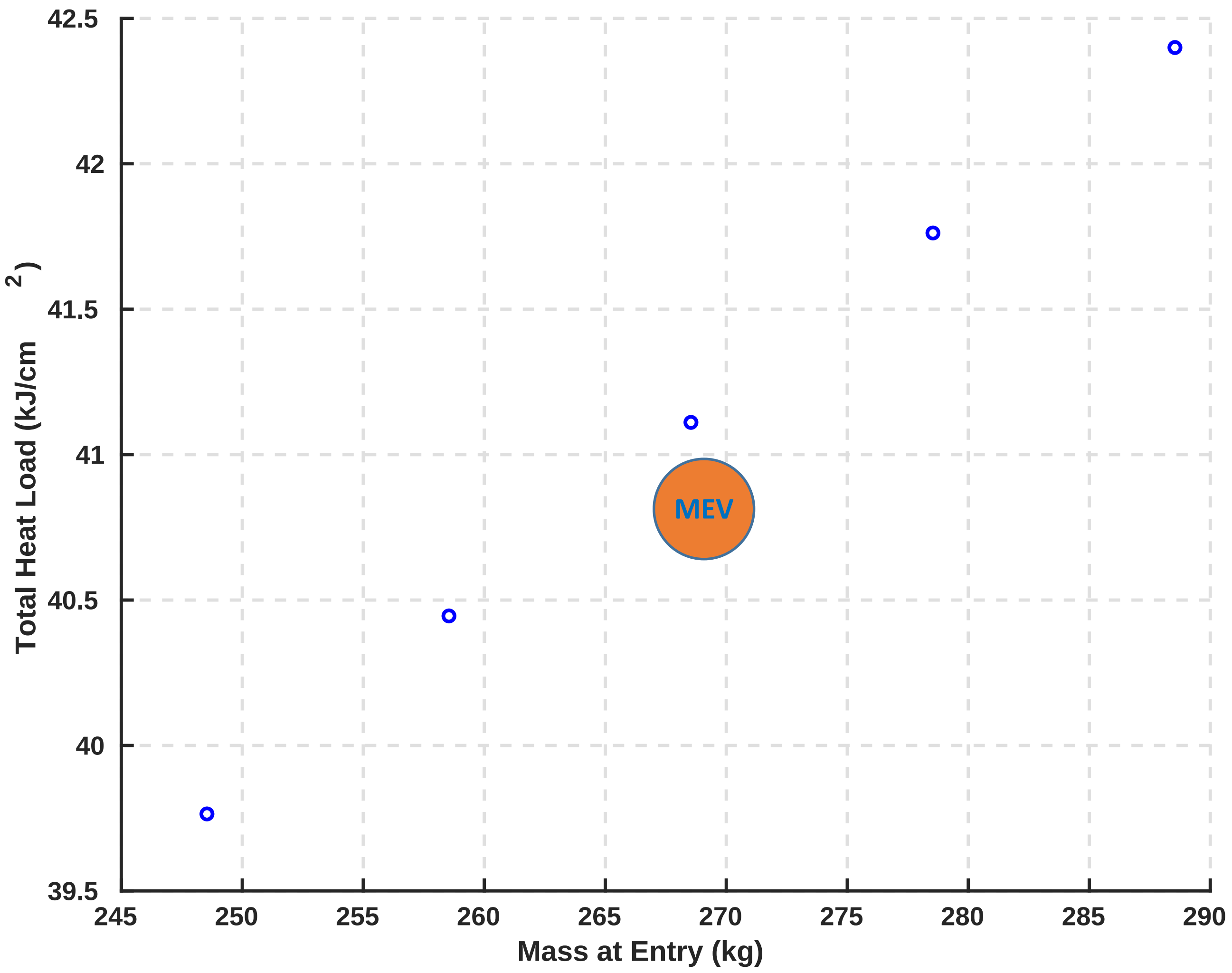
Max Sensed Acceleration



Max Heat Rate

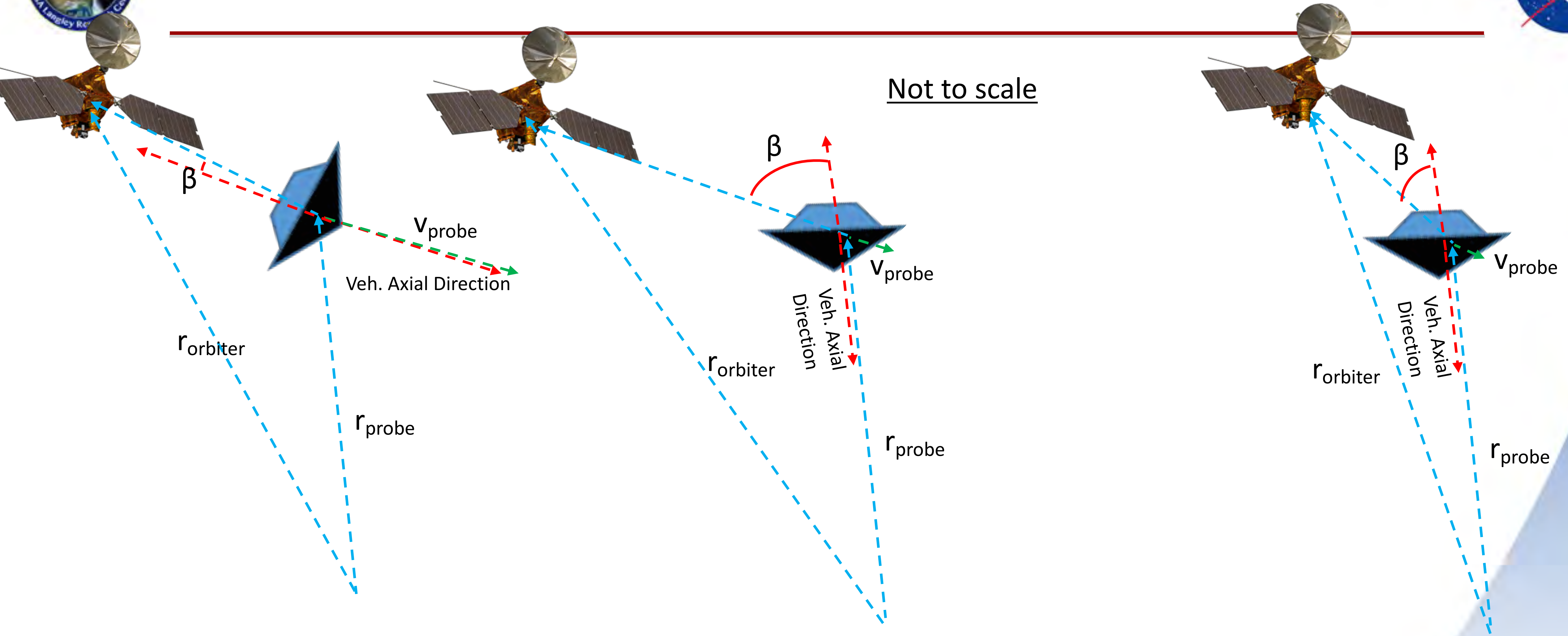


Max Heat Load



Cartoon of Orbiter-Probe Orientation

Not to scale



At Entry Interface (t = 0)
Backshell Angle ~ 14 deg

During peak deceleration (t ~ 400 s)
Backshell Angle close to 90 deg

During parachute flight (t ~ 1500 s)
Backshell Angle decreasing from 90 deg

Uranus Orbiter Probe (UOP) Entry Environment Estimation and HEEET TPS Sizing

June 1, 2021

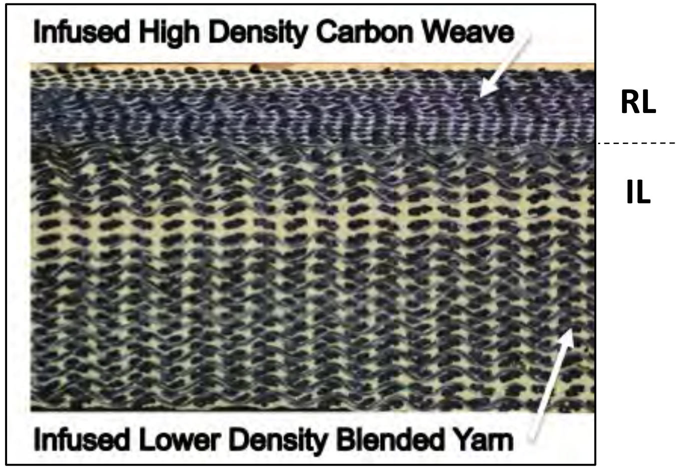
NASA Ames Research Center
Helen Hwang, Josh Monk, Dinesh Prabhu, John Thornton, and Gary Allen

HEEET Overview

Heatshield for Extreme Entry Environments Technology

- **HEEET is an integrally 3-D woven, dual-layer, resin infused, ablative system**
  - An efficient, optimized, carbon phenolic TPS using modern manufacturing & materials
- **Dense outer <u>recession layer</u> (RL)** is designed to be robust in highest heat flux & pressure environments
- **Inner <u>insulation layer</u> (IL)** handles the heat load with its lower density & thermal conductivity yielding reduced TPS mass fraction
- Existing 3D loom capabilities **<u>constrain manufacturable layer thicknesses</u>** (~5.5 cm)
- Dual layer HEEET has been funded by NASA and is at TRL 6 for a tiled configuration
- Single layer HEEET is the current baseline for MSR EEV (1.25m) with no seams. Forming trials have been successful.

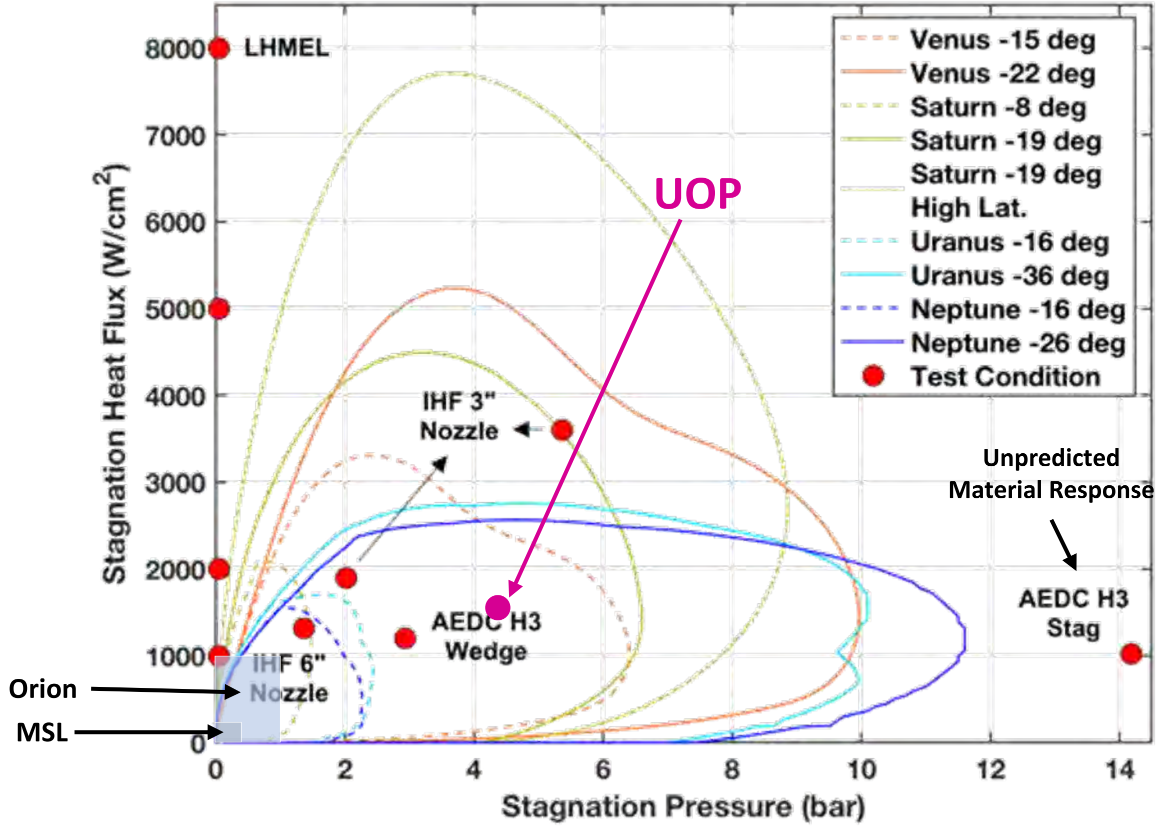
HEEET 3D Woven Preform



1-meter diameter HEEET engineering test unit

Mission designs need to consider manufacturing limitations (thickness)

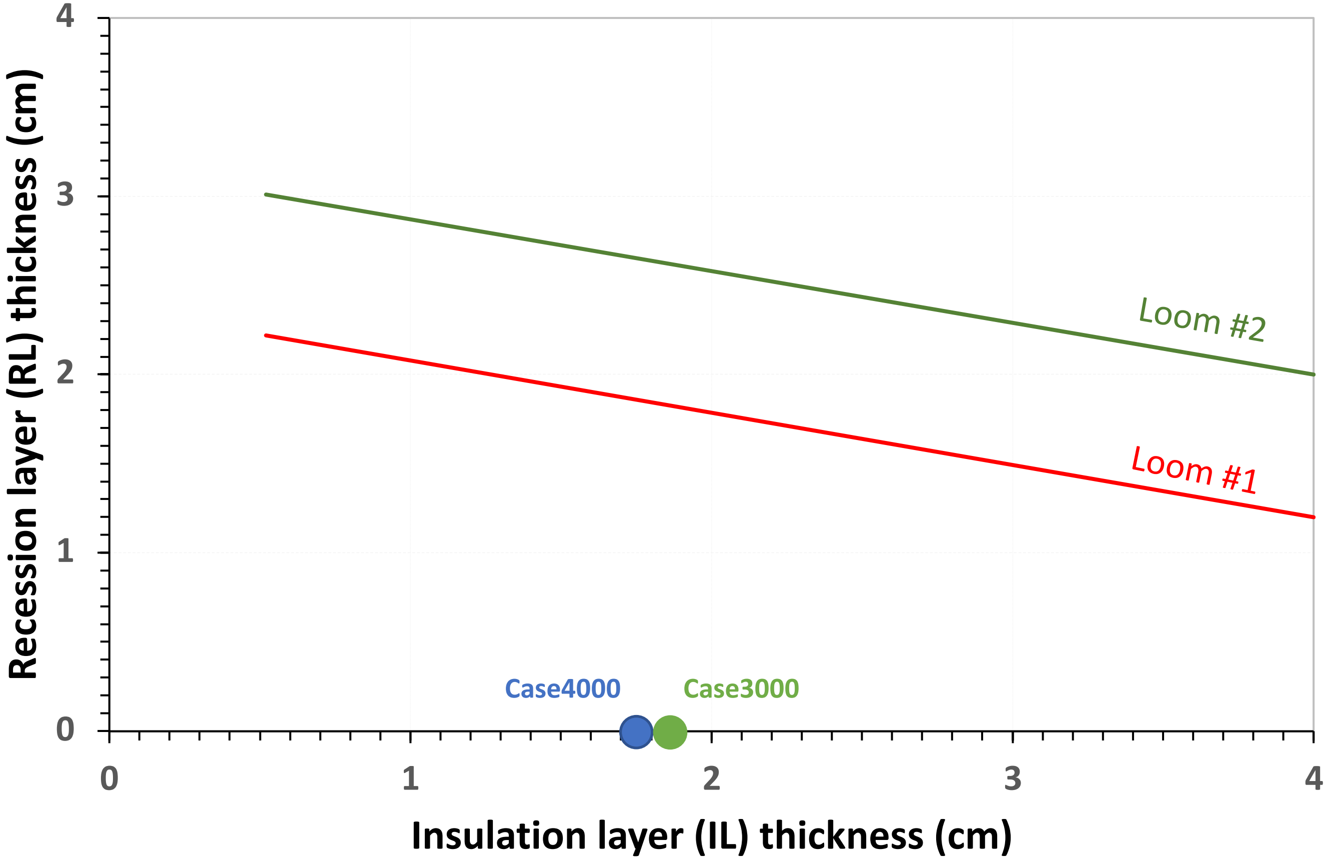
HEEET Arc Jet Testing Overview with Notional Mission Environments



- **Current testable heat fluxes and pressures in arc jets are shown**
- **HEEET (both dual layer and single layer) have been tested up to ~3600 W/cm² and ~5.4 bar**

- **Trajectories considered for UOP are well within testable bounds of arc jet environments**
- **HEEET single-layer material is within limits and will have predictable performance**

HEEET Weaving Capability & TPS Sizing



*Max thickness capability shown for 2 loom options

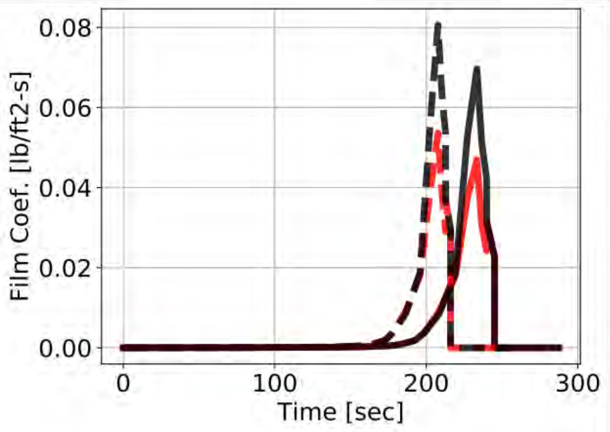
*Loom #1 is preferred due to larger panel manufacturing (60 cm vs 30 cm width)

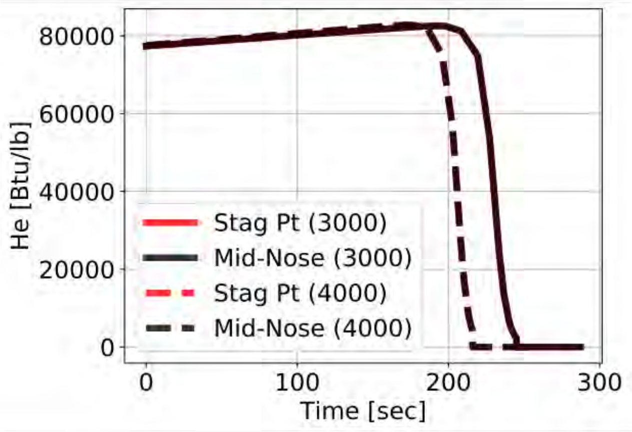
- **Weaving Insulation Layer (without Recession Layer) HEEET is possible on the current Loom #1 for Uranus Orbiter and Probe for the selected trajectory cases**

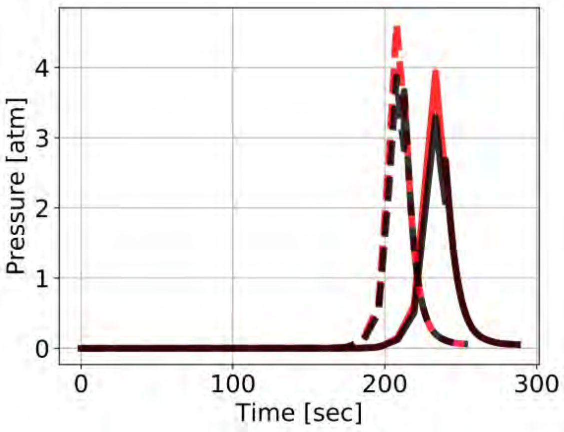
HEEET Sizing Analysis

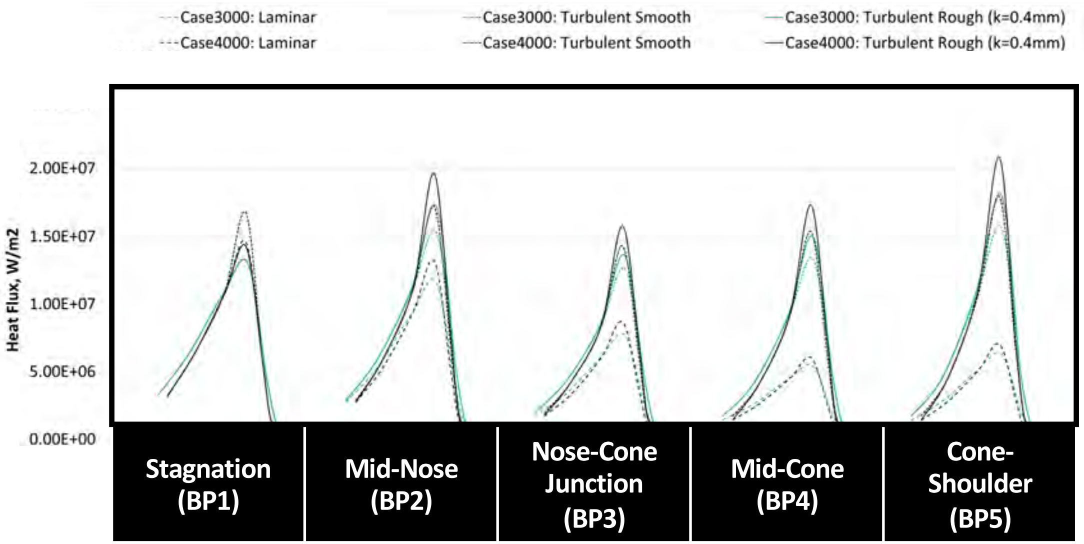
- For the Uranus probe, aerothermal heating was calculated using:
  - Mid-fidelity tools (Traj) to calculate stagnation point heating and HEEET sizing
  - High-fidelity tools (DPLR and FIAT) to calculate sizing along flank body points
- Constant thickness heatshield was assumed for the mass estimate, using the highest thickness point
- For comparison, the heatshield mass for dual-layered HEEET for the Neptune Odyssey probe was 43.3 kg (CBE).

Aerothermal Environmental Inputs for FIAT TPS Sizing (Case 4000 and Case 3000)

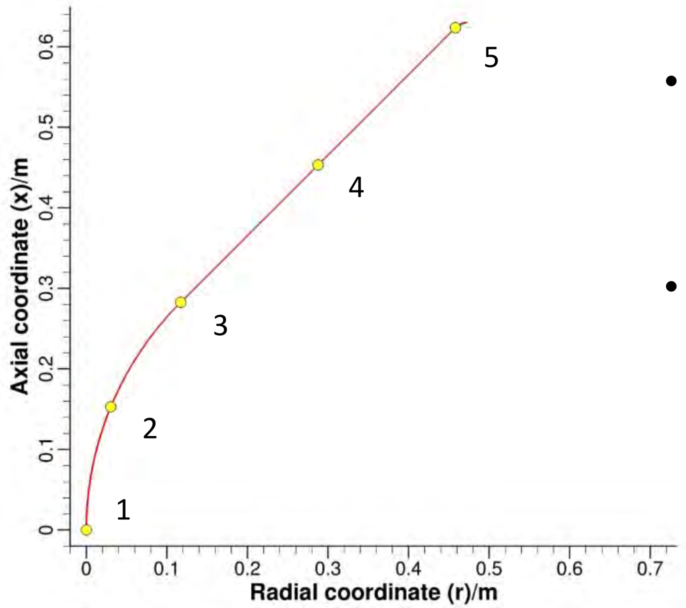








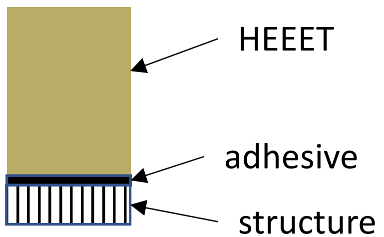
*Shifted time for Case3000 to align peak heating with Case4000



- Case4000 shows higher heating, but for shorter duration than Case3000
- Heat load drives TPS sizing therefore Case3000 requires thicker Single Layer HEEET

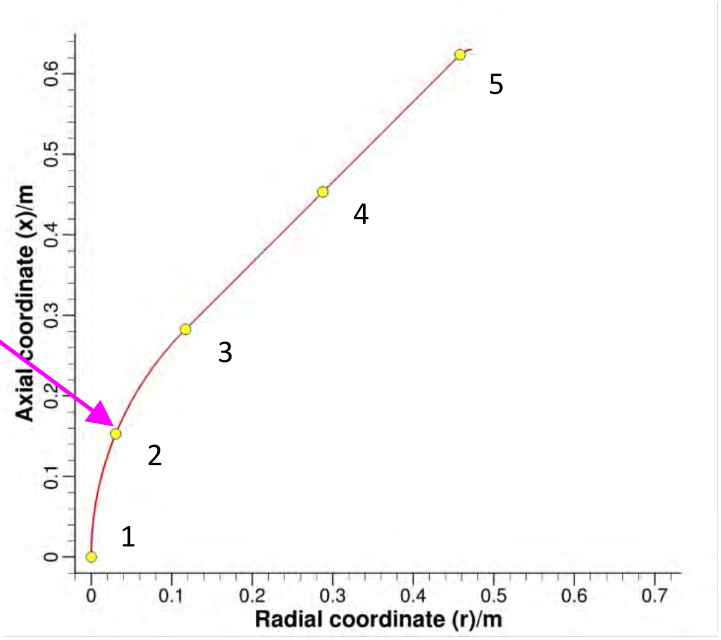
FIAT TPS Sizing Results (Case 4000 and Case 3000)

Case	Stagnation	Mid-Nose	Nose-Cone Junction	Mid-Cone	Cone-Shoulder Junction
4000	1.721 cm	1.783 cm	1.732 cm	1.739 cm	1.765 cm
3000	1.837 cm	1.892 cm	1.849 cm	1.854 cm	1.872 cm



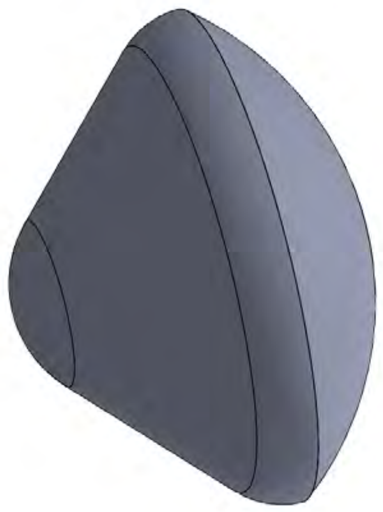
- Analysis assumes single layer HEEET for cases 3000 and 4000.
- Aerothermal and material margins included for FIAT TPS sizing process.

Case	Max Heat Flux	TPS Thickness	Current Best Estimate
4000	2080 W/cm2	1.783 cm	25 kg
3000	1800 W/cm2	1.892 cm	27 kg



Final TPS Mass Estimate

- **Using Neptune Odyssey's CBE for the TPS, both heatshield and backshell, is conservative.**
- **<u>Backshell:</u>**
  - **PICA backshell TPS sizing estimated assuming ~15% aerothermal heating of the heatshield stagnation point**
  - **Backshell shape assumed to be spherical for simplicity**
  - **PICA assumed to be constant thickness, leading to a total of 9 kg for PICA and adhesive**



Assumed Uranus Entry Probe geometry

Case4000 (Max thickness Mid-Nose)	CBE Mass, kg
Heatshield (Single Layer HEEET)	25
Backshell (PICA)	9
Total mass estimate for MEL	34
MEV (1.3x)	44

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Uranus Orbiter and Probe Mission Operations

Andy Calloway

APL Low Cost Operations Model

- UOP Mission Operations can be supported by the APL Low Cost Operations model, leveraging heritage and experience for pre-launch, Cruise, and Science phases
  - No unique mission phases or spacecraft subsystems, ground system elements, tools, staffing profiles
  - Optical navigation pipeline from downlink to processing is well established
  - Straight-forward mission design from an Ops planning and support perspective; no solar conjunctions
  - Trajectory elements and critical events have significant APL experience from previous missions including MESSENGER, NH, PSP: two planetary flybys and corresponding targeting and clean-up maneuvers, a DSM, hibernation / beacon / wake-up checkout cruise profile, DDOR contacts, 34m x-band and Ka band tracks, use of DSN scheduling team; orbit insertion, operating with long RTLTs, multi-year Cruise phase, knowledge retention strategies, training, ground systems
  - Payload suite and corresponding science planning cycle and data pipeline architecture is comparable to scope and complexity of other APL missions
- Enhanced operational focus will be on the one new APL activity type: probe operations, from release, parachute deployments, to data relay. Will be thoroughly tested, simulated, and rehearsed in pre-launch mission sim and multiple times during flight in ORTs

Mission Profile

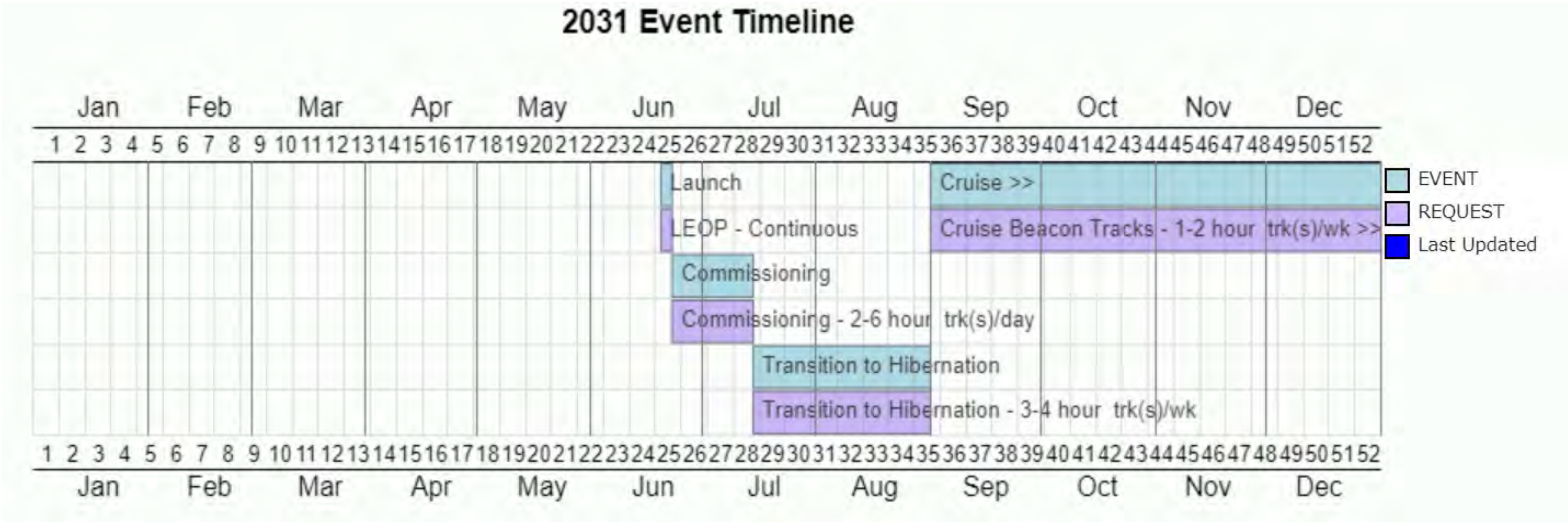
- The UOP mission consists of a 13.5 year Cruise phase highlighted by a Deep Space Maneuver (DSM), an Earth Flyby, a Jupiter Flyby, and Uranus Orbit Insertion (UOI); no science is baselined for Cruise although instrument calibrations and stray light characterizations are not precluded for the flybys
- We have a four year prime science phase that begins following a six month post UOI transition period; the probe release/entry and a periapsis raising maneuver (PRM) occur during the transition period
- 34m DSN supports are scheduled for all mission phases; X-band operations during Cruise, Ka band for higher rate downlink in science; dual X/Ka band downlink for RS is optional; DDORs preceding flybys and UOI; Safe mode communications close with chosen antenna suite on-board in all phases

- The in-flight operations begin after launch in June 2031 with standard health assessment and the commissioning phase, which concludes in mid July 2031; Phase E then officially begins
- The low cost model calls for a spin-stabilized hibernation/semi-annual 3-axis wake-up profile for Cruise; this warrants an initial transition period of three 4-hr tracks per week through the end of August 2031
- Hibernation begins in September 2031 employing a short weekly 2-hr DSN beacon track for health checks similar to NH; a proven response strategy is defined for red beacon tracks
- The entirety of Cruise is designed with two 3-axis wake-up periods of two weeks each in March and September each year. These periods consist of daily 8-hr supports. Activities can be recurring with system and payload health checks or an alternating strategy may be employed

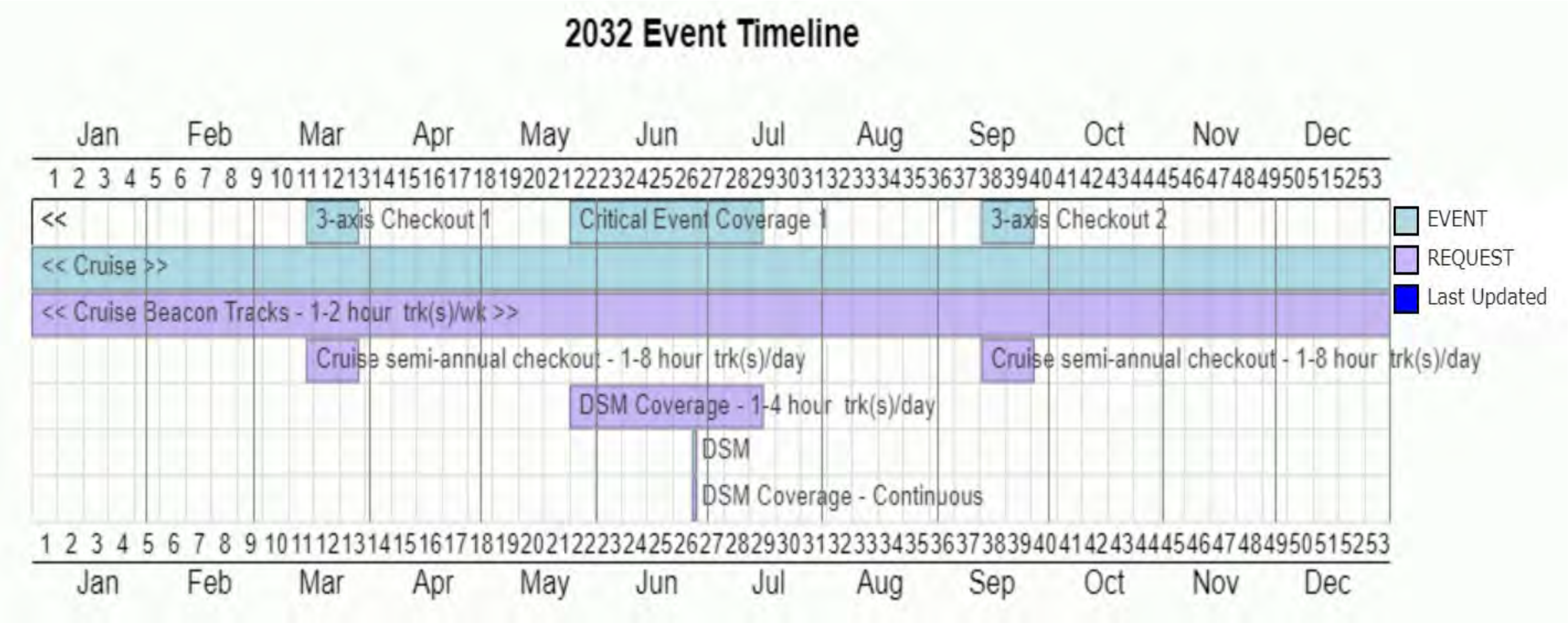
Mission Profile continued

- The highlight in 2032 is the large Deep Space Maneuver (DSM) on June 27th. The spacecraft is brought out of hibernation in late May and extends three weeks after the maneuver. This window ensures adequate coverage for Navigation with an appropriate Data Cutoff (DCO) for the final maneuver design, plus data downlink and reconstruction following the maneuver. The maneuver timing is flexible and may be split into two as a risk reduction measure.
- The Earth Gravity Assist (EGA) occurs April 27, 2033; although some maneuvers may be performed while in spin mode, to be conservative, we are baselining a hibernation exit 100 days prior. This window supports EGA preparations and maneuvers at -90d, -30d, -10d, and a clean-up at +20d, with a return to hibernation eight days later to incorporate all data downlink; 8 weeks of DDORs, 2 per week, are scheduled for EGA approach
- The Jupiter Gravity Assist (JGA) occurs December 20, 2035. The same approach and cleanup timing and strategy is employed for JGA as with the EGA described above
- Uranus Orbit Insertion (UOI) is scheduled for December 05, 2044. The same approach timing and strategy is employed for UOI as with the EGA and JGA
- Following the post UOI health checks there is a six month transition and environment characterization period with one daily 4-hr track. The key events here are the probe release/spacecraft divert maneuver and probe science, plus the periapsis raising maneuver (PRM)
- The four years of science are supported by daily 8-hr Ka band higher rate data downlinks. The first two years are focused on Uranus science and Titania while the orbit plane is brought into co-planar alignment, and the second two years are focused on the moons of the Uranian system

