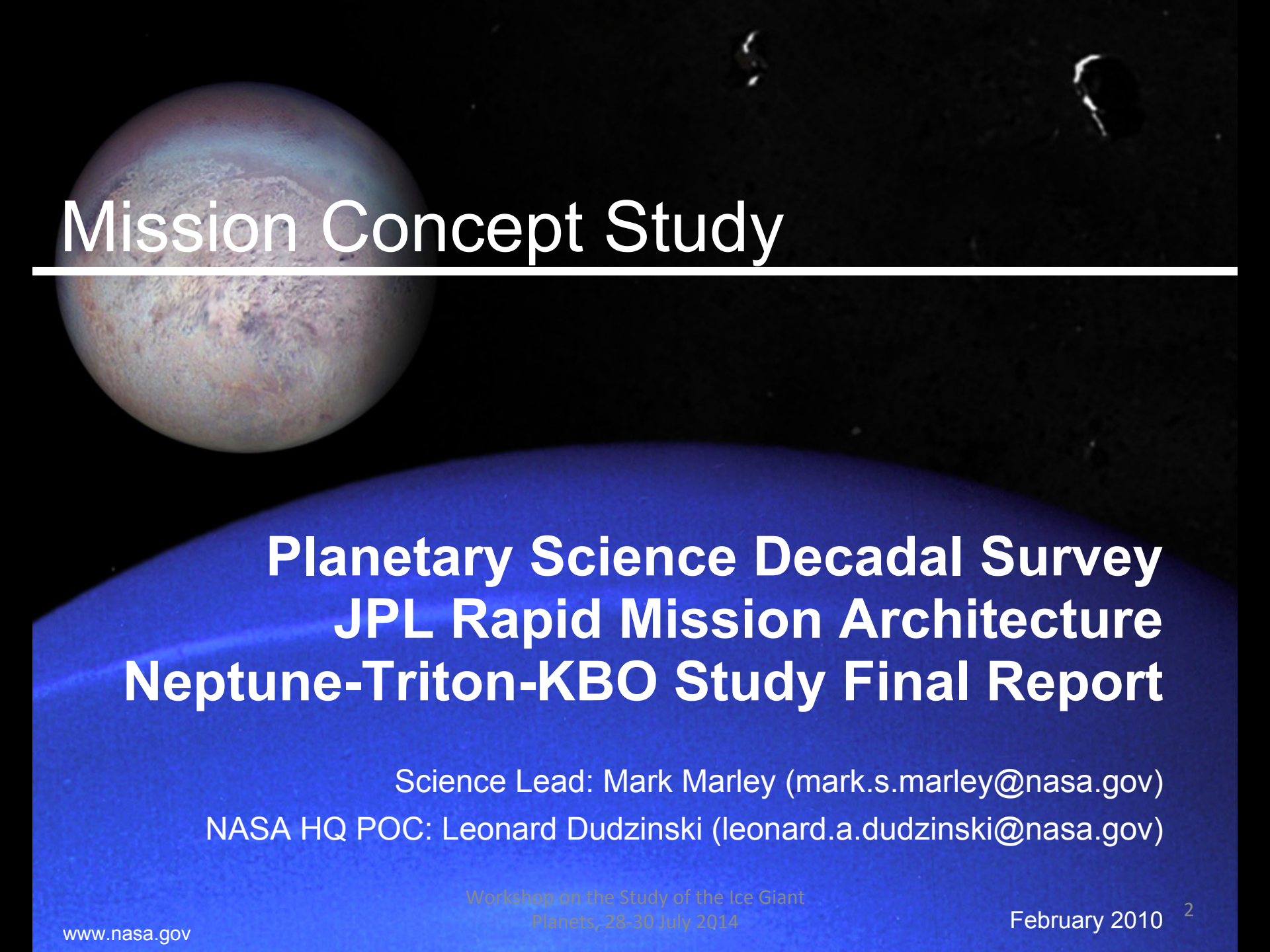
Overview of ice giant mission studies performed for 2013-2022 decadal survey