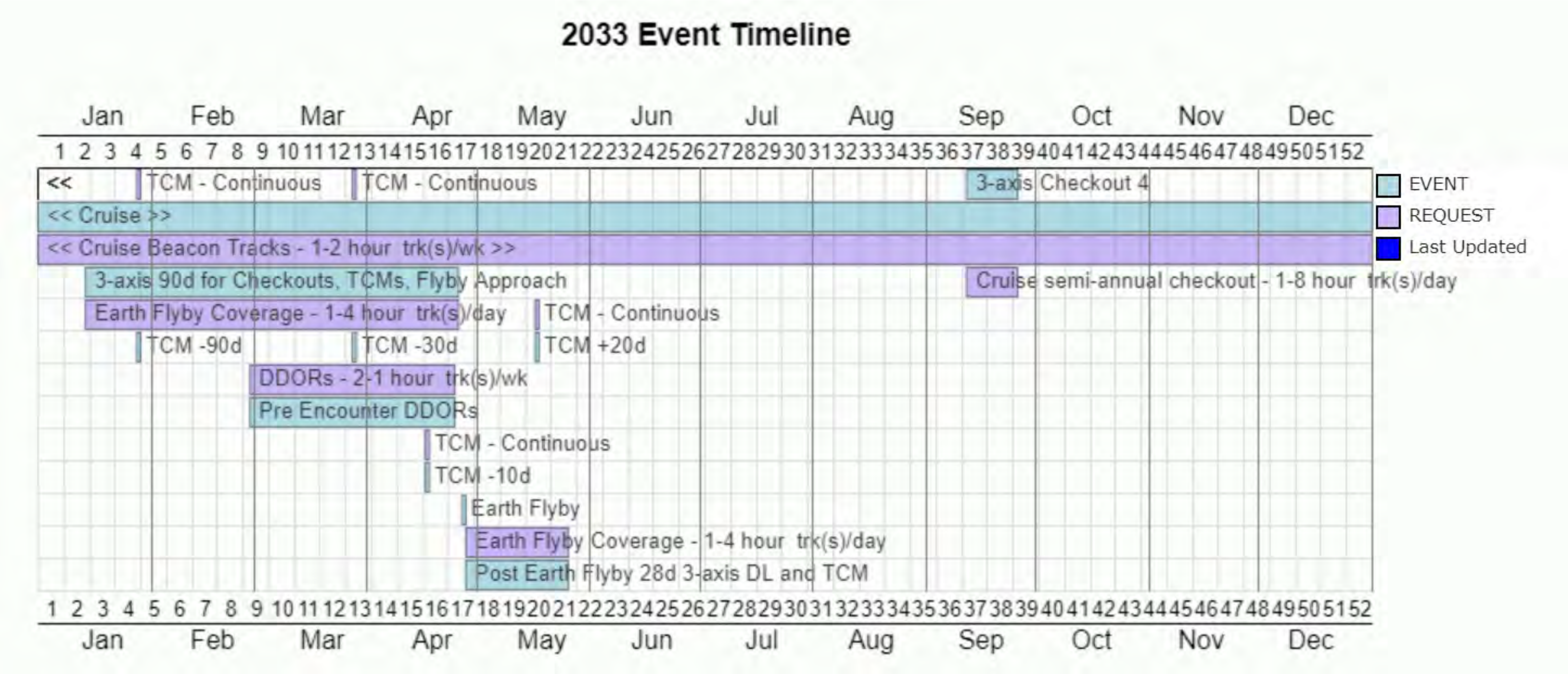
Mission Timeline Screenshots



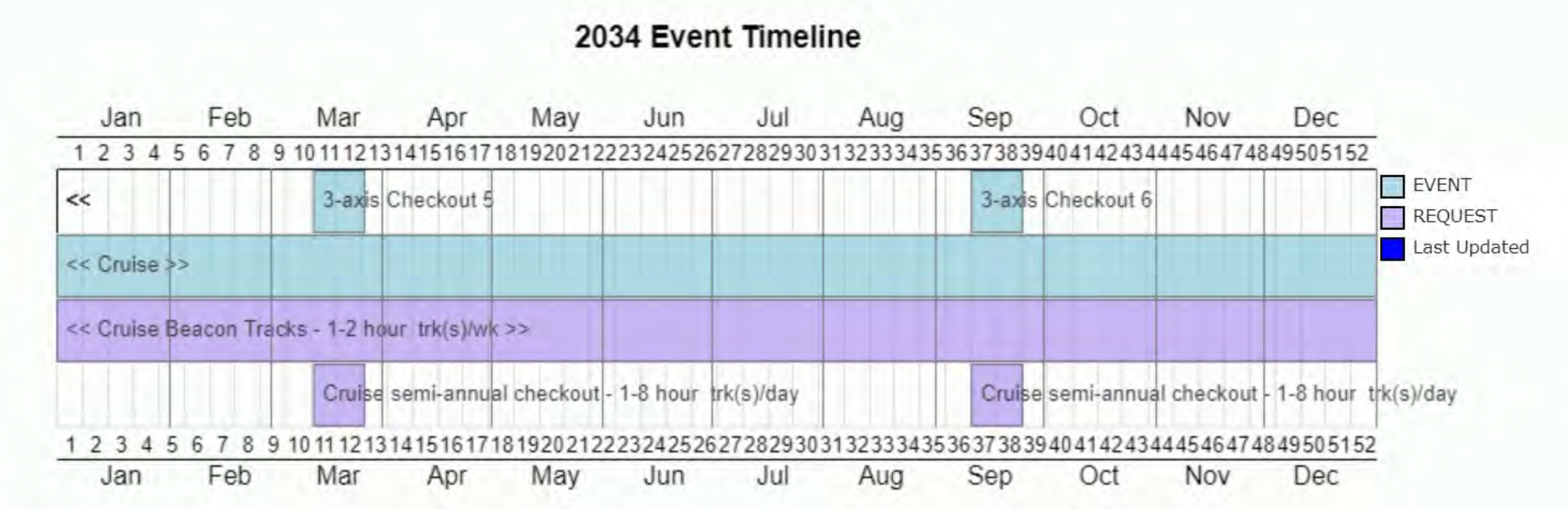
Mission Timeline Screenshots



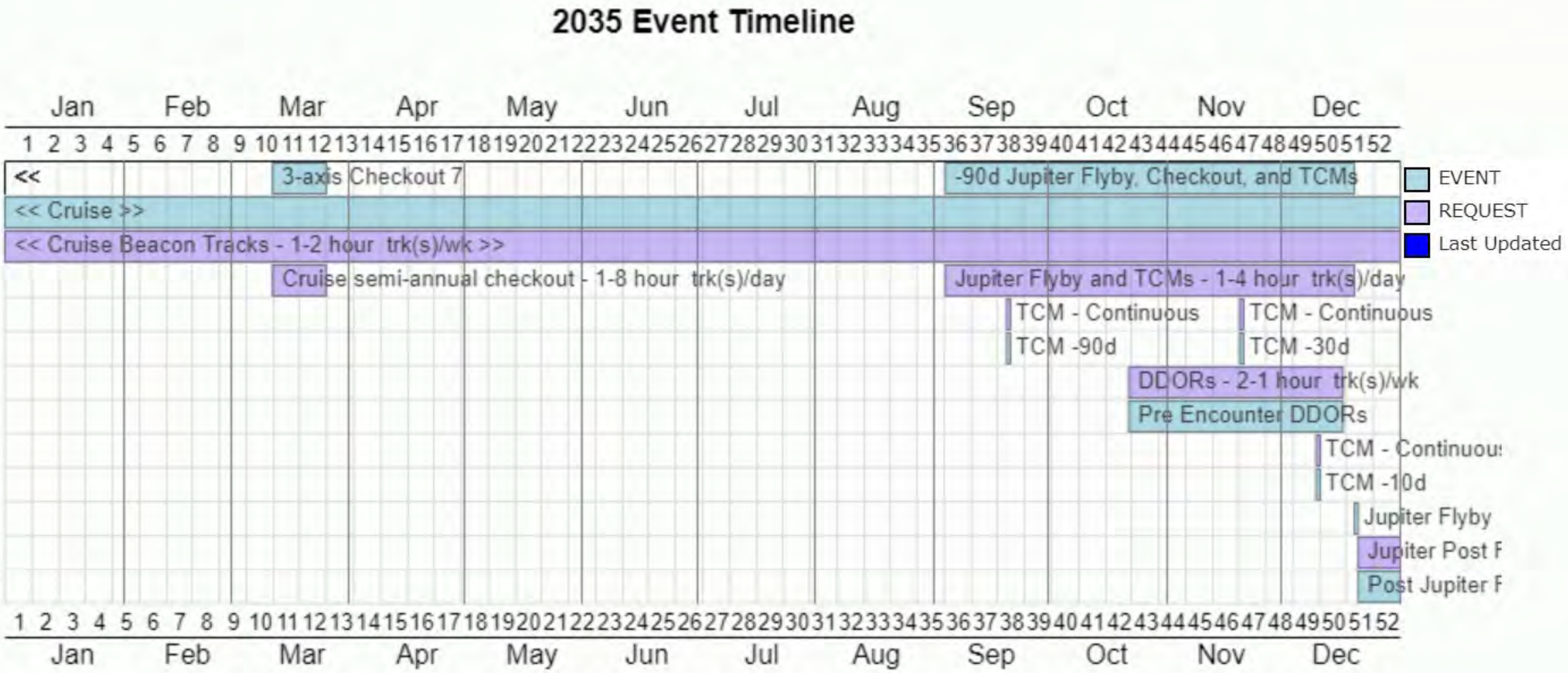
Mission Timeline Screenshots



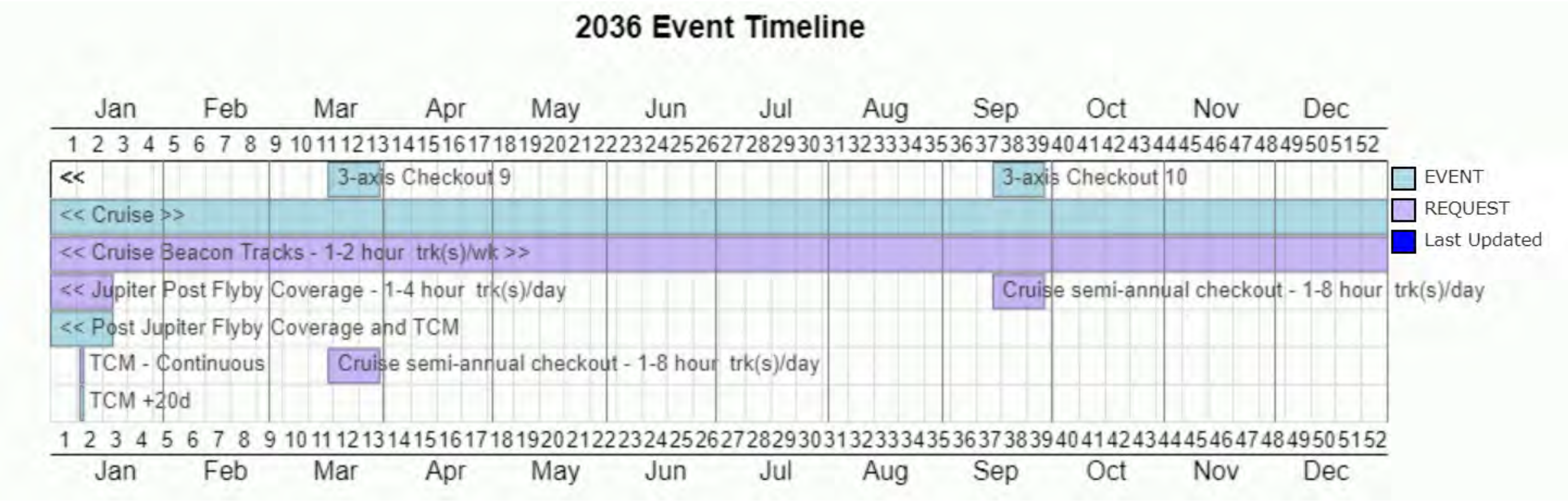
Mission Timeline Screenshots



Mission Timeline Screenshots

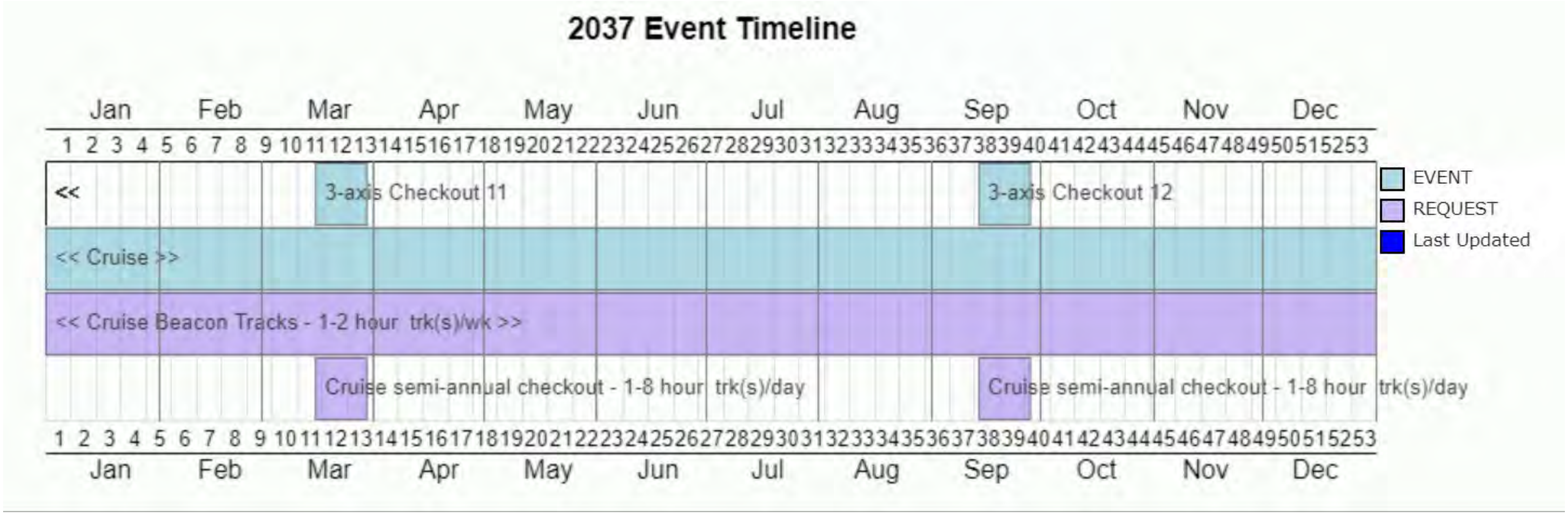


Mission Timeline Screenshots

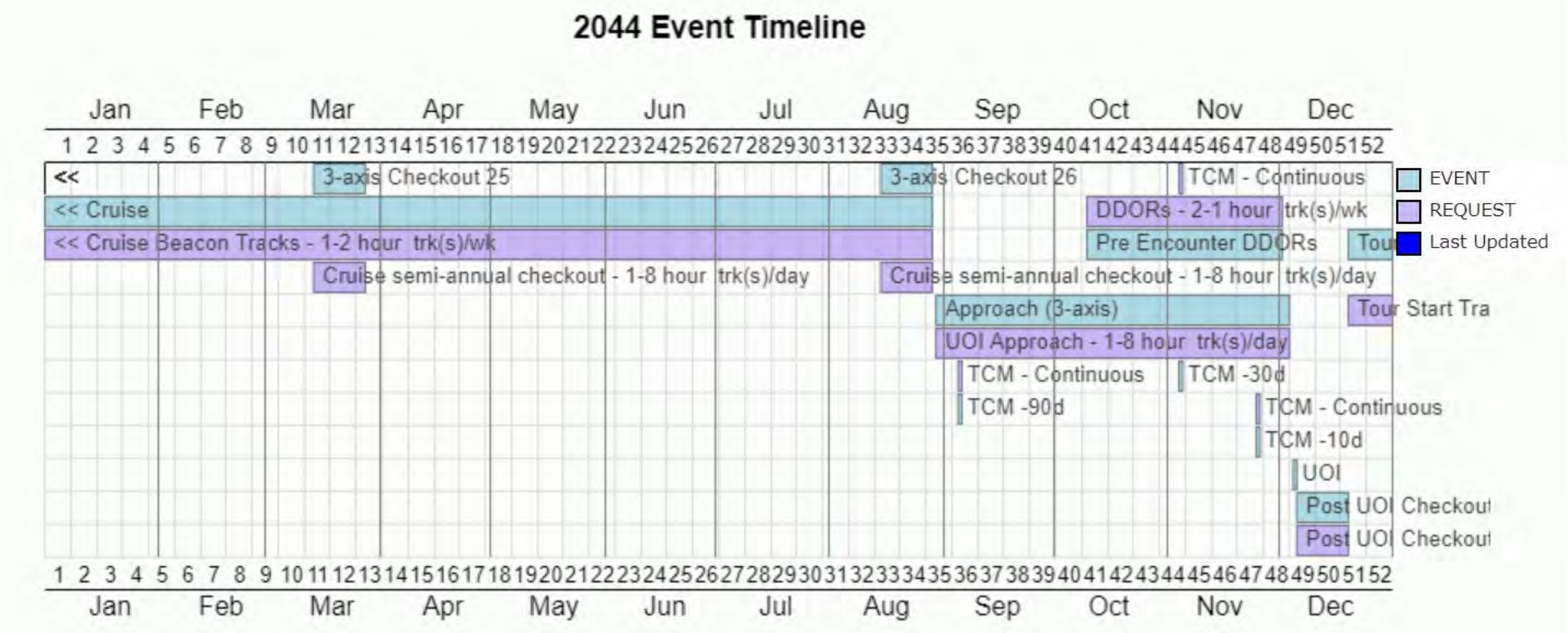


Mission Timeline Screenshots

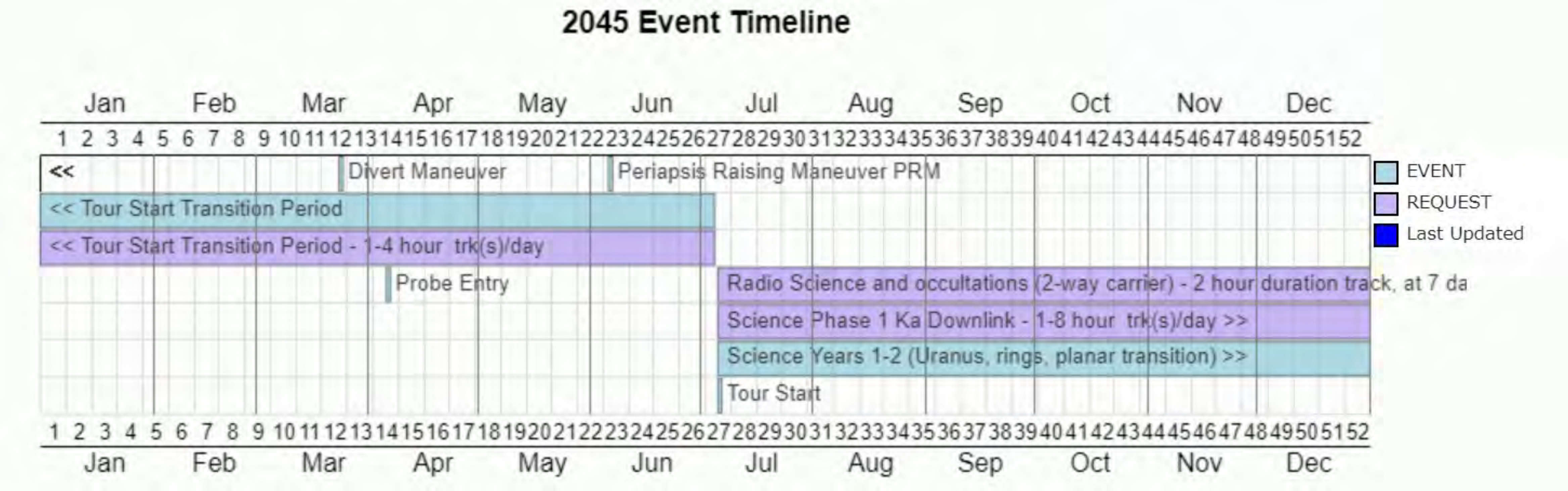
Repeat 2037 – 2043 yearly profile



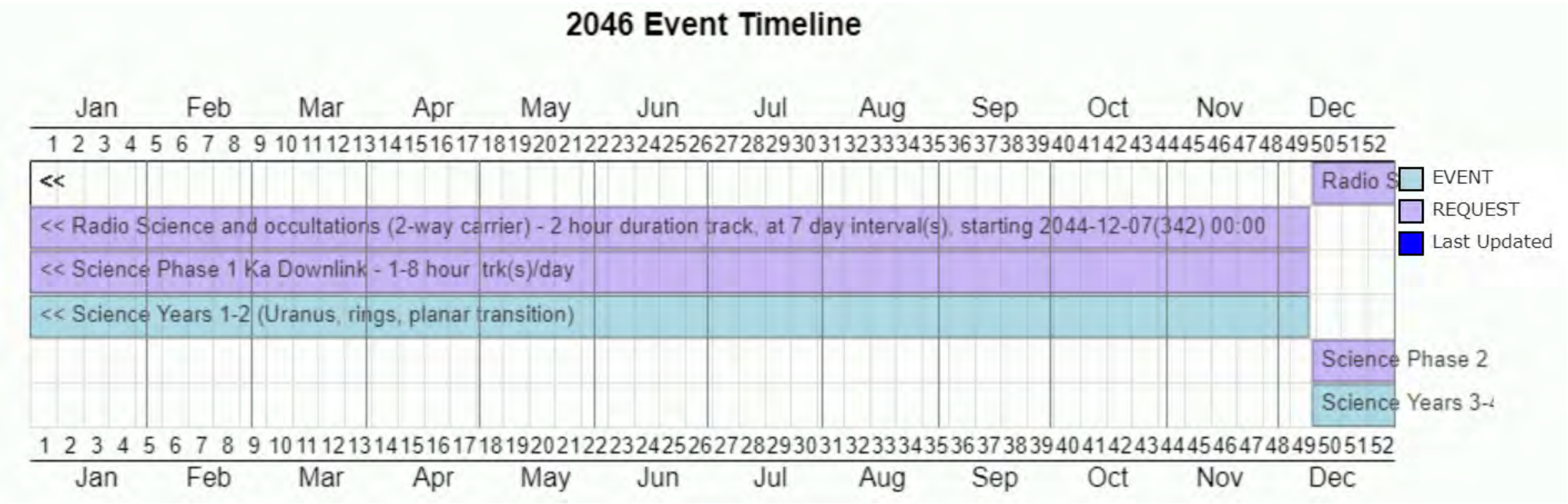
Mission Timeline Screenshots



Mission Timeline Screenshots

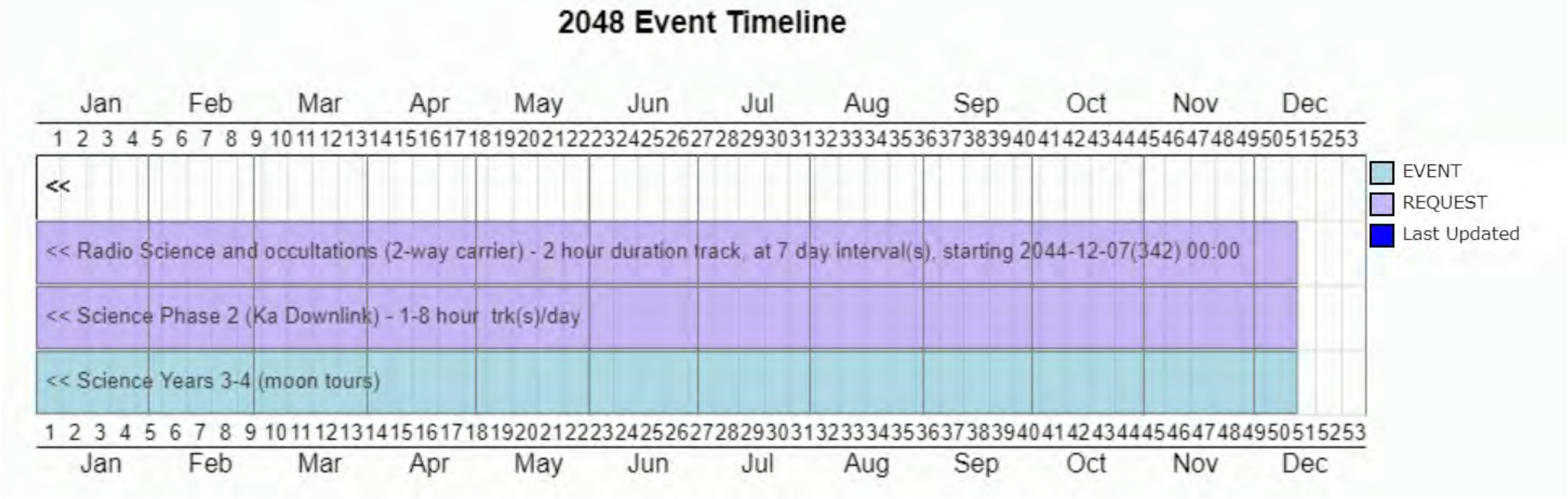


Mission Timeline Screenshots



Mission Timeline Screenshots

Mission Timeline Screenshots



UOP Study – Data Return Analysis

Deb Chattopadhyay

End-to-End Data Story - Assumptions

- Jun 13, 2031 launch date
- Orbital period during tour ~34 days
  - Assume need to get 1 orbit worth of data down in 34 days to clear flash by next flyby
- General downlink strategy –
  - Cruise – X-band only ~ 1x/week 8 hr pass
  - Tour - Ka-band science DL, 1x/day 8 hr pass
  - Possible additional passes for critical events and nav purposes (not really too relevant to data story)
  - OpNavs required - assume it is part of SC data coming down at high priority in each pass. (DV estimate is small, for now including within an estimate for SC data)
- Compression assumption – average, assume 2:1 or 3:1 for now
    - For now assuming 2x for all
- Storage - 128 Gbits of flash for high-rate instrument data (IIC card), 256 Gbits in NAND flash
  - Instruments might have some of their own storage, but for simplicity assuming that all data goes directly to IIC flash as the starting point
- Solar conjunction not a problem during any of the critical events

Scenarios

- Cruise - June 2031 launch
  - Assume Xband 1x/week for beacon for most of cruise
  - every 6 months wake up for some checkouts and telemetry DL, 1x 8 hr pass/day for a few days
  - Assume can use HGA for DL during cruise when needed for checkouts and flyby periods so get at least 5.45 kbps (end of cruise rate). Can probably make do with the MGA, for most of cruise.
  - Major cruise events:
    - DSM June 2032
    - Gravity assist flybys of Earth (~ Apr 2033) and Jupiter (Dec 2035) – assume no science data collection or driving downlink scenario
  - Not expecting many science activities, low DV
  - Assume this will work with low volume of SC data + opnavs
- Probe relay -
  - Probe data streamed back to Orbiter and stored, not expecting any bent-pipe relay back to earth
  - Assuming no time criticality to send the probe instrument data back to Earth, but probably want soon
- Tour -
  - Ka-band DL 1x/day 8 hrs
  - Assume need to get 1 orbit worth of data down in 30 days to clear flash by next flyby
  - Not all instruments on at the same time - selected instruments based on type of orbit
  - Orbit types:
    - Uranus/Rings Remote sensing
    - F&P& Mag
    - Satellite flyby w/ remote sensing
    - Multiple satellite flyby (equatorial phase, if appropriate)

Calculation for Cruise

- Cruise - June 2031 launch
  - Assume X-band 1x/week for beacon for most of cruise
  - every 6 months wake up for some checkouts and telemetry DL, 1x pass/day for a few weeks
  - Not expecting many science activities, low DV
  - Assume can use/point HGA for DL during cruise when needed during checkouts and critical events, so get at least 5.45 kbps (end of cruise rate) - 3axis
  - Major cruise events:
    - DSM June 2032
    - Gravity assist flybys of Earth (~ Apr 2033) and Jupiter (Dec 2035) – assume no science data collection or driving downlink scenario
      - 1 8 pass/day about 3 weeks after each event will be sufficient to get checkout/commissioning data down

  - Assume this will work with low volume of SC data + opnavs, given these assumptions – no further detailed analysis completed

Calculation for Probe Relay

- Total probe instrument data = 16-17 Mbits
  - Not worried about storage space onboard orbiter, given small volume of science data
  - Probe send data to SC, data stored for future downlink
  - There is no requirement for immediate return of data to Earth, but this easily fits within one 8-hr Ka-band downlink after the probe release, even assuming high-priority probe engineering data DL - should be able to get probe data back within a few days.

- Time available for relay from probe to orbiter = ~50 min link duration (after backshell sep)
  - If duration decreases significantly, could be an issue since the link budget is tight.
  - Eventually (in later studies/development) will need to assess in further detail – will have to buffer some data from initial release to backshell sep time, and transmit that data along with the new data being generated.

- UHF link check
  - Assume fixed data rate on UHF, but stepping might be available
    - See Telecom analysis package for details on this topic

Calculation for Tour Orbit

- Assume 30 days avg orbit
- ~ 25-35 orbits in overall tour
- Per orbit calculation of data volumes
- Orbiter onboard 256 Gbits NAND storage is enough for about ~6 orbits of science data with current assumptions (so have sufficient margin in case we are not able to DL for some period of time – DSN issues, etc.)
- Available DL -
  - Total DL via Ka-band during orbit (8 hr pass/day w/ rate stepping) @ 19.475 kbps
    - 1.68*10^10 bits -i.e., 16.8 Gbits/orbit or 2.1 GB per orbit or 2100 MB
    - Already have 3dB margin in link budget
    - Assume an additional 5% data margin for dropouts, overhead etc. so overall available science downlink = 1995 MB/orbit
- Assumptions
  - Data volume estimates provided by Science (See Data Volume estimates attachment)
  - Compression factor of 2x (and Mag instrument has internal compression of 2.7x in addition)
  - Assuming 1 kbps for SC data, including any Op Nav data (probably conservative..)
  - Mag assumption – full rate for 5% of orbit, and used 0.5 kbps as representative low/survey data rate (more comparable to Ice Giants and Neptune ODY reports)
  - F&P suite instruments – will have to think about more
    - Decided to go ahead with strategy of allocating remainder of DV (after other instruments accounted for) for each orbit to F&P
    - Sanity checked with data rates and a representative
- See spreadsheet for draft data accounting for the 4 different types of science orbits (next slide)

Tour Orbit Type 1: Uranus Remote Sensing

Uranus/Rings Remote Sensing Dedicated, No Sat Flybys				**Notes**
	DV generated (MB)	Post-onboard compression (MB)	Compression factor	
NAC	165.00	82.50	2	Updated for more imaging/orbit
TIR	0.50	0.25	2	
Vis/NIR	1000.00	500.00	2	Updated for more imaging/orbit
WAC	16.70	8.35	2	
Mag	336.96	62.40	2.7x within instrument, and 2x overall	Assumed full rate of 11.3 kbps for 5% of the orbit. Then used 0.5 kbps a representative low/survey data rate for rest of orbit.
F&P	2359.00	1179.50	2	Allocation remaining after all the other instruments accounted for
SC data	324.00	162.00	2	Assuming 1kbps
Total/ orbit	4202.16	1995.00		
Total available DL/orbit		1995.00		Assumes 5% downlink margin

Tour Orbit 2: F&P and Mag Dedicated

F&P and Mag Dedicated				
	DV generated (MB)	Post-onboard compression (MB)	Compression Factor	
NAC	100.00	50.00	2	
TIR		0.00	2	
Vis/NIR		0.00	2	
WAC		0.00	2	
Mag	511.92	94.80	2.7x within instrument, and 2x overall	Assumed full rate of 11.3 kbps for 10% of the orbit. Then used 0.5 kbps a representative low/survey data rate for rest of orbit.
F&P	3376.40	1688.20	2	Allocation remaining after all the other instruments accounted for
SC data	324.00	162.00	2	Assuming 1kbps
Total/ orbit	4312.32	1995.00		
Total available DL/orbit		1995.00		Assumes 5% downlink margin

Tour Orbit Type 3: Remote Sensing w/ Satellite Flyby

Remote Sensing w/ Satellite Flyby				
	DV generated (MB)	Post-onboard compression (MB)	Compression Factor	
NAC	165.00	82.50	2	Updated for more imaging/orbit
TIR	0.01	0.00	2	
Vis/NIR	1500.00	750.00	2	Updated for more imaging/orbit
WAC	0.00	0.00	2	Science input says do when we can here
Mag	336.96	62.40	2.7x within instrument, and 2x overall	Assumed full rate of 11.3 kbps for 5% of the orbit. Then used 0.5 kbps a representative low/survey data rate for rest of orbit.
F&P	1876.20	938.10	2	Allocation remaining after all the other instruments accounted for
SC data	324.00	162.00	2	Assuming 1kbps
Total/ orbit	4202.16	1995.00		
Total available DL/orbit		1995.00		Assumes 5% downlink margin

Tour Orbit Type 4: Multiple Satellite Flyby (equatorial phase if appropriate)

Multiple Satellite Flyby (equitorial phase, if appropriate)				
	DV generated (MB)	Post-onboard compression (MB)	Compression Factor	
NAC	165.00	82.50	2	Updated for more imaging/orbit
TIR	0.01	0.00	2	
Vis/NIR	1500.00	750.00	2	
WAC	16.70	8.35	2	
Mag	336.96	62.40	2.7x within instrument, and 2x overall	Assumed full rate of 11.3 kbps for 5% of the orbit. Then used 0.5 kbps a representative low/survey data rate for rest of orbit.
F&P	1859.50	929.75	2	Allocation remaining after all the other instruments accounted for
SC data	324.00	162.00	2	Assuming 1kbps
Total/ orbit	4202.16	1995.00		
Total available DL/orbit		1995.00		Assumes 5% downlink margin

F&P Instruments Data Scenarios

- Used this for sanity check – do the allocations per orbit for F&P instruments (per the previous slides) roughly match the expected data generation.
  - Given the analog instrument suite data rates provided by Science, see below
  - Data volumes are in general ballpark, assuming F&P instrument data rates/duty cycles are customizable, and can carryover some data between orbits if needed.

If we select all F&P instruments as suggested -

hi res total	432.00 kbps		
average	113.31 kbps		
low	12.61 kbps		
for an orbit that is 2% high res, rest low		4801.48 MB	applied duty cycle of 0.5 outside of periapsis
just low res on all the time		4085.96 MB	

if we throttle the high data rate instrument (assume that use the avg rate as max)

hi res total	120.80 kbps		
average	113.31 kbps		
low	12.61 kbps		
for an orbit that is 2% high res, rest low		2786.20 MB	applied duty cycle of 0.5 outside of periapsis
for an orbit that is 5% high res, rest low		3901.03 MB	applied duty cycle of 0.5 outside of periapsis

dropping the high data rate instrument (assume on for very short periods, low rest of the time)

hi res total	39.00		
average	31.51		
low	12.61		
for an orbit that is 10% high res, rest avg		5253.66 MB	applied duty cycle of 0.5 outside of periapsis
for an orbit that is 10% high res, rest low		3100.68 MB	applied duty cycle of 0.5 outside of periapsis

Conclusions

- Tour orbits are the driver for the data story, but with 1 8-hr Ka-band downlink per day, there are no major concerns with the data story on this mission
  - Fields and Particles data generation and compression might need to be investigated further, if per orbit allocations seem too low (Science/Instr can consider)
  - Possible knobs to turn if needed
    - Higher compression
    - Carryover data between orbits
      - Have sufficient onboard data storage for ~6 orbits worth of data
    - Different assumptions for duty cycles for F&P instruments
  - Further comment on compression: The mission is assuming a FSW capability to zip data files, which could be used by instruments to compress data prior to sending to the spacecraft- potentially helping with instrument complexity, CPU loading, etc.

- Eventually (in later studies/development) will need to assess the Probe relay to Orbiter in further detail – will have to buffer some data from initial release to backshell sep period, and transmit that data along with the new data being generated.

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Uranus Orbiter and Probe Flight System Mass and Power Summary

Rich Anderson

Max Harrow

Flight System Mass Summary

UOP Flight System Mass Summary	CBE	Cont.	MEV	MPV
Orbiter Total Dry Mass (Excluding RTGs)	1571 kg	16%	1822 kg	2246 kg
Orbiter Bus	1510 kg	16%	1756 kg	
Structures	668 kg	21%	812 kg	
Propulsion	390 kg	12%	436 kg	
Avionics	28 kg	10%	31 kg	
Electrical Power (Excluding RTGs)	82 kg	11%	91 kg	
Attitude Determination and Control	73 kg	5%	77 kg	
Thermal Control	62 kg	20%	75 kg	
RF Communications	92 kg	13%	104 kg	
Harness	114 kg	15%	131 kg	
Orbiter Instrument Payload Total	60 kg	8%	65 kg	
Probe Total Mass	233 kg	15%	268 kg	333 kg
Descent Module	125 kg	17%	146 kg	
Mechanical	48 kg	19%	57 kg	
Avionics	2 kg	10%	3 kg	
Electrical Power	15 kg	23%	19 kg	
Thermal Control	5 kg	19%	6 kg	
RF Communications	5 kg	12%	5 kg	
Probe-Orbiter Separation System	22 kg	15%	25 kg	
Instrument Payload	20 kg	11%	22 kg	
Harness	8 kg	17%	10 kg	
Entry and Descent System Total	108 kg	12%	121 kg	
Flight System Dry Mass (Excluding RTGs)	1804 kg	16%	2089 kg	2579 kg
Dry Mass Margin (Excluding RTGs)				776 kg
Dry Mass Margin % (Excluding RTGs)				30%
RTG Total Mass (Delivered as GFE)	168 kg	5%	176 kg	176 kg
Total Flight System Dry Mass (Tanks Empty)				2756 kg
N2H4 Residuals at 20°C				51 kg
Oxidizer (NTO-MON3) Residuals at 20°C				32 kg
GHe Pressurant				28 kg
Usable N2H4 Propellant and Oxidizer				4368 kg
Flight System MPV Launch Mass				7235 kg
LV Payload Adapter (Leave Behind) MPV Mass				45 kg
Launch Vehicle Capability (FHE, C_3=29.36 km^2/s^2)				8345 kg
Unused Launch Vehicle Capability				1065 kg
PMF				60.4%

Flight System Power Summary and Margin

- Battery on orbiter required for UOI case, and to meet margin requirements for momentum dump case

	Launch	Cruise Checkout	Cruise Hibernation	Safe/Acquisition	Momentum Dump	Delta V Preheat	DSM/UOI	DSM/UOI with 65% battery DOD	Probe Operations	Tour Science	Radio Science	Science Downlink
CBE Load, watts	158	341	197	325	348	304	643	643	342	297	335	336
MET, years	0	13.4	13.4	18	18	18	13.4	13.4	13.7	18	18	18
Available Power, watts	676	523	523	479	479	479	523	955	520	479	479	479
Margin, watts	518	182	326	154	131	175	-120	312	178	182	144	143
Margin per QMS *	328%	53%	165%	47%	38%	57%	-19%	49%	52%	61%	43%	42%
Margin Per Study *	77%	35%	62%	32%	27%	36%	-23%	33%	34%	38%	30%	30%

** Margins shown based on RTG power available, does not include supplemental energy supplied by orbiter secondary battery. (see Electrical Power Subsystem presentation for details)*

Master Equipment List (MEL) – 1 of 6

UOP 2021 MASTER EQUIPMENT LIST							
ORBITER -- BUS Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
Structures			**668.48**	**21%**	**811.53**		
Primary Structure	427.80	1	427.80	15%	491.97	Europa Clipper	Aluminum Propulsion Cylinders, Top Honeycomb Enclosure
RTG Bracket	30.00	3	90.00	15%	103.50	New Horizons	
1-lb Thruster Supports (total)	25.00	1	25.00	15%	28.75	Europa Clipper, scaled	
Probe Release System	22.00	1	22.00	15%	25.30	Estimated, similar to Cassini	
Pressurant Tank Support Structure	36.10	1	36.10	15%	41.52	Europa Clipper, scaled	
Miscellaneous Secondary Structure	42.78	1	42.78	115%	91.98	Typical	Allocation of 10% of Primary Structure for unaccounted items
Launch Vehicle Interface HW (S/C side)	24.80	1	24.80	15%	28.52	Europa Clipper	
Propulsion			**390.08**	**12%**	**436.41**		
Oxidizer Tank (Custom Ox)	57.79	1	57.79	10%	63.57	New, custom tank design	Maximizes diameter and minimizes height to fit within structure
N2H4 Tank (Custom Fuel)	132.10	1	132.10	10%	145.31	New, custom tank design	Maximizes diameter and minimizes height to fit within structure
GHe Tank (Custom Pressurant)	40.95	2	81.90	10%	90.09	Modified (resized) from existing design	
Leros 1B	4.50	2	9.00	3%	9.27	Flight Qualified	
5 lbf Thruster (MR-106E)	0.73	4	2.92	3%	3.01	Aerojet, numerous	
1 lbf Thruster (MR-111G)	0.37	16	5.92	3%	6.10	Aerojet, numerous	
Fuel Check Valve	0.23	1	0.23	3%	0.24	Typical, many missions	
Ox Check Valve	0.25	1	0.25	3%	0.26	Typical, many missions	
Fuel/Ox Service Valve	0.15	2	0.30	3%	0.31	Typical, many missions	
Helium Service Valve	0.07	4	0.28	3%	0.29	Typical, many missions	
Latch Valve	0.34	5	1.70	3%	1.75	Typical, many missions	
High-Pressure Latch Valve	0.52	2	1.04	3%	1.07	Typical, many missions	
Pressure Regulators	1.20	2	2.40	3%	2.47	Typical, many missions	
Test Port	0.03	2	0.06	3%	0.06	Typical, many missions	
Pressure Transducer	0.23	6	1.38	3%	1.42	Typical, many missions	
Filter	0.16	6	0.96	3%	0.99	Typical, many missions	
Orifice	0.03	2	0.06	3%	0.06	Typical, many missions	
Tubing / Fasteners / Tube Clamps / Etc.	40.86	1	40.86	20%	49.03	Typical, many missions	
Thermal Hardware (thermostats, etc.)	15.66	1	15.66	20%	18.79	Typical, many missions	
Cabling (Wire, Harness, Supports)	35.27	1	35.27	20%	42.32	Typical, many missions	

Master Equipment List (MEL) – 2 of 6

ORBITER -- BUS Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
Avionics			**28.14**	**10%**	**30.95**		
IEM	13.98	1	13.98	10%	15.38	Parker Solar Probe, Van Allen Probes	includes 4.48 kg of additional radiation shielding
PDB	3.18	4	12.72	10%	13.99	Europa Clipper	includes 1 kg per unit of additional radiation shielding
RIU	0.09	16	1.44	10%	1.58	Parker Solar Probe	
Electrical Power			**250.00**	**7%**	**267.30**		
Shunt Regulator Unit (SRU)	23.00	1	23.00	10%	25.30	New Horizons, Van Allen Probes	Includes 9.2 kg of additional radiaiton shielding
Power Switching Unit (PSU)	22.50	2	45.00	10%	49.50	Derived from Dragonfly working concept	Includes 10.5 kg per unit of additional radiation shielding
Battery	7.00	2	14.00	15%	16.10	ABSL cells, 20Ah per each pack	Implemented as two half-packs, each 8S16P
NG-RTG (Mod 1)	56.00	3	168.00	5%	176.40	Estimated as minor mod of GPHS-RTG	Will use the 5% margined number as MPV in mass summary
Attitude Determination and Control			**73.37**	**5%**	**76.97**		
Sodern Hydra Star Tracker - Sensor Head	1.40	3	4.20	3%	4.33	IMAP	
Sodern Hydra Star Tracker - Electronics Unit	1.80	2	3.60	3%	3.71	IMAP	
Northrop Grumman Scalable-SIRU	7.10	1	7.10	3%	7.31	MESSENGER, PSP, NEAR, many more	
Adcole Digital Sun Sensor - Sensor Head	0.25	5	1.25	3%	1.29	PSP, DART, IMAP, New Horizons, Juno, etc	
Adcole Digital Sun Sensor - Electronics Unit	1.50	2	3.00	3%	3.09	PSP, DART, IMAP, New Horizons, Juno, etc	
Adcole Fine Spinning Sun Sensor - Sensor Head	0.11	2	0.22	3%	0.23	New Horizons	
Collins Aerospace RSI 68-75/60 Reaction Wheel Assembly	8.50	4	34.00	3%	35.02	PSP, MESSENGER (similar)	
Radiation Shielding Allocation	20.00	1	20.00	10%	22.00	Estimate	Primarily for Reaction Wheel Assemblies, electronics boxes
Thermal Control			**62.20**	**20%**	**74.64**		
MLI Blankets (66.1 m^2))	41.40	1	41.40	20%	49.68	Typical, many missions	
Heaters	0.10	50	5.00	20%	6.00	Typical, many missions	
PRT	0.01	200	2.00	20%	2.40	Typical, many missions	
Louvers	1.00	4	4.00	20%	4.80	Typical, many missions	
Heat Pipes	1.00	8	8.00	20%	9.60	Typical, many missions	
ChoSeal	0.10	8	0.80	20%	0.96	Typical, many missions	
Paint/Coatings	1.00	1	1.00	20%	1.20	Typical, many missions	

Master Equipment List (MEL) – 3 of 6

ORBITER -- BUS Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
RF Communications			**92.36**	**13%**	**104.23**		
Radio	2.65	2	5.30	10%	5.83	APL Frontier Radio, many missions	
X-Band EPC	1.42	2	2.84	5%	2.98	Europa Clipper	
Ka-Band EPC	1.42	2	2.84	5%	2.98	Europa Clipper	
Low Noise Amplifiers (LNAs)	0.01	4	0.04	10%	0.04	Europa Clipper	
USO	0.50	2	1.00	15%	1.15	Many missions	
Fanbeam Antenna	1.00	2	2.00	10%	2.20	Parker Solar Probe	
Medium Gain Antenna	1.20	1	1.20	5%	1.26	New Horizons	
Low Gain Antenna	0.43	3	1.29	5%	1.35	Europa Clipper	
HGA Assembly	31.51	1	31.51	15%	36.24	Europa Clipper (3.1-m diameter)	
HGA Radome	0.62	1	0.62	15%	0.71	Europa Clipper (3.1-m diameter)	
RF Mini Vault (under HGA)	28.80	1	28.80	15%	33.12	Europa Clipper	
Ka-Band Hybrid	0.05	1	0.05	5%	0.05	Europa Clipper	
X-Band Hybrid	0.03	1	0.03	5%	0.03	Europa Clipper	
Ka-Band TWTA	1.05	2	2.10	10%	2.31	Europa Clipper	
X-Band TWTA	1.20	2	2.40	10%	2.64	Europa Clipper	
X-Band Isolator	0.53	2	1.06	5%	1.11	Europa Clipper	
X-Band Diplexer	1.00	2	2.00	5%	2.10	Europa Clipper	
X-Band Coaxial Transfer Switch	0.13	2	0.26	10%	0.29	Europa Clipper	
X-Band SP3T Switch	1.10	4	4.40	10%	4.84	Europa Clipper	
X-band semi-rigid Coax	0.12	8	0.96	5%	1.01	Europa Clipper	
X-Band Waveguide	0.18	1	0.18	10%	0.20	Europa Clipper	
Ka-band semi-rigid Coax	0.12	2	0.24	5%	0.25	Europa Clipper	
Ka-Band Waveguide	0.18	2	0.36	10%	0.40	Europa Clipper	
Ka-Band Isolator	0.10	2	0.20	5%	0.21	Europa Clipper	
UHF semi-rigid Coax	0.12	4	0.48	5%	0.50	Europa Clipper	
Orbiter Subsystems Subtotal Dry Mass (Excluding Harness)			**1564.63**	**--**	**1802.04**		
Harness *(SC Subsystems Subtotal Dry + Payload Dry) * 7%*			**113.76**	**15%**	**130.80**	*Average percentage based on prior mission actuals*	
Orbiter Bus Total Dry Mass			**1678.4**	**15%**	**1932.8**		

Master Equipment List (MEL) – 4 of 6

ORBITER -- PAYLOAD Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
Magnetometer Instrument	1.43	1	1.43	10%	1.57	MESSENGER, Cassini/Juno	
Magnetometer Boom	0.47	1	0.47	20%	0.56	Galileo, Cassini	Scaled down from 11-m to 5-m length, .093 kg / m
Narrow Angle Camera	8.80	1	8.80	10%	9.68	New Horizons LORRI	Framing, 10-urad/pix, Panchromatic - excudes mass of NH electronics box, will interface directly to spacecraft avionics
Thermal IR Camera	11.00	1	11.00	10%	12.10	LRO Diviner	~7-100um
Fields and Particles Package (Suite Subtotal)			11.78	10%	12.96		
LPW (w/o EUV)	3.58	1	3.58	10%	3.94	MAVEN	
MSC	0.80	1	0.80	10%	0.88	TRACERS, Van Allen Probes	Search Coil Magnetometer
FIPS	1.40	1	1.40	10%	1.54	MESSENGER	
SWEAP/SPAN-B	2.50	1	2.50	10%	2.75	Parker Solar Probe	
EPI-Lo	3.50	1	3.50	10%	3.85	Parker Solar Probe	
Vis/NIR Imaging Spectrometer and WAC	27.00	1	27.00	10%	29.70	Lucy L'Ralph	250 urad/pix, 0.8-5 micron
Orbiter Payload Total Dry Mass			**60.5**	**10%**	**66.6**		
Orbiter Total Dry Mass (Bus + Payload)			**1738.9**	**15%**	**1999.4**		

Master Equipment List (MEL) – 5 of 6

PROBE Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
Descent Module – Mechanical			**48.00**	**19%**	**57.30**		
Descent Module (DM) Primary Structure	30.00	1	30.00	20%	36.00	Sized for 0.7 m diameter, entry conditions and descent to 10 bar	
DM Secondary Structure (shelves/brackets)	15.00	1	15.00	20%	18.00	Estimated	
Aeroshell Release Mech (heatshield to BS)	0.50	3	1.50	10%	1.65	Typical, various	
Backshell Release Mech (backshell to DM)	0.50	3	1.50	10%	1.65	Typical, various	
DM – Avionics			**2.40**	**10%**	**2.64**		
PEM - Coresat SBC	0.50	2	1.00	10%	1.10	DART	
PEM - SCIF/MISC	0.70	2	1.40	10%	1.54	DART	
DM – Electrical Power			**15.26**	**23%**	**18.84**		
PEM - Power Distribution/Switching/Timer Unit	2.00	2	4.00	10%	4.40	DART Coresat form factor, scaled for entry loads	
PEM - Power Conversion	0.50	2	1.00	10%	1.10	DART Coresat	
Battery & Support Structure	8.55	1	8.55	30%	11.12	Timer: SAFT LS33600, 1S36p; Primary: SAFT LSH20, 8s4p	Primary and Secondary(Coast Timer) Batteries
Battery Brackets	1.71	1	1.71	30%	2.22	Estimated	
DM – Thermal Control			**4.63**	**19%**	**5.52**		
Heaters, temp sensors, blankets	2.83	1	2.83	20%	3.40	Estimated 6% of electronics mass	
RHU	0.04	20	0.80	15%	0.92	Per RPS Office	
Insulative descent module encapsulation	1.00	1	1.00	20%	1.20	2/5 inch thich aerogel	
DM – RF Communications			**4.74**	**12%**	**5.31**		
PEM - UHF Radio/Transmitter	0.50	2	1.00	10%	1.10	Frontier-Lite radio card, scaled for entry loads	
USO	0.37	2	0.74	10%	0.81	Typical, various	
SSPA (PA+PCU)	1.00	2	2.00	10%	2.20	Estimated	
Antenna	0.50	2	1.00	20%	1.20	Baseline: 2 LP monopoles	
Orbiter-Probe Sepration System (Probe Side)			**22.00**	**15%**	**25.30**		
Baseplate	10.18	1	10.18	15%	11.71	Typical, various	
Mechanism	11.82	1	11.82	15%	13.59	Typical, various	
Probe Payload (Instruments)			**19.70**	**11%**	**21.87**		
Mass Spectrometer	16.20	1	16.20	10%	17.82	Rosetta DFMS	1-150 amu resolution > 1000
Atmospheric Structure Instrument	2.50	1	2.50	10%	2.75	(many missions)	T, P sensors and accelerometer
Ortho-Para Hydrogen Sensor	1.00	1	1.00	30%	1.30	Currently in development	Sound Speed
Descent Module & Sep Sys Subtotal Dry Mass (without Harness)			**116.73**	**--**	**136.78**		
Harness *(Descent Module and Sep Systems)* ***x 7%***			**8.17**	**17%**	**9.57**	*Estimated as 7% of Descent Module and Separation System (excludes Entry & Descent System mass)*	

Master Equipment List (MEL) – 6 of 6

PROBE Subsystem/Component	Unit Mass CBE (kg)	No. of Units	Total Mass CBE (kg)	Contin-gency	Total MEV Mass (kg)	Heritage Basis	Notes
Entry & Descent System			**107.96**	**12%**	**121.20**		
TPS-Heat Shield (not including adhesive) *	45.20	1	45.20	15%	51.98	Single layer HEEET	0.4-m nose radius, 210kg/m^2 ball. coeff. Using value computed for 2020 Neptune Orbiter Study. ** Note: EDL analysis has determined that an updated HEEET CBE of 25 kg could be achieved for the selected UOP study trajectory and entry conditions.*
TPS-Heat Shield Adhesive	3.00	1	3.00	10%	3.30	Typical, various	
TPS-Back Shell (including adhesive)	9.00	1	9.00	12%	10.08	PICA	
Mechanical-TPS Support Structure (Heatshield)	20.00	1	20.00	10%	22.00	Sized for 0.7 m diameter descent probe and entry vehicle characteristics (see report)	(brackets, struts, snubbers, port covers, local enforcement, etc.)
Mechanical-TPS Support Structure (Backshell)	9.94	1	9.94	10%	10.93	T300	(heat shield & backshell)
Main/HS separation chute Deployable	2.79	1	2.79	10%	3.07	Conical Ribbon, 2.5 m diameter	
Descent chute Deployable	0.43	1	0.43	10%	0.47	Ringsail, 1.8 m diameter	
Secondary Structure	10.00	1	10.00	10%	11.00	Sized to 0.7 m diameter descent probe	
ESI Sensors and Harness	7.60	1	7.60	10%	8.36	Many missions	
Probe System Total Dry Mass			**232.9**	**15%**	**267.5**		
Flight System (Orbiter + Probe) Total Dry Mass			**1971.7**	**15%**	**2267.0**		

Orbiter Power Equipment List (PEL) – 1 of 2

UOP ORBITER POWER EQUIPMENT LIST - Spacecraft Power Phasing

Subsystem/Component	UNIT POWER: Steady-State CBE (W)	UNIT POWER: Contin-gency	UNIT POWER: Steady-State MEV (W)	QTY	LAUNCH: # ON	LAUNCH: Duty Cyc	LAUNCH: CBE (W)	LAUNCH: MEV (W)	CRUISE CHECKOUT: # ON	CRUISE CHECKOUT: Duty Cyc	CRUISE CHECKOUT: CBE (W)	CRUISE CHECKOUT: MEV (W)	CRUISE HIBERNATION: # ON	CRUISE HIBERNATION: Duty Cyc	CRUISE HIBERNATION: CBE (W)	CRUISE HIBERNATION: MEV (W)
Propulsion							0.0	0.0			0.0	0.0			0.0	0.0
Leros 1B Valves	62.0	3%	63.9	2	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Leros 1B Valve Heater	5.8	3%	6.0	2	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Leros 1B Flange/Injector Heater	9.8	3%	10.1	2	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Valve	25.3	3%	26.1	4	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Valve Heater	3.3	3%	3.4	4	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Cat Bed Heater	6.5	3%	6.7	4	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Valve	8.3	3%	8.5	16	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Valve Heater	1.5	3%	1.6	16	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Cat Bed Heater	6.3	3%	6.5	16	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Latch Valve (1/4" Vacco)	18.0	3%	18.5	5	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
High-Pressure Latch Valve	45.8	3%	47.2	2	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Pressure Transducer	0.9	3%	0.9	6	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Avionics							27.0	29.7			27.0	29.7			26.7	29.4
IEM	26.7	10%	29.4	1	1	100%	26.7	29.4	1	100%	26.7	29.4	1	100%	26.7	29.4
RIU	0.038	10%	0.041	16	8	100%	0.3	0.3	8	100%	0.3	0.3	0	0%	0.0	0.0
Electrical Power							34.6	38.1			34.6	38.1			34.6	38.1
Shunt Regulator Unit (SRU)	15.6	10%	17.2	1	1	100%	15.6	17.2	1	100%	15.6	17.2	1	100%	15.6	17.2
Power Switching Unit (PSU)	19.0	10%	20.9	2	1	100%	19.0	20.9	1	100%	19.0	20.9	1	100%	19.0	20.9
Attitude Determination and Control							0.0	0.0			124.8	128.5			0.0	0.0
Sodern Hydra Star Tracker - Sensor Head	0.8	3%	0.8	3	0	0%	0.0	0.0	3	100%	2.4	2.5	0	0%	0.0	0.0
Sodern Hydra Star Tracker - Electronics Unit	6.0	3%	6.2	2	0	0%	0.0	0.0	2	100%	12.0	12.4	0	0%	0.0	0.0
Northrop Grumman Scalable-SIRU	30.0	3%	30.9	1	0	0%	0.0	0.0	1	100%	30.0	30.9	0	0%	0.0	0.0
Adcole Digital Sun Sensor - Electronics Unit	0.4	3%	0.4	2	0	0%	0.0	0.0	1	100%	0.4	0.4	0	0%	0.0	0.0
Collins Aerospace RSI 68-75/60 Reaction Wheel Assembly	20.0	3%	20.6	4	0	0%	0.0	0.0	4	100%	80.0	82.4	0	0%	0.0	0.0
Thermal Control							10.2	12.2			15.0	18.0			54.0	64.8
Prop Subsystem op/surv heaters	60.0	20%	72.0	1	1	17%	10.2	12.2	1	25%	15.0	18.0	1	90%	54.0	64.8
RF Communications							63.5	69.8			111.7	122.9			57.1	62.9
Frontier Radio - X-Band Rx	6.3	10%	7.0	2	2	100%	12.7	13.9	0	0%	0.0	0.0	1	100%	6.3	7.0
Frontier Radio - X-Band Tx Rx	10.9	10%	12.0	2	0	0%	0.0	0.0	1	100%	10.9	12.0	0	0%	0.0	0.0
Frontier Radio - Ka-Band Tx, X-band Rx	11.5	10%	12.7	2	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
USO 1	0.6	15%	0.7	1	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7
USO 2	0.6	15%	0.7	1	1	27%	0.2	0.2	1	27%	0.2	0.2	1	27%	0.2	0.2
X-Band TWTA - Tx	100.0	10%	110.0	1	0	0%	0.0	0.0	1	100%	100.0	110.0	0	0%	0.0	0.0
X-Band TWTA - Standby	50.0	10%	55.0	1	1	100%	50.0	55.0	0	0%	0.0	0.0	1	100%	50.0	55.0
Ka-Band TWTA - Tx	100.0	10%	110.0	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Ka-Band TWTA - Standby	50.0	0%	50.0	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band Coaxial Transfer Switch	0.1	10%	0.1	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band SP3T Switch	1.1	10%	1.2	4	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
SPACECRAFT SUBTOTAL POWER							135.3	149.8			313.1	337.2			172.4	195.1

Subsystem/Component	SAFE / ACQUISITION: # ON	SAFE / ACQUISITION: Duty Cyc	SAFE / ACQUISITION: CBE (W)	SAFE / ACQUISITION: MEV (W)	MOMENTUM DUMP: # ON	MOMENTUM DUMP: Duty Cyc	MOMENTUM DUMP: CBE (W)	MOMENTUM DUMP: MEV (W)	DELTA-V PREHEAT: # ON	DELTA-V PREHEAT: Duty Cyc	DELTA-V PREHEAT: CBE (W)	DELTA-V PREHEAT: MEV (W)	DSM / UOI: # ON	DSM / UOI: Duty Cyc	DSM / UOI: CBE (W)	DSM / UOI: MEV (W)
Propulsion			0.0	0.0			28.2	29.1			0.0	0.0			334.2	344.3
Leros 1B Valves	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	2	100%	124.0	127.7
Leros 1B Valve Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	2	100%	11.6	11.9
Leros 1B Flange/Injector Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	2	100%	19.6	20.2
5 lbf Thruster Valve	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	4	20%	20.2	20.8
5 lbf Thruster Valve Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	4	20%	2.6	2.7
5 lbf Thruster Cat Bed Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	4	100%	26.2	26.9
1 lbf Thruster Valve	0	0%	0.0	0.0	3	10%	2.5	2.6	0	0%	0.0	0.0	16	5%	6.6	6.8
1 lbf Thruster Valve Heater	0	0%	0.0	0.0	3	10%	0.5	0.5	0	0%	0.0	0.0	16	50%	12.3	12.7
1 lbf Thruster Cat Bed Heater	0	0%	0.0	0.0	4	100%	25.3	26.0	0	0%	0.0	0.0	16	100%	101.1	104.2
Latch Valve (1/4" Vacco)	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	5	0%	0.0	0.0
High-Pressure Latch Valve	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	2	5%	4.6	4.7
Pressure Transducer	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	6	100%	5.4	5.6
Avionics			27.0	29.7			27.0	29.7			27.0	29.7			27.0	29.7
IEM	1	100%	26.7	29.4	1	100%	26.7	29.4	1	100%	26.7	29.4	1	100%	26.7	29.4
RIU	8	100%	0.3	0.3	8	100%	0.3	0.3	8	100%	0.3	0.3	8	100%	0.3	0.3
Electrical Power			34.6	38.1			34.6	38.1			34.6	38.1			34.6	38.1
Shunt Regulator Unit (SRU)	1	100%	15.6	17.2	1	100%	15.6	17.2	1	100%	15.6	17.2	1	100%	15.6	17.2
Power Switching Unit (PSU)	1	100%	19.0	20.9	1	100%	19.0	20.9	1	100%	19.0	20.9	1	100%	19.0	20.9
Attitude Determination and Control			98.0	100.9			98.0	100.9			98.0	100.9			98.0	100.9
Sodern Hydra Star Tracker - Sensor Head	2	100%	1.6	1.6	2	100%	1.6	1.6	2	100%	1.6	1.6	2	100%	1.6	1.6
Sodern Hydra Star Tracker - Electronics Unit	1	100%	6.0	6.2	1	100%	6.0	6.2	1	100%	6.0	6.2	1	100%	6.0	6.2
Northrop Grumman Scalable-SIRU	1	100%	30.0	30.9	1	100%	30.0	30.9	1	100%	30.0	30.9	1	100%	30.0	30.9
Adcole Digital Sun Sensor - Electronics Unit	1	100%	0.4	0.4	1	100%	0.4	0.4	1	100%	0.4	0.4	1	100%	0.4	0.4
Collins Aerospace RSI 68-75/60 Reaction Wheel Assembly	3	100%	60.0	61.8	3	100%	60.0	61.8	3	100%	60.0	61.8	3	100%	60.0	61.8
Thermal Control			19.8	23.8			19.8	23.8			60.0	72.0			0.0	0.0
Prop Subsystem op/surv heaters	1	33%	19.8	23.8	1	33%	19.8	23.8	1	100%	60.0	72.0	0	0%	0.0	0.0
RF Communications			118.1	129.9			111.7	122.9			57.1	62.9			111.7	122.9
Frontier Radio - X-Band Rx	1	100%	6.3	7.0	0	0%	0.0	0.0	1	100%	6.3	7.0	0	0%	0.0	0.0
Frontier Radio - X-Band Tx Rx	1	100%	10.9	12.0	1	100%	10.9	12.0	0	0%	0.0	0.0	1	100%	10.9	12.0
Frontier Radio - Ka-Band Tx, X-band Rx	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
USO 1	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7
USO 2	1	27%	0.2	0.2	1	27%	0.2	0.2	1	27%	0.2	0.2	1	27%	0.2	0.2
X-Band TWTA - Tx	1	100%	100.0	110.0	1	100%	100.0	110.0	0	0%	0.0	0.0	1	100%	100.0	110.0
X-Band TWTA - Standby	0	0%	0.0	0.0	0	0%	0.0	0.0	1	100%	50.0	55.0	0	0%	0.0	0.0
Ka-Band TWTA - Tx	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Ka-Band TWTA - Standby	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band Coaxial Transfer Switch	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band SP3T Switch	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
SPACECRAFT SUBTOTAL POWER			297.5	322.4			319.3	344.5			276.7	303.6			605.6	635.9

Subsystem/Component	PROBE OPERATIONS: # ON	PROBE OPERATIONS: Duty Cyc	PROBE OPERATIONS: CBE (W)	PROBE OPERATIONS: MEV (W)	TOUR SCIENCE: # ON	TOUR SCIENCE: Duty Cyc	TOUR SCIENCE: CBE (W)	TOUR SCIENCE: MEV (W)	RADIO SCIENCE / NAV: # ON	RADIO SCIENCE / NAV: Duty Cyc	RADIO SCIENCE / NAV: CBE (W)	RADIO SCIENCE / NAV: MEV (W)	SCIENCE DOWNLINK: # ON	SCIENCE DOWNLINK: Duty Cyc	SCIENCE DOWNLINK: CBE (W)	SCIENCE DOWNLINK: MEV (W)
Propulsion			0.0	0.0			0.0	0.0			0.0	0.0			0.0	0.0
Leros 1B Valves	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Leros 1B Valve Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Leros 1B Flange/Injector Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Valve	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Valve Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
5 lbf Thruster Cat Bed Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Valve	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Valve Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
1 lbf Thruster Cat Bed Heater	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Latch Valve (1/4" Vacco)	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
High-Pressure Latch Valve	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Pressure Transducer	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Avionics			27.0	29.7			27.0	29.7			27.0	29.7			27.0	29.7
IEM	1	100%	26.7	29.4	1	100%	26.7	29.4	1	100%	26.7	29.4	1	100%	26.7	29.4
RIU	8	100%	0.3	0.3	8	100%	0.3	0.3	8	100%	0.3	0.3	8	100%	0.3	0.3
Electrical Power			34.6	38.1			34.6	38.1			34.6	38.1			34.6	38.1
Shunt Regulator Unit (SRU)	1	100%	15.6	17.2	1	100%	15.6	17.2	1	100%	15.6	17.2	1	100%	15.6	17.2
Power Switching Unit (PSU)	1	100%	19.0	20.9	1	100%	19.0	20.9	1	100%	19.0	20.9	1	100%	19.0	20.9
Attitude Determination and Control			98.0	100.9			98.0	100.9			98.0	100.9			98.0	100.9
Sodern Hydra Star Tracker - Sensor Head	2	100%	1.6	1.6	2	100%	1.6	1.6	2	100%	1.6	1.6	2	100%	1.6	1.6
Sodern Hydra Star Tracker - Electronics Unit	1	100%	6.0	6.2	1	100%	6.0	6.2	1	100%	6.0	6.2	1	100%	6.0	6.2
Northrop Grumman Scalable-SIRU	1	100%	30.0	30.9	1	100%	30.0	30.9	1	100%	30.0	30.9	1	100%	30.0	30.9
Adcole Digital Sun Sensor - Electronics Unit	1	100%	0.4	0.4	1	100%	0.4	0.4	1	100%	0.4	0.4	1	100%	0.4	0.4
Collins Aerospace RSI 68-75/60 Reaction Wheel Assembly	3	100%	60.0	61.8	3	100%	60.0	61.8	3	100%	60.0	61.8	3	100%	60.0	61.8
Thermal Control			36.0	43.2			36.0	43.2			36.0	43.2			36.0	43.2
Prop Subsystem op/surv heaters	1	60%	36.0	43.2	1	60%	36.0	43.2	1	60%	36.0	43.2	1	60%	36.0	43.2
RF Communications			118.1	129.9			57.1	62.9			111.7	122.9			112.3	123.6
Frontier Radio - X-Band Rx	1	100%	6.3	7.0	1	100%	6.3	7.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Frontier Radio - X-Band Tx Rx	1	100%	10.9	12.0	0	0%	0.0	0.0	1	100%	10.9	12.0	0	0%	0.0	0.0
Frontier Radio - Ka-Band Tx, X-band Rx	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	1	100%	11.5	12.7
USO 1	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7
USO 2	1	27%	0.2	0.2	1	27%	0.2	0.2	1	27%	0.2	0.2	1	27%	0.2	0.2
X-Band TWTA - Tx	1	100%	100.0	110.0	0	0%	0.0	0.0	1	100%	100.0	110.0	0	0%	0.0	0.0
X-Band TWTA - Standby	0	0%	0.0	0.0	1	100%	50.0	55.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Ka-Band TWTA - Tx	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	1	100%	100.0	110.0
Ka-Band TWTA - Standby	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band Coaxial Transfer Switch	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
X-Band SP3T Switch	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
SPACECRAFT SUBTOTAL POWER			313.7	341.8			252.7	274.8			307.3	334.8			307.9	335.5

Orbiter Power Equipment List (PEL) – 2 of 2

UOP ORBITER POWER EQUIPMENT LIST - Spacecraft Power Phasing

Subsystem/Component	UNIT POWER			QTY	LAUNCH				CRUISE CHECKOUT				CRUISE HIBERNATION			
	Steady-State CBE (W)	Contin-gency	Steady-State MEV (W)		# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)
Magnetometer							1.5	1.7			1.5	1.7			1.5	1.7
Op	2.0	10%	2.2	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1.5	10%	1.7	1	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7
Narrow Angle Camera							6.0	6.6			6.0	6.6			6.0	6.6
Op	8.0	10%	8.8	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Decontamination	10.0	10%	11.0	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	6.0	10%	6.6	1	1	100%	6.0	6.6	1	100%	6.0	6.6	1	100%	6.0	6.6
Thermal IR Camera							3.4	3.7			3.4	3.7			3.4	3.7
Op	4.5	10%	5.0	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	3.4	10%	3.7	1	1	100%	3.4	3.7	1	100%	3.4	3.7	1	100%	3.4	3.7
MAVEN/LPW (w/o EUV)							2.0	2.2			2.0	2.2			2.0	2.2
Op	2.7	10%	3.0	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	2.0	10%	2.2	1	1	100%	2.0	2.2	1	100%	2.0	2.2	1	100%	2.0	2.2
TRACERS/SCM							0.6	0.7			0.6	0.7			0.6	0.7
Op	0.8	10%	0.9	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	0.6	10%	0.7	1	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7
MESSENGER/FIPS							1.4	1.6			1.4	1.6			1.4	1.6
Op	1.9	10%	2.1	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1.4	10%	1.6	1	1	100%	1.4	1.6	1	100%	1.4	1.6	1	100%	1.4	1.6
PSP/SWEAP/SPAN-B							1.5	1.7			1.5	1.7			1.5	1.7
Op	2.0	10%	2.2	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1.5	10%	1.7	1	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7
PSP/EPI-Lo							1.9	2.1			1.9	2.1			1.9	2.1
Op	2.5	10%	2.8	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1.9	10%	2.1	1	1	100%	1.9	2.1	1	100%	1.9	2.1	1	100%	1.9	2.1
Vis/NIR Imaging Spec/WAC							0.0	0.0			0.0	0.0			0.0	0.0
Op	5.3	10%	5.8	1	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	4.0	10%	4.4	1	1	100%	4.0	4.4	1	100%	4.0	4.4	1	100%	4.0	4.4
PAYLOAD SUBTOTAL POWER							18.3	20.2			18.3	20.2			18.3	20.2
Harness Loss (3% of SC+Payload)							4.6	5.1			9.9	10.7			5.7	6.5
TOTAL POWER LOADS (W)							158.2	175.1			341.4	368.1			196.5	221.7

Subsystem/Component	SAFE / ACQUISITION				MOMENTUM DUMP				DELTA-V PREHEAT				DSM / UOI			
	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)
Magnetometer			1.5	1.7			1.5	1.7			1.5	1.7			1.5	1.7
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7
Narrow Angle Camera			6.0	6.6			6.0	6.6			6.0	6.6			6.0	6.6
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Decontamination	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	6.0	6.6	1	100%	6.0	6.6	1	100%	6.0	6.6	1	100%	6.0	6.6
Thermal IR Camera			3.4	3.7			3.4	3.7			3.4	3.7			3.4	3.7
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	3.4	3.7	1	100%	3.4	3.7	1	100%	3.4	3.7	1	100%	3.4	3.7
MAVEN/LPW (w/o EUV)			2.0	2.2			2.0	2.2			2.0	2.2			2.0	2.2
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	2.0	2.2	1	100%	2.0	2.2	1	100%	2.0	2.2	1	100%	2.0	2.2
TRACERS/SCM			0.6	0.7			0.6	0.7			0.6	0.7			0.6	0.7
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7	1	100%	0.6	0.7
MESSENGER/FIPS			1.4	1.6			1.4	1.6			1.4	1.6			1.4	1.6
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.4	1.6	1	100%	1.4	1.6	1	100%	1.4	1.6	1	100%	1.4	1.6
PSP/SWEAP/SPAN-B			1.5	1.7			1.5	1.7			1.5	1.7			1.5	1.7
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7	1	100%	1.5	1.7
PSP/EPI-Lo			1.9	2.1			1.9	2.1			1.9	2.1			1.9	2.1
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.9	2.1	1	100%	1.9	2.1	1	100%	1.9	2.1	1	100%	1.9	2.1
Vis/NIR Imaging Spec/WAC			0.0	0.0			0.0	0.0			0.0	0.0			0.0	0.0
Op	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	4.0	4.4	1	100%	4.0	4.4	1	100%	4.0	4.4	1	100%	4.0	4.4
PAYLOAD SUBTOTAL POWER			18.3	20.2			18.3	20.2			18.3	20.2			18.3	20.2
Harness Loss (3% of SC+Payload)			9.5	10.3			10.1	10.9			8.9	9.7			18.7	19.7
TOTAL POWER LOADS (W)			325.3	352.8			347.8	375.6			303.9	333.5			642.6	675.8

Subsystem/Component	PROBE OPERATIONS				TOUR SCIENCE				RADIO SCIENCE / NAV				SCIENCE DOWNLINK			
	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)	# ON	Duty Cyc	CBE (W)	MEV (W)
Magnetometer			1.5	1.7			2.0	2.2			1.5	1.7			1.5	1.7
Op	0	0%	0.0	0.0	1	100%	2.0	2.2	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.5	1.7	0	0%	0.0	0.0	1	100%	1.5	1.7	1	100%	1.5	1.7
Narrow Angle Camera			6.0	6.6			14.0	15.4			6.0	6.6			6.0	6.6
Op	0	0%	0.0	0.0	1	100%	8.0	8.8	0	0%	0.0	0.0	0	0%	0.0	0.0
Decontamination	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	6.0	6.6	1	100%	6.0	6.6	1	100%	6.0	6.6	1	100%	6.0	6.6
Thermal IR Camera			3.4	3.7			4.5	5.0			3.4	3.7			3.4	3.7
Op	0	0%	0.0	0.0	1	100%	4.5	5.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	3.4	3.7	0	0%	0.0	0.0	1	100%	3.4	3.7	1	100%	3.4	3.7
MAVEN/LPW (w/o EUV)			2.0	2.2			2.7	3.0			2.0	2.2			2.0	2.2
Op	0	0%	0.0	0.0	1	100%	2.7	3.0	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	2.0	2.2	0	0%	0.0	0.0	1	100%	2.0	2.2	1	100%	2.0	2.2
TRACERS/SCM			0.6	0.7			0.8	0.9			0.6	0.7			0.6	0.7
Op	0	0%	0.0	0.0	1	100%	0.8	0.9	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	0.6	0.7	0	0%	0.0	0.0	1	100%	0.6	0.7	1	100%	0.6	0.7
MESSENGER/FIPS			1.4	1.6			1.9	2.1			1.4	1.6			1.4	1.6
Op	0	0%	0.0	0.0	1	100%	1.9	2.1	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.4	1.6	0	0%	0.0	0.0	1	100%	1.4	1.6	1	100%	1.4	1.6
PSP/SWEAP/SPAN-B			1.5	1.7			2.0	2.2			1.5	1.7			1.5	1.7
Op	0	0%	0.0	0.0	1	100%	2.0	2.2	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.5	1.7	0	0%	0.0	0.0	1	100%	1.5	1.7	1	100%	1.5	1.7
PSP/EPI-Lo			1.9	2.1			2.5	2.8			1.9	2.1			1.9	2.1
Op	0	0%	0.0	0.0	1	100%	2.5	2.8	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	1.9	2.1	0	0%	0.0	0.0	1	100%	1.9	2.1	1	100%	1.9	2.1
Vis/NIR Imaging Spec/WAC			0.0	0.0			5.3	5.8			0.0	0.0			0.0	0.0
Op	0	0%	0.0	0.0	1	100%	5.3	5.8	0	0%	0.0	0.0	0	0%	0.0	0.0
Survival	1	100%	4.0	4.4	0	0%	0.0	0.0	1	100%	4.0	4.4	1	100%	4.0	4.4
PAYLOAD SUBTOTAL POWER			18.3	20.2			35.7	39.3			18.3	20.2			18.3	20.2
Harness Loss (3% of SC+Payload)			10.0	10.9			8.7	9.4			9.8	10.7			9.8	10.7
TOTAL POWER LOADS (W)			341.9	372.8			297.1	323.5			335.4	365.7			336.0	366.3

Probe Power Equipment List (PEL)

UOP PROBE POWER EQUIPMENT LIST - Power Phasing											
	UNIT POWER						Uranus Entry & Descent				
Subsystem/Component	Steady-State CBE (W)	Converter Efficiency	CBE	Contin-gency	Steady-State MEV (W)	Total Units	# ON	Duty Cycle	CBE (W)	MEV (W)	
Payload/Instruments									**34.5**	**39.1**	
Mass Spectrometer	19.0		19.0	10%	20.9	1	1	100%	19.0	20.9	
Atmospheric Structure Instrument	3.5		3.5	10%	3.9	1	1	100%	3.5	3.9	
Ortho-Para Hydrogen Sensor	3.5		3.5	30%	4.6	1	1	100%	3.5	4.6	
ESI (Engineering Science Investigation)	8.5		8.5	15%	9.8	1	1	100%	8.5	9.8	
Avionics									**22.8**	**26.2**	
PEM - SBC	5.0	0.65	7.7	15%	8.8	2	2	100%	15.4	17.7	{TIMER CIRCUIT ONLY DURING APPROACH}
PEM - SCIF/MISC	2.4	0.65	3.7	15%	4.2	2	2	100%	7.4	8.5	
Electrical Power									**13.8**	**15.9**	
PEM - Power Distribution/Switching/Timer Unit	3.5	0.65	5.4	15%	6.2	2	2	100%	10.8	12.4	
PEM - Power Conversion	1.0	0.65	1.5	15%	1.8	2	2	100%	3.1	3.5	
Thermal Control									**0.0**	**0.0**	
RHUs	0.0		0.0	0%	0.0	20	20	100%	0.0	0.0	
RF Communications									**59.3**	**64.8**	
PEM - Frontier Radio (UHF-band Tx only)	4.0		4.0	5%	4.2	2	2	100%	8.0	8.4	
USO	0.6		0.6	10%	0.7	2	2	100%	1.3	1.4	
UHF SSPA (10W RF)	25.0		25.0	10%	27.5	2	2	100%	50.0	55.0	
Mechanisms									**0.0**	**0.0**	
Main/Separation Chute (mortar fire)	0.0		0.0	0%	0.0	1	0	0%	0.0	0.0	transient only
Aeroshell Release Mechanism	0.0		0.0	0%	0.0	3	0	0%	0.0	0.0	transient only
Backshell Release Mechanism (pulls descent chute)	0.0		0.0	0%	0.0	3	0	0%	0.0	0.0	transient only
TOTAL PROBE POWER LOADS (W)									**130.4**	**146.0**	

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Uranus Orbiter and Probe: Orbiter Structures and Mechanisms

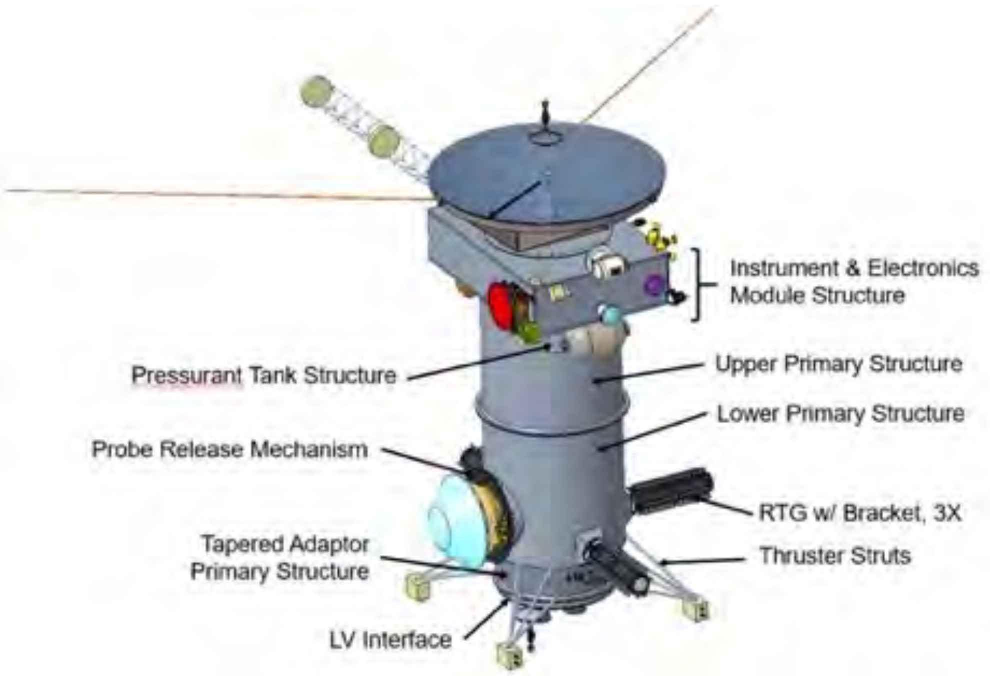
Erich Schulze

Dave Weir

Orbiter Structure

Structure consists of the primary structure, secondary structure and Launch Vehicle (LV) interface and is largely based upon the Europa Clipper spacecraft.

- Launch Vehicle (LV) Interface
  - Standard 60 inch LV provided design
- Tapered Ring
  - Reduces cylinder structure from 70 inch to 60 inch diameter
  - Height: 20 inches
  - Machined fitting (7075-T6)
- Lower Cylindrical Structure
  - Houses Hydrazine Propulsion Tank
  - Size: Ø70.5 inches x 74 inch tall
  - Four rolled sheet metal segments joined with a splice plate (7075-T6)
  - Machined fitting on each end (7075-T6)
- Upper Cylinder Structure
  - Houses Oxidizer Propulsion Tank
  - Size: Ø70.5 inches x 67 inches tall
  - Machined fitting on each end (7075-T6)
  - Four rolled sheet metal segments joined with a splice plate (7075-T6)
  - Machined fitting on each end (7075-T6)
- Instrument Cylinder Structure
  - Houses Mini-Vault
  - Size: Ø70.5 inches x 28 inches tall
  - Two rolled sheet metal segments joined with a splice plate (6061-T6)
  - Machined fitting on each end (7075-T6)
- Instrument and Electronics Module
  - Attaches to the Instrument Cylinder Structure
  - Aluminum Honeycomb Structure
    - Top Plate .75 inch thick
    - Bottom Plate 1.5 inch thick
    - Removable End Plates: Both .75 & 1.0 inch thick



Orbiter Structural Components

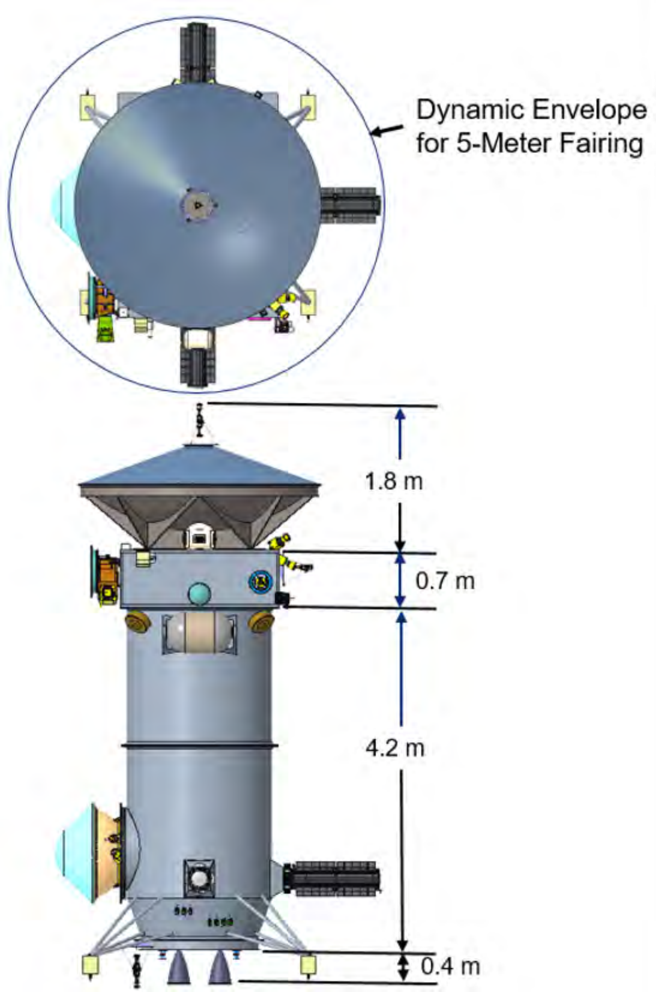
- Secondary structure:
  - Consists of brackets that support the two externally mounted pressurant tanks, three RTGs, Probe, X-Band antennas, thrusters, propellant lines, and many of the instruments.

Structural Mass Details and Launch Envelope

- Primary Structure
  - Cylinder Structure based upon Europa spacecraft mass fractions
  - Instrument & Electronics Module (Direct calculation)
- Secondary Structure
  - Partially estimated from similar hardware
  - Plus 10% of primary structure
- LV Interface
  - Estimated based upon Europa spacecraft
- Breakdown of structural mass is detailed in the MEL

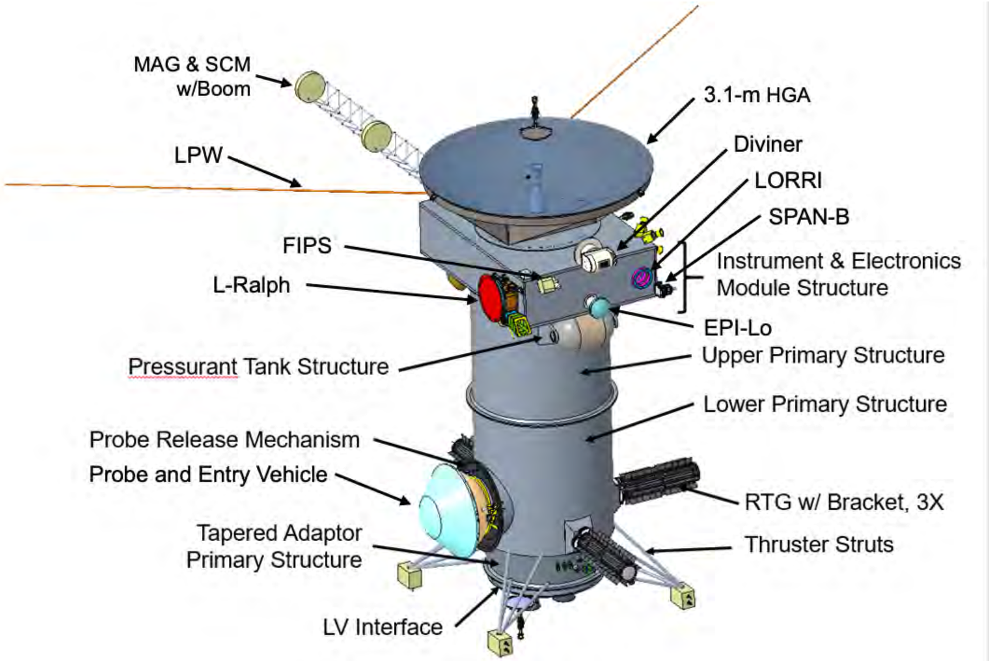
Description	CBE Mass (kg)	CBE Mass Fraction	MPV Mass (kg)	MPV Mass Fraction
Primary Structure	427.8	6.1%	611.7	7.6%
Secondary Structure	244.6	3.5%	349.8	4.4%
LV Interface	24.8	0.3%	35.5	0.4%
Structure Total	697.2	9.9	997.0	12.5%

- The spacecraft primary structure is 4.9 meters from the LV interface to the top of the instrument and electronics module and was driven by the size of the propellant tanks.



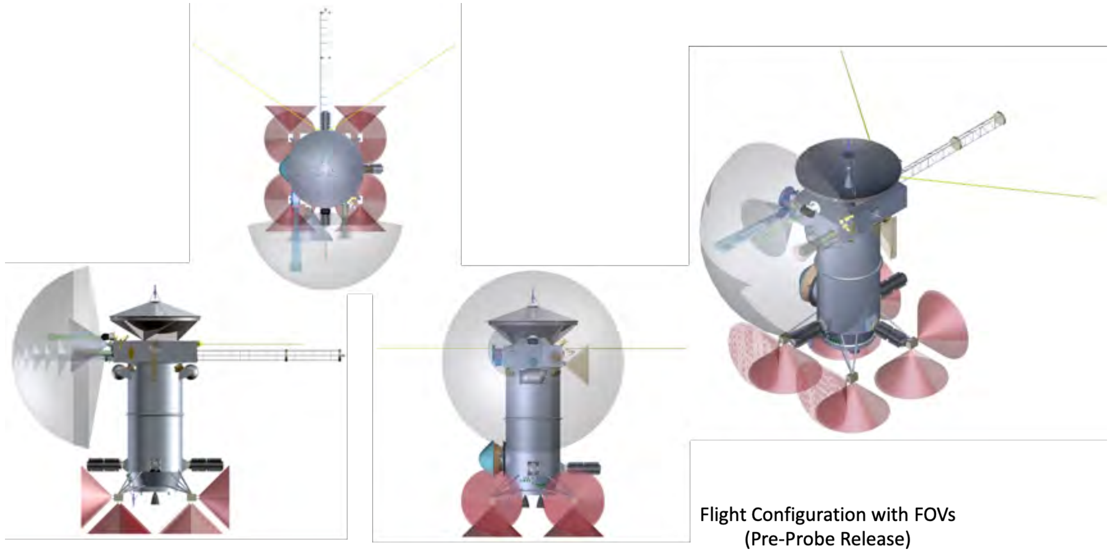
Orbiter Envelope Dimensions

Orbiter Payload Layout and Additional Views



Launch Configuration

Flight Configuration
(Pre-Probe Release)



Flight Configuration with FOVs
(Pre-Probe Release)

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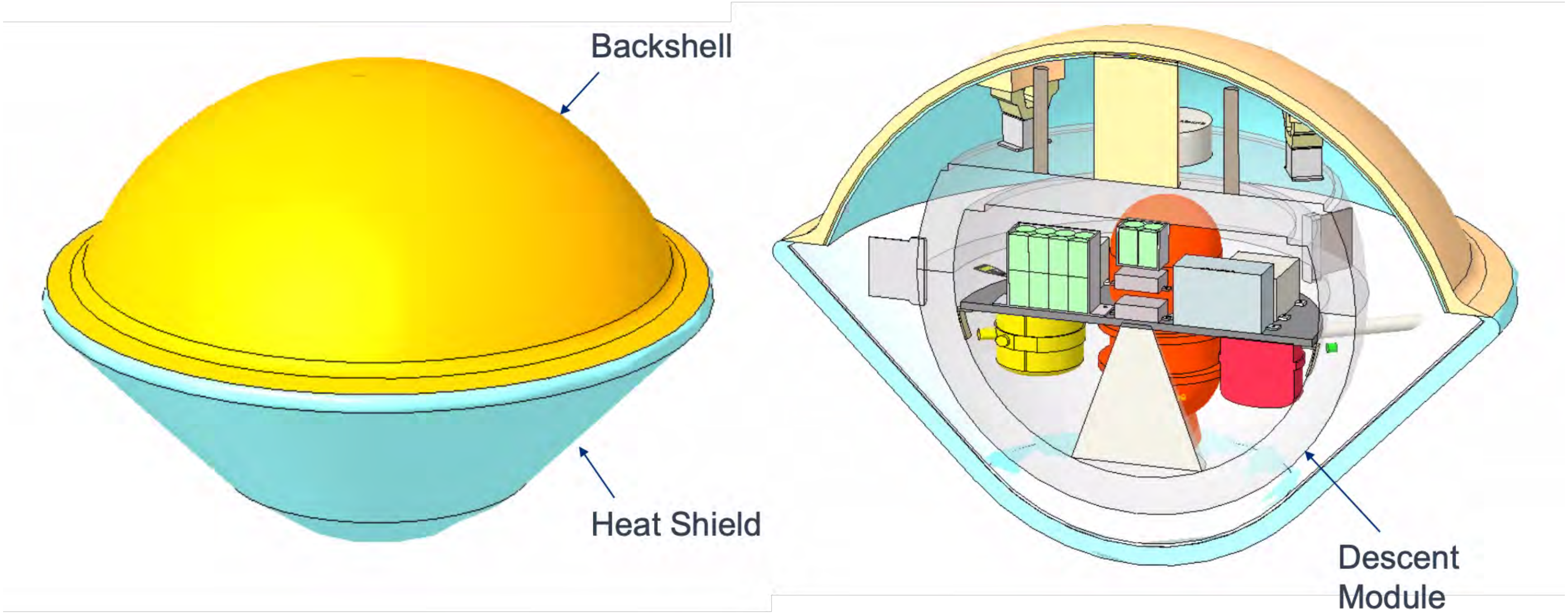
Uranus Orbiter and Probe: Probe Mechanical

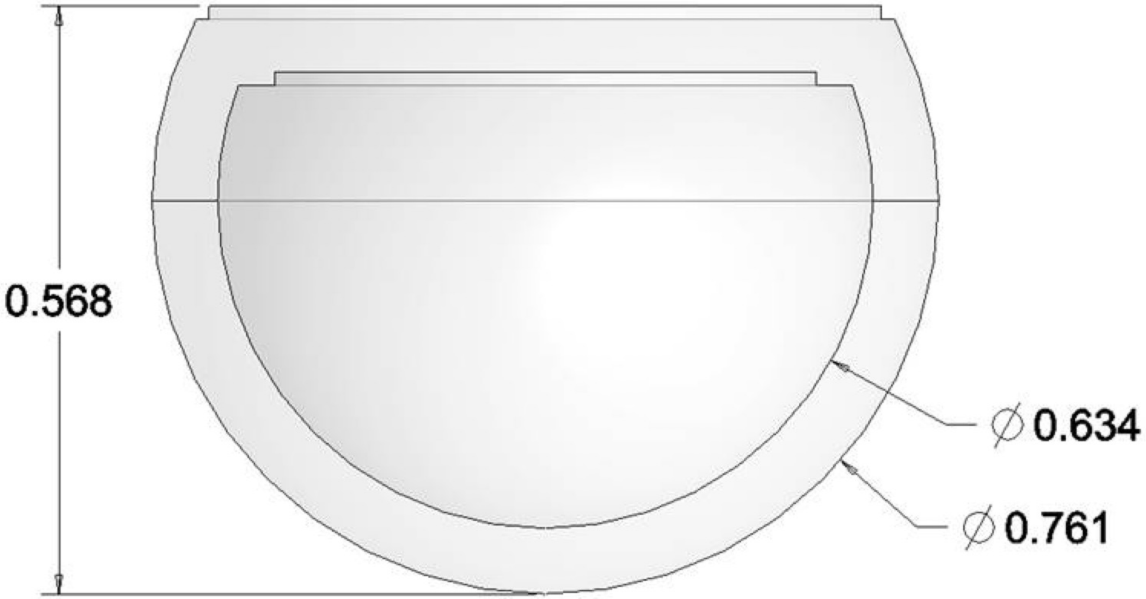
Adapted from 2020 Neptune Odyssey PMCS Study Design

Uranus Probe



Descent Module

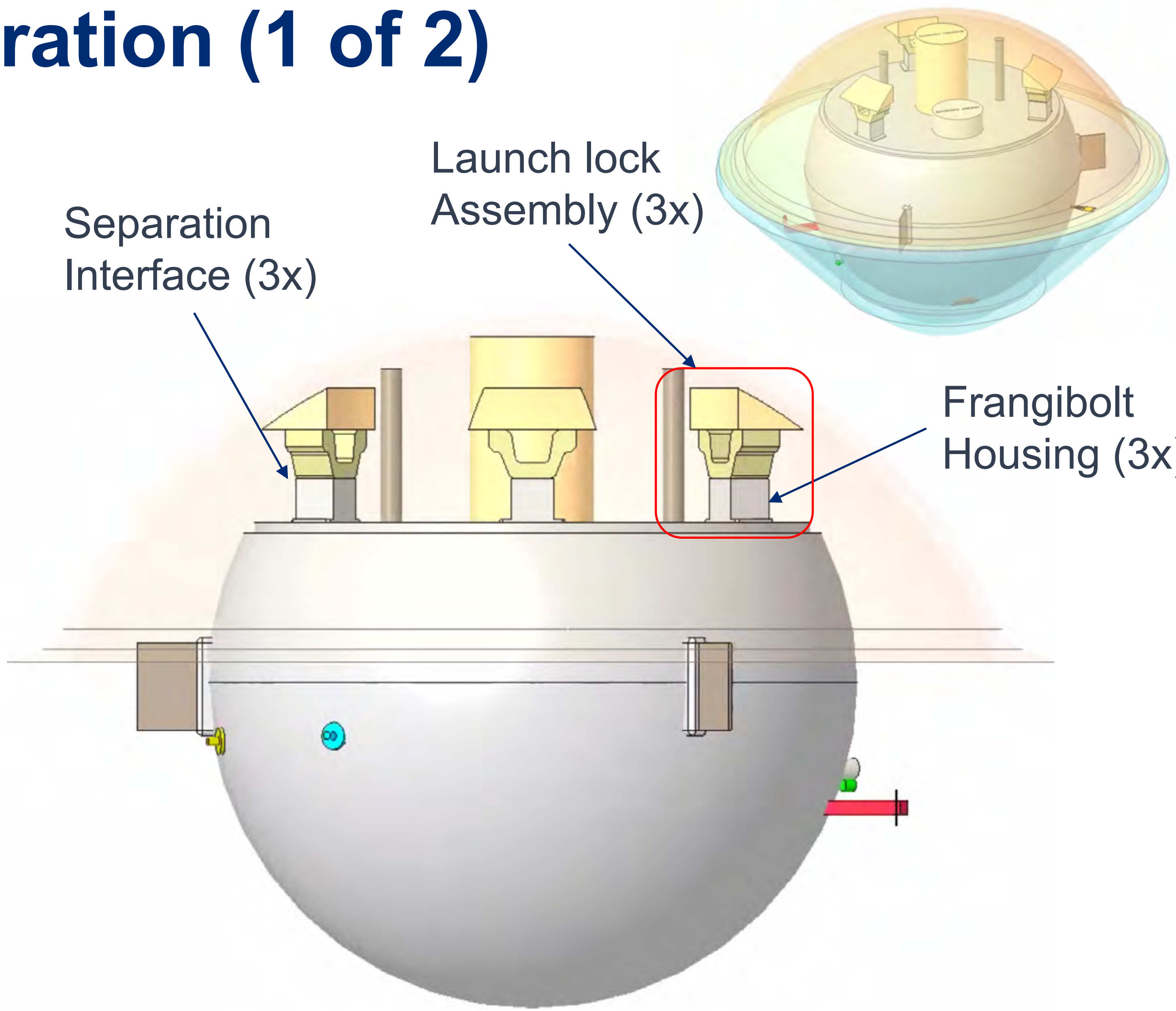
Honeycomb structure with composite facesheet on outside and inside, with 2.5” core filled with aerogel for thermal protection



Unit: meter

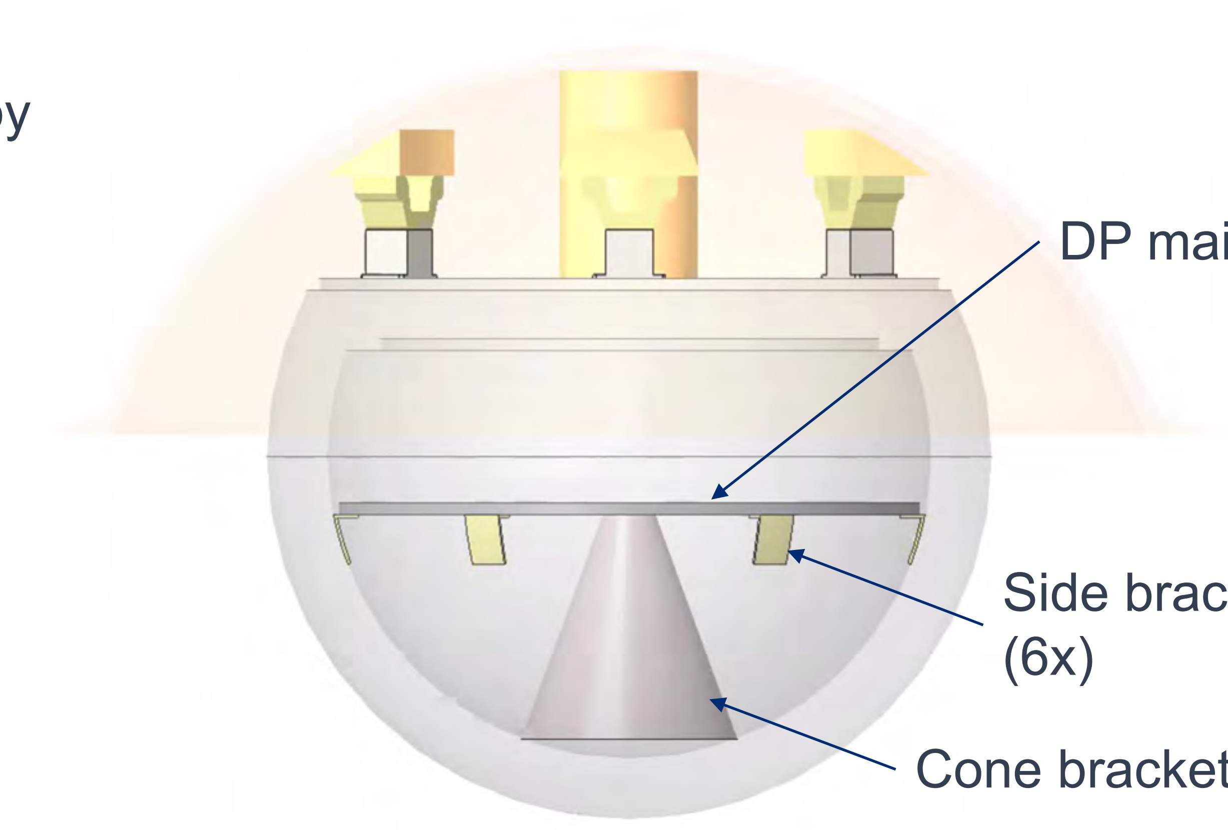
Mechanical Configuration (1 of 2)

- The heat shield is mechanically secured to the Back shell with separation interfaces at the mating perimeter
- There is no connection between DP and the heat shield
- Descent Module (DP) is interfacing to the back shell via three launch lock assemblies
- Frangibolt actuator to take the axial load, and cup/cone separation interface to take lateral loads