Zibi Turtle, JHU/APL

Full mission study reports available at:
http://sites.nationalacademies.org/SSB/SSB_059331.htm



Mission Concept Study

Planetary Science Decadal Survey
JPL Rapid Mission Architecture
Neptune-Triton-KBO Study Final Report

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Study level

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Science Objectives

- Determine temporal variations of Neptune's atmosphere.
- Characterize the chemistry of Neptune's atmosphere.
- Develop an understanding of the structure, dynamics, and composition of Neptune's magnetosphere.
- Develop an understanding of the chemistry, structure, and surface interaction of Triton's atmosphere.
- Develop an understanding of the interior structure of Triton.
- Determine the age and geologic processes that shape the surface of Triton/KBOs.
- Develop an understanding of the spatial distribution of surface composition and how the composition is coupled to geologic processes on a given KBO.

Mission Design

- Seven flyby architectures
  - Varying complexity and focus on Neptune, Triton, or KBOs
  - All flyby options used chemical propulsion exclusively
- Seven orbiter architectures
  - "minimal" orbiter of Neptune
  - five simple orbiter concepts (one including a shallow atmospheric probe, and another separate KBO-flyby spacecraft)
  - "high-performance" orbiter, with up to 300 kg payload mass
  - Used solar-electric propulsion system
  - One simple orbiter and high-performance orbiter used aerocapture for NOI
  - Others used chemical propulsion
- Most architectures included 25-kg or 60-kg primary instrument payload (New Horizons heritage)
- All missions called for the use of three to six ASRGs, depending on the mission architecture.

Model Payload

Instrument Type	Instrument Function
Narrow angle imager	Approach imaging at low resolution for multiple rotations of Neptune; high-resolution imaging of Triton and KBO
Medium angle imager	Color imaging of all targets
Near IR spectrometer (1–2.5 microns)	Composition of all targets
UV imaging spectrometer	Small particulate scattering (Rings, Neptune), composition, ions, and trace atmospheres (all targets)
Thermal Mapper	Thermal structure of Neptune atmosphere, surface temperatures (Triton, KBOs), and thermal inertia (Triton)
Magnetometer	Fields for all targets
Plasma spectrometer	Space weathering, low energy ions and electrons
Ultra-stable oscillator (USO)	Earth occultations for atmospheric structure, composition
Mass spectrometer	Atmospheric composition (Neptune, Triton)
Atmospheric probe	Atmospheric structure, noble gas, and isotopic composition for Neptune

Tier 1 Science Objective	Measurement	Instrument
Neptune - Determine how Neptune's clouds, atmospheric thermal structure, gasses, and winds vary over timescales of hours to months to seasons.	Global imaging on time scales from hours to months (seasons by linking to Voyager and Earth-based observations); thermal mapping; spatially-resolved spectroscopic information; radio occultation	Narrow and wide angle visible imagers; Thermal mapper; UV/vis/near-infrared mapping spectrometer; RSS link with USO; gimballed HGA
Neptune - Understand the structure, dynamics, and composition of Neptune's magnetosphere.	Particles and field measurements	Magnetometer; Plasma spectrometer
Neptune - Measure the molecular composition, noble gas abundances, hydrogen ortho/para ratio, and isotopic adundances in Neptune's atmosphere.	In-situ measurements	Mass Spectrometer
Triton - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity is ongoing or dates largely from the time of Triton's capture by Neptune.	Imaging capability, surface reflectance spectroscopy	Narrow-angle visible imager; gimballed HGA; near-infrared mapping spectrometer;
Triton - Understand the chemistry and structure of Triton's atmosphere and its interaction with the surface, including the seasonal volatile cycle and plume activity.	Imaging & spectroscopic mapping capability; radio occultation; UV stellar occultations; direct sampling of atmosphere via close flybys	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer; RSS link with USO; gimballed HGA; mass spectrometer for direct samples
Triton - Understand the interior structure of Triton, particularly whether it is differentiated, and whether there is a subsurface ocean.	Magnetic field, gravity, shape measurements	Magnetometer; gimbaled HGA; visible imagers
KBO - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity has ever occurred and relate that to its collisional history via the cratering record.	Imaging capability	Narrow-angle visible imager
KBO - Understand the spatial distribution of surface composition and how the composition is coupled to geologic processes. Included in the surface composition investigation is the need to understand the nature and degree of space weathering on the surface.	Spectroscopic mapping capability	Uv/vis/near-infrared mapping spectrometer

Tier 2 Science Objective	Measurement	Instrument
Neptune - Place new constraints on the internal structure of Neptune by refining and extending knowledge of the gravitational harmonics of the planet.	Higher order harmonics from orbiter	Main spacecraft
Triton – Understand the interaction between Triton and Neptune's magnetosphere.	Particles and field measurements	Magnetometer; Plasma spectrometer; mass spectrometer
Rings - Measure the composition, size, and dynamical properties of ring particles and associated small satellites, and determine how they interact to control structure and evolution.	Imaging and spectroscopic capability, occultations	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer; RSS link with USO
Small Neptune moons - Determine the surface composition, size and orbits of the small inner satellites and Nereid.	Imaging and spectroscopic capability	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer
KBO - Determine bulk properties such as the mass and volume, search for satellites, and measure the bolometric and Bond albedos and constrain or measure the surface temperature	Imaging capability; bolometric measurements	Narrow and wide angle visible imagers; Thermal mapper with far IR ensitivity
KBO - Understand the interaction between the KBO and the solar wind, keeping in mind that the slightest presence of an atmosphere will have a profound effect on the structure and nature of the interaction region.	Particles and field measurements	Magnetometer; Plasma spectrometer

Tier 1 Science Objective	Measurement	Instrument	Functional Requirement
Triton - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity is ongoing or dates largely from the time of Triton's capture by Neptune.	Imaging capability, surface reflectance spectroscopy. Hemispheric imaging at < 0.25 km/pixel with phase angle 20 – 70 degrees for good topography. Coverage of selected targets, especially plume sources, at < 100 m/pixel	Narrow-angle visible imager (best plausible resolution 4 μrad); near-infrared mapping spectrometer (best plausible resolution 30 μrad);	Flyby adequate; orbiter provides global coverage of the surface
Triton - Understand the chemistry and structure of Triton's atmosphere and its interaction with the surface, including the seasonal volatile cycle and plume activity.	Imaging & spectroscopic mapping capability 1 – 2.5 micron global spectra with <10 km resolution; radio occultation; UV stellar occultations; direct sampling of atmosphere via close flybys	Narrow and wide angle visible imagers; Near-infrared mapping spectrometer (best plausible resolution 30 μrad); UV spectrometer, RSS link with USO; gimballed HGA; mass spectrometer for direct samples	Flyby adequate; orbiter provides global coverage of the surface, potential of direct atmospheric sampling, and possibility for direct observation of seasonal change on the surface and atmosphere

Challenges

- Long duration missions
- Scheduling constraints identified for all but the high-performance option -- availability of a Jupiter gravity assist maneuver w/ launch between 2016 and 2018 -- reduced-performance opportunities thereafter, even with SEP
- Neptune mission without a Jupiter-flyby gravity assist requires aerocapture for orbit insertion -- adds complexity and risk and makes probe delivery and orbits that allow Triton encounters more challenging

Conclusions

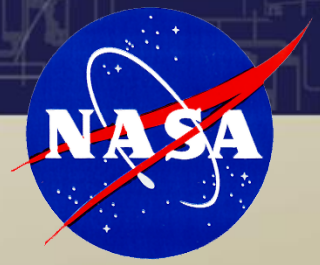
- Flyby mission architectures capable of achieving significant science progress beyond Voyager + additional KBO science
- Even the simplest flyby mission exceeded New Frontiers cost cap and offered low science return relative to cost
- More complex missions and orbiters provided vast gains in science at increased cost
- More detailed design work of a “sweet spot” mission design identified technical risks that made a Uranus mission more favorable for the coming decade
- Technology development needed to increase feasibility of a future Neptune orbiter mission