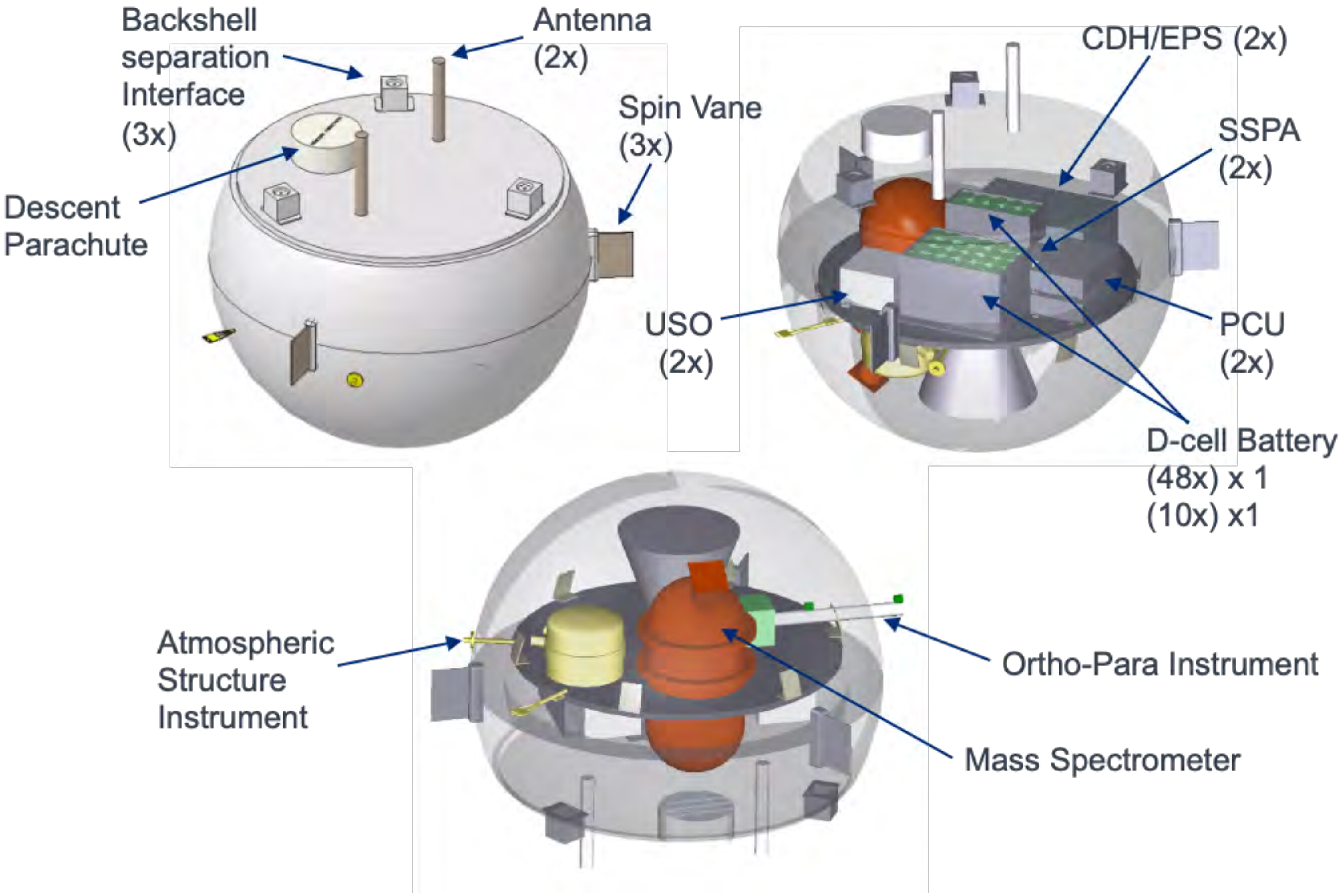


Mechanical Configuration (2 of 2)

- The DP main deck is supported by six side brackets and one center cone bracket



Descent Module Layout



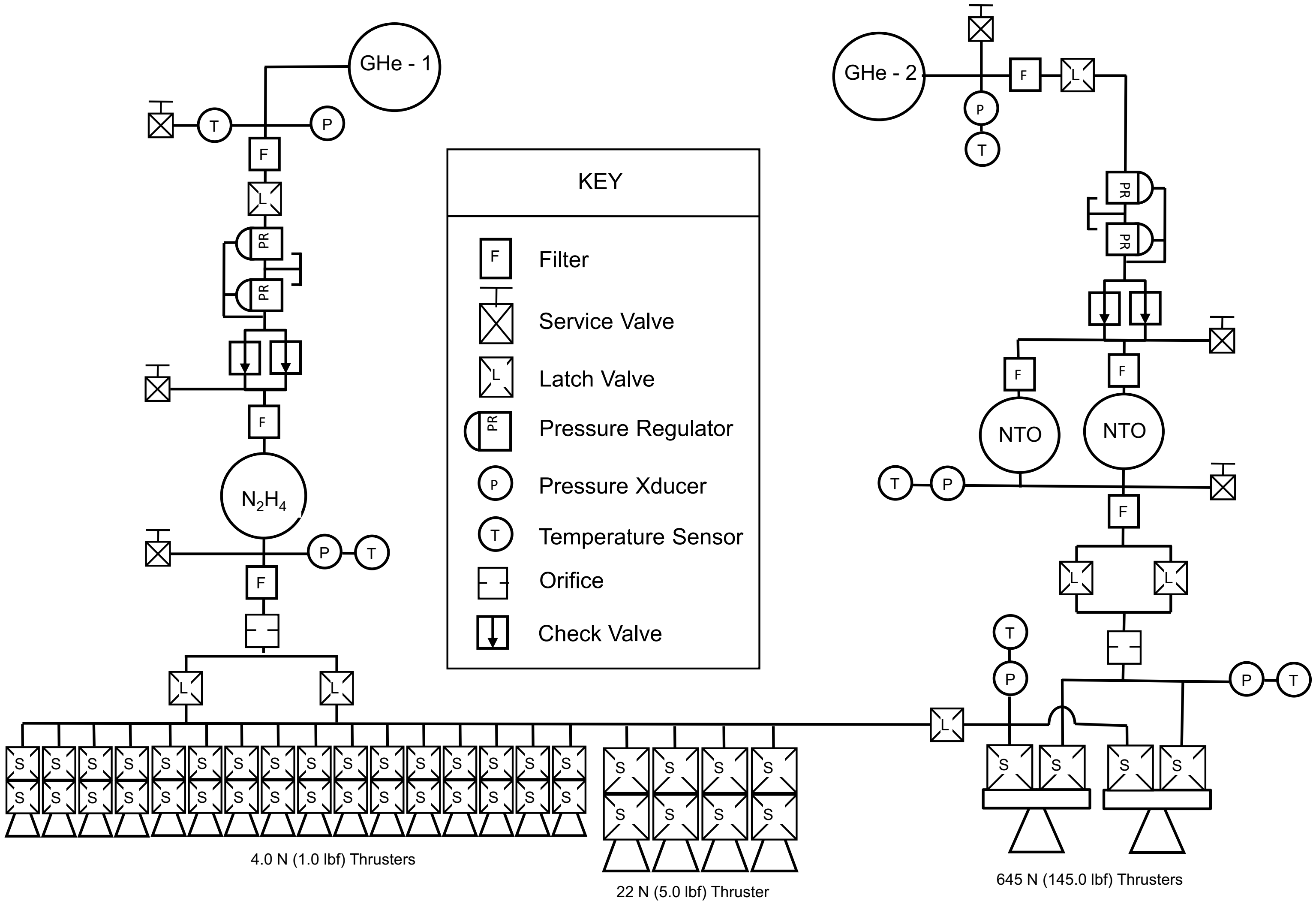
Uranus Orbiter and Probe

Jeremy John

Propulsion System Description

- The propulsion system is baselined as a pressurized, bi-propellant system
  - The system will be pressurized to 350 psi for the mission
- The system consists of the following:
  - 2 bi-propellant main engines
  - 4 monopropellant steering thrusters
  - 16 monopropellant ACS thrusters
  - 1 fuel tank, 2 oxidizer tanks, 2 pressurant tanks
  - Plumbing to support the main component layout
- The system is initially sized to provide a total 2708 m/s delta-V for a maximum launch mass of 7235 kg

Propulsion Schematic



Thrusters – Leros 1B

LEROS 1b – Flight Qualified

Design

Propellant .... Hydrazine/NTO
Steady State Thrust .... 145 lbf (645 N) @ 235 psia
Feed Pressure .... 207 – 284 psia (14.3 – 19.6 bar)
Nozzle Expansion 150:1
Mixture Ratio 0.85
Valve .... Solenoid (MOOG)
Valve Power .... 62 watts
Mass .... 9.1 lbm (4.1 kg)
Length .... 25.5 in (647 mm)

Performance

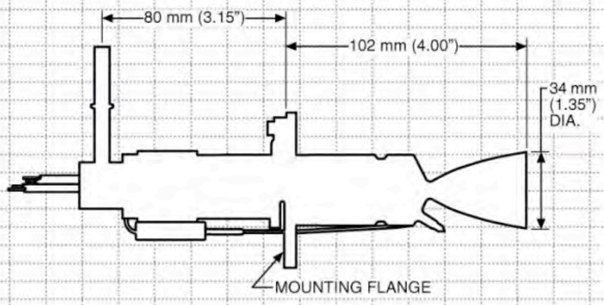
Specific Impulse .... 318 secs
Total Impulse .... 2,900,000 lbf-sec (12,900,000 N-sec)

Thrusters – MR-106E

MR-106E 22 N (5.0-lbf) ROCKET ENGINE ASSEMBLY - 28 Vdc

P/N 34310-301

ICD 34311



Design Characteristics

- Propellant . . . . Hydrazine
- Catalyst LCH-227/202
- Thrust/Steady State . . . . 30.7 – 11.6 N (6.9 – 2.6 lbf)
- Feed Pressure . . . . 24.1 – 6.9 bar (350 – 100 psia)
- Chamber Pressure . . . . .12.4 – 4.5 bar (180 – 65 psia)
- Expansion Ratio. 60:1
- Flow Rate . . . . . . 13.1 – 5.0 g/sec (0.0289 – 0.011 lbm/sec)
- Valve . . . . Dual Seat
- Cat. Bed Heater Pwr . . . 6.53 Watts Max @ 28 Vdc & 21°C
- Valve Heater Power . . . . 3.27 Watts @ 28 Vdc & 21°C
- Valve Power . . . . 25.3 Watts Max @ 28 Vdc & 21°C
- Mass . . . . 0.635 kg (1.4 lbm) Max

Performance

- Specific Impulse . . . . 235 – 229 sec (lbf-sec/lbm)

	REA 'A'	REA 'B'	Mars*
Total Impulse	36,000 N-sec	125,000 N-sec	90,587 N-sec
. . . .	(26,958 lbf-sec)	(28,044 lbf-sec)	(20,366)
Total Pulses	12,405	186	66,631

- Minimum Impulse Bit . . . . . . 0.46 N-sec @ 12.8 bar & 16 ms ON
  . . . . (0.103 lbf-sec @ 185 psia & 16 ms ON)
- Steady State Firing . . . . 2,000 sec – Single Firing
  . . . . 4,670 sec – Cumulative

Status

- Flight Proven

**Mars Odyssey Test Program – December, 2000*

Reference

- AIAA-2001-3632
- AIAA-1999-2469

Rev. Date: 4/24/06

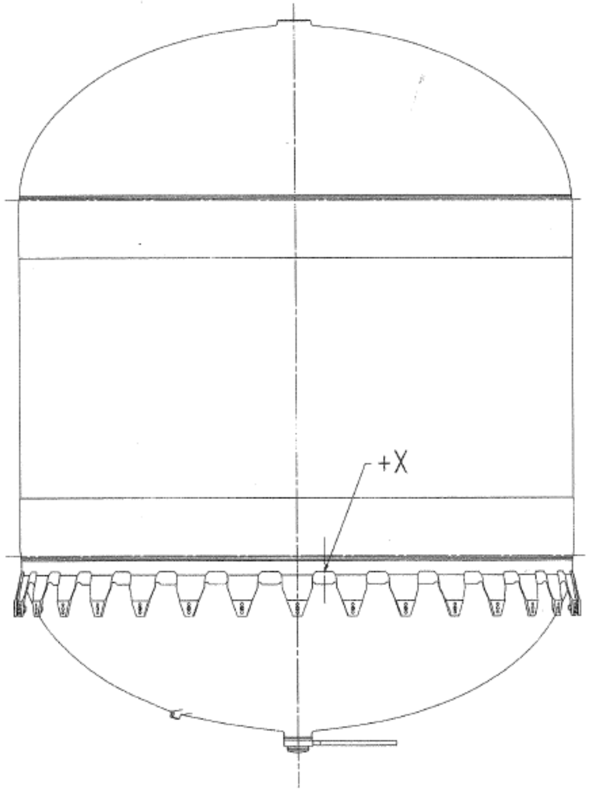
11411 139th Place NE • Redmond, WA 98052
(425) 885-5000 FAX (425) 882-5747

AEROJET

Approved for public release and export

Propellant Tanks - Fuel

- A single, custom fuel tank is baselined
- A development and qualification program will be required for the tank

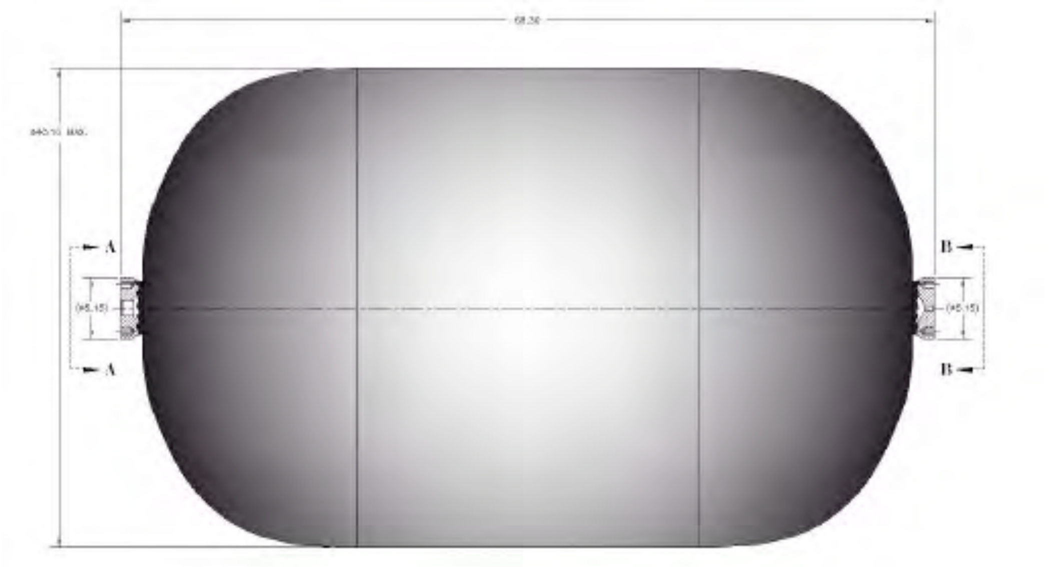


Propellant Tanks - Oxidizer

- Two PMD metal tanks will be used for the oxidizer
- Custom tanks in family with existing designs are baselined
- COTS tanks will be evaluated to eliminate delta-qualification costs

Propellant Tanks - Pressurant

- Two COPV pressurant tanks will be used
- Custom tank based on existing design to minimize qualification costs
- MEOP for the tank will be 4500 psi



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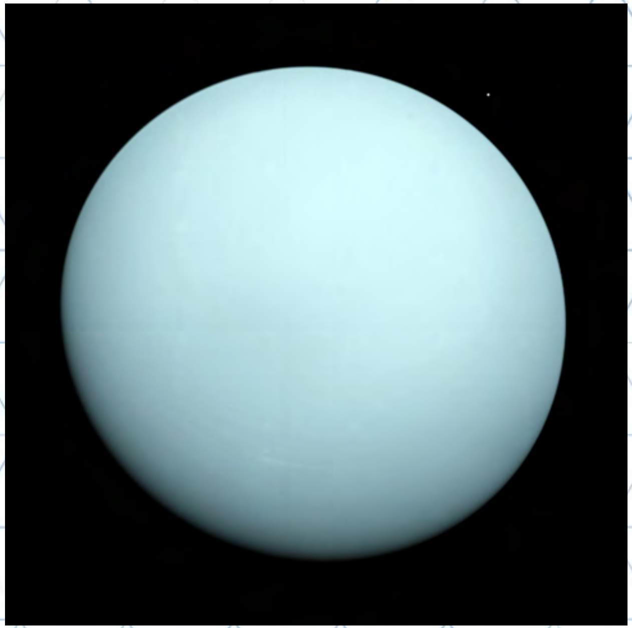
Uranus Orbiter and Probe (UOP)

Planetary Mission Concept Study (PMCS)
ACE Run G&C Design

John Wirzburger
Becca Foust



G&C Scope

- **The G&C subsystem shall operate in two modes (spin-stabilization and 3-axis) and be able to accomplish the following primary tasks:**

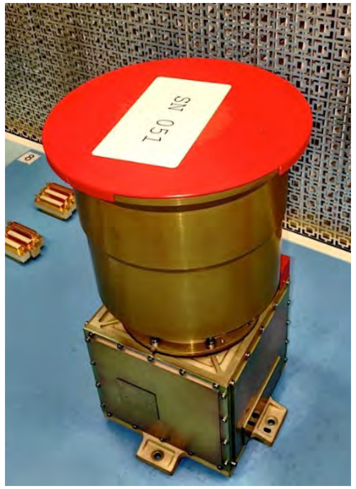
- **Provide spacecraft momentum axis control during the 13-year cruise phase out to 20 AU**
  - Passive spin-stabilized attitude control during hibernation
  - Active spin axis precession control during Earth pointing and TCM events
  - Active 3-axis control during Earth pointing and TCM events

- **Provide 3-axis attitude control during the 4-year tour phase**
  - Burn vector steering during the UOI burn
  - Stability during Probe deployment
  - Communications through MGA during Probe entry
  - Spacecraft pointing control during Moon flybys
    - High rate scans handled internally in instruments
  - Imaging instruments
    - Low jitter
  - Slew capability to any inertial orientation
  - TCM events

G&C Requirements

Title	Requirement	Rationale/Clarification
Operational Modes		
Spin Stabilized Mode	The spacecraft shall support a spin stabilized mode during the Cruise phase	Provides passive dynamic stability
Three-Axis Mode	The spacecraft shall support a three-axis stabilized mode during the Cruise and Tour phases	Necessary for precise pointing, slewing, and tracking
Hibernation Mode	The G&C subsystem concept of operations shall support a low power hibernation mode with all sensors and actuators powered off	Resource management during long cruise stage
Trajectory Correction Maneuvers	The G&C subsystem shall be able to perform TCMs in any commanded inertial direction during the Cruise and Tour phases	Required for orbit maneuvers and refinement of trajectory errors, may use Spin Stabilized or Three-Axis Modes
Uranus Orbit Insertion and Deep Space Maneuver	The G&C subsystem shall be able to perform the UOI and Deep Space Maneuver burn in a turn-and-burn fashion using the main engines	Two 1134 N thrusters are planned to reduce burn time to decrease propellant penalty during UOI
Performance During the Cruise Phase		
Spin Axis Inertial Pointing Accuracy	The G&C subsystem shall be able to point the spin axis to within 0.5 deg TBR of a commanded inertial direction while in spin-stabilized mode	MGA has a half angle beamwidth of 1.9 deg
Performance During the Tour Phase		
Three-Axis Inertial Pointing Accuracy	The G&C subsystem shall be able to point the spacecraft to within 0.06 deg (per axis) of a commanded inertial orientation while in three-axis mode	Pointing of the HGA boresight for Ka-band downlink requires 1 mrad (0.06 deg) accuracy
Three-Axis Tracking Accuracy	The G&C subsystem shall be able to point the spacecraft to within 0.06 deg TBR (per axis) of a commanded time-varying tracking orientation	The tracking command will be based on the type of science mode, such as hi-res imaging or radio science
Slew Rate	The G&C subsystem shall be able to slew the spacecraft at a rate up to TBD deg/sec on wheels and TBD deg/sec on thrusters	High slew rates dictated by need to track features on surface during flybys mitigated by pivot platforms

Star Trackers



- Leonardo AA-STR
  - Accuracy: <53 micro rad boresight knowledge/tracker
  - Lifetime 18 years in GEO, max tracking rate 2 deg/s
  - Flight Heritage – PSP, older generation – MESSENGER, STEREO, New Horizons
  - Suggested by: Neptune Odyssey, Calypso ACE, Enceladus ACE, Neptune ACE
    - suggested 3 placed orthogonally.
- Sodern Hydra
  - Accuracy: 6.3 in boresight, 49.6 about boresight
  - Lifetime 18 years in GEO, max tracking slew 8 deg/s, max accel in tracking 7 deg/s^2
  - Flight Heritage:
  - Suggested by: Enceladus ACE (backup)
- **Star Tracker selection depends on cruise spin rate, some trackers can't manage some spin rates**

Star Tracker Options

		Mass per unit (kg)	Power per unit (W)	Attitude Knowledge		Max Spinrate while Tracking (deg/s)	Size per unit (m)
				Of Boresight (arcsec, 3σ)	About Boresight (arcsec, 3σ)		
Leonardo AASTR		2.6	5.6	6	50	2	0.164 x 0.156 x 0.348
Sodern Hydra TC	Optical head	1.4	0.8 (1 max)	6.3	49.6	8	0.166 x 0.160 x 0.283
	Electrical unit	3.9	6 (7 max)				0.194 x 0.166 x 0.159
Sodern Hydra	Optical head	1.4	0.8 (1 max)	6.3	49.6	8	0.166 x 0.160 x 0.283
	Electrical unit	1.8	6 (7 max)				0.170 x 0.146 x 0.103

IMU

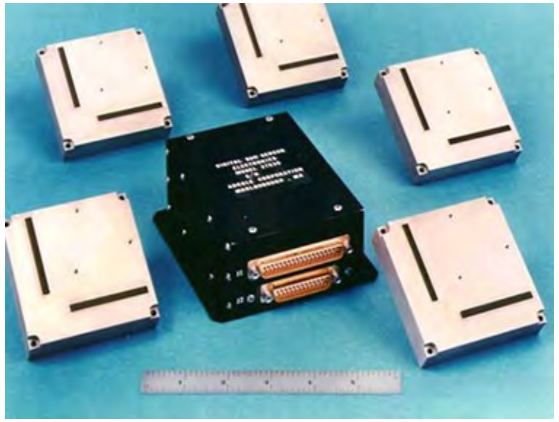
- Northrop Grumman Scalable-SIRU
  - Accuracy: expected performance <0.00015 deg/rt-hr (ARW)
    - Contains redundant, cross strapped gyros and accelerometers
  - Flight Heritage: MESSENGER, PSP, NEAR, many more
  - Suggested by: Neptune Odyssey, Enceladus ACE, Neptune ACE
- Honeywell MIMU
  - Accuracy: 0.005 deg/rt-hr (ARW, 1sig)
  - Flight Heritage: New Horizons, Dragonfly
  - Suggested by: Calypso ACE, Enceladus ACE (backup)
    - Fly 2 for backup because noisy / lifetime issues, mitigated by hibernation

IMU Options

	Mass per unit (kg)	Power per unit (W)	ARW (deg/rt-hr)	Size per unit (m)
Northrop Grumman Scalable-SIRU	7.1	30 (43 max)	0.00015	0.289 x 0.180 x 0.149
Honeywell MIMU	4.7	22 (max 32)	0.005	0.233 x 0.233 x 0.169

Sun Sensors

- Adcole DSS
  - Accuracy: expected <0.5 deg
  - Flight Heritage: PSP, DART, IMAP, New Horizons, Juno, so many
  - Suggested by: Neptune Odyssey, Enceladus ACE, Neptune ACE
    - Suggested 2 electronics boxes, 2 heads, 64x64 deg FOV
- Adcole Fine Spinning Sun Sensor
  - Accuracy:
  - Flight Heritage: same as above
  - Suggested by: Calypso ACE
- Adcole Fine Sun Sensor
  - Accuracy:
  - Flight Heritage: same as above
  - Suggested by: Calypso ACE

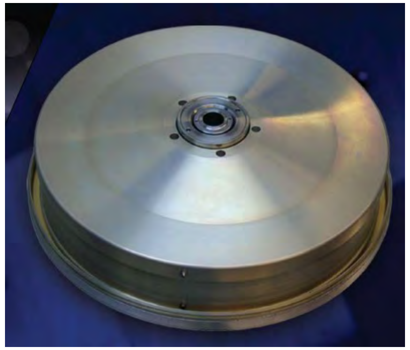


Sun Sensors

		Mass per unit (kg)	Power per unit (W)	Attitude Knowledge (deg)	FOV (deg)	Size per unit (m)
Adcole DSS	Sensor Head	0.25	0	0.25	128 x 128	0.0808 x 0.0808 x 0.0495
	Electronics Unit	1.5	0.4 nom (3.3 max)			0.2731 x 0.1423 x 0.0546
Adcole Fine Spinning Sun Sensor	Sensor Head	0.109	0	0.1-0.6	64 fan	0.066 x 0.033 x 0.025
	Electronics Unit	0.725	0.4 nom			0.051 x 0.082 x 0.089
Adcole Fine Sun Sensor				0.01-0.05	100 x 100	
Bradford Fine Sun Sensor		0.375	0.25 nom	0.03 arcsec	128 x 128	0.108 x 0.108 x 0.053

Reaction Wheels

- Rockwell-Collins RSI 68-75/60
  - Ability: 68 Nms ang mom storage, 75 mNm torque each
  - Flight Heritage: similar to STEREO, MESSENGER but larger wheel
  - Suggested by: Neptune Odyssey
    - Suggested using 4 for fine attitude control only, coarse control and momentum dumps by thrusters
- Rockwell Collins RSI 25-75/60
  - Ability:
  - Flight Heritage: similar to PSP, Messenger
  - Suggested by: Enceladus ACE Run
- UOP from 2010 used 200 mNm torque



Reaction Wheels

	Mass per unit (kg)	Power per unit (W)	Torque at nom speed (mNm)	Nominal Angular Momentum (Nms)	Size per unit (m)
Rockwell Collins RSI 25-75/60	6.3	22 nom 90 peak	75	25	0.35 diameter x 0.118
Rockwell-Collins RSI 68-75/60	8.5	20 nom 90 peak	75	68	0.35 diameter x 0.118
Bradford W45E	7.5	29 nom 168 peak	248	45	0.37 diameter x 0.125
Honeywell Constellation HR16	9-12	22 nom 195 peak	100-200, 400 extended	50-100	
Rockwell-Collins RSI 30-280/30	8.5	20 nom 150 peak	280	30	0.35 diameter x 0.124

Propellant Usage

Control Operation	Approximate Formula for Fuel Mass	Assumptions
Spin Up / Down Maneuvers	$m_f \approx \frac{2 * \Delta H}{I_{sp} * g * D}$	• 2 thrusters separated by moment arm D
Precession Maneuver	$m_f \approx \frac{2 * H * \Delta\theta}{I_{sp} * g * D}$	• 2 thrusters separated by moment arm D
Slew Maneuver	$m_f \approx \frac{4 * I * \dot{\theta}_{max}}{I_{sp} * g * D}$	• 2 thrusters separated by moment arm D • 2 burns (start, stop separated by coast phase) • Coast rate $\dot{\theta}_{max}$

Propellant Usage

	Per Maneuver	Num Maneuvers Expected	Total
Spinup Maneuver Mass [kg]	0.23	200	46.44
Precession Maneuver Mass [kg]	0.36	30	10.94
Slew Maneuver Mass [kg]	0.03	200	5.4
Momentum Dump Mass [kg]	0.04	100	3.88
TCM Attitude Control [kg]	0	0	0
		Grand Total	66.67
		Propellant Allocation	200
Assumptions			
Ixy	12000	kg-m^2	
Izz	3000	kg-m^2	
Octagon diameter	2.2	m	
Octagonal prism length	4.9	m	
Cruise Spinrate	0.05	rad/s	approx = to 0.5 rpm
Max Slew Rate	10	deg/min	same as Triton ACE
Precession angle	90	deg	same as Triton ACE

Hibernation Repointing

- Weekly hibernation communications tracks will require more frequent precession maneuvers than 1 per 6 months
  - Assuming an MGA 1.9 degree half angle requirement begins at 2.8 AU, frequency is ~ 10 times a year, decreasing to ~3 times a year a 12.5 AU (Jupiter, 2035) and 1 per year at Uranus
- Option exists to perform some/all precessions in an active spin mode, by enabling spinning sun sensors and optionally trackers
  - During regular checkouts, repointing can be performed in 3-axis, non-propulsively, on wheels

Future Work

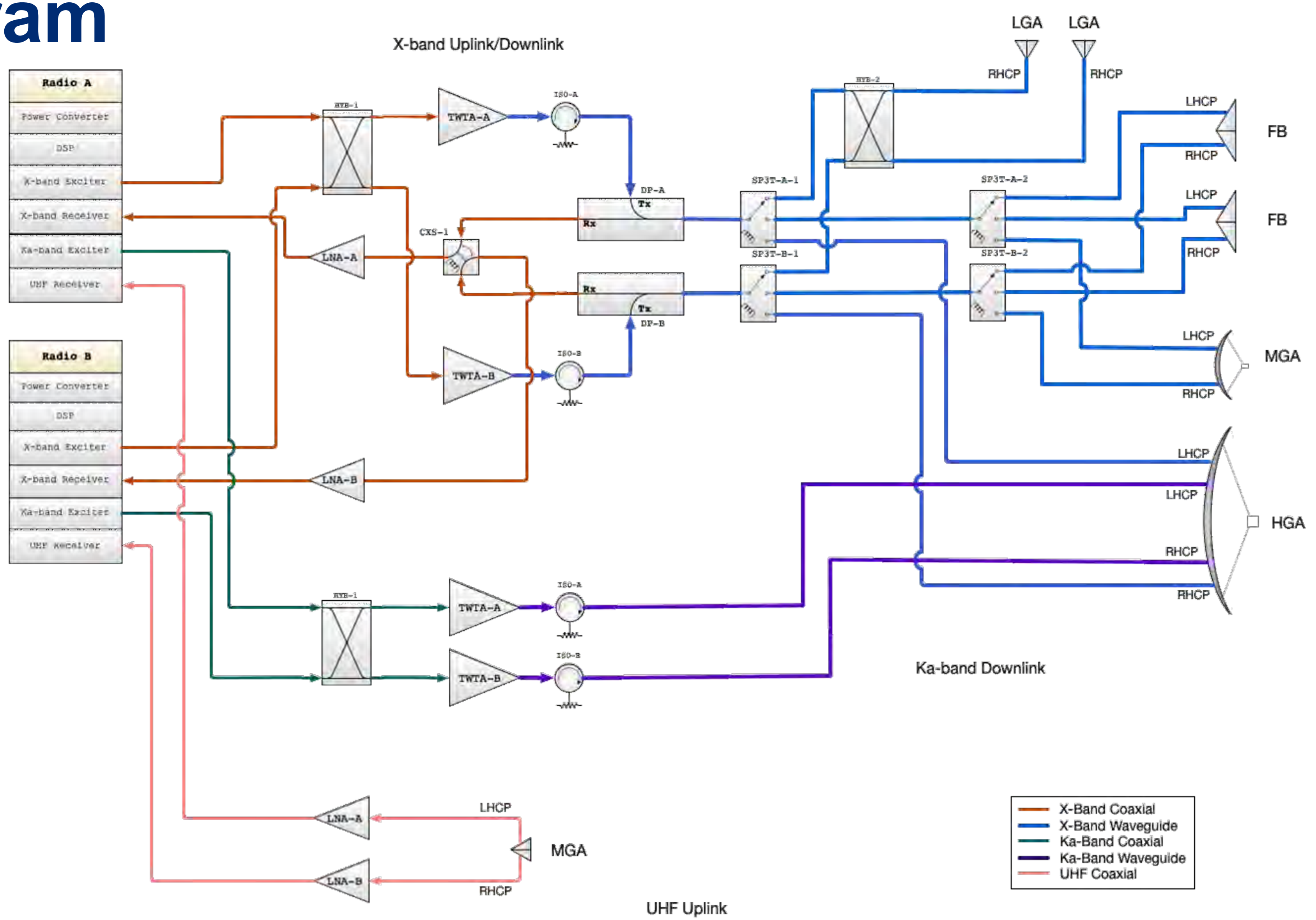
- Tracking Probe during entry
  - Requirement is within 5 degrees of boresight of MGA
    - Any requirement to perform observations with instruments in the same direction as the probe/MGA is pointing?
  - Will require some amount of spacecraft rotation during the hour descent
    - Optical tracking requirement post release, post divert maneuver?
  - May require thrusters to track

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Uranus Orbiter Communication System

Reza Ashtari, PhD

Block Diagram



Command and Telemetry

Command & Telemetry

Uplink

Frequency	7.2 GHz	7.2 GHz	7.2 GHz	7.2 GHz
Transmit Power	20 kW	20 kW	20 kW	20 kW
Ground Station	DSN (34 m)	DSN (34 m)	DSN (34 m)	DSN (34 m)
Range	4 AU	14.7 AU	19.3 AU	19.3 AU
Antenna	LGA (5.4 dBi)	FB (13.8 dBi)	MGA (0.37 m)	HGA (3.1 m)
Pointing Error	35°	3°	1.9°	0.2°
Command Data Rate	7.9 bps*	7.9 bps*	104 bps*	7.66 kbps*

NOTES: Assumes +6 dB command margin (uncoded, BER = 1e-6), 0.9 rad pk data mod., regenerative ranging
*X-band Uplink, DSS-54

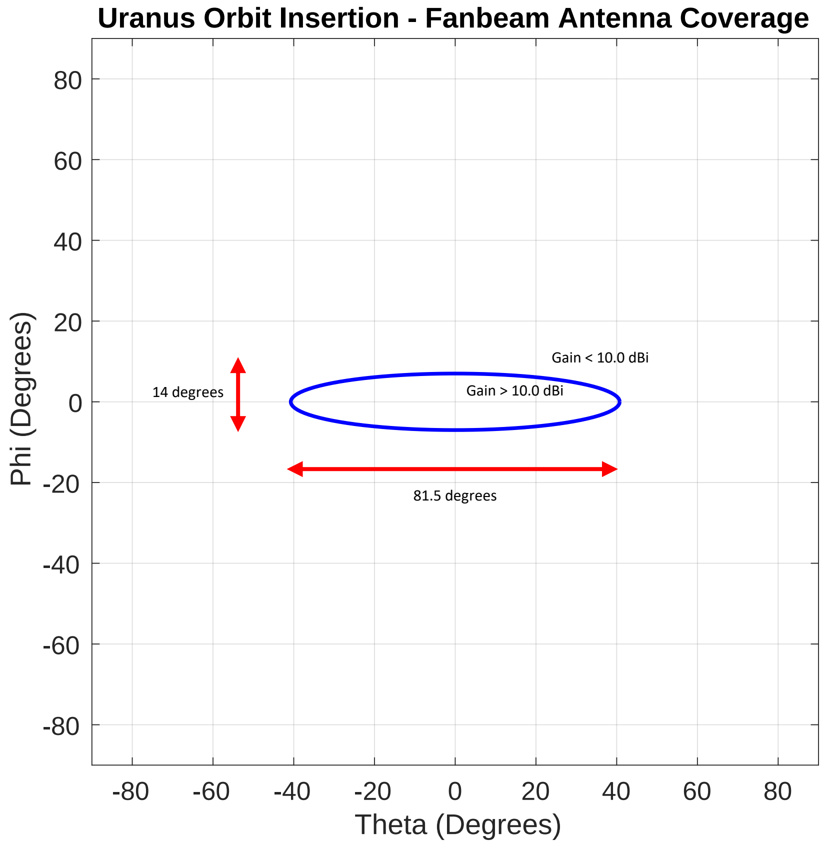
Downlink

Frequency	8.4 GHz	8.4 GHz	8.4 GHz	8.4 GHz	8.4 GHz	31.9 GHz
Transmit Power	58 W	58 W	58 W	58 W	58 W	58 W
Antenna	LGA (5.4 dBi)	FB (15.4 dBi)	MGA (0.37 m)	HGA (3.1 m)	HGA (3.1 m)	HGA (3.1 m)
Pointing Error	35°	3°	1.9°	0.2°	0.06° (3A)	0.06° (3A)
Range	2.8 AU	14.1 AU	19.3 AU	19.3 AU	19.3 AU	19.3 AU
Ground Station	DSN (34 m)	DSN (34 m)	DSN (34 m)	DSN (34 m)	DSN (34 m)	DSN (34 m)
Telemetry Data Rate	5.6 bps*	4.3 bps*	73.6 bps*	6.08 kbps*	7.28 kbps*	19.47 kbps**

NOTES: 58 W_{RF} from TWTA based on 100 W_{DC} from RTG at End-of-Life. (STEREO TWTA, 58% DC-to-RF Efficiency)
Assumes +3 dB Margin, 1.23 rad pk data mod. (0.85, 0.8, 0.75 rad pk for LGA, FB, MGA), regenerative ranging, 1/6 Long Frame Turbo
*X-band Downlink, DSS-54 @ 20 deg EL (0.9 CD)
**Ka-band Downlink, DSS-54 @ 20 deg EL (0.85 CD)

Data Volume per Week = Data Rate x Pass Length x Passes per Week
~3.925 Gb per week = 19475 bps x (8hrsx60minx60sec) x 7 passes per week

Orbit Insertion – Fanbeam Antenna Coverage



Assumptions:

Beacon Mode

Pt = 58 W_{RF}

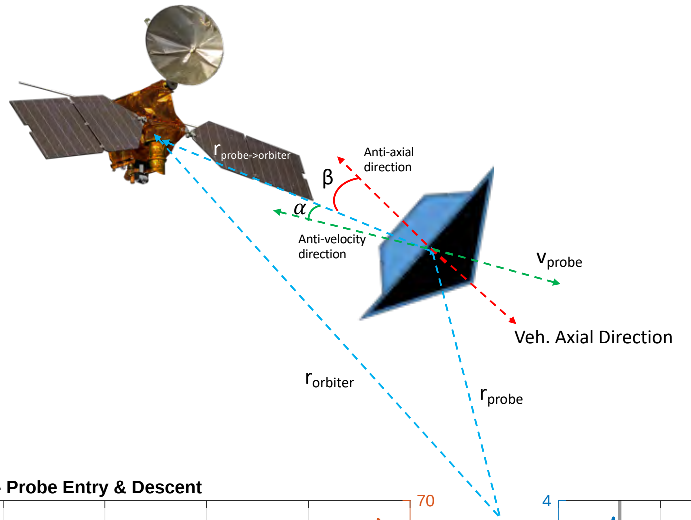
Range = 19.3 AU

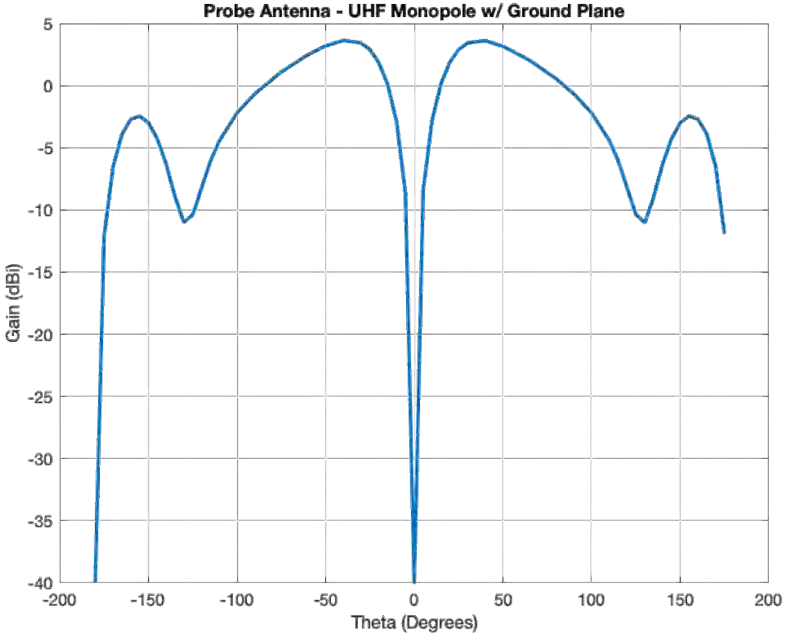
DSN - 4x34m , 20 deg EL (0.9 CD)

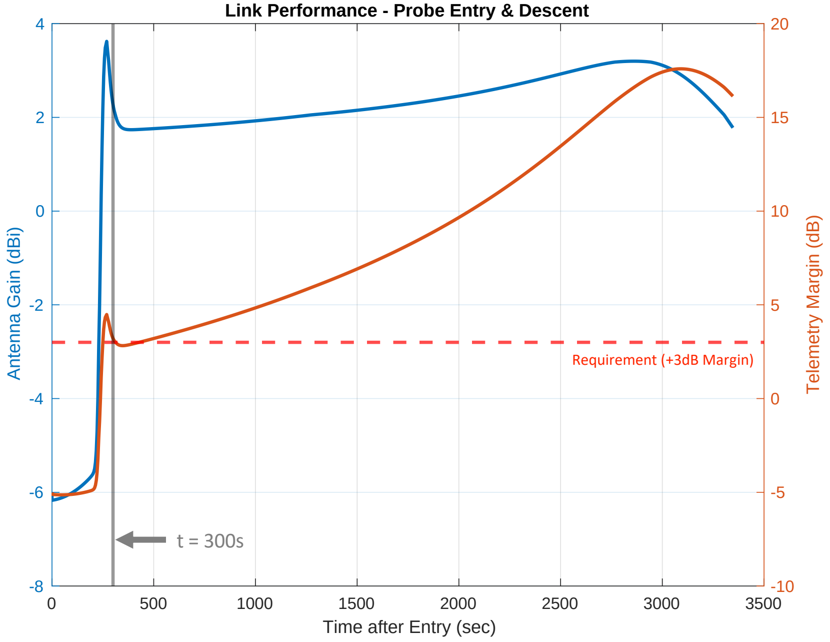
Pt/No = 12dB-Hz

*10 dBi of gain required to meet Pt/No requirement into 4x34m's from maximum Uranus distance of 19.3 AU

Probe – Entry and Descent



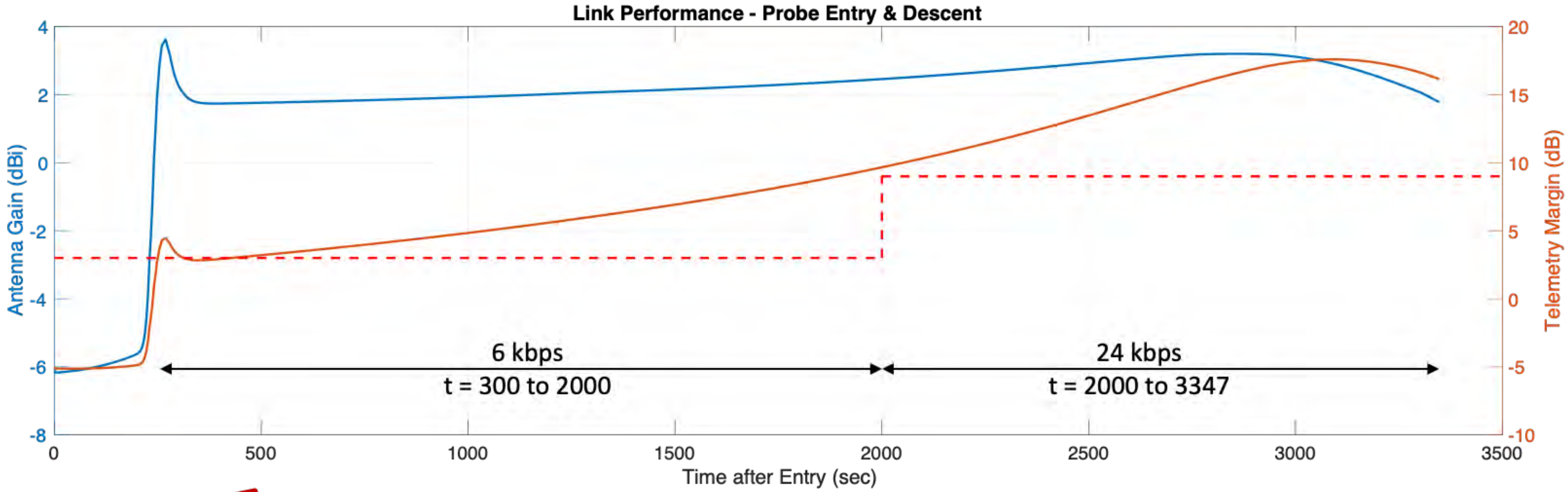




Data Volume (bits) = Link Duration (sec) x Data Rate (bits/sec)
18.28 MB = 3047s x 6000bps

NOTE: Assumes trajectory Case 4000, P_t = 10 W_{RF}, Data Rate = 6 kbps, Data Mod. Index = 1.23, T_{Uranus} = 300 K, Spacecraft Pointing Accuracy = 5 deg, Required Eb/No = 1.3 dB (½ LDPC)

Probe – Entry & Descent – Rate Step

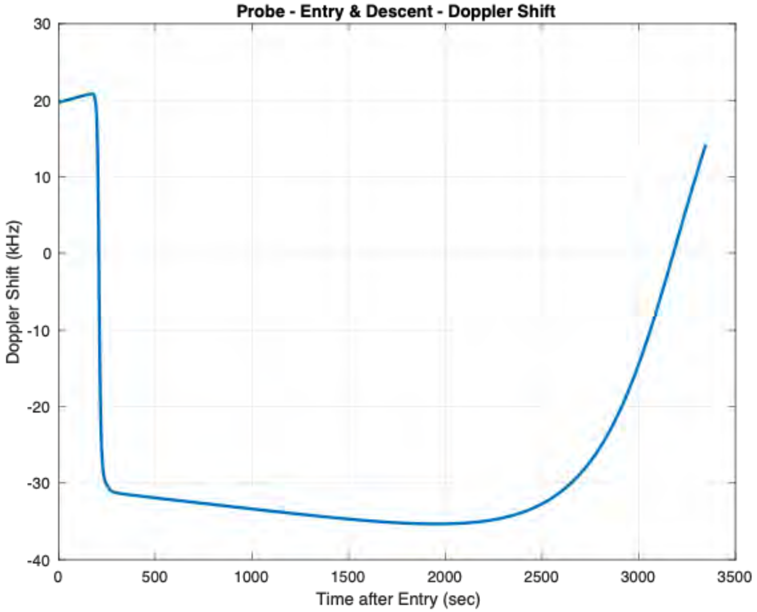


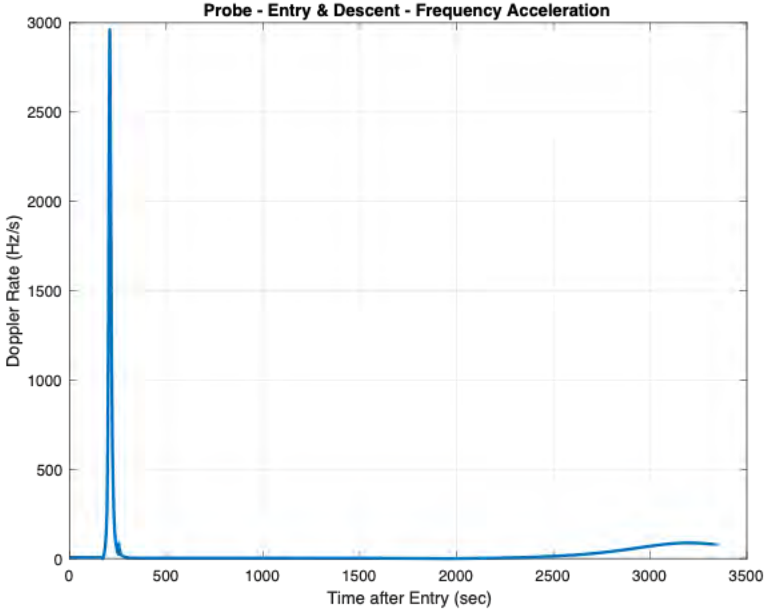
Consideration for Phase A / Phase B Study

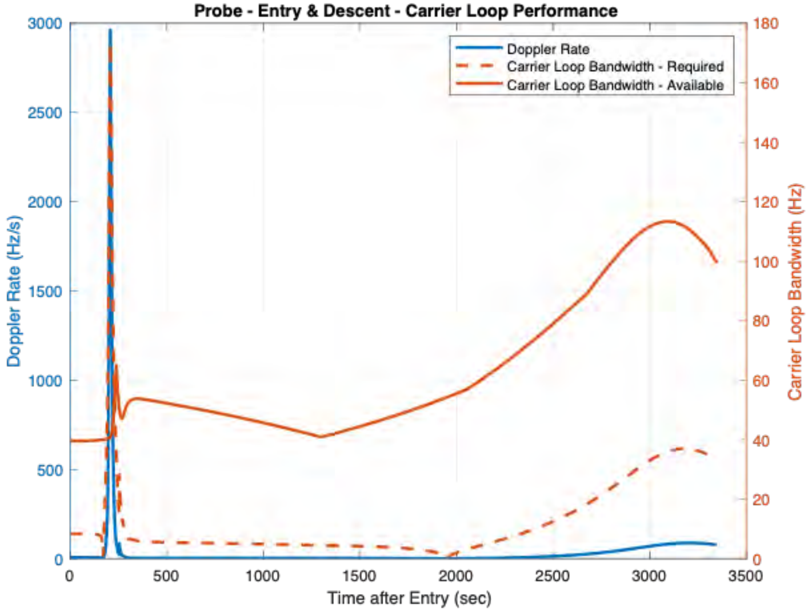
Data Volume (bits) = Link Duration (sec) x Data Rate (bits/sec)
42.52 MB = (1700s x 6000bps) + (1347s x 24000bps)

NOTE: Assumes trajectory Case 4000, P_t = 10 W_{RF}, Data Rate = 6 kbps → 24 kbps, Data Mod. Index = 1.23, T_{Uranus} = 300 K, Spacecraft Pointing Accuracy = 5 deg, Required Eb/No = 1.3 dB (½ LDPC)

Probe – Entry & Descent – Carrier Acquisition & Lock

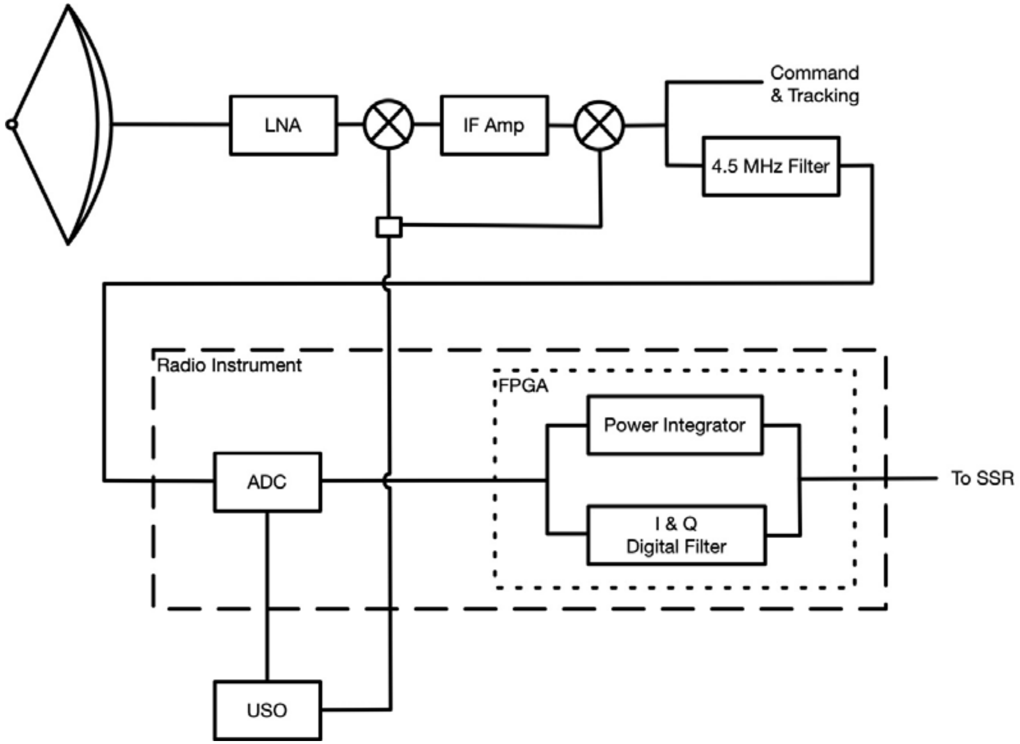




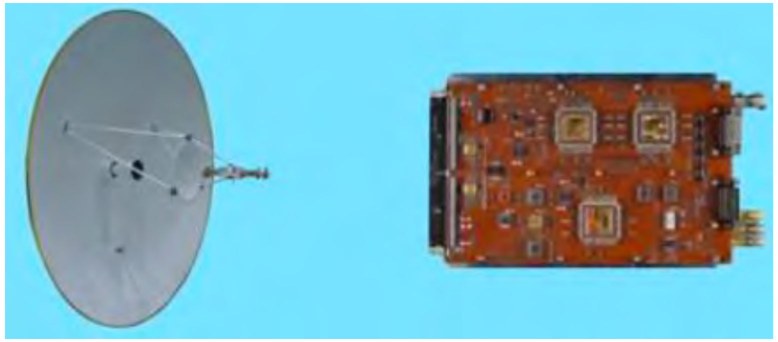


Able to successfully acquire lock on carrier from probe after initial spike of frequency acceleration experienced at ~200 seconds after entry.

Radio Science Instrument



Instrument Block Diagram



Antenna + Instrument Card (0.16 kg, 2.1 W)

Instrument Characteristics & Performance

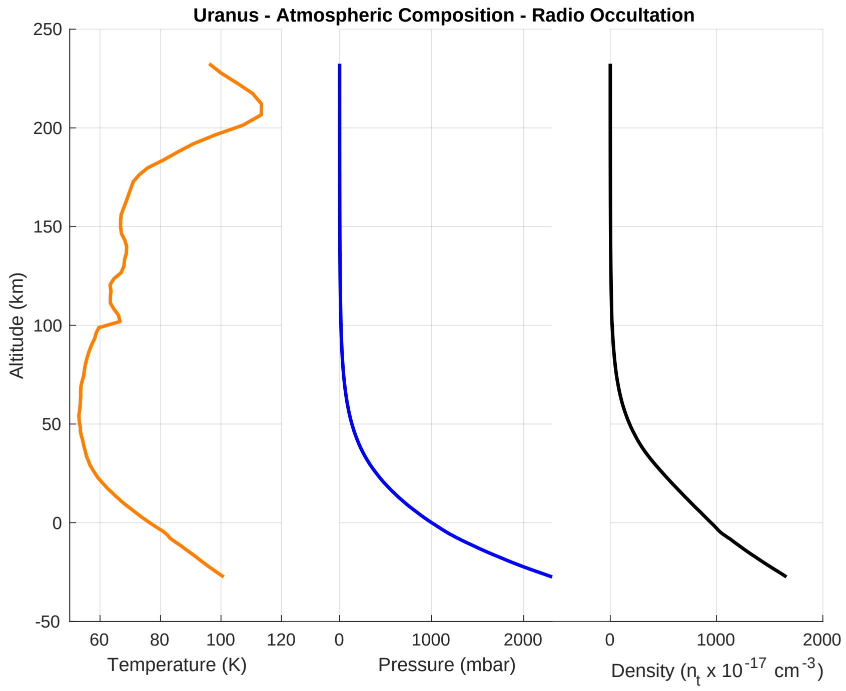
Wavelength	4.17 cm
HGA Diameter (Effective Aperture)	3.1 m (5.27 m^2)
Gain (HPBW)	45.8 dB (0.89°)
System Noise Temperature	150 K
RF Bandwidth	250 MHz
IF Bandwidth	4.5 MHz
Power Uncertainty	0.06 dB
Frequency Uncertainty	2×10^{-13}
Temperature Sensitivity (σ)	34.8 mK
SEFD | $SEFD_{RMS}$ (σ)	7.86×10^4 Jy | 7.86 Jy

Radio Science – HGA

	One-Way (DSN to Orbiter)	One-Way (DSN to Orbiter)
Frequency	7.182 GHz	7.182 GHz
Wavelength	4.17 cm	4.17 cm
Transmit Power	20 kW	80 kW
Transmit Antenna	DSN (34 m)	DSN (34 m)
Range	19.3 AU	19.3 AU
SC Pointing Error	0.06° (-0.06 dB)	0.06° (-0.06 dB)
Receive Antenna	HGA (3.1 m)	HGA (3.1 m)
Pt	-115.2 dBm	-109.2 dBm
Carrier Loop BW	57 Hz	136.4 Hz
Carrier Loop SNR	31.3 dB	37.5 dB

	Two-Way (Orbiter to DSN)	Two-Way (Orbiter to DSN)
Frequency	8.438 GHz	31.859 GHz
Wavelength	3.55 cm	0.94 cm
Transmit Power	58 W	58 W
Transmit Antenna	HGA (3.1 m)	HGA (3.1 m)
Range	19.3 AU	19.3 AU
SC Pointing Error	0.06° (-0.06 dB)	0.06° (-0.06 dB)
Receive Antenna	DSN (34 m)	DSN (34 m)
Pt	-141 dBm	-131 dBm
P_c/N_0	43 dB-Hz*	47.7 dB-Hz*
Carrier Margin	41 dB (RSR)*	45.7 (RSR)*

Note: X-band Downlink, DSS-54 @ 20 deg EL (0.9 CD)
*DSN threshold: P_c / N_0 = 7 dB-Hz (Block V,CL), 2 dB-Hz (RSR,OL)



Radio Science – MGA

	One-Way (DSN to Orbiter)	One-Way (DSN to Orbiter)
Frequency	7.182 GHz	7.182 GHz
Wavelength	4.17 cm	4.17 cm
Transmit Power	20 kW	80 kW
Transmit Antenna	DSN (34 m)	DSN (34 m)
Range	19.3 AU	19.3 AU
SC Pointing Error	0.4° (-0.05 dB)	0.4° (-0.05 dB)
Receive Antenna	MGA (0.37 m)	MGA (0.37 m)
Pt	-133 dBm	-127 dBm
Carrier Loop BW	40 Hz	65 Hz
Carrier Loop SNR	17.8 dB	20.7 dB

	Two-Way (Orbiter to DSN)
Frequency	8.438 GHz
Wavelength	3.55 cm
Transmit Power	58 W
Transmit Antenna	MGA (0.37 m)
Range	19.3 AU
SC Pointing Error	0.4° (-0.05 dB)
Receive Antenna	DSN (34 m)
Pt	-160 dBm
P_c/N_0	24 dB-Hz*
Carrier Margin	22 dB (RSR)*

Note: X-band Downlink, DSS-54 @ 20 deg EL (0.9 CD)
*DSN threshold: P_c / N_0 = 7 dB-Hz (Block V,CL), 2 dB-Hz (RSR,OL)

Uranus Orbiter Probe Avionics

Kirk Volland

Avionics

- Driving Requirements / Key Technical Assumptions
- Design Overview
  - AVI Block Diagram
  - Hardware Implementation Overview and Heritage
  - MEL/PEL inputs
- Risks, Concerns, Future Work, Open Trades

Driving Requirements (Avionics shall…)

- Environmental requirements: Radiation TID, SEE, parts level, thermal, vibe, mission lifetime, availability or reset rate
  - Radiation
    - Total Ionization Dose level is 220 krad, but not expected to be a driving requirement
      - TID estimate ~220 krad (Si) (behind 100 mils Al, RDMx2)
      - **100 krad part hardness requirement achievable** given the ~6 R_J Jupiter flyby
    - Upset rate/Reset Rate is TBD
  - Operational Lifetime
    - 18 years
  - Reliability
    - Level 2 EEE parts selection in accordance with EEE-INST-002
- Low Mass / Low Power
  - Mass and power allocation is TBD

Driving Requirements (Avionics shall…)

- Support C&DH and G&C FSW with a Processor, clock rate, SRAM, MRAM, overall control loop
  - UT700 at 100MHz Processor
  - 64MB SDRAM w/EDAC, 8MB MRAM
  - 256Gbit Non-volatile storage total for science and engineering telemetry data
  - Instrument data rate collection is TDB
  - Downlink up to 60 Kbps
  - Processing support for 50Hz (TBD) Control Loop
- Solid-state Recorder volume, volatile/non-volatile, usage profile for Program/Erase cycles if Flash
  - Current design includes 256Gbits total NAND Flash (on each SBC) for low power and high capacity
  - Required Data Storage for Uranus Orbiter is TBD

Driving Requirements (Avionics shall…)

- SC Bus Command and Telemetry Interfaces (SpaceWire, UARTs, custom)
  - (Document assumed G&C component interfaces)
- Instrument Command and Telemetry Interfaces (SpaceWire, UARTs, custom)
  - (Document assumed Instrument interfaces)

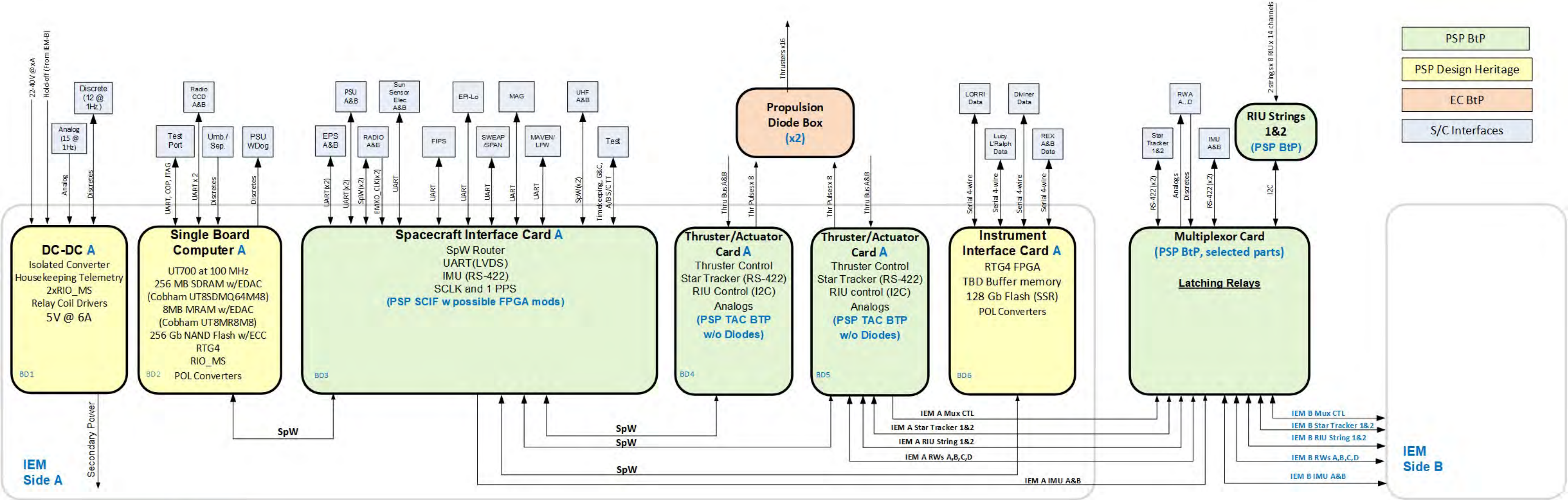
Driving Requirements (Avionics shall…)

- High-rate Thruster Control *like PSP*
  - (RBSP had "low-rate" thrusters in the PDU; control logic was in Avionics)
  - Thruster control adequacy is TBD
    - 16 1-lbf thrusters similar to PSP's prop system
    - 4 5-lbf monopropellant steering thrusters
    - 2 145-lbf Biprop main engines for main delta-V is controlled by power subsystem
- Analog and Discrete Inputs (see block diagram)
- Temperature telemetry channels, accuracy and sensor type
  - One RIU provides 14 temp channels, +/-100degC, accuracy of +/-4degC (TBR)
  - Improved accuracy can be achieved with a new RIU mode with a constrained temp range; or cherry-picking RIO-MS ASICs and specific channels

Driving Requirements (Avionics shall…)

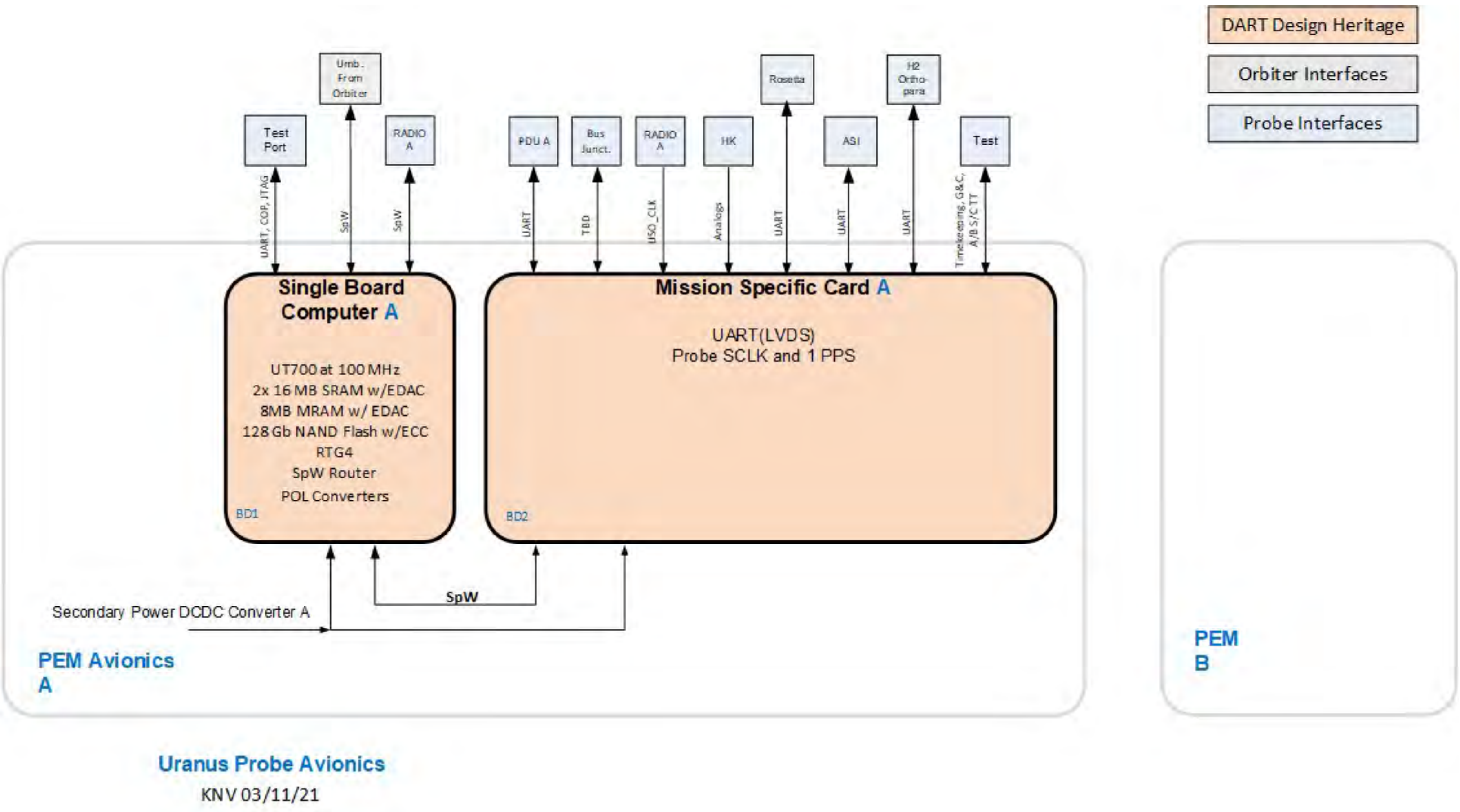
- Fault Management support (Single string/block redundant/cross-strapped)
  - Avionics can provide support fault and redundancy management as long as these concepts or requirements are defined
    - Redundant Electronics is expected
    - CCD, Multiplexer, cold/hot spare, cross-strapping as required by systems and FM design req.
- Timekeeping support with oscillator, MET, PPS/Time Code Distribution – similar to PSP
- Others:
  - High rate dedicated instrument interfaces: LORRI, L'Ralph, Diviner, (TBD)

Avionics Block Diagram



Uranus Orbiter Avionics
KNV 03/10/21

Probe Avionics Block Diagram



Implementation Overview and Heritage

- Orbiter Spacecraft Avionics based on PSP, VAP, Europa Clipper
  - Integrated Electronics Module (IEM) (x1)
    - PSP Single Board Computer (SBC) (x2)
    - PSP Spacecraft Interface Card (SCIF) (x2)
    - PSP Thruster/Actuator Card (TAC) (x4)
    - PSP Multiplexer Card (MUX) / PSP Mode Controller (MC) (x1)
    - PSP DC/DC Converter Card (DC/DC) (x2)
  - PSP Remote Interface Unit (RIU) (x16)
  - EC Propulsion Diode Box (PDB) (x4)
- Probe Avionics based DART CORESAT with EPS Slices
  - Probe Electronics Module (PEM) (x2)
    - DART CORESAT Single Board Computer (SBC) (x1)
    - Mission Specific Card (MiSC) (x1)

Uranus Orbiter IEM Anticipated Cards

SCIF: S/C Interface Slice

- 8-Port SpW Router
- SCIF SpW node
- 2xRTAX2000 FPGA
- 4MB SRAM w/EDAC
- 13 bidir serial ports

TAC: Thruster Actuator Slice

- TAC SpW node
- RTAX2000 FPGA
- 12 Thruster coil drives
- RIU power and I2C bus master

SBC/SSR Single Board Computer

- UT700-100MHz
- 64MB SRAM w/EDAC
- 8MB MRAM w/EDAC
- 256Gb Flash
- RIO-MS Hskp Tlm
- RTG4 FPGA
- Sleep Mode
- 4 SpW nodes

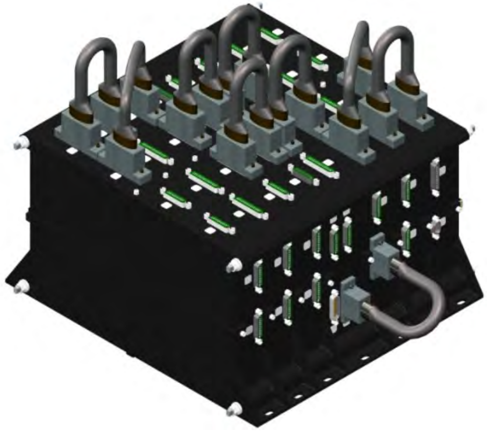
DC-DC Converter Slice

- Isolated converter
- +5V, 12V, -2V, 8V outputs
- 2xRIO_MS hkg tlm
- 8 relay coil drivers

MUX Slice: Redundancy Multiplexer

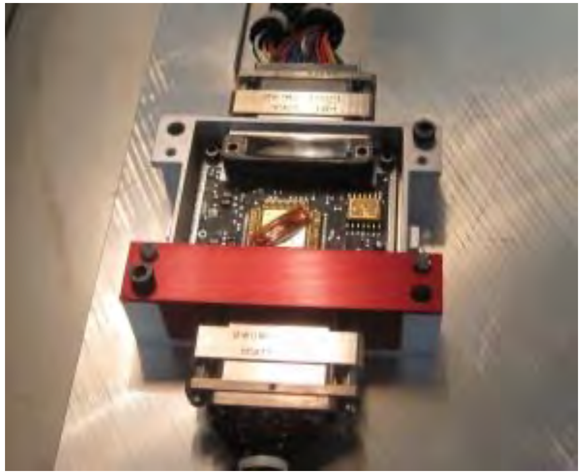
- A/B cross-strapping relays:
- Star tracker
- RWA
- IMU
- RIU

PSP Redundant Electronics Module

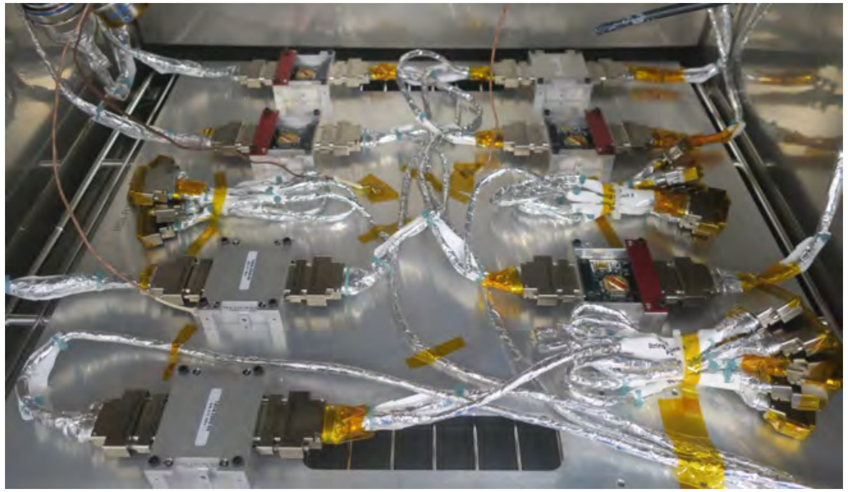


PSP Remote Interface Unit (RIU)

- Distributed multichannel data acquisition unit for housekeeping data
  - Temperature, voltage, etc.
  - Connected in serial chain via I2C
- Build to print for Uranus Orbiter from PSP
- 14 input channels/RIU
- Number of RIU needed is mission dependent
  - Spacecraft configuration assumes x16 RIUs
  - 224 channels per avionics side per element



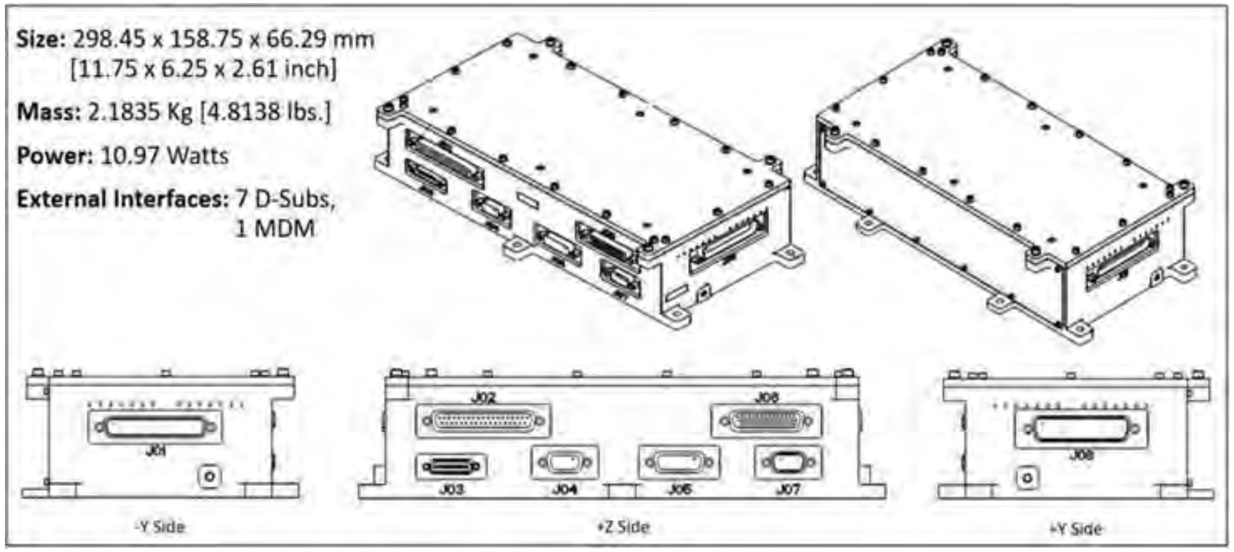
PSP Flight RIU Module

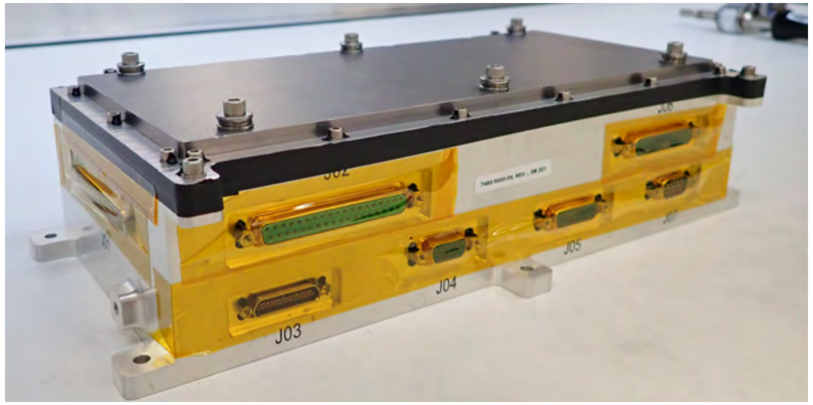


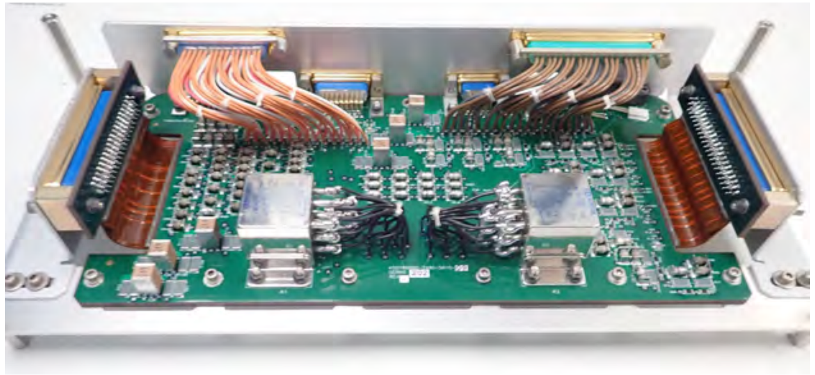
PSP Flight RIU String

EC Propulsion Diode Box (PDB)

- Provide power interface to Thrusters and inductive kickback protection to the TACs
- Current Europa Clipper Design can interface up to 12 Thrusters



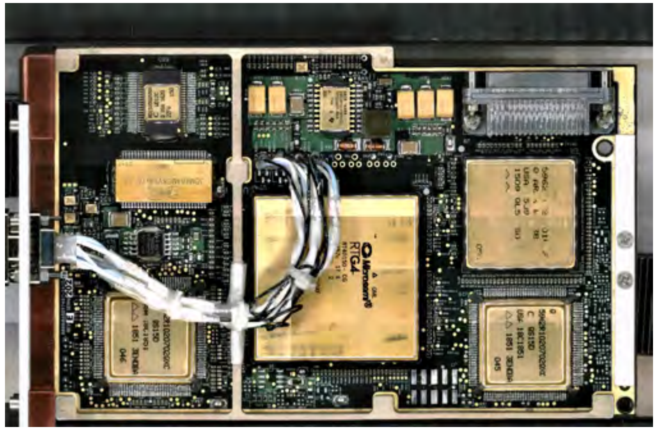




Probe Electronics

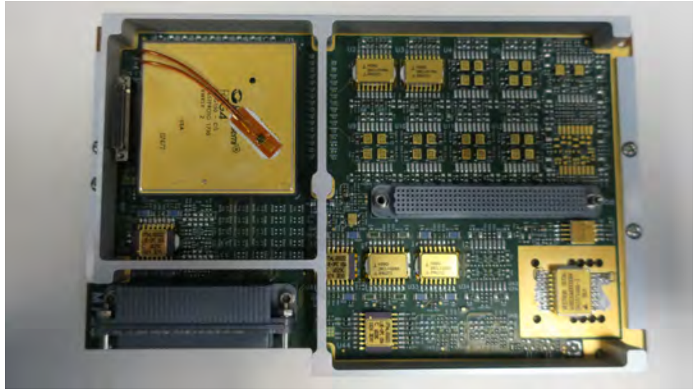
- SBC from DART CORESAT heritage
- Mission Specific Card (MiSC)

DART CORESAT SBC



UT700
RTG4 FPGA
SpW Router
128 Gbit Flash
16 MB SRAM,
16 MB SRAM via FPGA,
8 MB MRAM

DART MiSC



RTG4 FPGA
SpW node
Inst & S/C UARTs
Analog I/O

MEL / PEL Inputs Orbiter and Probe

	Mass (kg)	QTY (mass)	Mass Margin	Total Mass (kg)	Power (W)	QTY (powered)	Pwr wo margin	Pwr Margin	Total Power (W)	*Power assumptions*
IEM										
SBC	0.7	2	1.15	1.61	5.12	1	5.12	1.15	5.89	
SCIF	0.6	2	1.15	1.38	2.63	1	2.63	1.1	2.89	*Using 10% margin for BTP*
IIF	0.6	2	1.15	1.38	2.63	1	2.63	1.15	3.02	
TAC	0.7	4	1.15	3.22	2.63	2	5.26	1.1	5.79	*Using 10% margin for BTP*
DCDC Board	0.9	2	1.15	2.07	1.50	1	1.50	1.15	1.73	
DCDC Loss							9.55	1	10.76	*65% eff in DCDC converters*
MUX	0.75	1	1.15	0.86				1	0.00	
Harness	0.35	1	1.15	0.40	0.05	1	0.05	1.15	0.06	
PDB	2.18	4	1.15	10.03	0	4	0	1	0.00	*IVO est.,* ***11W*** *thermal diss/box*
RIU	0.09	16	1.15	1.66	0.0375	16	0.6	1.1	0.66	
				22.61			**27.34**		**30.79**	

	Mass (kg)	QTY (mass)	Mass Margin	Total Mass (kg)	Power (W)	QTY (powered)	Pwr wo margin	Pwr Margin	Total Power (W)	*Power assumptions*
PEM										
SBC	0.5	2	1.15	1.15	5	2	10	1.15	11.50	*Power w/out DCDC eff. Loss*
MiSC	0.7	2	1.15	1.61	2.4	2	4.8	1.15	5.52	*Power w/out DCDC eff. Loss*
DCDC Loss								1	7.29	*Assume 70% eff in DCDC converters*
				2.76			**14.80**		**24.31**	

Risks and Assumptions

- Identifying high-density Flash Memories
- No specific instrument or S/C Subsystem interfaces identified
  - Anticipate RS-422 and LVDS UART, I^2C, as well as SpaceWire, and custom high-speed interfaces
  - Data rates to be defined
  - All instruments provide redundant serial digital interfaces
  - Interfaces are dependent upon Instrument selection.
  - Interfaces are dependent upon G&C Component procurements
- Power Assumptions
  - IEM Power conversion efficiencies from heritage PSP design
  - Margins on board power 10% for BtP/heritage and 15% on boards with more design changes
- System design
  - SC power during cruise periods does not require hibernation controller to curtail power
- Avionics portion of Probe Electronics modified from CORESAT SBC
  - NVM memory can be identified to replace existing MRAM in the DART heritage design
  - DCDC conversion from battery bus is provided by EPS board

Key Phase A Trades, Risk-reduction items, Future Work

- Flash memory evaluation and radiation testing.
- Evaluate RIO_MS die banking, evaluate design updates to improve accuracy.
- Processor performance benchmarking with FSW.
- Analysis of Uranus radiation environment for suitability of Probe Avionics components
- Programmatics: cost and schedule will be evaluated for future work

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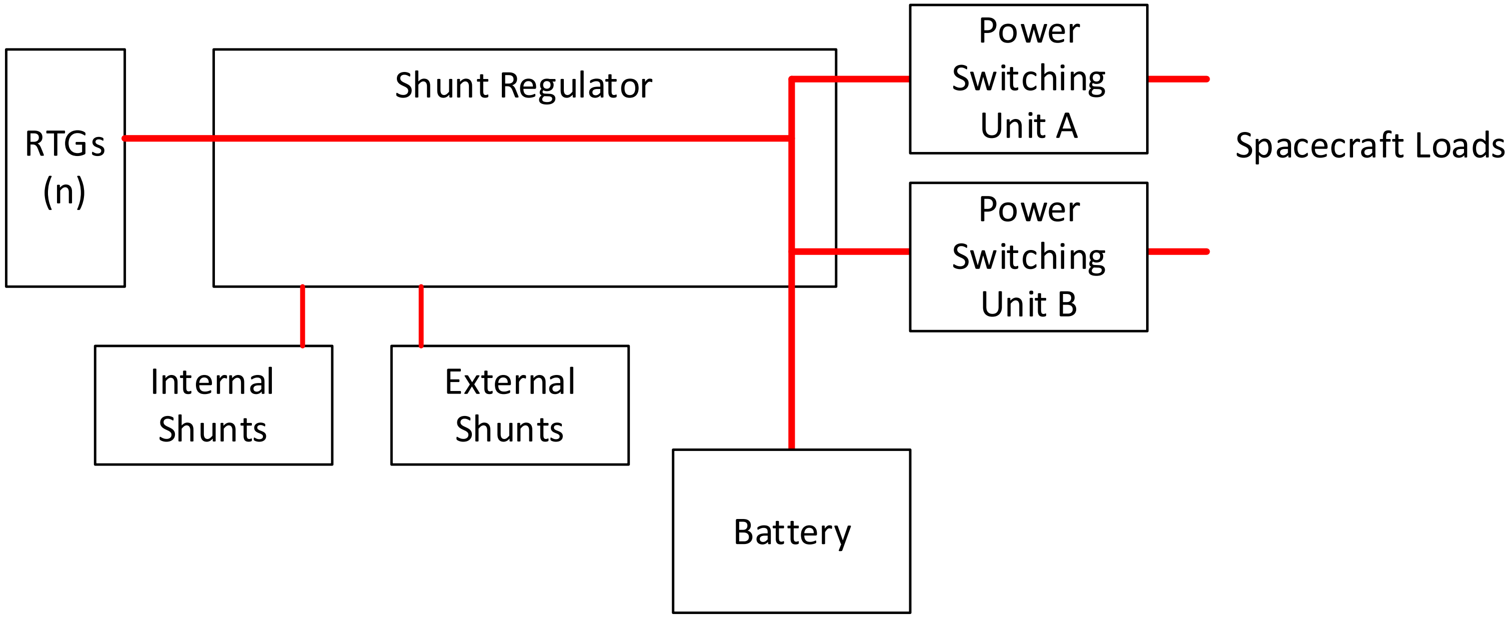
Uranus Orbiter Probe Electrical Power Subsystem

Dan Gallagher

EPS Topology & Block Diagram

- RTG powered direct energy transfer
  - Fault tolerant linear shunt regulator provides RTG output power regulation
  - Block redundant power switching units provide switched, pulsed, safety services
  - Secondary battery to support peak loads



Power and Service Requirements

- Power Requirement
  - Reference
    - 2021-04-20-1700 UOP MEL-PEL.xlsx
  - Includes UOI 1 hour burn

- Power Services
  - Reference
    - 2021-03-12-1302 UOP MEL-PEL.xlsx
  - For each A and B side
    - 71 non-safety services
    - 45 safety services

Requirements and Assumptions

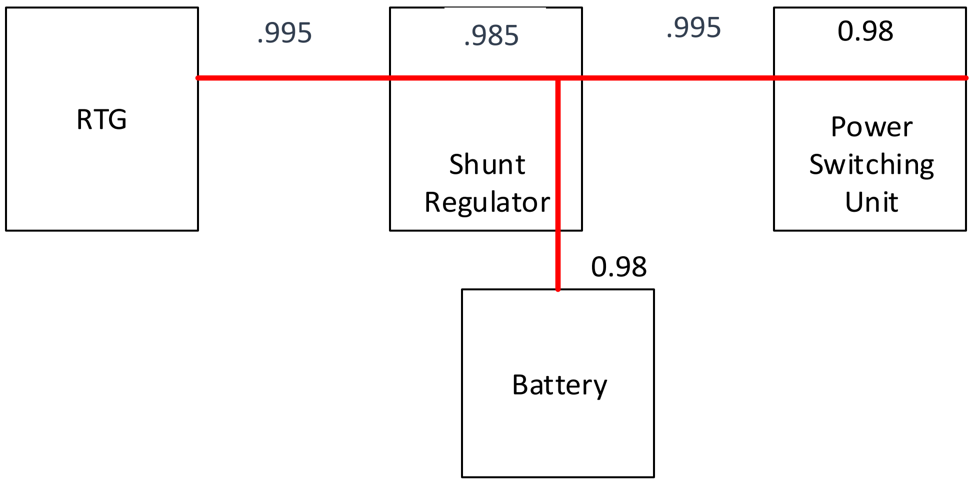
- Power Source is 3 Mod 1 RTGs
- Margins
  - Margins calculated per study instructions
    - CBE+30% equivalent to QMS CBE + 43%
- Class A mission
  - Single point failure tolerant implementation
- Power requirements are specified at the power switching unit output
- Avionics provides
  - Thruster drive control
  - Separation detection
- Total dose radiation requirement 100krad design with 240 mils equivalent Al
- No requirements for
  - magnetically clean hardware
  - electrostatically clean hardware
  - deep dielectric discharge mitigation
  - pyrotechnic safety implementation

RTG Selected

Parameter	GPHS-RTG	MMRTG	Next Gen Mod 0	Next Gen Mod 1	Next Gen Mod 2	DRPS
P_{BOL} (We)	291	110	293	245	400	300 to 400
Mass (Kg)	58	45	56	56	56	100 to 200
Q_{BOL} (Wth)	4410	2000	4500	4000	4000	1500
$P_{EODL} = P_0 * e^{-rt}$ (We)	NA	63	208	177	290	241 to 321
Maximum Average annual power degradation, r (%/yr)	1.54	3.8	1.9	1.9	1.9	1.3
Fueled storage life, t (years)	2	3	3	3	3	3
Flight Design Life, t (yrs)	16	14	16	14	14	14
Design Life, t (yrs)	18	17	18	17	17	17
Allowable Flight Voltage Envelope (V)	22-34	22-34	22-34	22-36	22-36	22-36
Planetary Atmospheres (Y/N)	N	Y	N	N	N	Y
Launch Date Availability	N/A	Now	2026	2029	2034	2030
Cost for 1 RPS ($M)	N/A	$54	$50	$70	$70	$64

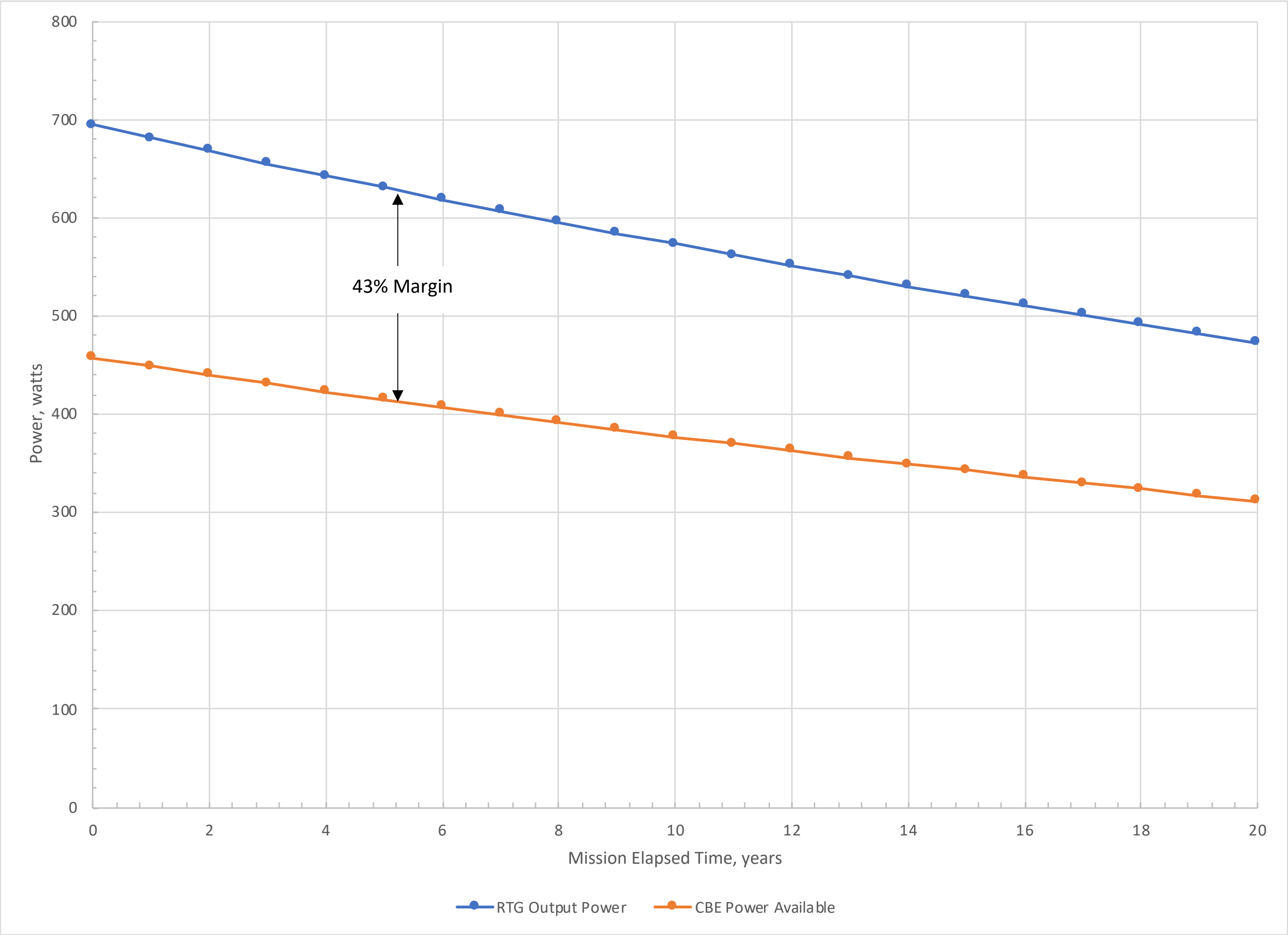
RTG EPS Distribution Losses

Simple Preliminary Model



Available Power

3x Mod 1 RTGs fueled 3 years before launch



Power Margin

- Battery required for UOI case, and to meet margin requirements for momentum dump case