Ice Giants Decadal Survey Results Summary

May 4, 2010

(Revision — 6/3/2010)

Ice Giants Decadal Study: Appendix C



APL

The Johns Hopkins University

APPLIED PHYSICS LABORATORY

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Study Request

- **Two Full Mission Studies – one for Uranus and one for Neptune – but the science and constraints are to be as similar as possible. The goal of the two studies is to identify any system-specific requirements (i.e., requirements imposed by the Uranus or Neptune systems themselves) that drive cost and/or risk.**
  - Neptune dropped due to higher complexity, e.g. aerocapture, lifetime risks
- **Ice Giant Orbiter/Probe Mission: define concept for a floor mission to an Ice Giant System with two components: (1) a orbiter with limited instrument suite, and (2) a shallow atmospheric probe.**
- **The main goal of the concept study is to define a solution with the $1.5B to $1.9B cost range.**
- **Secondary study goals are to: clarify the costs associated with possible variations or additions to the primary mission, i.e., look at potential up-scopes to the orbiter instrument payload (with costs identified) and identify descopes to keep to the cost cap.**

Study Level

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
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Prioritized Objectives

1) Deliver a small payload into orbit around the planet and conduct a limited orbital tour of that ice giant system for roughly two years with primary science being atmospheric and magnetospheric characterization.
2) Deliver a shallow probe into the planet's atmosphere.
3) Determine distribution of thermal emission from the planet's atmosphere.
4) If possible, refine the gravitational harmonics of the planet.
5) Conduct close flybys of any large satellites.

These results will build upon Voyager's remote-sensing data obtained with technology launched more than a generation ago, as well as more recent data from Earth-based telescopes. The mission results, along with similar measurements from the Galileo probe/ orbiter and the Cassini orbiter, will constrain models of giant planet and Solar System formation and extend our understanding of extrasolar planetary systems, the bulk of which are ice giants.

Study Requirements

- $1.5B-$1.9B cost range (NOT flagship missions)
- Need a basic science payload inserted into planetary orbit. (Flyby trajectories should not be considered.)
- SEP is allowable.
- Aerocapture is allowable, but must be costed appropriately (perhaps a flight qualification).
- Need a shallow probe (depth of 1-5 bars). The data from the probe must be retrievable.
- If the orbiter must be encased for aerocapture, consideration should be given to alternatives, e.g., relay data from SEP stage.
- Launch window: 2020-2023.
- Assume no JGA.

Study Requirements

- Need to understand how the cost estimate is affected by limiting the probe instrument suite to a mass spectrometer, T-P sensors and accelerometers, versus adding a nephelometer and/or other instruments.
- Need to understand the margins provided by given mission architectures that could allow possible scale back to maintain the $1.9B cost cap.
- Scope the range of feasible missions within the mid-range cost cap (assume $1.5B - $1.9B) that can obtain fundamental new measurements for an ice giant system, including: atmospheric dynamics and chemistry; magnetic field measurements; in situ measurements of elemental and isotopic abundances; constraints on internal structure; and observations of the retinue of rings and satellites, particular the larger satellites.
- Identify any requirements imposed by the Uranus or Neptune systems that drive cost or risk.