	Launch	Cruise Checkout	Cruise Hibernation	Safe/Acquisition	Momentum Dump	Delta V Preheat	DSM/UOI	DSM/UOI with 65% battery DOD	Probe Operations	Tour Science	Radio Science	Science Downlink
CBE Load, watts	158	341	197	325	348	304	643	643	342	297	335	336
MET, years	0	13.4	13.4	18	18	18	13.4	13.4	13.7	18	18	18
Available Power, watts	676	523	523	479	479	479	523	955	520	479	479	479
Margin, watts	518	182	326	154	131	175	-120	312	178	182	144	143
Margin per QMS	328%	53%	165%	47%	38%	57%	-19%	49%	52%	61%	43%	42%
Margin Per Study	77%	35%	62%	32%	27%	36%	-23%	33%	34%	38%	30%	30%

Supplemental Battery Requirement

Design Case

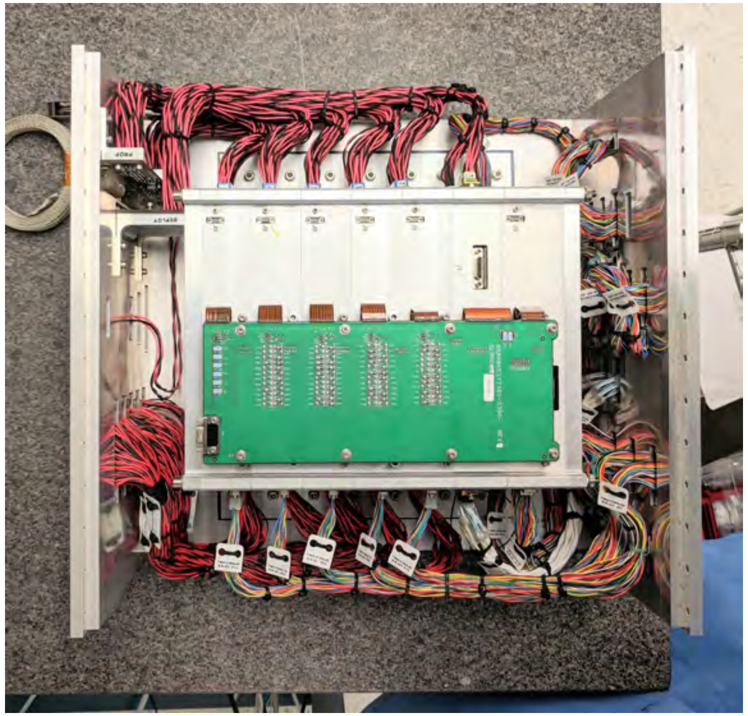
- DSM/UOI
  - 643W CBE for 1 hour
- Battery Parameters
  - 35% battery capacity degradation at UOI
    - Extrapolated from IVO analysis, will need vendor analysis
    - 18 year life will be challenging
  - 65% depth of discharge (measured against residual capacity) allowed

- Battery Configuration
  - ABSL battery constructed from 18650 cells
  - 32 parallel strings of 8 series cells required to meet energy requirements
  - Can be broken into two packs if needed
- Residual Depth of Discharge =59%

Radiation Shielding for Electronics

- Box in a box concept, similar to EC PME
  - Standard slice based unit
    - Thicker endplates for line of sight radiation shielding
  - Internal cables connect interior unit to external connector plates
  - Shielding provided primarily by outer box

- EC PME implemented a “high Z/low Z” shielding
  - Combination of aluminum and tantalum

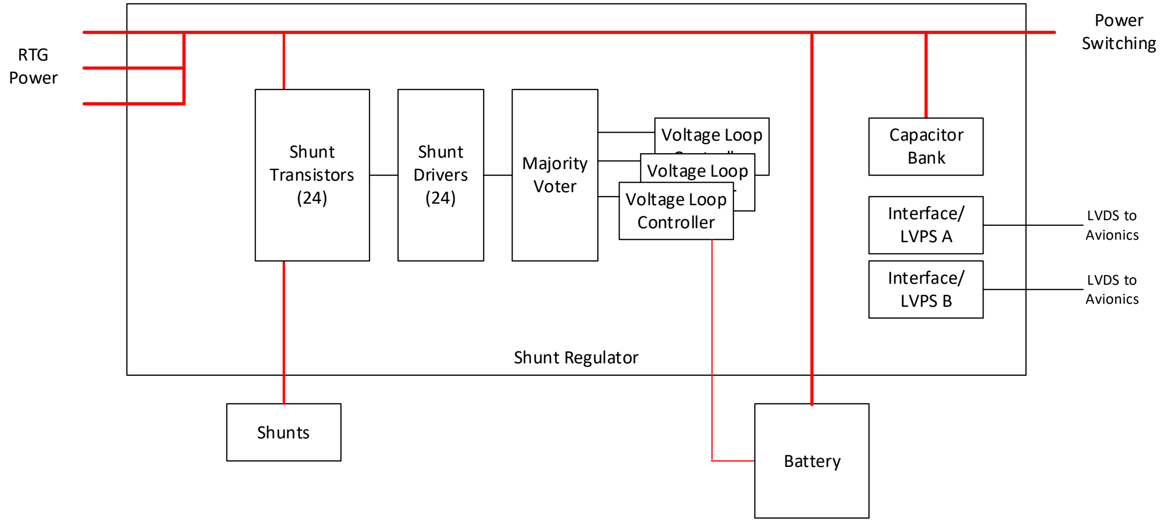


Sides and top not installed

30V Shunt Regulator

- Concept
  - Sequential linear design derived from RBSP and New Horizons
  - Box in a box packaging for radiation
- Slice allocations
  - RTG junction
  - Capacitor bank/battery junction
  - Controller
    - Fault tolerant design incorporating 3 voltage regulators and majority voter
  - Shunt drive slice, 3
  - Interface/LVPS slice x 2 (A, B)
- Shunt dissipaters are located external to box

- MEL/PEL
  - Mass: 23 kg
  - Volume: 18L x 14W 8H inches
  - Power consumed: 15.6W
  - Power Dissipated: variable, ~48W
- Block Diagram



Shunt Dissipaters

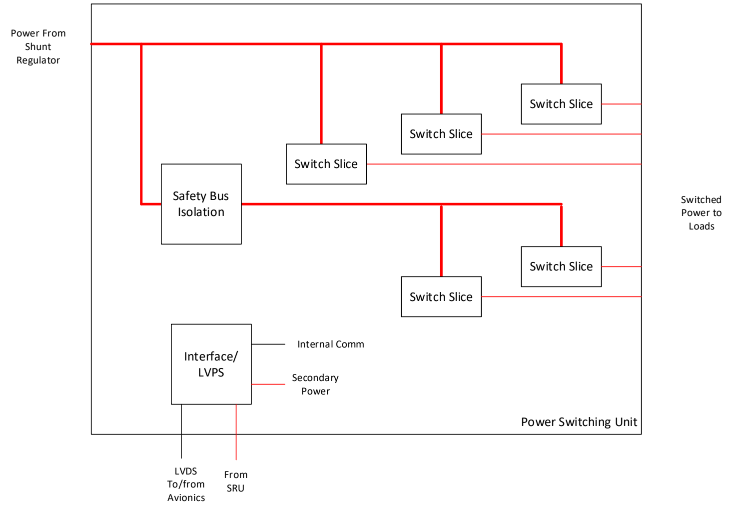
- Concept
  - Heaters or power resistors located as needed around spacecraft

- MEL/PEL
  - Mass depends on implementation
    - Number=8*(number of RTGs)
  - 0W consumed
  - ~50W dissipated per active shunt

30V Power Switching Unit

- Concept
  - Power switching for spacecraft loads derived from Dragonfly working concept
  - Includes current sensing and circuit breakers
  - Safety services disabled when not needed to reduce power consumption
  - Box in a box packaging for radiation
- Block redundant
  - Two units, A and B
- Slice allocation (each unit)
  - Switching: 5
    - 3 primary, 2 safety
  - Safety relay: 1
  - LVPS: 1
  - Motherboard, power harness

- MEL/PEL (each of 2 units)
  - Mass 19 kg
  - Volume 14L x 14W x 8H inches
  - Power Consumed: 19W
  - Power Dissipated: consumed + 2% of load
- Block Diagram



PSU Service Margins

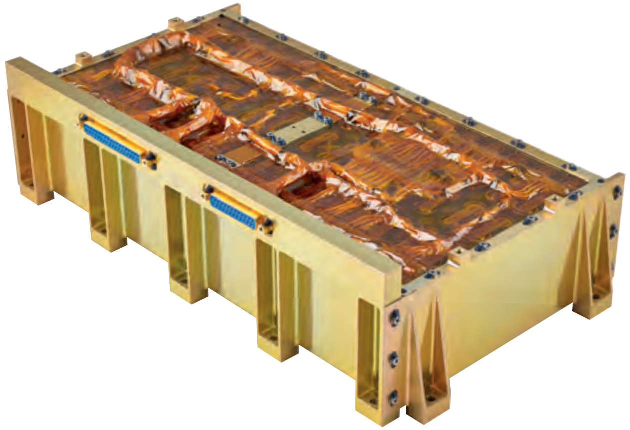
Each PSU

	Switched	Safety	Total
Total Services Required	71	45	116
Required Margin			15%
Total Margined Services			134
Number of services per Slice			24
Switch Slices Required			6
Slices Allocated	4	2	6
Services Available	96	48	144
Calculated Margin	35%	7%	24%

Battery

2 half packs, each 8S16P

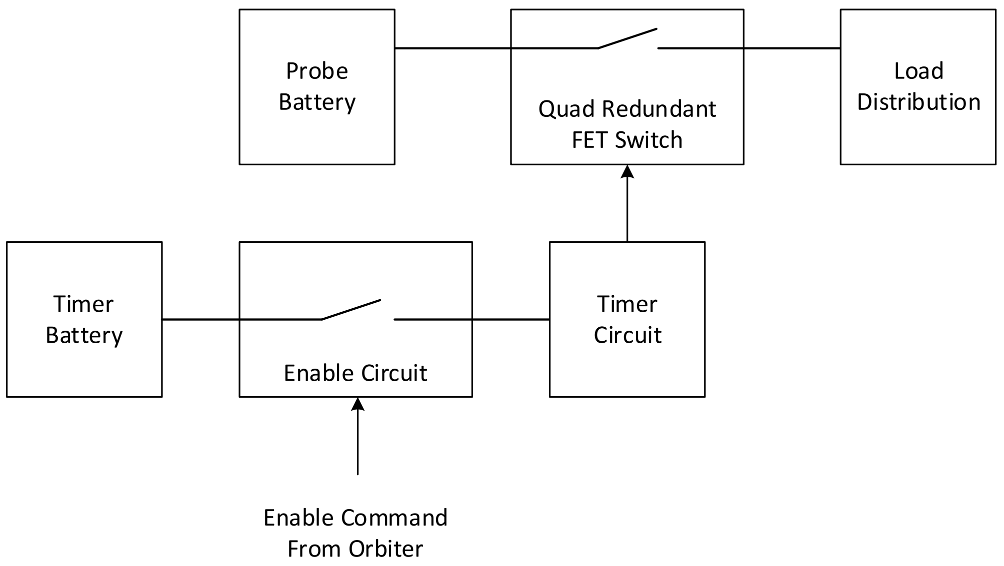
- Concept
  - Lithium Ion “small cell” battery
  - Eliminates battery management electronics
  - No use during cruise
    - Maintain at low state of charge to minimize capacity loss
  - Allow high 65% (of residual) DOD
    - Few cycles
- Requirement is for an 8S32P battery
- MEL, each of 2
  - Mass 6.8kg
  - Volume 358L x 198W x 98H mm



Facts at a Glance	
ABSL™ Cell	18650HCM
Configuration	8s16p
Nameplate Capacity	20 Ah
Energy	691 Wh
Mass	6.8 kg
Footprint	358 x 198 mm
Height	98 mm
Nominal Voltage	28V
Voltage Range	20 – 33.6V

Probe EPS

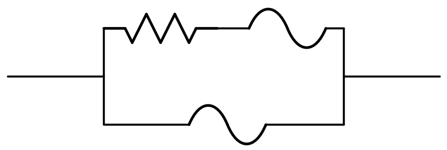
- Unregulated battery powered bus
- Battery powered timer activated at probe release
- Timer expiration powers remainder of probe
- CBE Load
  - Probe = 118W
  - Timer = 0.5W
    - Redundant timers assumed 0.25W each



Probe EPS
Load Distribution

- Load distribution implements simple redundant fusing
  - No switching required
  - Minimizes PWA requirements

- Each power service includes a pair of fuses with a current steering resistor
  - Primary fuse fails with SEU type transient, load still operates on secondary fuse
  - Both fuses clear for hard failure



- Timer and fuse cards
  - WAG mass of 2kg (each of 2)
  - Form factor to fit integrated probe avionics

- EPS also provides DC/DC converter cards for EPS and Avionics electronics

Probe EPS

Lithium Thionyl Chloride Primary Batteries

Timer battery

- Provides 0.5W CBE for 65 days
- SAFT LS33600 cells
  - 20 year life
  - <1% per year capacity loss
- Configuration 1s36p
- BOL capacity 468AH
- Total Battery Mass ~5Kg
- Estimated DOD 80%

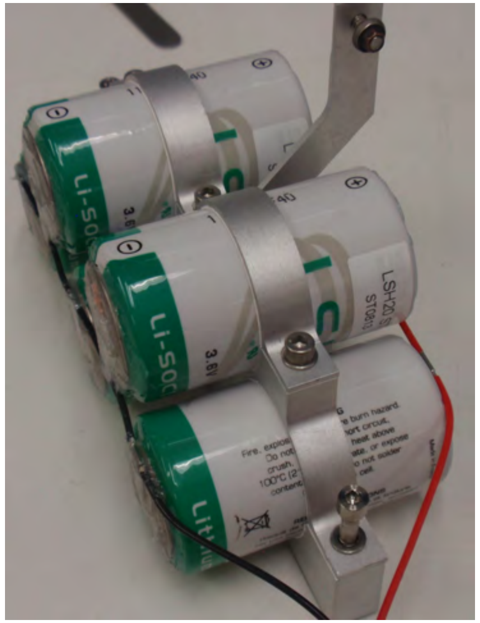
Probe battery

- Provides 131W CBE for 1 hour
- SAFT LSH20 cells
  - Storage life requires verification (unspecified)
  - <3% per year capacity loss
- Configuration 8s4p
- BOL capacity 32AH
- Total Battery Mass ~5Kg
- Estimated DOD 35%
  - Cells are rate limited

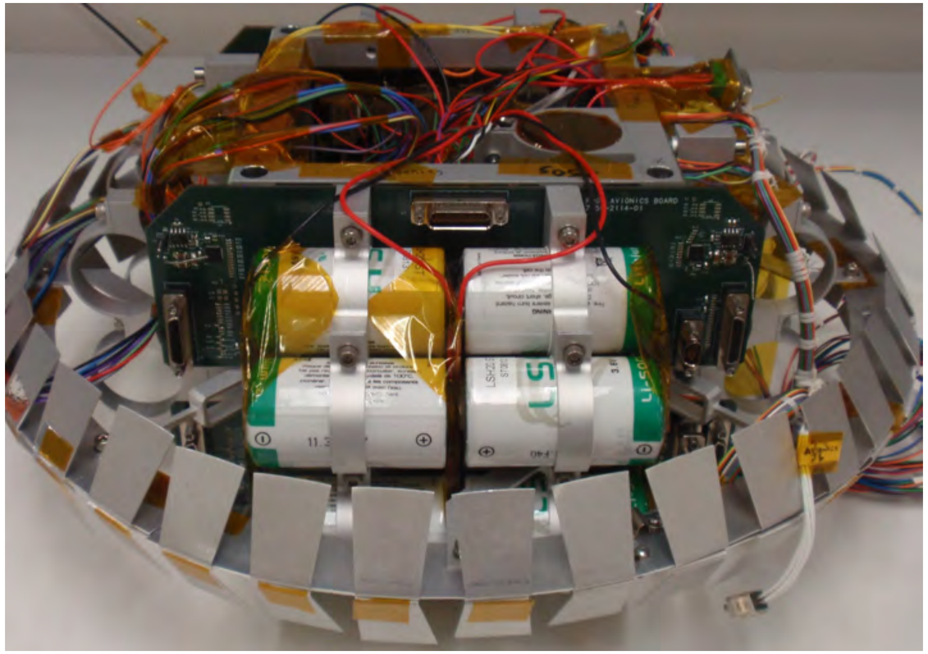
Probe Battery Packaging

- Cells are D size (62mm tall x 33.4 mm diameter)
- Packaging could be similar to POGO batteries
  - Configuration to be determined by probe accomodation

5 Cell Group



Cells mounted in POGO



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Uranus Orbiter Probe Thermal Subsystem

Bruce Williams

Thermal Assumptions

- Use waste heat from RTG's to keep prop module warm.
- Most components are conductively tied to the bus, including:
  - Propulsion subsystem:
    - Propellant tank, latch valves, pressure transducers, bus prop lines, service valves
      - Except engines/valves and prop lines in PM structure,.
  - Electronics boxes, star cameras, RW's, etc..
- Items thermally isolated from bus:
  - Instruments (possibly partially tied to minimize heater power)
  - HGA, MGA and 1 LGA
  - Prop engines, including valves and PM prop lines (heaters needed here, TBD)
  - RTG's
  - Shunts (4 plates needed to reject 440 W max to space)
- Minimize the use the electric heaters.

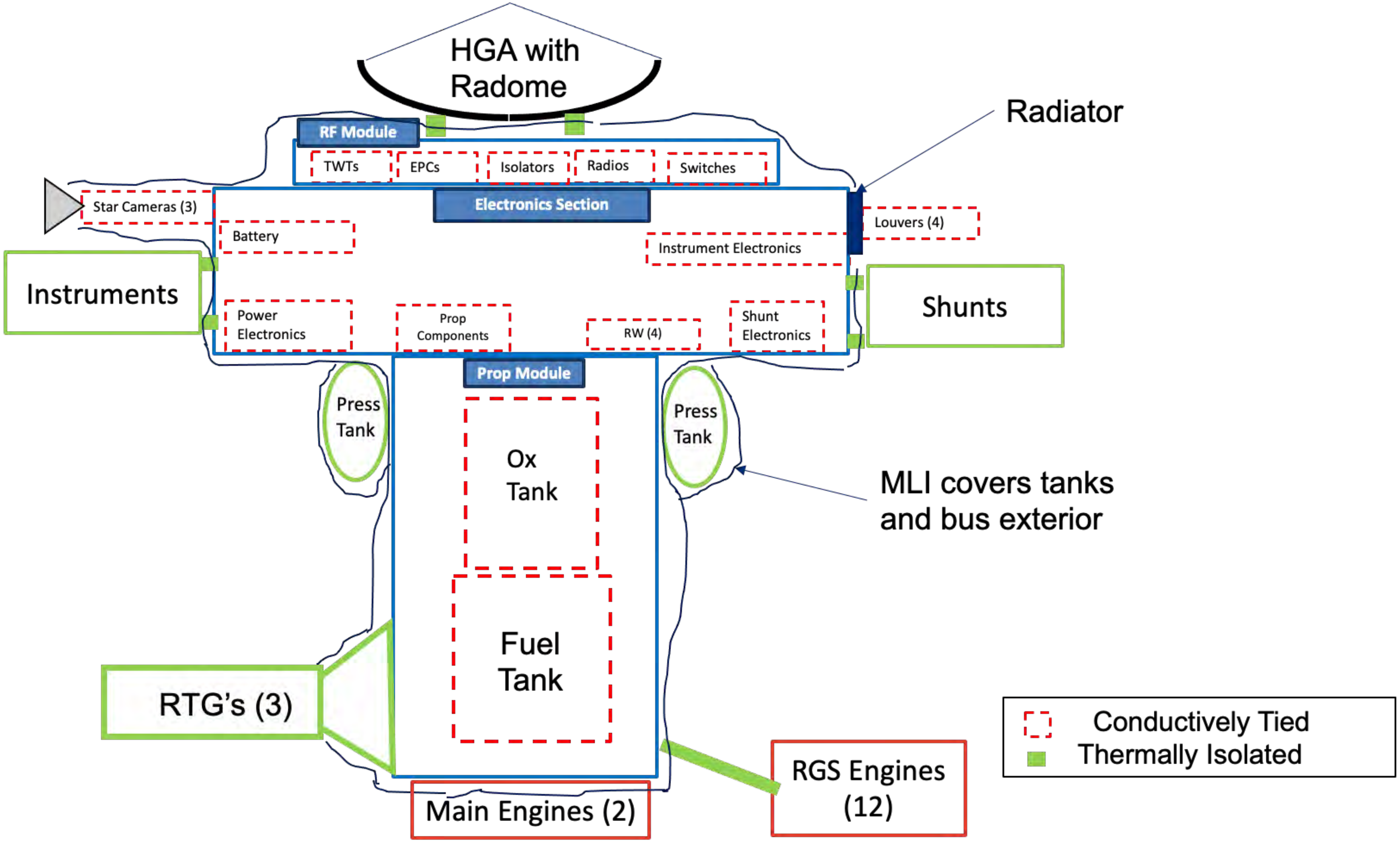
Thermal Assumption

- Temperature requirements:
  - Chemical Prop system: 10 to 50 C
  - Electronics boxes: -25 to 55 C
  - Star trackers: -30 to 60 C (prefer below 0 C. TEC turns on above 20 C)
  - Battery (TBD)
  - Anything else?

Thermal Design

- Using waste heat from RTG’s to heat prop tank via conduction through brackets.
- Radiators on S/C bus sides used to reject up to 320 W of internal heat.
- Louvers used to release excess heat during inner cruise and during Ka transmitter operations.
- Switched shunts inside bus and on prop tank possible to augment thermal control.
- Shunt plates are thermally isolated from S/C.
- Heat pipes required under TWT’s to spread high heat loads (42 W).

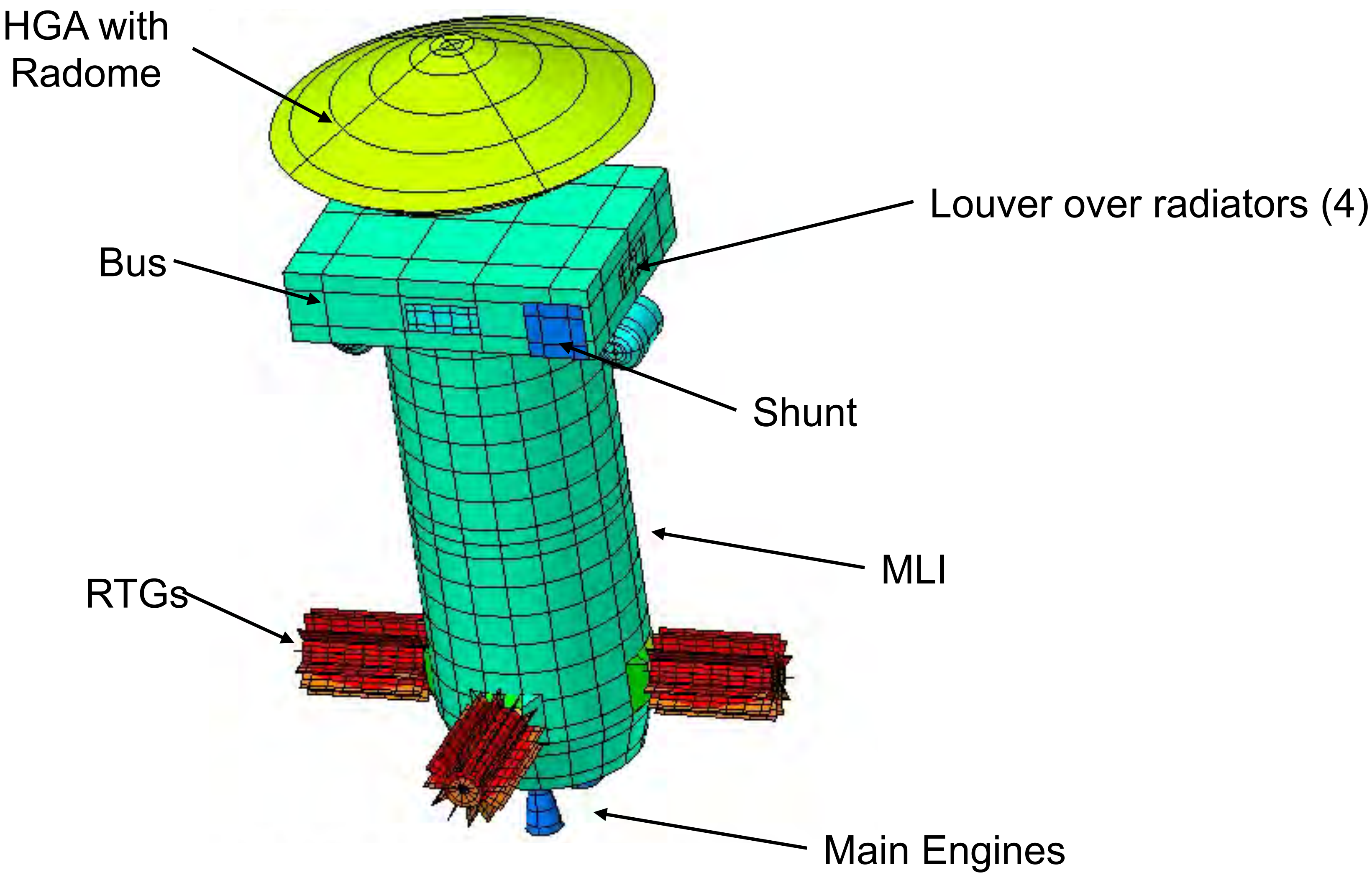
UOP Thermal Block Diagram



Thermal Design

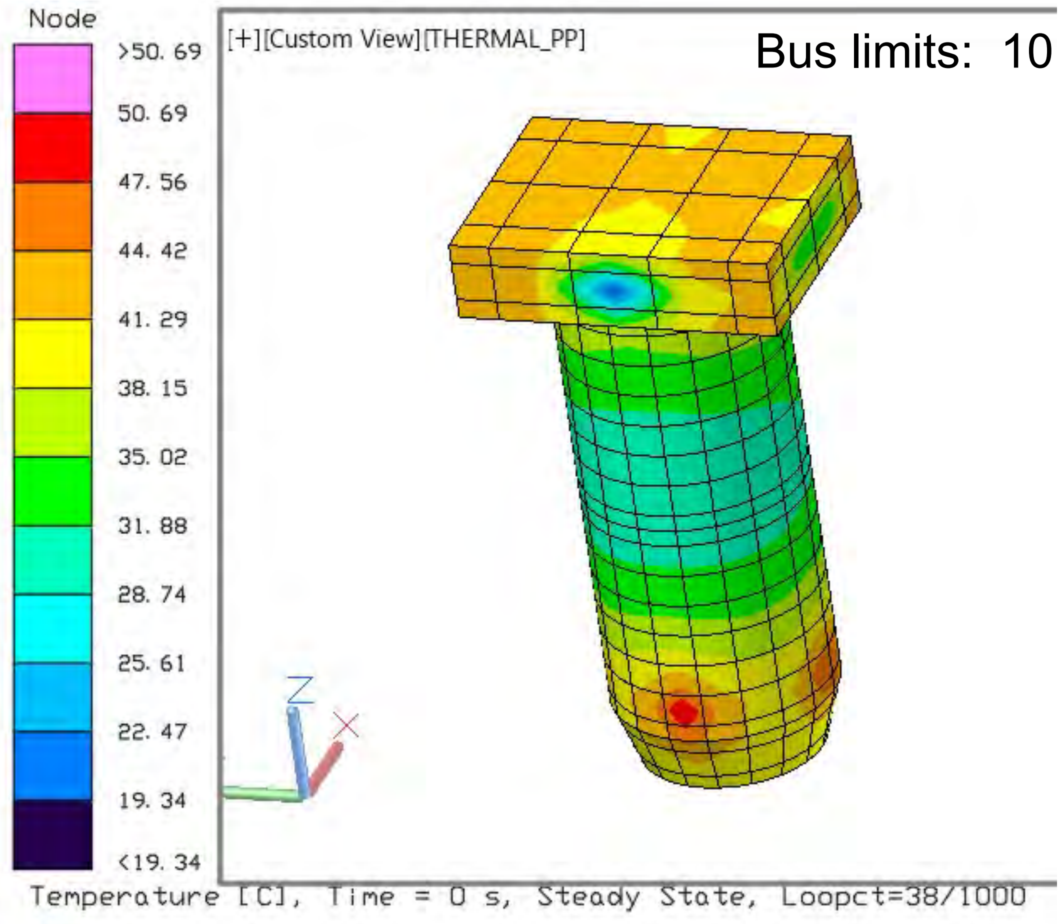
- Thermal blankets cover as much as possible to minimize heat leak to space.
- Three thermal modes are being investigated: Earth, 2AU, Tour

Thermal Design



Temperature Predictions: SC Bus

Near Earth, Commissioning, Hot



Bus limits: 10 to 50 C

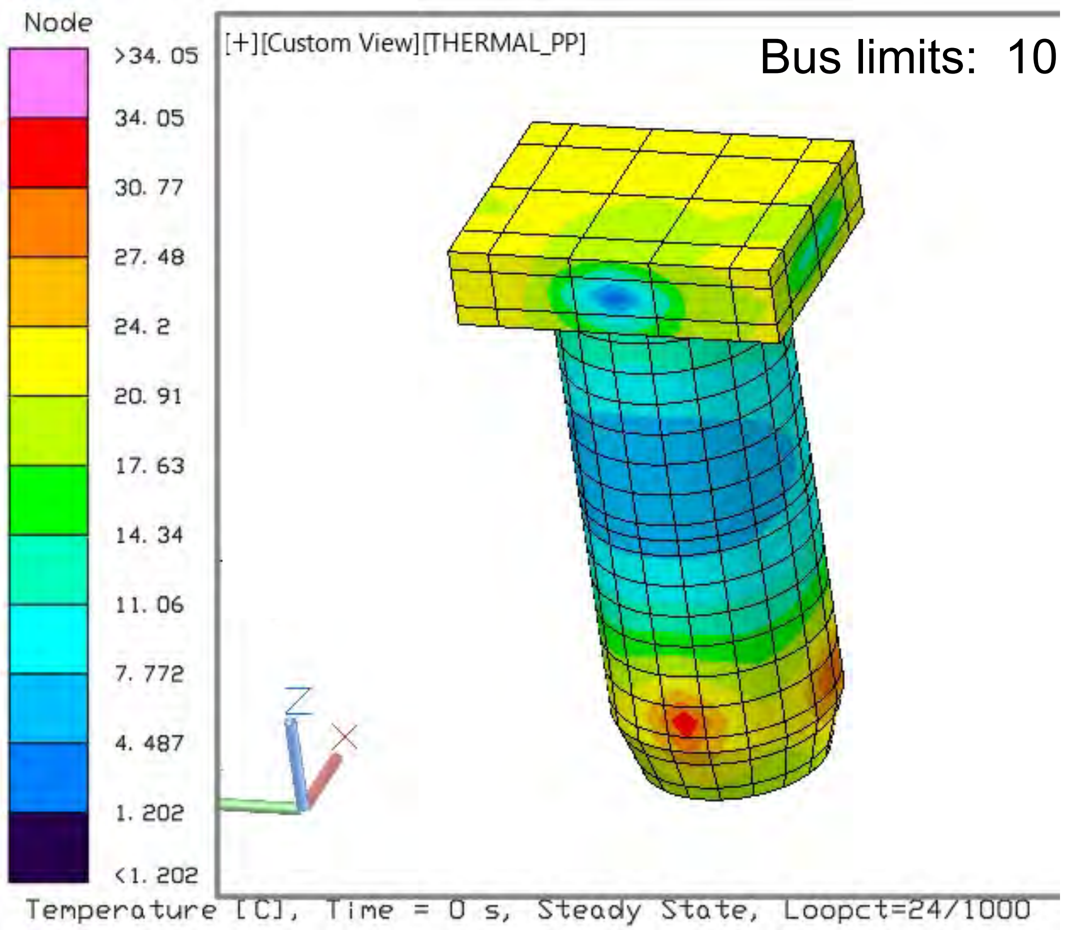
Model Parameters:

MLI e* = 0.015
Louver Open (e=0.75)
Radiator area 6.7 ft2 (blue area)
Bus heat = 310.5 W
Shunt heat = 16.5 W

Electronics within limits

Temperature Predictions: SC Bus

Near Earth, Commissioning, Cold



Bus limits: 10 to 50 C

Model Parameters:

MLI e* = 0.03

Louver Open (e=0.75)

Radiator area 6.7 ft2 (blue area)

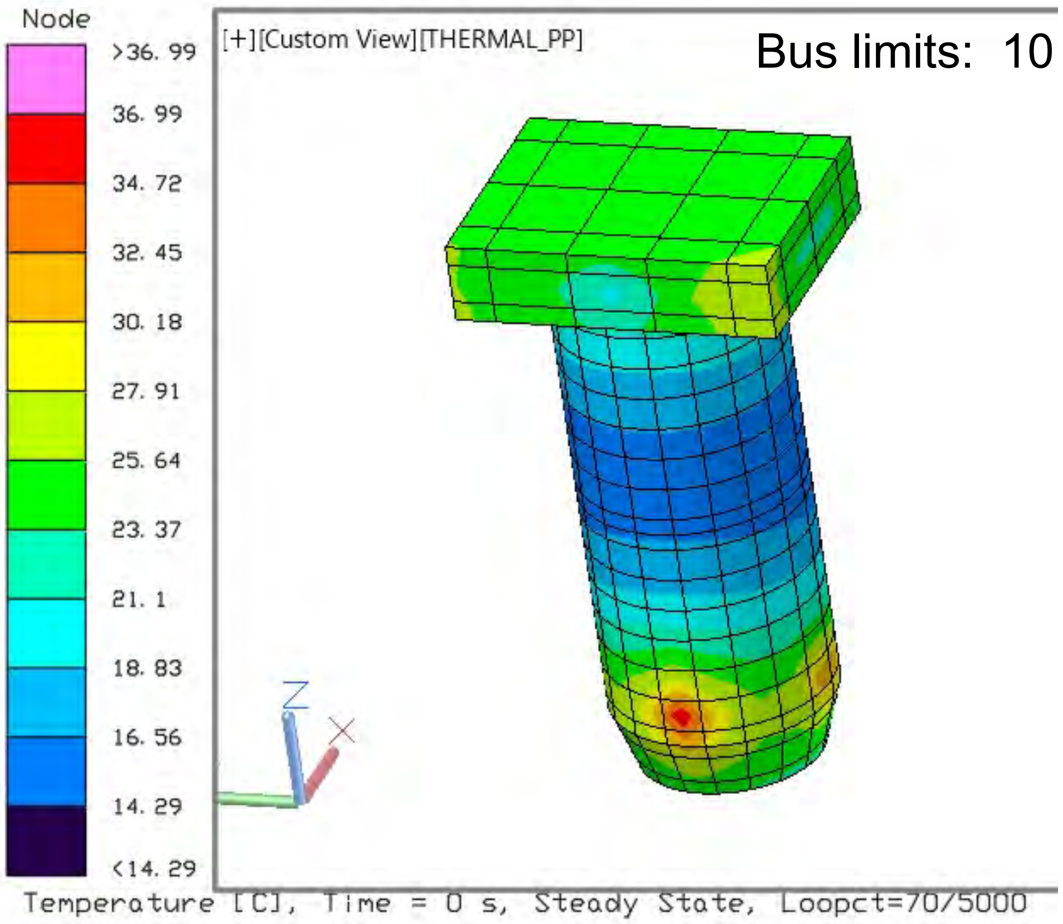
Bus heat = 310.5 W

Shunt heat = 16.5 W

Electronics within limits

Temperature Predictions: SC Bus

2AU Hibernation Cruise, Hot



Bus limits: 10 to 50 C

Model Parameters:

MLI e* = 0.015

Louver Closed (e=0.15)

Radiator area 6.7 ft2 (blue area)

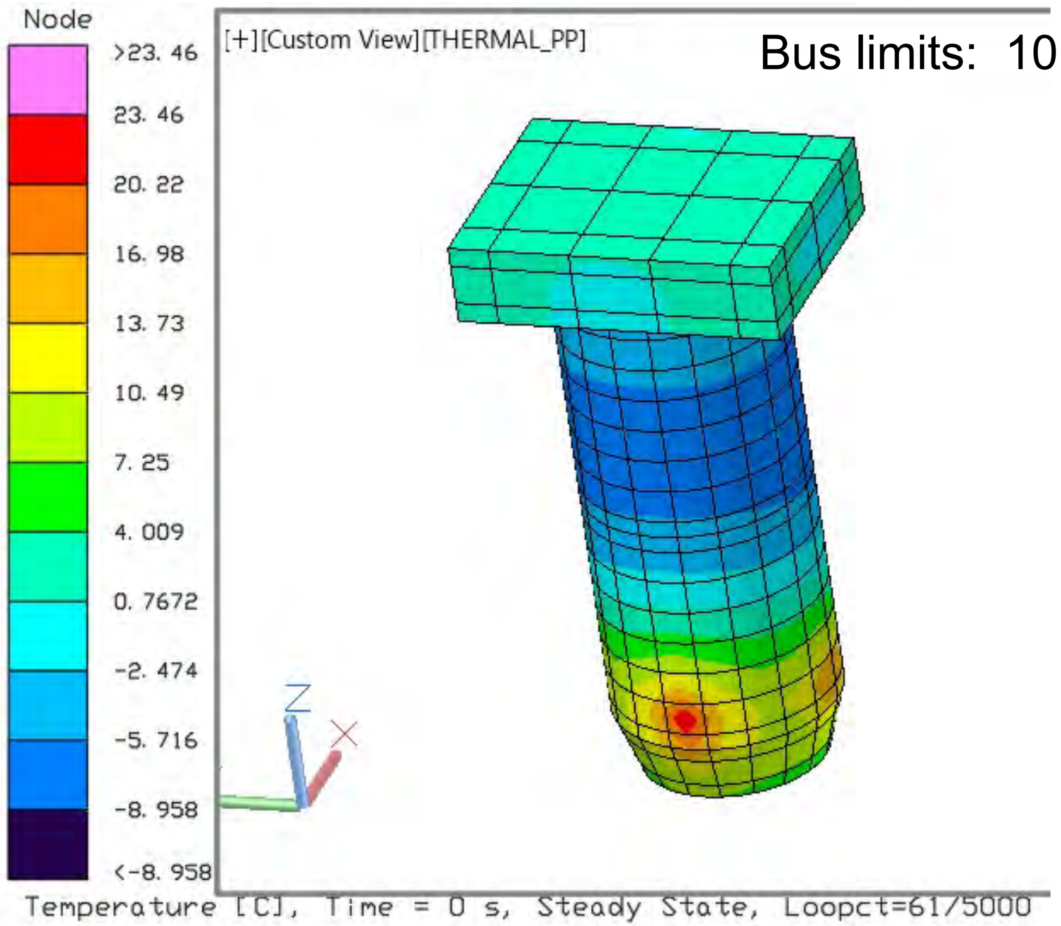
Bus heat = 171 W

Shunt heat = 221.9 W

Electronics within limits

Temperature Predictions: SC Bus

2AU Hibernation Cruise, Cold



Bus limits: 10 to 50 C

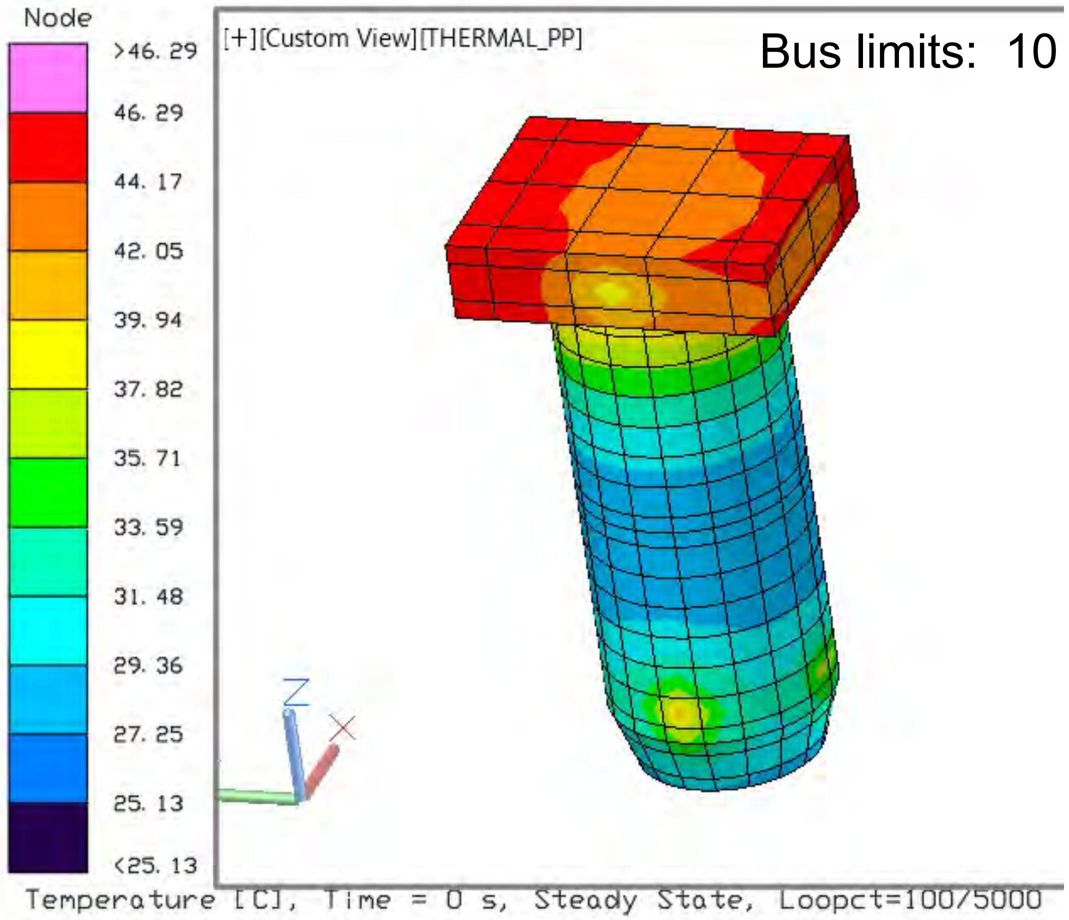
Model Parameters:

MLI e* = 0.03
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 157 W
Shunt heat = 198 W

Electronics a bit cold.
Might need heaters.
Heater power available.