Study Results Summary (1)

- **Uranus was selected over Neptune for 2020-2023 time frame**
  - Uranus is much more accessible without a Jupiter gravity assist within a reasonable mission duration
  - For a cruise time of ≤ 15 year, a mission to Neptune would have required aerocapture which is still a developing technology
- **A robust mission to Uranus can be technically achieved within this timeframe meeting full set of objectives and instrument suite including a shallow entry probe and a satellite tour.**
  - A trajectory using a solar electric propulsion stage along with a single Earth flyby allows for launch opportunities every year.
  - Capture is achievable with a low risk, chemical propulsion solution for a 13 year cruise time
    - Cruise times of less than 13 years would require an aero capture solution

Study Results Summary (2)

- **The mission was designed to accommodate a descent probe with the full instrument suite**
  - 1 hour of measurements from 0.1 – 5 bars
  - Communications allows for 720 kbits of probe data
- **The primary mission accommodates at least 20 orbits highly inclined orbit (431 days)**
  - Average data return of 3200 images per day + plasma and magnetometer data
- **The mission concept accommodates a total of 10 targeted flybys of 5 Uranus satellites (424 days)**

Science Objectives – Tier 1

Tier 1 Science Objectives – Orbiter

- Determine the atmospheric zonal winds, composition, and structure at high spatial resolution, as well as the temporal evolution of atmospheric dynamics.

- Understand the basic structure of the planet's magnetosphere as well as the high-order structure and temporal evolution of the planet's interior dynamo.

Science Objectives – Tier 2

Tier 2 Science Objectives – Enhanced Orbiter + Probe

- **Determine the noble gas abundances (He, Ne, Ar, Kr, and Xe) and isotopic ratios of H, C, N, and O in the planet's atmosphere and the atmospheric structure at the probe descent location.**
- **Determine internal mass distribution.**
- **Determine horizontal distribution of atmospheric thermal emission, as well as the upper atmospheric thermal structure and changes with time and location at low resolution.**
- **Remote sensing observations of large satellites.**

Science Objectives – Tier 3

Tier 3 Science Objectives – Enhanced Orbiter + Enhanced Probe

- **Measure the magnetic field, plasma, and currents to determine how the tilted/offset/rotating magnetosphere interacts with the solar wind over time.**
- **Remote sensing observations of small satellites and rings.**
- **Determine the vertical profile of zonal winds as a function of depth in the atmosphere, in addition to the location, density, and composition of clouds as a function of depth in the atmosphere.**

Traceability Matrix – Tier 1

Tier 1 Science Objective	Measurement	Instrument	Functional Requirement
Determine the atmospheric zonal winds, composition, and structure at high spatial resolution, as well as the temporal evolution of atmospheric dynamics	Spatially-resolved scattering properties of the atmosphere	Wide-angle visible imager; visible/near-infrared mapping spectrometer	Orbiter with 2-year tour
Understand the basic structure of the planet's magnetosphere as well as the high-order structure and temporal evolution of the planet's interior dynamo	Make continuous measurements of vector magnetic field (1 sec resolution)	Magnetometer	Orbiter

Traceability Matrix – Tier 2

Tier 2 Science Objective	Measurement	Instrument	Functional Requirement
Determine the noble gas abundances (He, Ne, Ar, Kr, and Xe) and isotopic ratios of H, C, N, and O in the planet's atmosphere and the atmospheric structure at the probe descent location.	Measure the noble gases and isotopic ratios in the atmosphere assuming that the atmosphere is well-mixed, and measure temperature and pressure as a function of depth	Mass Spectrometer with sufficient resolution; Pressure-temperature sensors sampling at frequent intervals	Single probe that reaches at least 1 bar with a stretch goal of below 5 bars
Determine internal mass distribution	Measure higher-order gravitational harmonics from orbiter gravitational moments	USO	Orbital periapsis visible from Earth
Determine horizontal distribution of atmospheric thermal emission, as well as the upper atmospheric thermal structure and changes with time and location at low resolution.	Measure temperature as a function of latitude and longitude, from direct thermal emission and/or UV occultations	Mid-infrared thermal detector; UV imaging spectrograph	Orbiter
Remote sensing of large satellites	Spatially-resolved surface reflectance spectroscopy	Wide-angle visible imager; visible/near-infrared mapping spectrometer; narrow-angle camera	Orbiter with 2-yr tour