Temperature Predictions: SC Bus

Near Uranus, Hot



Bus limits: 10 to 50 C

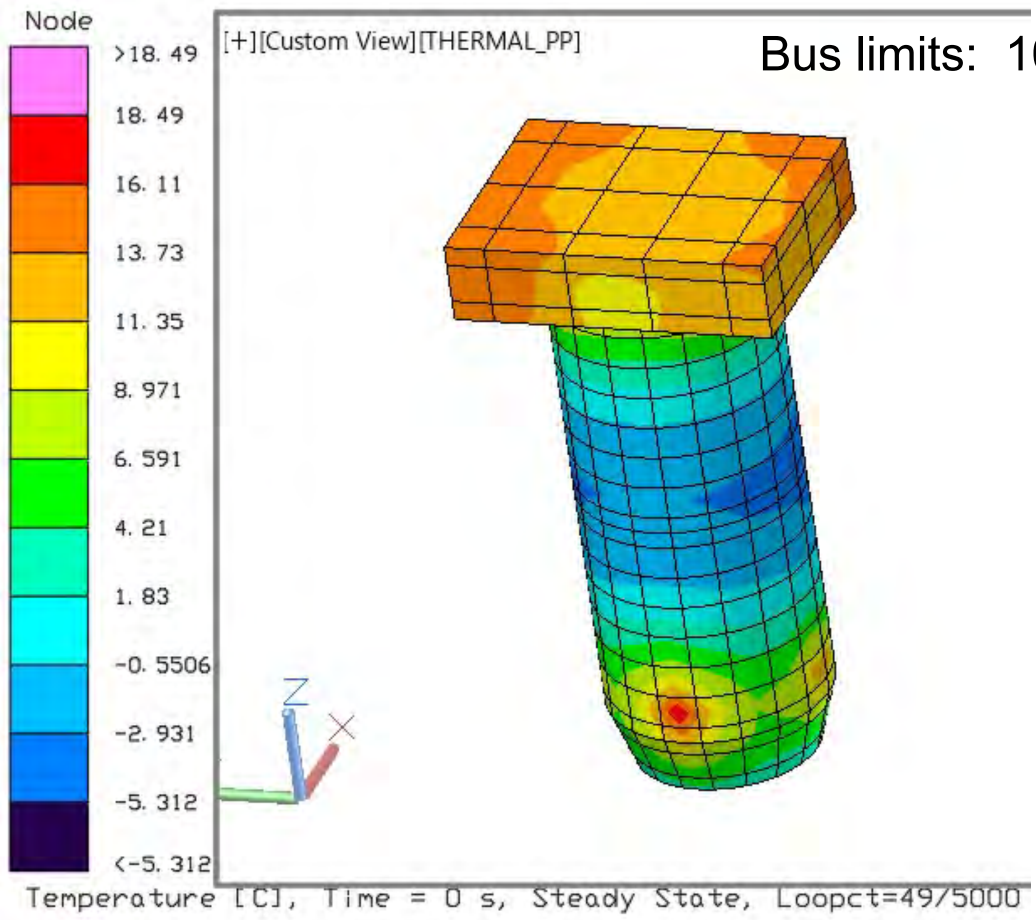
Model Parameters:

MLI e* = 0.015
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 263.7 W
Shunt heat = 0 W

Electronics within limits

Temperature Predictions: SC Bus

Near Uranus, Cold



Bus limits: 10 to 50 C

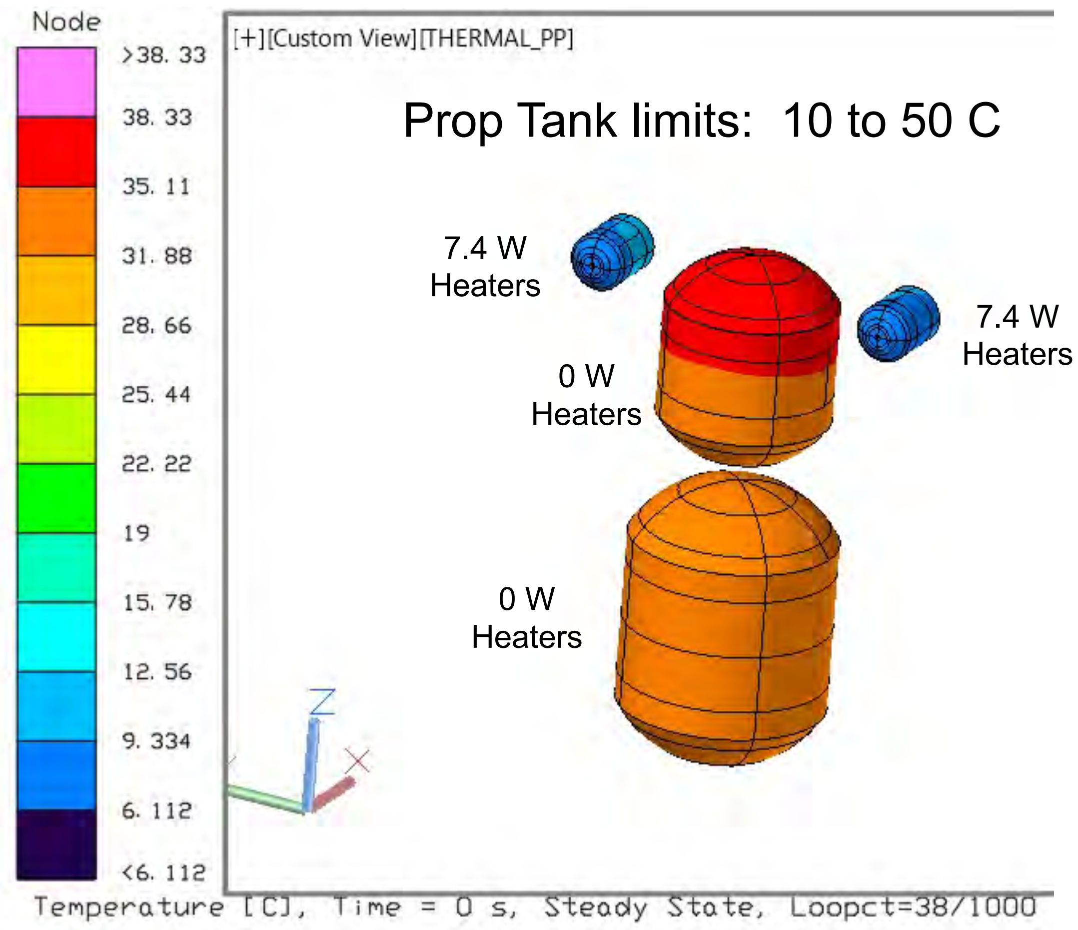
Model Parameters:

MLI e* = 0.03
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 263.7 W
Shunt heat = 0 W

Electronics within limits

Temperature Predictions: Tanks

Near Earth, Commissioning, Hot



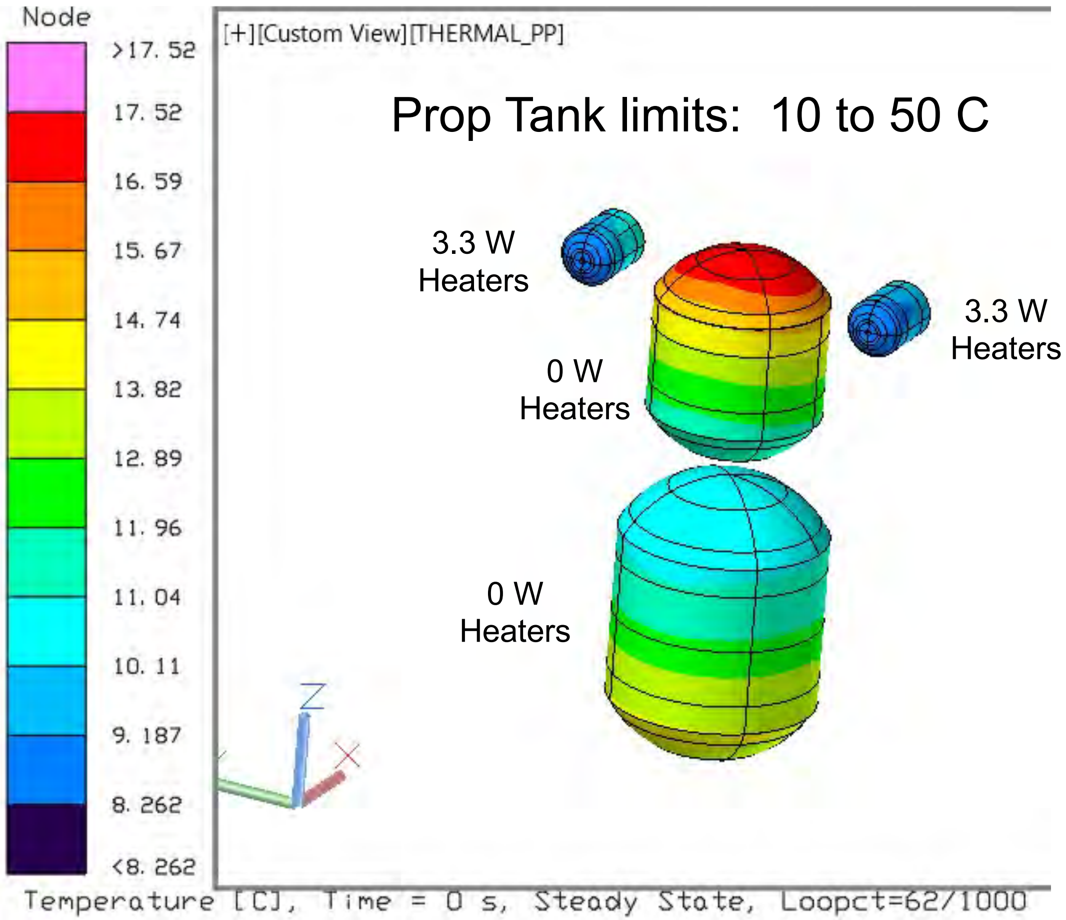
Model Parameters:

MLI e* = 0.015
Louver Open (e=0.75)
Radiator area 6.7 ft2 (blue area)
Bus heat = 310.5 W
Shunt heat = 16.5 W

Prop Tanks within limits
Pressurant tanks need heater power
(14.8 W Total)

Temperature Predictions: Tanks

Near Earth, Commissioning, Cold



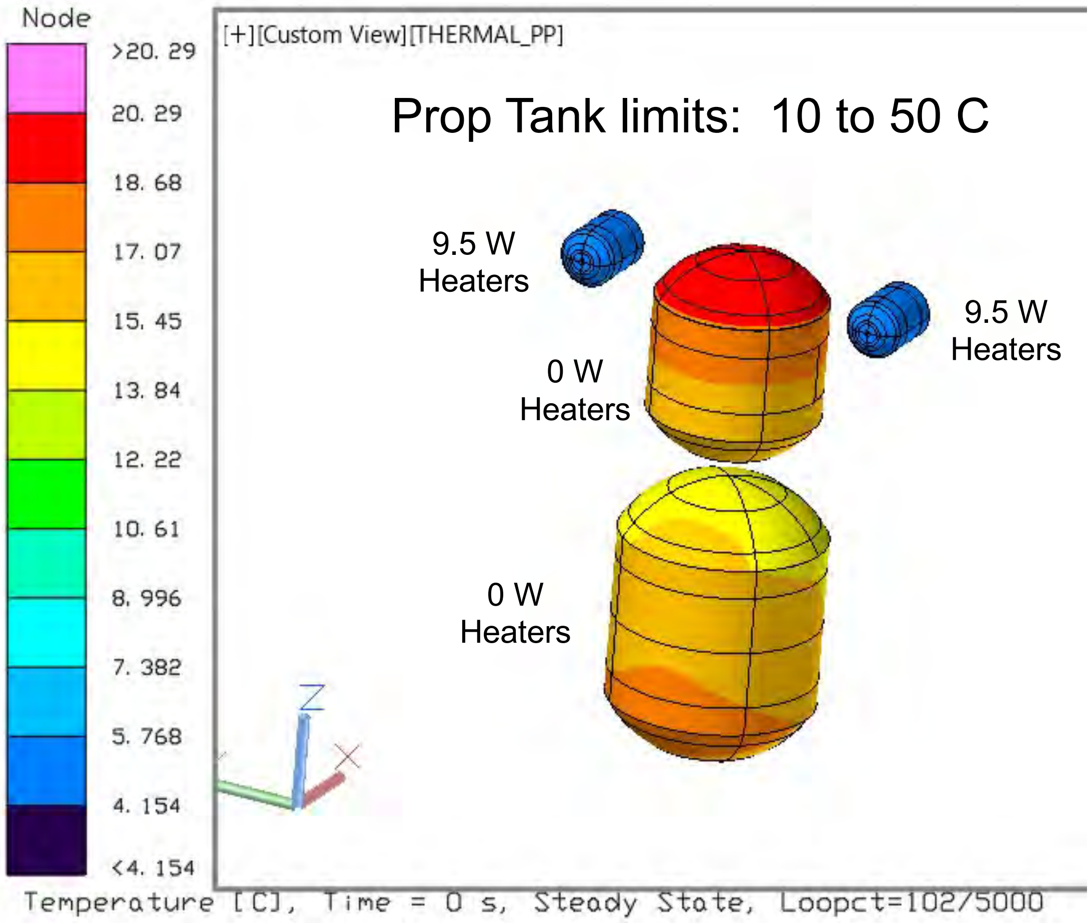
Model Parameters:

MLI e* = 0.03
Louver Open (e=0.75)
Radiator area 6.7 ft2 (blue area)
Bus heat = 310.5 W
Shunt heat = 16.5 W

Prop Tanks within limits
Pressurant tanks need heater power
(6.6 W Total)
(Less than hot case due to heat leak from bus)

Temperature Predictions: Tanks

2AU Hibernation Cruise, Hot



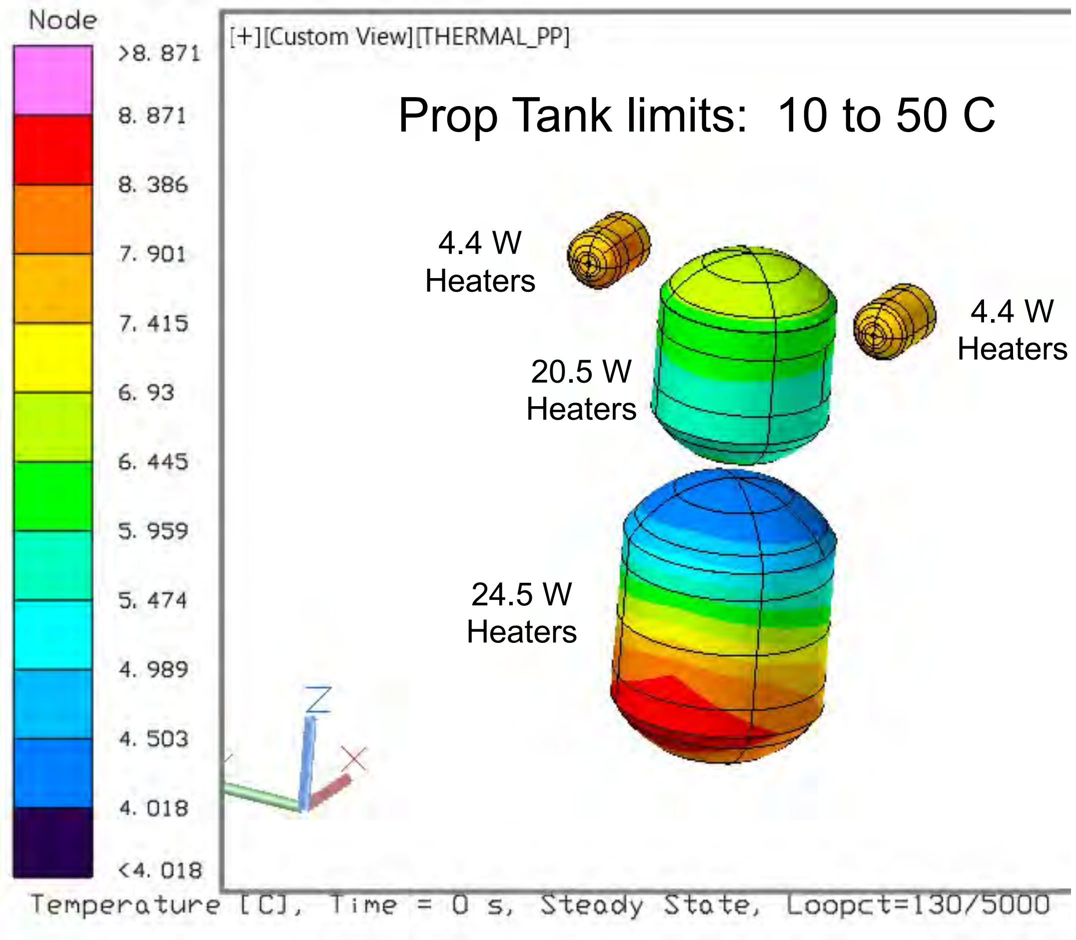
Model Parameters:

MLI e* = 0.015
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 171 W
Shunt heat = 221.9 W

Prop Tanks within limits
Pressurant tanks need heater power
(19.0 W Total)

Temperature Predictions: Tanks

2AU Hibernation Cruise, Cold



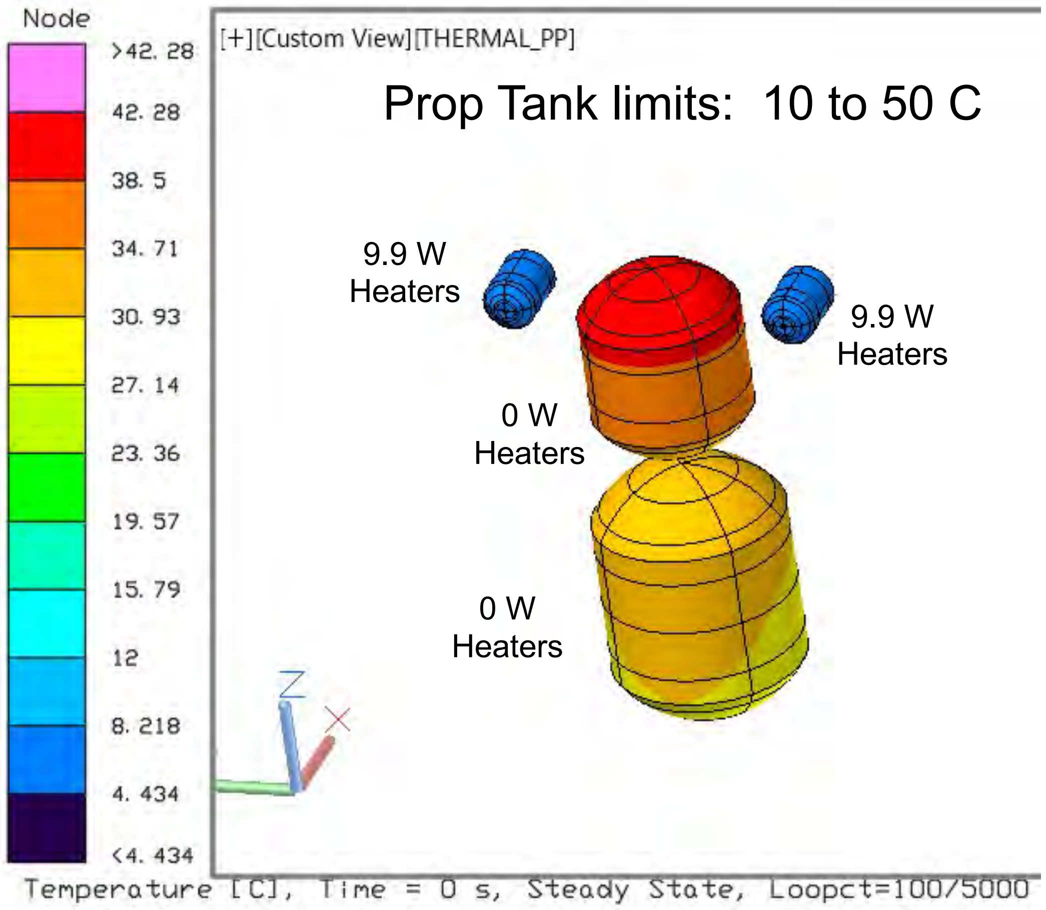
Model Parameters:

MLI e* = 0.03
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 157 W
Shunt heat = 198 W

Prop Tanks within limits
Prop and Pressurant tanks need heater power (53.8 W Total)

Temperature Predictions: Tanks

Near Uranus, Hot



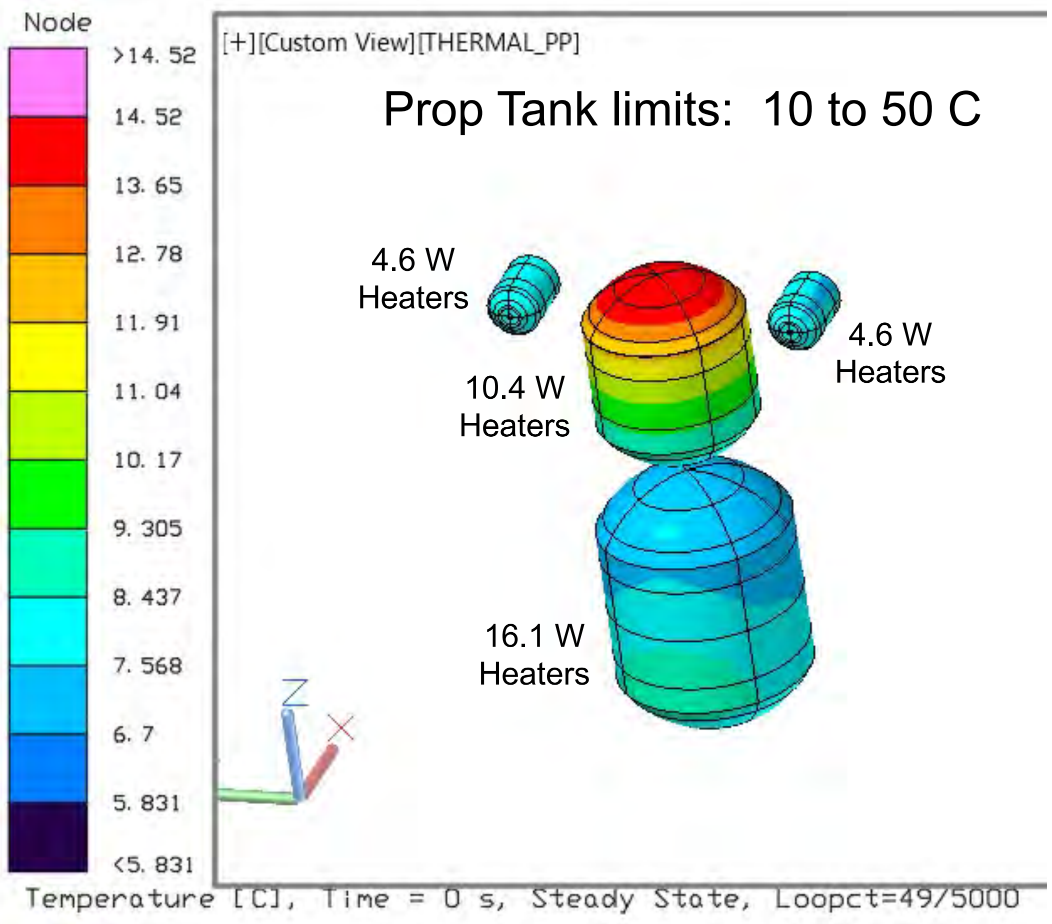
Model Parameters:

MLI e* = 0.015
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 263.7 W
Shunt heat = 0 W

Prop Tanks within limits
Pressurant tanks needs heater power (19.8 W Total)

Temperature Predictions: Tanks

Near Uranus, Cold



Model Parameters:

MLI e* = 0.03
Louver Closed (e=0.15)
Radiator area 6.7 ft2 (blue area)
Bus heat = 263.7 W
Shunt heat = 0 W

Prop Tanks within limits
Prop and Pressurant tanks need heater power (35.6 W Total)

Conclusion

- Conceptual design maintains hardware within limits with only minimal use of heater power.
- Investigate use of heat pipes in structure to spread RTG heat more to reduce heater power even more.
- Can add MLI enclosure around each pressurant tank to reduce heater power more.

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Uranus Orbiter ACE Run

Probe+Bus Harness

Jacklyn Perry
Vincent Bailey

Harness

- Composition:
  - Connector recommendations:
    - Crimp contacts for D-subminiature, micro-miniature, and M38999 circulars
  - Bundle shield only as required by radiation and EMI environments (limited use)
  - Wire
    - Mil 22759 Tefzel, MICA-Glass Insulated High Temp (RTG), Cheminax (LVDS)
    - SpaceWire (vendor fabricated), limited use
- Mass:
  - Estimate is derived from a percentage of the Probe and Orbiter Bus dry mass
  - Probe Mass
    - Dry mass X 7% = harness weight
      - Per MEL dry mass = 148 Kg
      - 148 Kg x 7% = 10.37 Kg
  - Orbiter Bus Mass
    - Dry mass X 7% = harness weight
      - Per MEL dry mass of bus plus payload = 1179 Kg
      - 1179 Kg x 7% = 91 Kg
  - Includes: connectors, wires, back shells, minimal shield, and installation hardware
  - Does not include: Instrument intra-harness, E-box intra-harness, and RF cabling

Harness Design Stages

- Phase B:
  - Schedule management
  - Requirements development
  - Early subsystem definition:
    - Top level block diagram
    - Identify flight parts and materials
    - Initial detailed design
  - Creo computer aided design of harness routing:
    - Routing paths (i.e. clearance, field joints, bundle size, etc.)
    - Wire lengths
    - Connector and backshell clearances
    - Mass input
- Phase C:
  - Schedule management
  - Development and certification of Fabrication Fixture (available to instrument teams for fit checks)
  - Spacecraft harness assembly and test
  - Harness bake out
  - Delivery and installation onto structure
  - Requirements verification/closure

Harness Labor and Cost

- Labor Phase B: Total 28 SM
  - Lead, Harness Designer, and Mechanical Router
    - Probe and Orbiter Bus are akin to two spacecraft and therefore will require two designs and sets of drawings
- Labor Phase C: Total 180 SM
  - Lead, Harness Designer (x2), Mechanical Router (x2), Manufacturing Lead, and Technicians (x3)
    - Probe and Orbiter Bus are akin to two spacecraft
- I&T Support: Total 18 SM
  - Lead, Designer, and Technician
- Parts and Materials (based off of Parker Solar Probe x2):
  - Flight parts ~ $700K
  - Materials and bake-out ~ $100K

Uranus Orbiter and Probe

Radiation

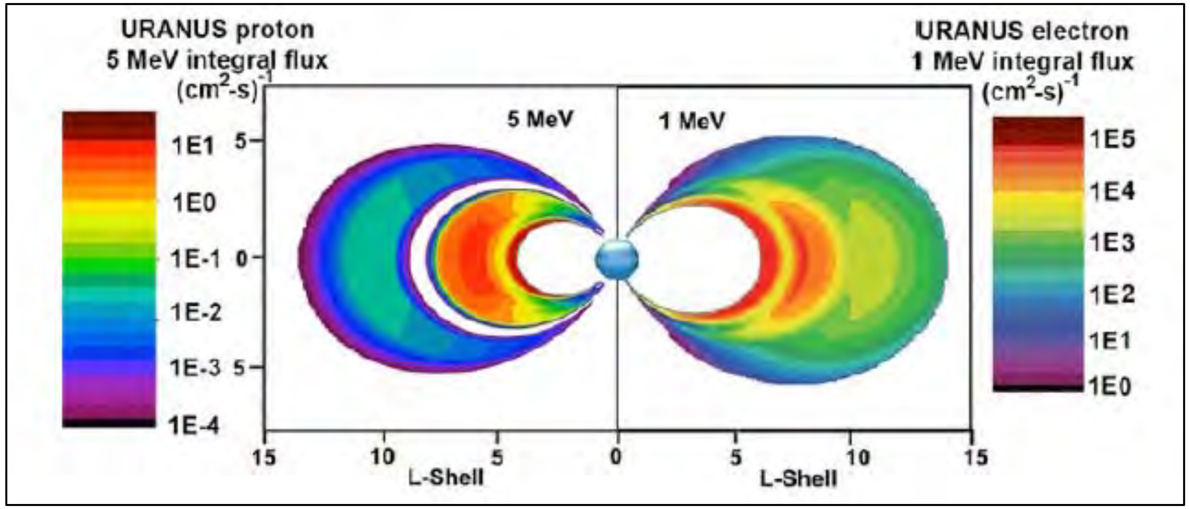
Michelle Donegan

Radiation – Summary

- Environment for cumulative dose (Total Ionizing Dose, TID) [RDMx2] :
  - RPS: Similar to NH RPS, ~15 krad (Si) except very close to RPS
  - Cruise: solar protons only, ~16 krad (Si) behind 100 mils Al
  - Jupiter flyby ~6 R_J: trapped protons and electrons, ~95 krad (Si) behind 100 mils Al
  - Uranus / moon tour: very roughly, ~30krad(Si)/year behind 100 mils Al (120 krad for 4-year tour)
- TID estimate **~250 krad (Si) (behind 100 mils Al, RDMx2)** for UOP
  - Transport analysis can likely take credit for > 100 mils equivalent Al shielding in design
  - **100 krad part hardness requirement achievable** given the ~6 R_J Jupiter flyby
    - Would require **~240 mil Al equivalent shielding**
    - Possible exceptions very close to RPS
- TNID and Single Event Effects (SEE) expected in-family with other Jovian/long-duration missions
  - Consideration required for detectors that need to operate during Jupiter flyby (e.g. star trackers)
- Detector noise and charging at Uranus expected in-family with Earth-orbiting missions
- Refine Uranus environment definitions in Phase A
  - Environment at Uranus is major source of uncertainty for radiation for this mission

Radiation – Supporting Material

- RPS: Assume 3 units, similar to New Horizons, new/refueled units
- Solar protons: ESP-PSYCHIC, 95% confidence, scale 1/r outward with distance from Sun
- Jupiter flyby: fairly well modeled (GIRE3/Grid3p) (much refined model vs. New Horizons era)
- Uranus / moon flybys: trapped electrons; only engineering model is JPL UMOD; Voyager 2 data only
  - Figure shows UMOD output for 5 MeV proton and 1 MeV electron integral fluxes
  - JPL Pub 2015-11 estimates 100 rad(Si) behind 100 mils Al (RDMx1) for Voyager 2 Uranus flyby @ ~4 R_U
  - Estimate ~90 krad(Si) from 3-year tour, but highly uncertain



I. Jun, H. B. Garrett and R. W. Evans, *IEEE Trans. Plasma Sci.*, vol. 47, no. 8, pp. 3923-3930, Aug. 2019.

Radiation – Drivers

- RPS: # of units
- Solar protons: time in inner solar system (most of dose accumulated before Earth flyby)
- Earth flyby: not included in current estimate, expect ~1 krad
- Jupiter flyby: closest approach to Jupiter and time inside 10 R_J
  - Compare to IVO proposal (~40 krad/flyby at much higher inclination)
- Uranus / moon flybys: poorly constrained
  - Length of tour and time spent in belts will matter (3 year tour assumed here)
  - Will need model such as UMOD to somewhat better estimate
  - No data to feed model inside ~4 R_U
  - Will remain significant source of uncertainty

Uranus Orbiter ACE Run

Flight Software

T. Adrian Hill

Executive Summary – Software Cost

- Software Cost Estimate: **687.85 SM**
  - Flight Software: **428.85 SM**
  - Autonomy Development: **130.00 SM**
  - Testbed Software: **120.00 SM**

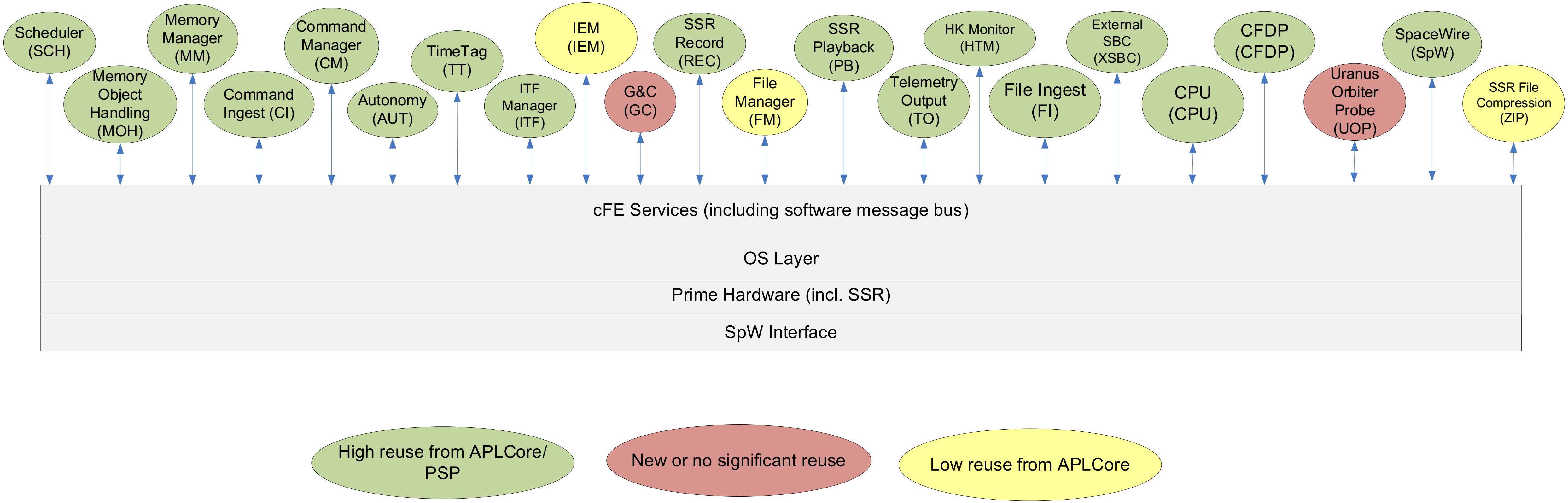
- *Does not cover Ground Software Development Costs*
  - *These costs were submitted separately by the ground data system lead*

Flight Software Cost Breakdown

- Total Flight Software Cost: 428.85 SM
  - Probe
    - FSW Lead: 65.50 SM
    - C&DH Team: 116.70 SM
    - GNC Integration Team: 81.95 SM
    - Independent Acceptance Test (IAT): 114.70 SM
  - Probe
    - Total SW Development and Test: 50.00 SM

- Basis of Estimate:
  - Probe
    - Re-use of APL FSWSystem codebase (cFE, RTEMS, etc)
    - CORESAT SBC (UT700 @ 100MHz, 256MB RAM, SpaceWire interface to SCIF)
    - Compression of recorded telemetry and science data offline (RBSP model), *but not* real-time telemetry
    - Instrument data rates to FSW and SSR are comparable to PSP
  - Orbiter
    - Assume a simple centralized DPU (similar to MESSENGER) to handle sensor interfaces and communications relay

Flight Software "Lollipop Diagram"



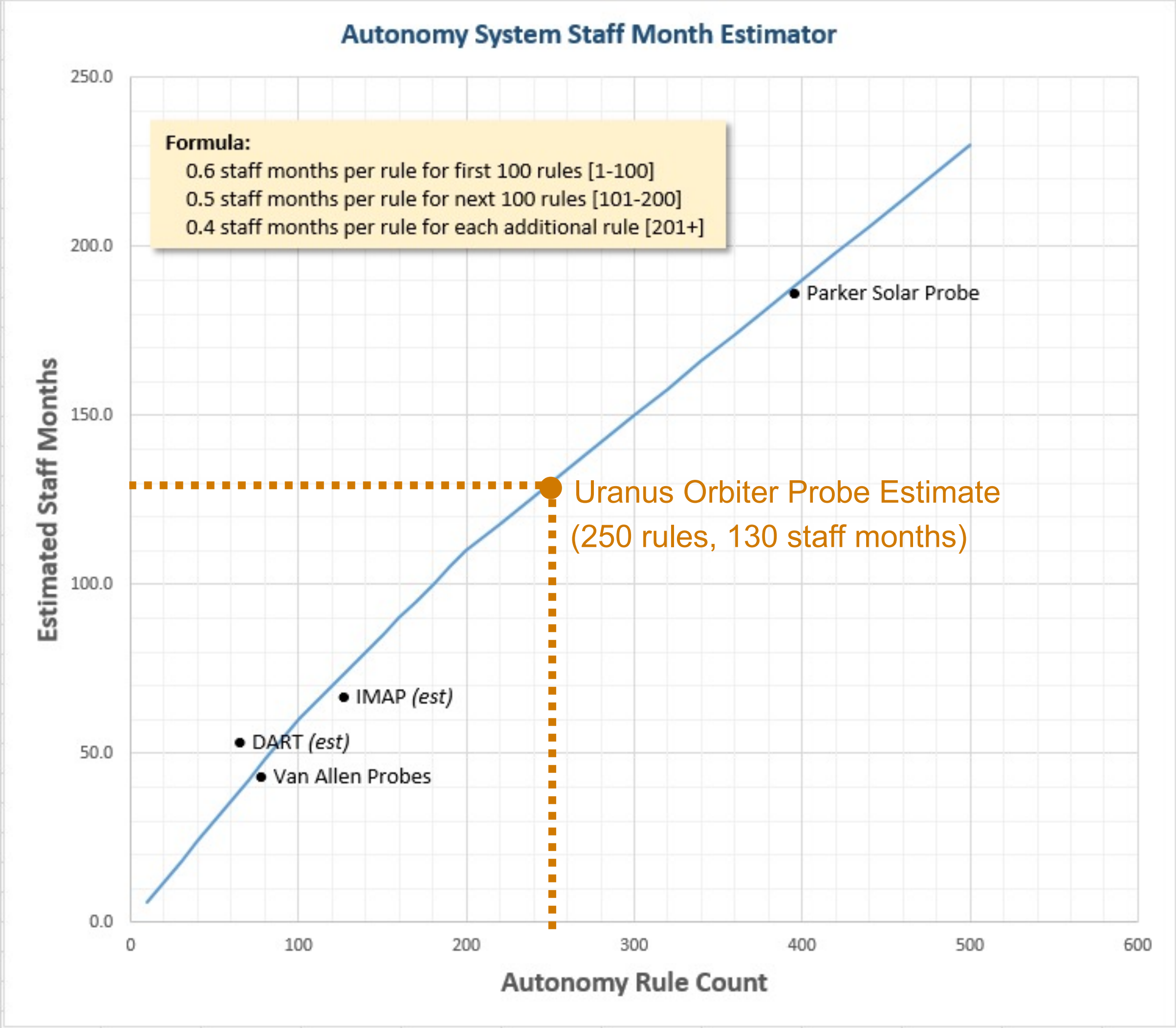
Flight Software

- FSW can re-use significant code from past missions for standard C&DH functions and interfaces, reducing cost and schedule
  - This is helped greatly by re-used avionics hardware designs, to reduce FSW changes
- CPU utilization estimate is 55% used *(45% free)* on UT700 CORESAT SBC
  - Assumptions:
    - 50 Hz GNC Control Loop
    - 20 kbps peak downlink rate
    - 250 Autonomy Rules
  - QMS guideline is >50% free pre-PDR. Currently YELLOW.

Program Phase	Total Margin (GREEN)	Total Margin (YELLOW)	Total Margin (RED)
Up to PDR	> 50%	40-50%	< 40%
CDR	> 35 %	25-35%	< 25%
Delivery to I&T	> 25 %	15-25 %	< 15%
PER to launch	> 10 %	5-10 %	< 5%

Autonomy

- Total Autonomy Cost: 130 SM
  - Covers complete development and test
- Basis of Estimate
  - Assumes 250 Autonomy Rules which would be in family for a redundant spacecraft with moderate complexity
  - SIE uses model (to the right →) to estimate Autonomy costs as a function of number of Autonomy Rules with demonstrated correlation to previous missions



Testbed Software

- Estimate taken from IVO proposal
  - Did not have time to perform a more in depth analysis

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Uranus Orbiter ACE Run

Ground Data Systems

Alice Berman
Patrick McCauley

Ground Data System: Assumptions

1. GSW will be based on the "Mission Independent Ground Software" MIGS.
2. The core command and telemetry system will be L3 Harris InControl. Costs would increase if a new COTS/GOTS was integrated.
3. I&T and Mission Operations at JHU/APL
4. Science Operations Center at JHU/APL
5. PSP-like CFDP uplink/downlink
6. SEQGEN style planning based on Dragonfly, with Planning & Scheduling software like SciBox
7. Critical optical navigation processing in the MOC is required.
8. High fidelity power model [from Power subsystem] is needed for constraint checking (Model integration costed, not model development)
9. The BOE does not include labor for testbed software.

Uranus Orbiter and Probe

Mission Cost Estimate

Kathy Kha

Introduction

- The cost estimate prepared for the UOP mission is of CML 4
- The payload and spacecraft estimates capture the resources required for a preferred point design and take into account subsystem level mass, power, and risk
- Estimates for Science, Mission Operations and Ground Data System elements whose costs are primarily determined by labor take into account the Phase A–D schedule and Phase E timeline
- The UOP Phase A–F mission cost, including unencumbered reserves of 50% (A–D) and 25% (E–F), is $2.8B in fiscal year 2025 dollars (FY$25)
- Excluding all LV related costs, the UOP Phase A-F mission cost is $2.6B FY$25

Ground Rules and Assumptions

- Estimating ground rules and assumptions are derived from the "Decadal Mission Study Ground Rules" dated February 2021
- Mission costs are reported using the level-2 (and level-3 where appropriate) work breakdown structure (WBS) provided in NPR 7120.5E.
- The mission does not require Technology Development dollars to advance components to TRL 6 as all UOP mission components will be at or above TRL 6 when required.

Mission Phases A-F Estimate

WBS		Ph A-D	Ph E-F	Total	Notes
		Uranus Orbiter & Probe Cost Estimate			
		Cost in FY25$K			
	Phase A	$ 7,628	$ -	$ 7,628	Assumption based on previous studies
1	PM	$ 162,077	$ -	$ 162,077	A-D: Wrap factor based recent NFs and APL missions E-F: Bookkept with WBS 7
2	SE				
3	MA				
4	Science	$ 27,192	$ 223,668	$ 250,860	Average $13.3M per year during Phase E
5	Payload	$ 180,247	$ -	$ 180,247	Hardware estimated via parametric models (NICM, SEER Space)
6	SC	$ 724,234	$ -	$ 724,234	Estimated via parametric models
7	MOps	$ 41,121	$ 299,053	$ 340,174	Ph E: DSN $21.3M, Average Ph E MOps based on APL historical costs
8	LV	$ 236,000	$ -	$ 236,000	Falcon Heavy Expendable ($210M) + $26M NEPA
9	Ground	$ 18,573	$ 19,313	$ 37,886	BOE
10	I&T	$ 114,869	$ -	$ 114,869	Based on APL historical I&T %, includes testbeds
	Reserves	$ 634,157	$ 135,508	$ 769,665	Per Decadal guidelines: 50% A-D, 25% E-F. LV excluded
	Total	$ 2,146,097	$ 677,542	$ 2,823,640	
	Total w/o LV	$ 1,910,097	$ 677,542	$ 2,587,640	

- Cost estimates are reported in Fiscal Year 2025 (FY25) dollars
- The NASA New Start inflation index was used to adjust to FY25 dollars
- Major cost drivers: spacecraft complexity, long mission duration, RTG

Payload

	Uranus Orbiter & Probe Cost Estimate	
	Cost in FY25$K	**Notes**
Payload	**$ 180,247**	Hardware estimated via parametric models (NICM, SEER Space)
Payload Mgmt	**$ 13,660**	Based on VAP, NH, MESSENGER, PSP
Orbiter Payload	**$ 140,501**	
Magnetometer	$ 4,781	
Narrow angle framing camera	$ 27,283	
Thermal IR camera	$ 38,242	
Fields & particles package	$ 29,803	
Plasma 1/ Electrons	*$ 8,357*	
Plasma 2/ Ions	*$ 7,106*	
Plasma 3/ Energetic Particles	*$ 10,147*	
Waves	*$ 4,194*	
Radio science/ USO	$ -	USO carried under orbiter comms costs
Vis/NIR imaging spec + WAC	$ 40,393	
Probe Payload	**$ 26,087**	
Mass spectrometer	$ 18,661	
Atmospheric Structure instrument	$ 4,153	
UltraStable Oscillator (USO)	$ -	USO carried under probe RF costs
Hydrogen ortho-para sensor	$ 3,274	

- Payload management based on average of APL historical costs estimated as a percentage of payload hardware (VAP, NH, MESSENGER, and PSP)
- Each instrument is estimated as an average of two parametric models (SEER Space and NICM)
  - Analog instrument costs are not used in the estimate due to the unique mission characteristics of UOP compared to heritage. Costs were used for crosscheck purposes only.

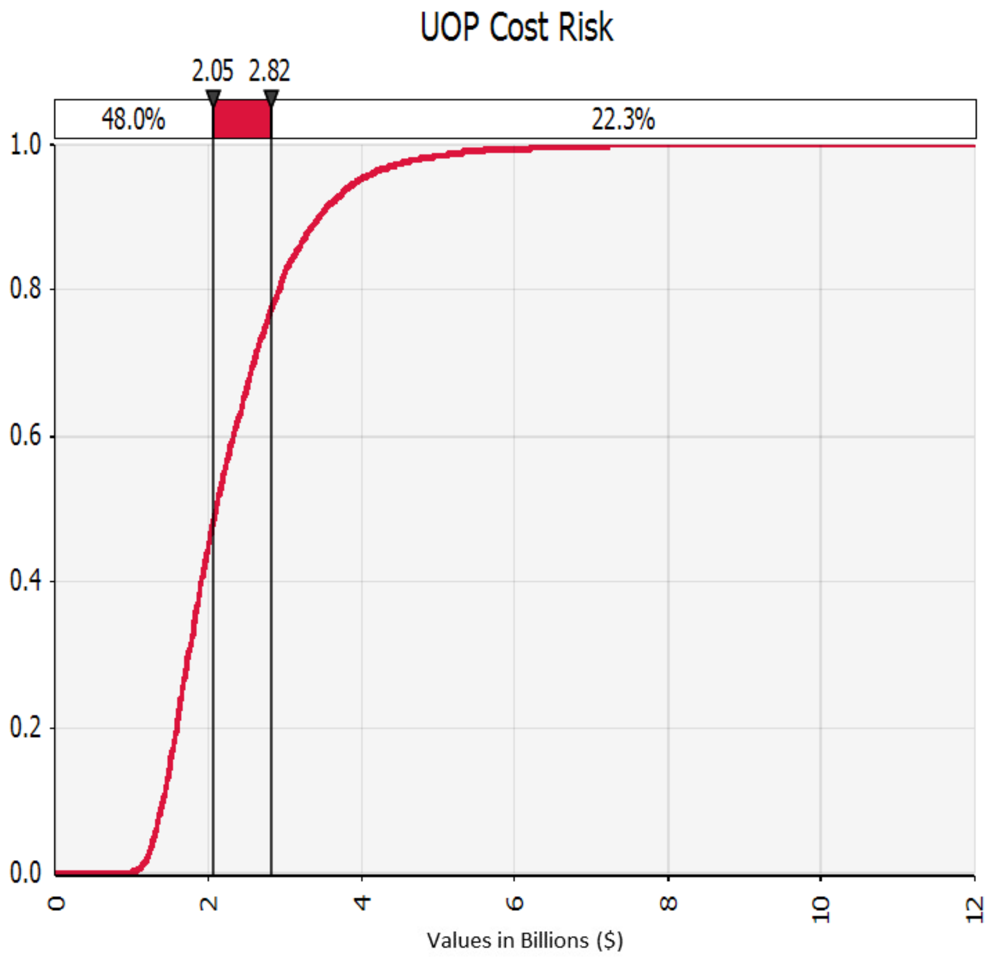
Spacecraft

	Uranus Orbiter & Probe Cost Estimate	
	Cost in FY25$K	Notes
SC	**$ 724,234**	Estimated via parametric models
Orbiter	**$ 445,873**	3 NextGen RTGs ($70M, $25M*2), SEER Space (prop and SW via ROM)
Probe	**$ 233,141**	SEER Space (FSW via ROM)
EDL/ Aeroshell	**$ 45,219**	Price TruePlanning estimate

- The SC is compromised of the Orbiter, Probe and EDL/Aeroshell.
  - Estimates for Orbiter, Probe and EDL/Aeroshell hardware are via parametric model, with the exception of propulsion that is estimated via an APL ROM
  - FSW estimate is an APL ROM
- SC PM/SE/MA carried in WBS 1-3
- The $120M RTG costs are added to the Orbiter costs

Risk Analysis

- Cost risk analysis demonstrates 77.7% confidence in baseline mission cost with reserves
- This confidence level is expected and reasonable for a pre-Phase A concept with this level of reserves



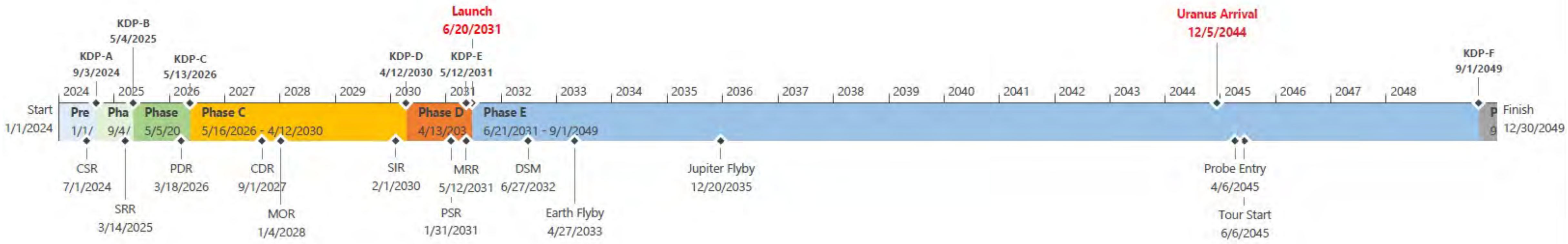
Johns Hopkins
Applied Physics Laboratory

Uranus Orbiter and Probe

Schedule

Faith Kahler

Uranus/Probe Top Level Milestones and Phases

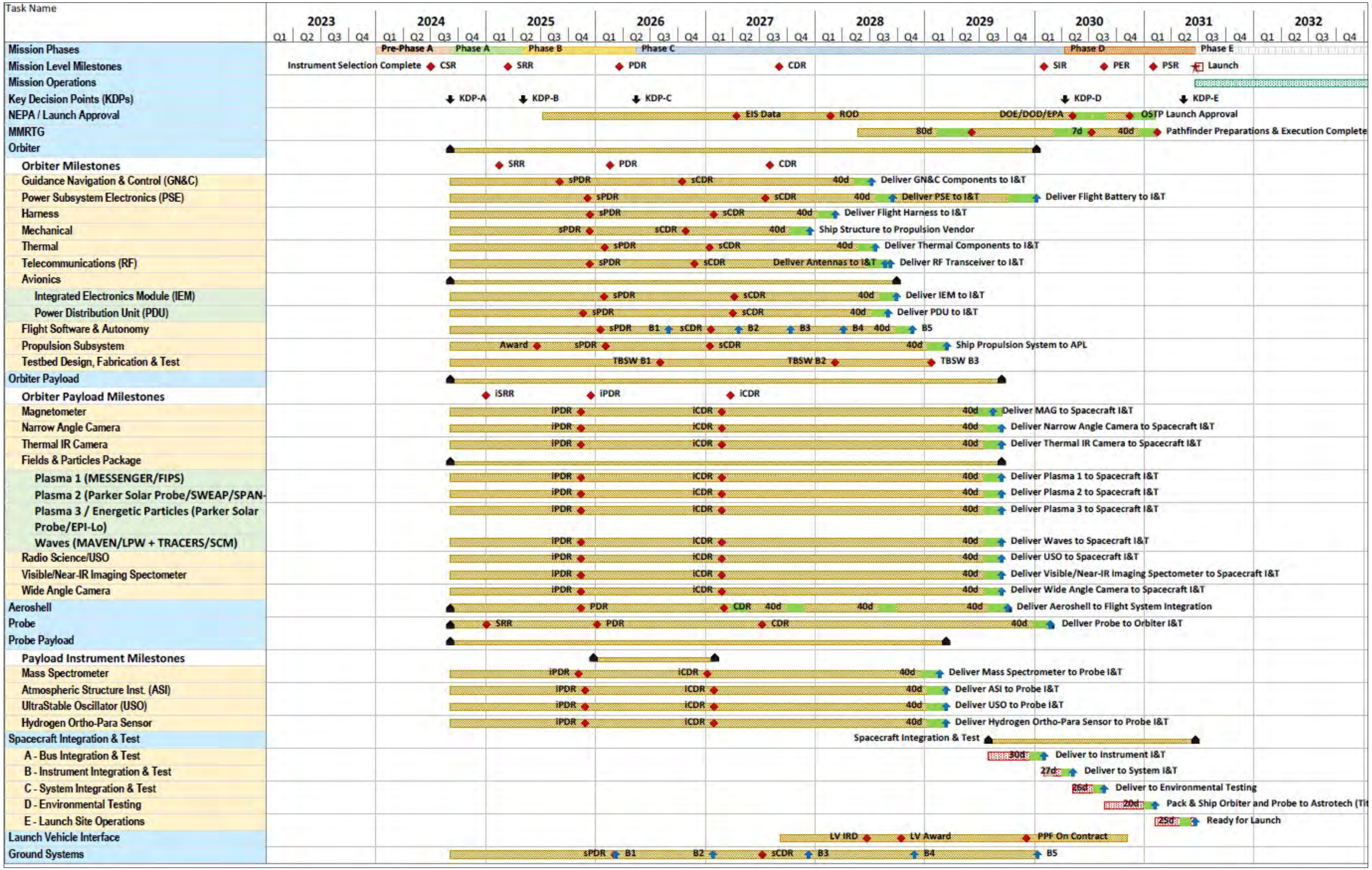


Task Name	Start	Finish
Mission Phases		
Pre-Phase A (Concept Study)	1/1/2024	9/3/2024
Phase A	9/4/2024	5/4/2025
Phase B	5/5/2025	5/15/2026
Phase C	5/16/2026	4/12/2030
Phase D	4/13/2030	6/20/2031
Phase E	6/21/2031	9/1/2049
Phase F	9/2/2049	12/30/2049
End of Mission	12/30/2049	12/30/2049

Task Name	Start	Finish
Mission Milestones		
NASA Instrument Competion/Selection Completed	6/30/2024	6/30/2024
CSR	7/1/2024	7/1/2024
Start	9/4/2024	9/4/2024
SRR	3/14/2025	3/14/2025
PDR	3/18/2026	3/20/2026
IBR	11/5/2026	11/5/2026
CDR	9/1/2027	9/3/2027
MOR	1/4/2028	1/6/2028
SIR	2/1/2030	2/1/2030
ORR	5/28/2030	5/28/2030
PER	8/20/2030	8/20/2030
PSR	1/31/2031	1/31/2031
MRR	5/12/2031	5/12/2031
SMSR	6/11/2031	6/11/2031
LRR	6/14/2031	6/14/2031
Launch	6/20/2031	6/20/2031
Launch	6/23/2031	7/14/2031

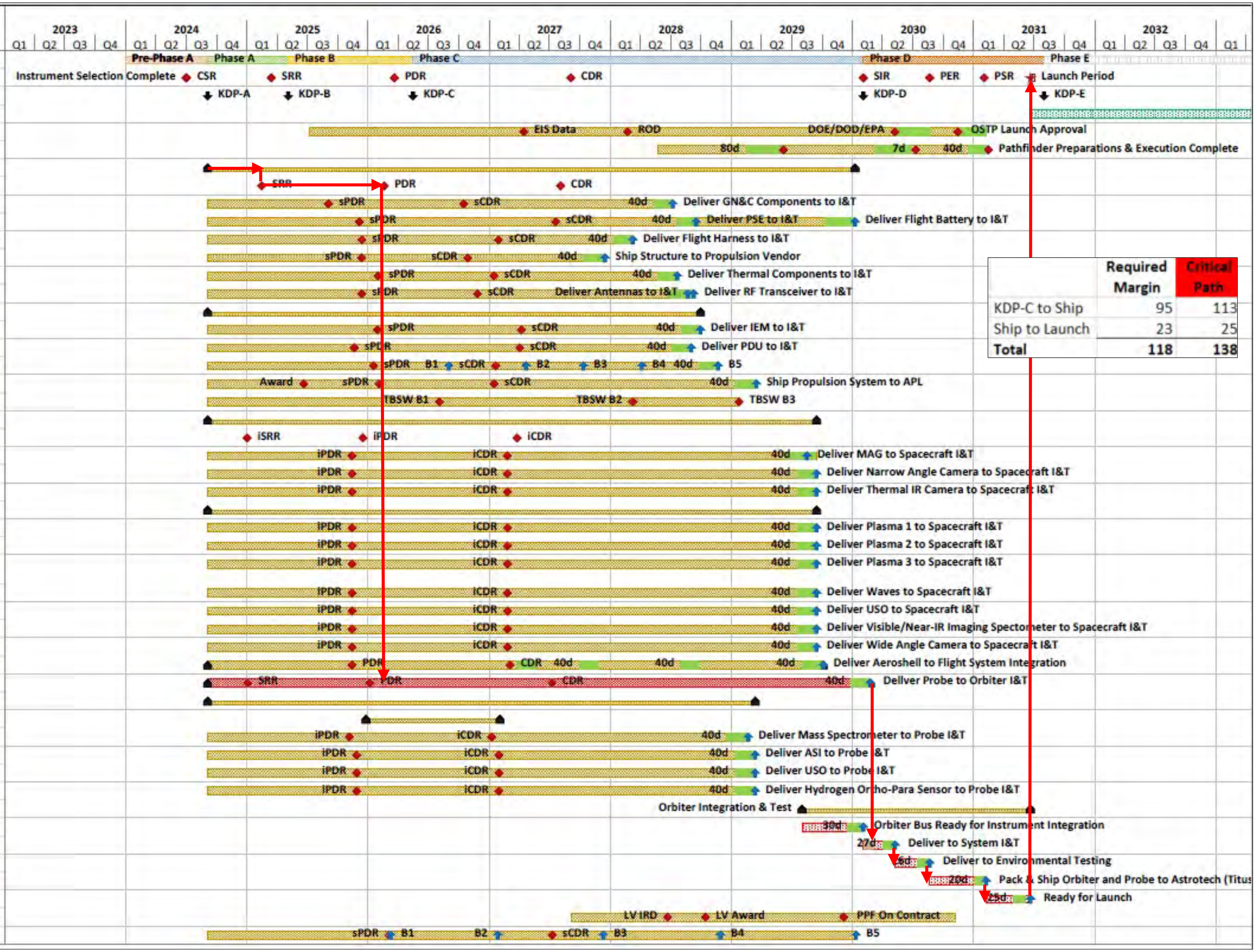
Task Name	Start	Finish
Trajectory Event		
Launch - Early Ops Checkout	6/20/2031	6/20/2031
DSM	6/27/2032	6/27/2032
Earth Flyby	4/27/2033	4/27/2033
Jupiter Flyby	12/20/2035	12/20/2035
Uranus Arrival (12/5/2044)	12/5/2044	12/5/2044
Capture Apoapsis / Entry Targeting	2/5/2045	2/5/2045
Probe Release	2/6/2045	2/6/2045
Divert Maneuver	3/24/2045	3/24/2045
Probe Entry	4/6/2045	4/6/2045
Orbiter Periapsis	4/6/2045	4/6/2045
Orbiter Apoapsis / PRM	4/6/2045	4/6/2045
Tour Start	6/6/2045	6/6/2045
Tour	6/6/2045	7/6/2049

Uranus Orbiter and Probe Executive Summary



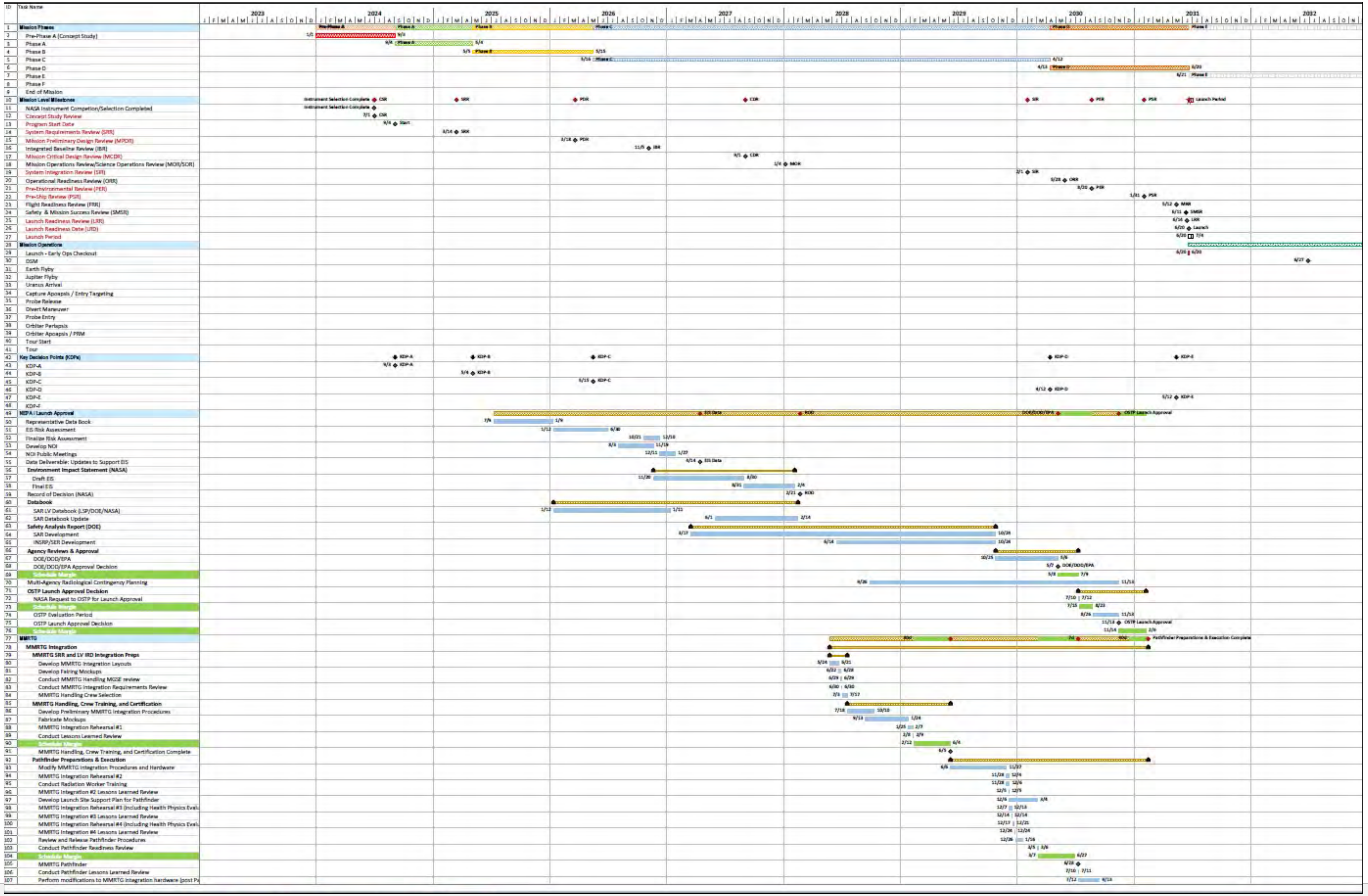
Uranus Orbiter and Probe Executive Summary & Critical Path

ask Name	Start	Finish
Mission Phases	1/1/2024	11/3/2049
Mission Level Milestones	6/30/2024	7/4/2031
Key Decision Points (KDPs)	9/3/2024	7/6/2049
Mission Operations	6/20/2031	7/6/2049
NEPA / Launch Approval	7/9/2025	2/6/2031
MMRTG	5/24/2028	2/13/2031
Orbiter	9/4/2024	1/7/2030
Orbiter Milestones	2/13/2025	8/3/2027
Guidance Navigation & Control (GN&C)	9/4/2024	7/7/2028
Power Subsystem Electronics (PSE)	9/4/2024	1/7/2030
Harness	9/4/2024	3/8/2028
Mechanical	9/4/2024	12/15/2027
Thermal	9/4/2024	7/20/2028
Telecommunications (RF)	9/4/2024	9/8/2028
Avionics	9/4/2024	9/28/2028
Integrated Electronics Module (IEM)	9/4/2024	9/28/2028
Power Distribution Unit (PDU)	9/4/2024	8/31/2028
Flight Software & Autonomy	9/4/2024	11/20/2028
Propulsion Subsystem	9/4/2024	3/15/2029
Testbed Design, Fabrication & Test	9/4/2024	1/22/2029
Orbiter Payload	9/4/2024	9/13/2029
Orbiter Payload Milestones	12/31/2024	3/25/2027
Magnetometer	9/4/2024	9/13/2029
Narrow Angle Camera	9/4/2024	9/13/2029
Thermal IR Camera	9/4/2024	9/13/2029
Fields & Particles Package	9/4/2024	9/13/2029
Plasma 1 (MESSENGER/FIPS)	9/4/2024	9/13/2029
Plasma 2 (Parker Solar Probe/SWEAP/SPAN-B)	9/4/2024	9/13/2029
Plasma 3 / Energetic Particles (Parker Solar Probe/EPI-Lo)	9/4/2024	9/13/2029
Waves (MAVEN/LPW + TRACERS/SCM)	9/4/2024	9/13/2029
Radio Science/USO	9/4/2024	9/13/2029
Visible/Near-IR Imaging Spectometer	9/4/2024	9/13/2029
Wide Angle Camera	9/4/2024	9/13/2029
Aeroshell	9/4/2024	10/3/2029
Probe	9/4/2024	2/22/2030
Probe Payload	9/4/2024	3/12/2029
Payload Instrument Milestones	12/25/2025	2/1/2027
Mass Spectrometer	9/4/2024	2/19/2029
Atmospheric Structure Inst. (ASI)	9/4/2024	3/12/2029
UltraStable Oscillator (USO)	9/4/2024	3/12/2029
Hydrogen Ortho-Para Sensor	9/4/2024	3/12/2029
Orbiter Integration & Test	8/1/2029	6/20/2031
A - Bus Integration & Test	8/1/2029	2/1/2030
B - Instrument Integration & Test	2/1/2030	5/8/2030
C - System Integration & Test	5/9/2030	8/20/2030
D - Environmental Testing	8/21/2030	2/6/2031
E - Launch Site Operations	2/7/2031	6/20/2031
Launch Vehicle Interface	9/7/2027	11/6/2030
Ground Systems	9/4/2024	1/10/2030

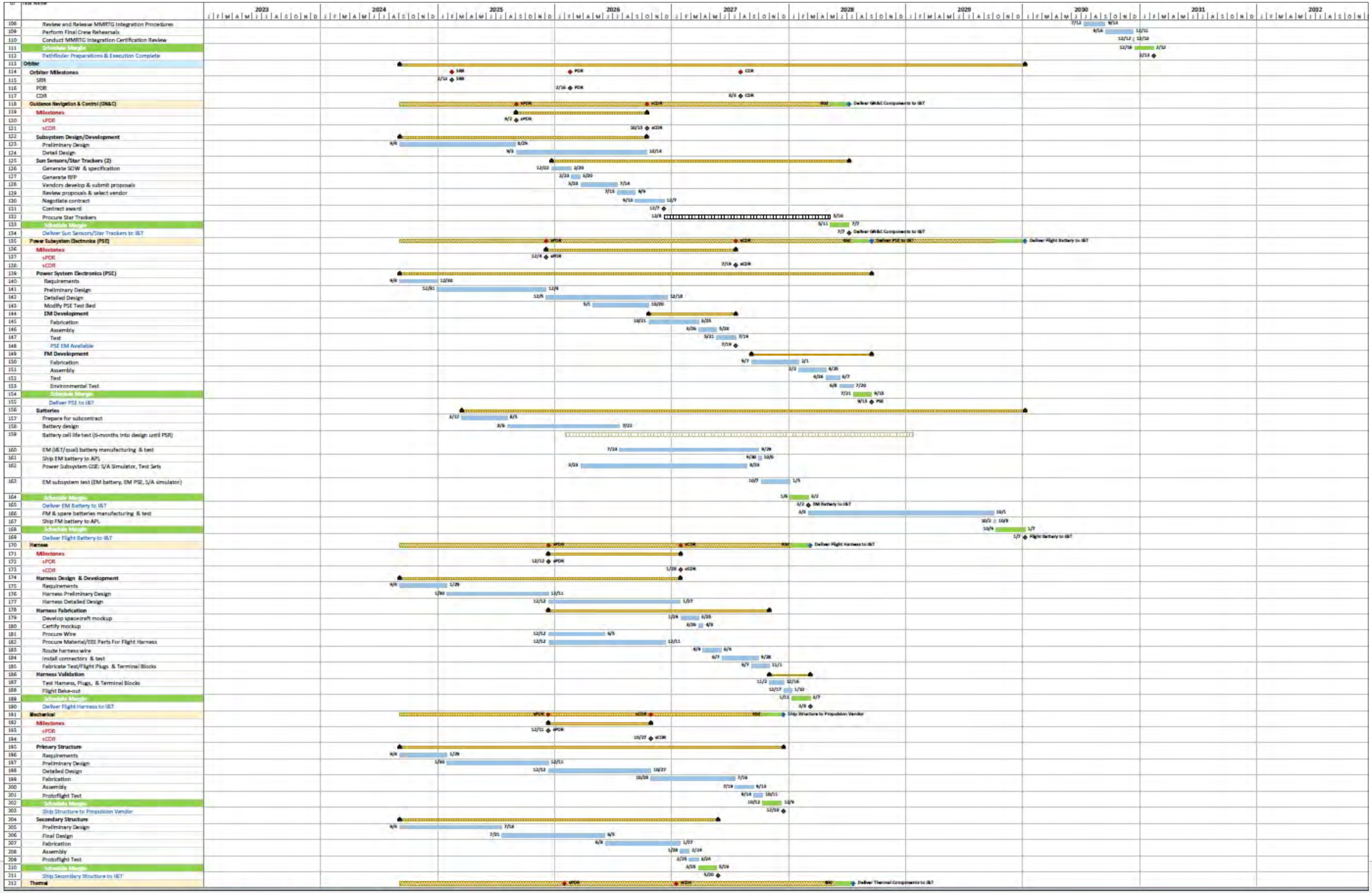


	Required Margin	Critical Path
KDP-C to Ship	95	113
Ship to Launch	23	25
Total	**118**	**138**

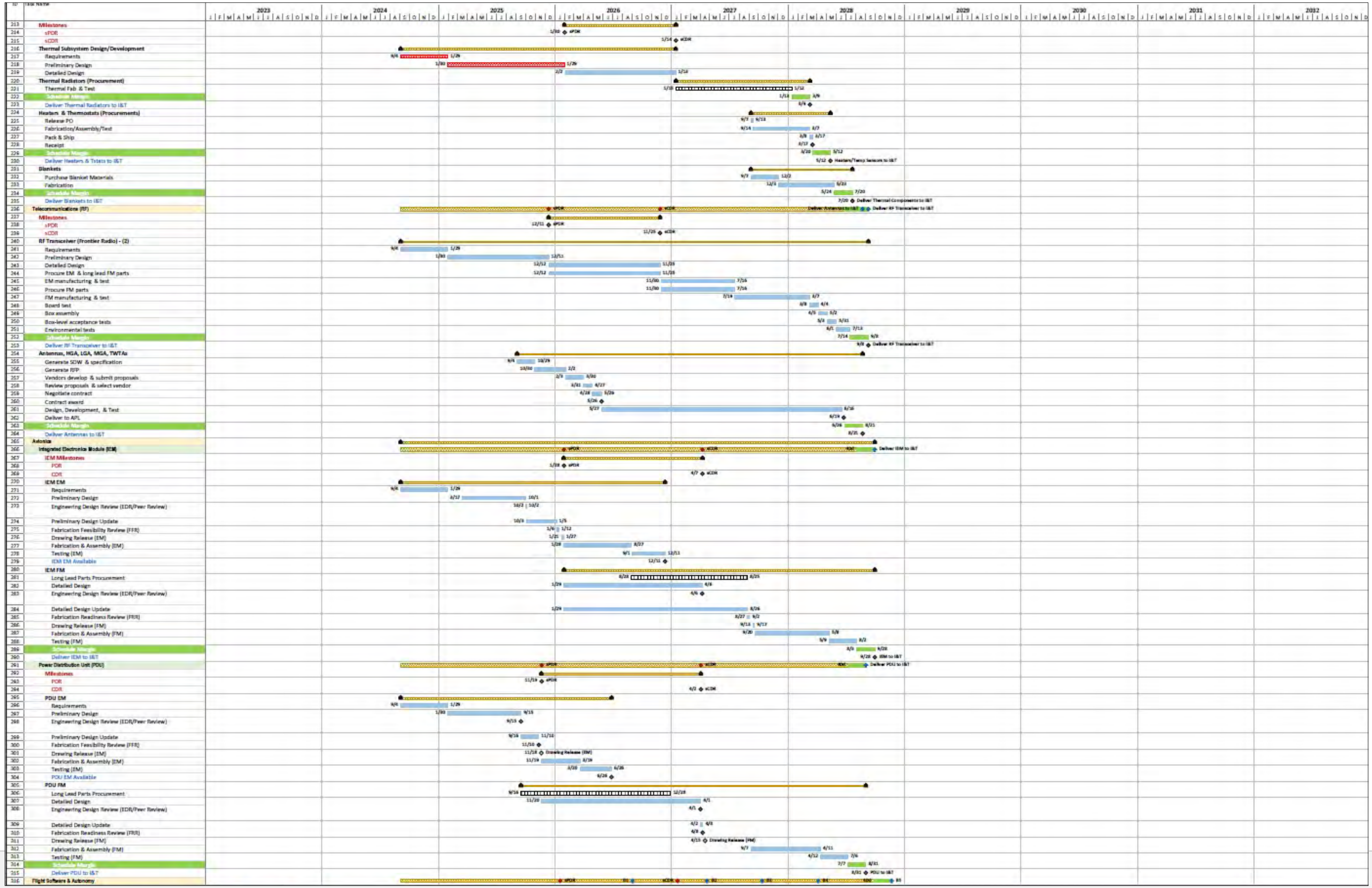
Uranus Orbiter and Probe Schedule Detail



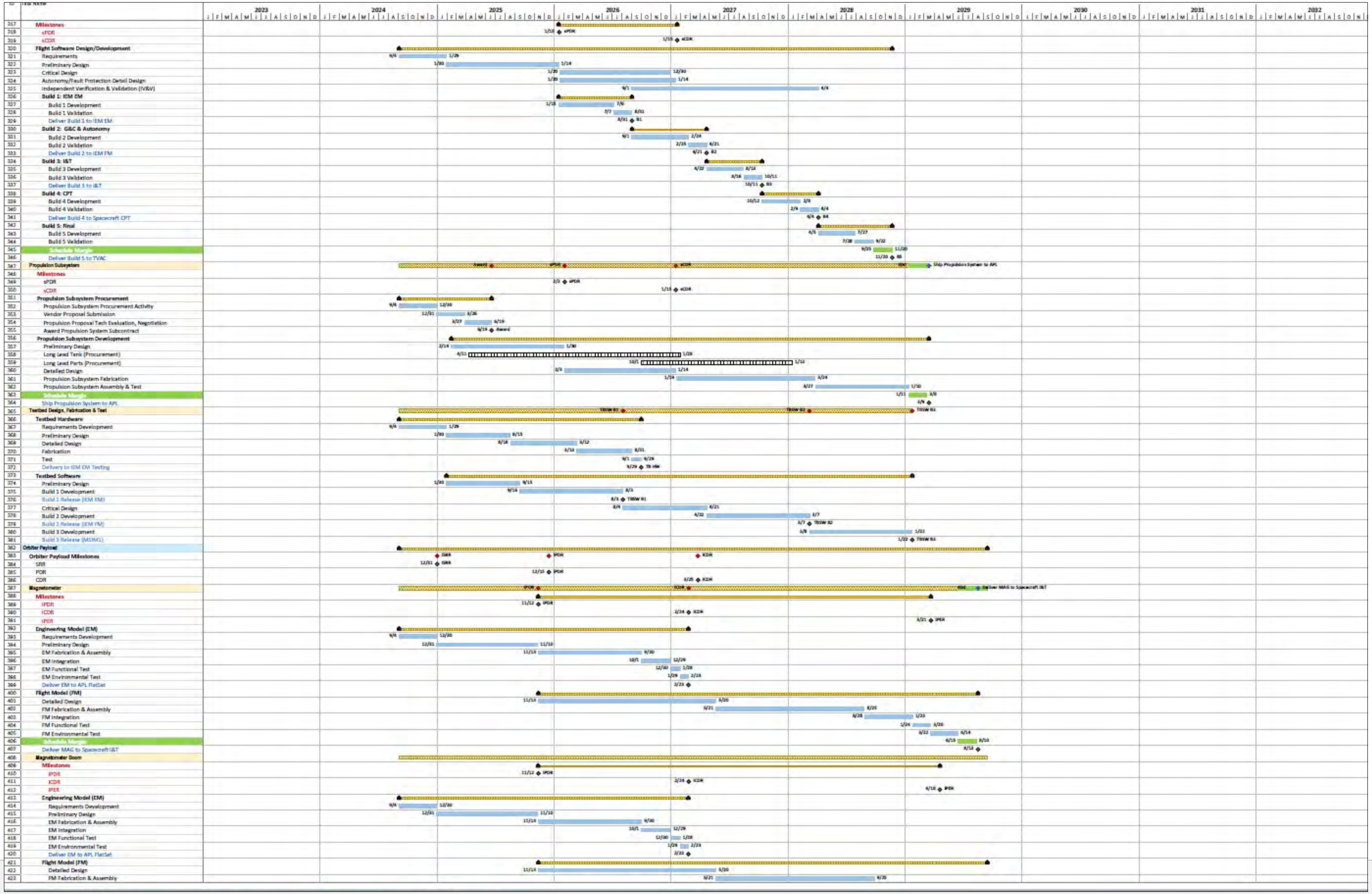
Uranus Orbiter and Probe Schedule Detail Continued



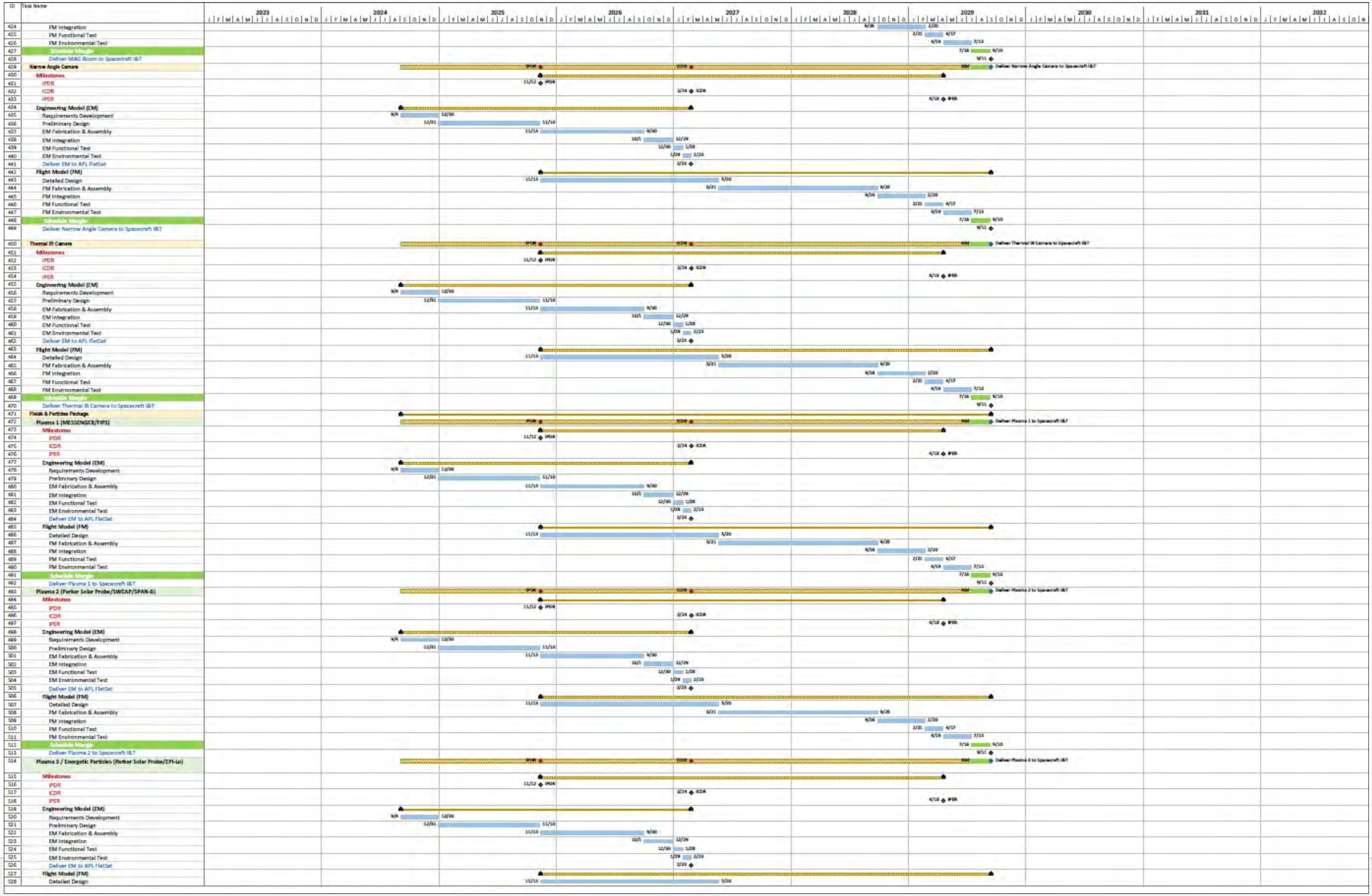
Uranus Orbiter and Probe Schedule Detail Continued



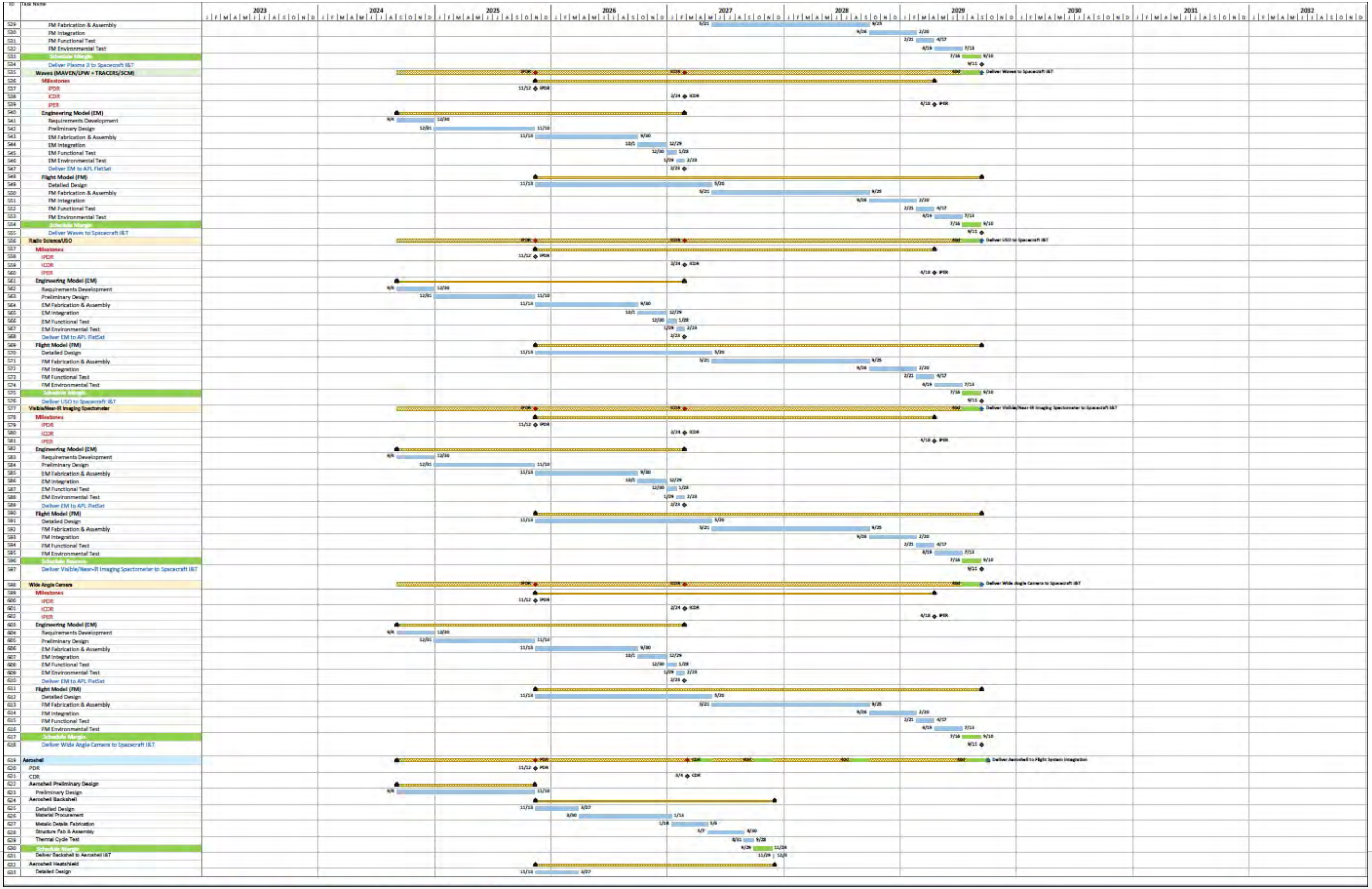
Uranus Orbiter and Probe Schedule Detail Continued



Uranus Orbiter and Probe Schedule Detail Continued



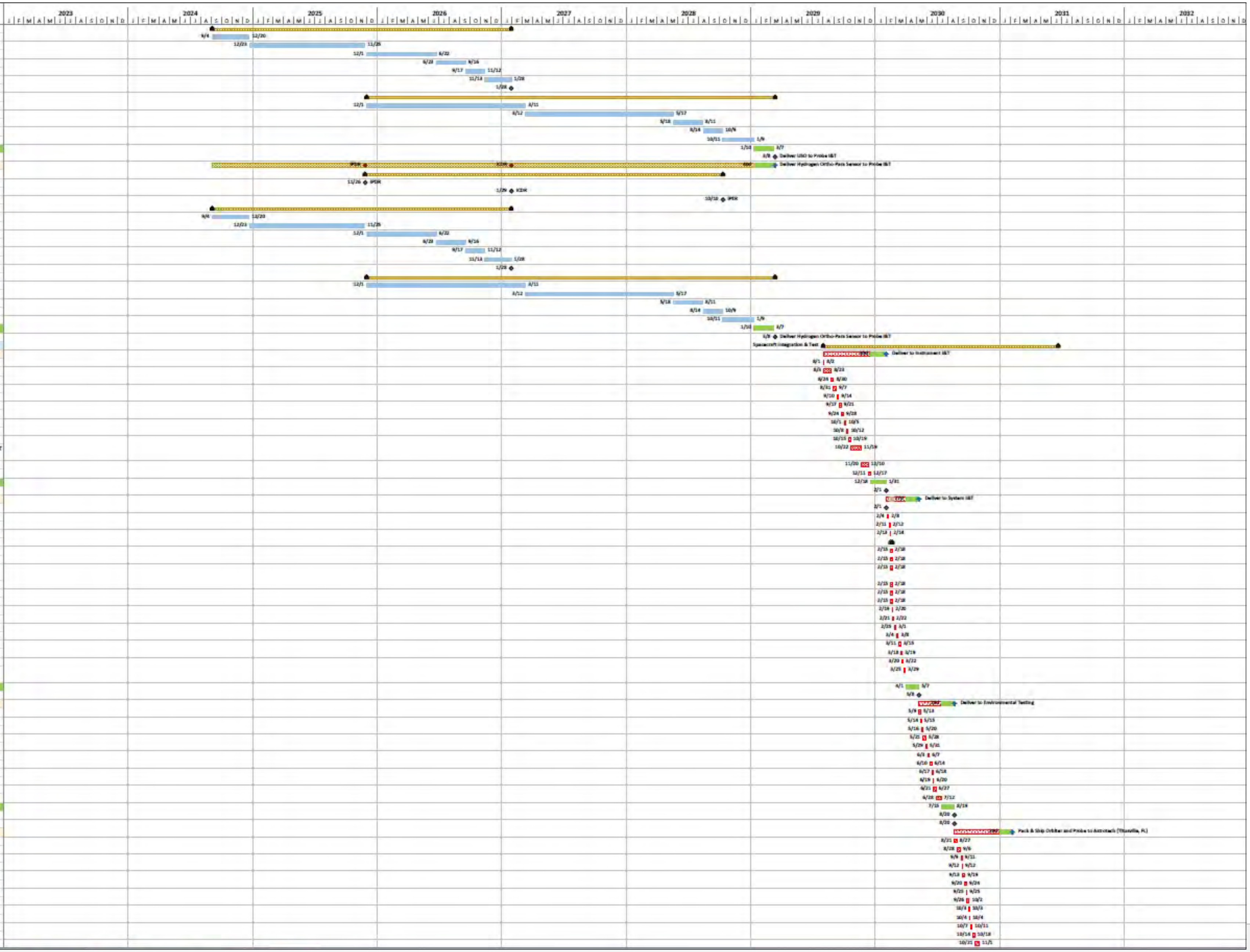
Uranus Orbiter and Probe Schedule Detail Continued



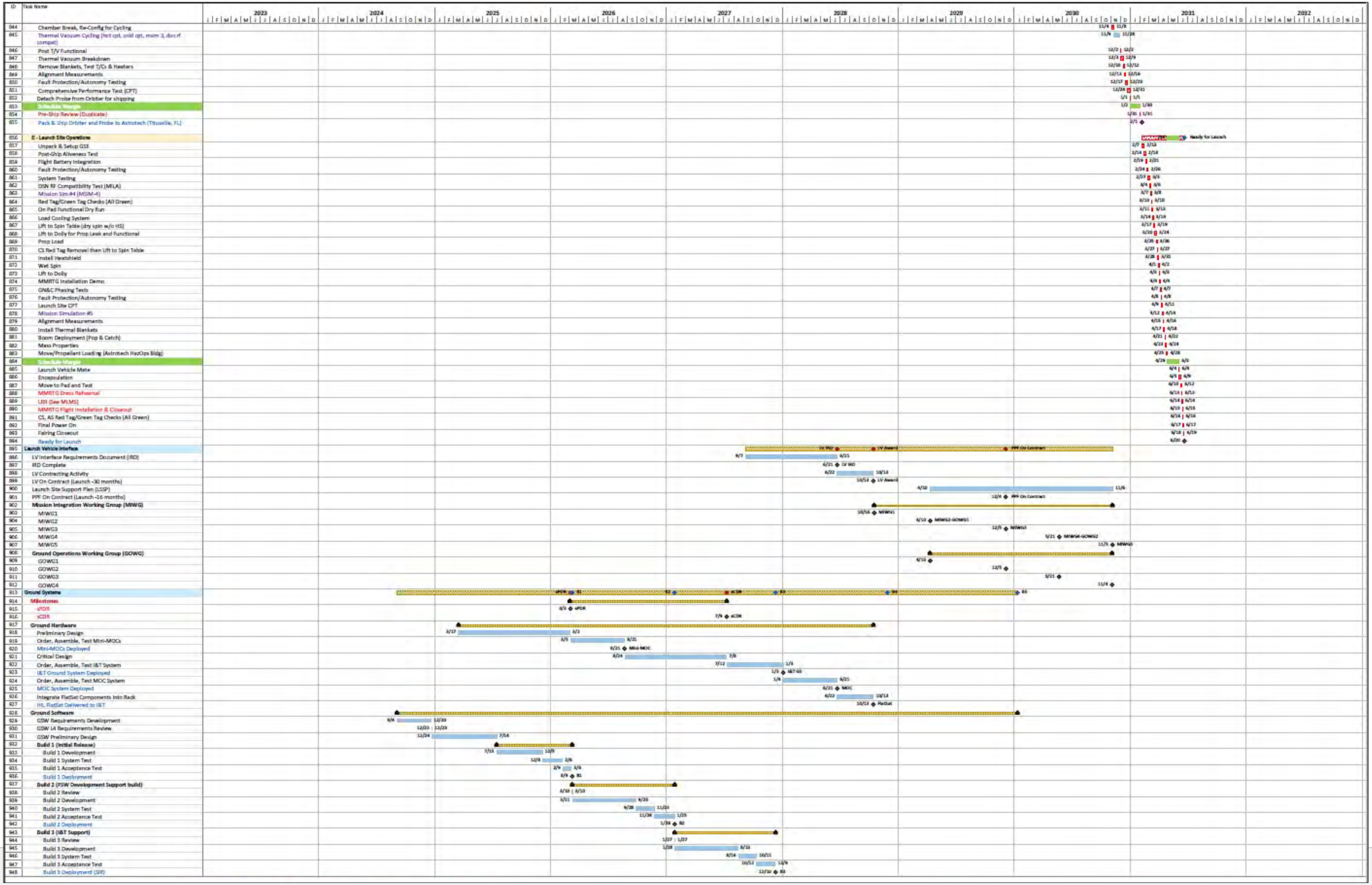
Uranus Orbiter and Probe Schedule Detail Continued

Uranus Orbiter and Probe Schedule Detail Continued

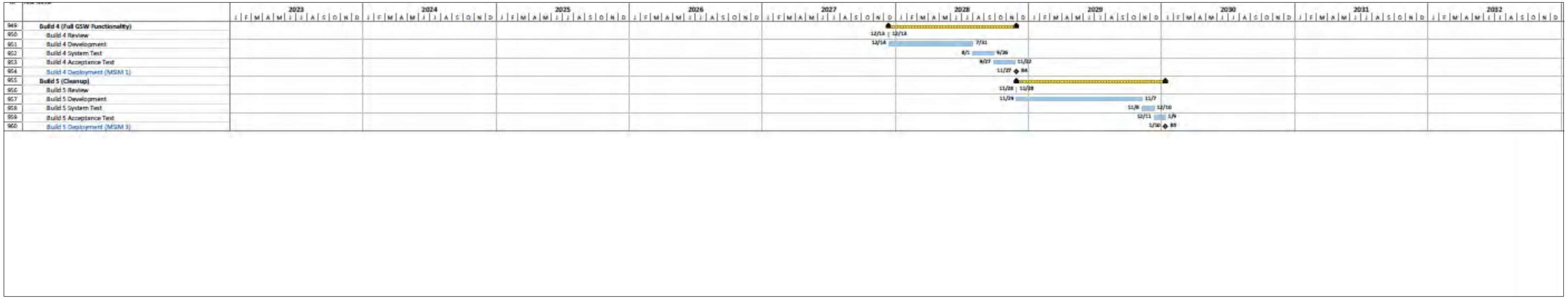
ID	Task Name
739	**Engineering Model (EM)**
740	Requirements Development
741	Preliminary Design
742	EM Fabrication & Assembly
743	EM Integration
744	EM Functional Test
745	EM Environmental Test
746	Deliver EM to APL FlatSat
747	**Flight Model (FM)**
748	Detailed Design
749	FM Fabrication & Assembly
750	FM Integration
751	FM Functional Test
752	FM Environmental Test
753	Schedule Margin
754	Deliver USO to Probe I&T
755	**Hydrogen Ortho-Para Sensor**
756	**Milestones**
757	IPDR
758	ICDR
759	IPER
760	**Engineering Model (EM)**
761	Requirements Development
762	Preliminary Design
763	EM Fabrication & Assembly
764	EM Integration
765	EM Functional Test
766	EM Environmental Test
767	Deliver EM to APL FlatSat
768	**Flight Model (FM)**
769	Detailed Design
770	FM Fabrication & Assembly
771	FM Integration
772	FM Functional Test
773	FM Environmental Test
774	Schedule Margin
775	Deliver Hydrogen Ortho-Para Sensor to Probe I&T
776	**Spacecraft Integration & Test**
777	**A - Bus Integration & Test**
778	Integrate Harness
779	Harness Continuity Tests
780	Integrate PDU
781	Integrate IEM
782	Integrate PSE
783	Integrate GNC Components
784	Integrate RF Components
785	Integrate Thermal Components
786	Integrate Propulsion Subsystem Electrical
787	Release Mechanism Electrical Verification
788	Bus Testing (ACS HW & Closed-loop Sims, Fault Management, CPT Dry Runs)
789	DSN RF Compatibility Test
790	Mission Sim #1 (Launch, Maneuvers, Bus Ops)
791	Schedule Margin
792	Deliver to Instrument I&T
793	**B - Instrument Integration & Test**
794	System Integration Start
795	Integrate DPU
796	Integrate Narrow Angle Camera
797	Integrate Mid-Infrared Thermal Detector
798	**Integrate Fields & Particle Package**
799	Plasma 1 (MESSENGER/FIPS)
800	Plasma 2 (Parker Solar Probe/SWEAP/SPAN-B)
801	Plasma 3 / Energetic Particles (Parker Solar Probe/EPI-Lo)
802	Waves (MAVEN/LPW + TRACERS/SCM)
803	Radio Science/USO
804	Integrate Visible/Near-IR Mapping Spectrometer
805	Integrate Wide Angle Camera
806	Integrate MAG/MAG Boom
807	Integrate Probe Sphere
808	Fault Protection/Autonomy
809	Comprehensive Performance Test (CPT)
810	Integrate Probe Sphere
811	Integrate Probe into Aeroshell
812	Mission Sim #2 (Instrument Commissioning, Day in Life)
813	Schedule Margin
814	Deliver to System I&T
815	**C - System Integration & Test**
816	Prop System Pressure Test & Functional
817	Prop System Water Fill
818	EMI/EMC
819	Fault Protection/Autonomy Testing
820	Mass Properties
821	Alignment Measurements
822	Integrate Mag Boom
823	Mag Boom Deployment (Pop & Catch)
824	Install Accelerometers
825	Install Thermal Blankets
826	Baseline CPT
827	Schedule Margin
828	PER (Duplicate - See MLMS)
829	Deliver to Environmental Testing
830	**D - Environmental Testing**
831	Acoustics Test
832	Vibration Test
833	Separation Test/Adapter Match & Mate
834	Post Vibe/Sep Functional
835	Alignment Measurements
836	Mag Boom Deployment
837	Remove Mag Boom
838	Drain & Dry Propulsion Tanks
839	Remove Thermal Blankets
840	Remove Accelerometers
841	Install Thermocouples, Heaters, Blankets
842	Thermal Vacuum Setup
843	Thermal Balance



Uranus Orbiter and Probe Schedule Detail Continued



Uranus Orbiter and Probe Schedule Detail Continued



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