Traceability Matrix – Tier 3

Tier 3 Science Objective	Measurement	Instrument	Functional Requirement
Measure the magnetic field, plasma, and currents to determine how the tilted/offset/ rotating magnetosphere interacts with the solar wind over time.	Measurements of plasma and energetic charged particles.	Plasma and Particle instrument	Orbiter
Remote sensing of small satellites and rings	Spatially-resolved surface reflectance spectroscopy	Wide-angle visible imager; visible/near-infrared mapping spectrometer; narrow-angle camera	Orbiter with 2-yr tour
Determine the vertical profile of zonal winds as a function of depth in the atmosphere, in addition to the presence of clouds as a function of depth in the atmosphere	Measure the zonal winds as a function of depth, and determine scattering properties of the atmosphere	Ultrastable oscillator on probe and on carrier; Nephelometer	Single probe that reaches at least 1 bar with a stretch goal of below 5 bars

Mission Requirements

- achieved
- achieved to limited extent
- cannot be achieved

Tier 1 science

- 2-year orbital tour
  - high-inclination, 21-day orbit; nominal mission is 20 orbits
- good coverage in magnetic latitude and longitude
  - well distributed in latitude and longitude
  - periapse limited to S Pole unless ring hazard is retired to enable alternative UOI scenario

Tier 2 science

- shallow probe: descent to at least 1 bar, 5 bars if possible
  - < ~1-hour descent to 5 bars
- Enhanced Orbiter Payload
- Encounters with Large Satellites
- low periapse, ~1.1 Ru
  - limited by safe ring-plane-crossing range ≥ 52,000 km (outside Epsilon ring)
  - lower to inside of rings at end of mission after **ring hazard assessment**?
  - atmospheric drag at 1.1 Ru is safe, but would degrade gravity measurement
- tracking during periapse
  - delta-v cost to rotate orbit is prohibitive

Tier 3 science

- Orbiter payload further enhanced
- Enhanced probe payload

Payload

Currently all fit w/i mass and power constraints; cost is TBD

Orbiter

Floor

- Wide-angle camera
- Magnetometer
- Visible/Near-IR mapping spectrometer

Enhanced

- USO
- Mid-IR thermal detector
- UV imaging spectrograph
- Narrow-angle camera
- Plasma instrument

Probe

Floor

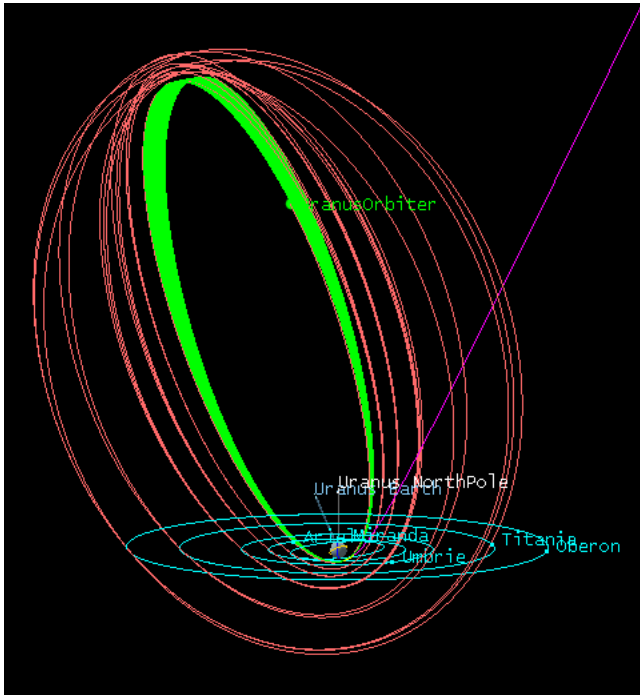
- Mass spectrometer
- Temperature-pressure sensors

Enhanced

- USO
- Nephelometer

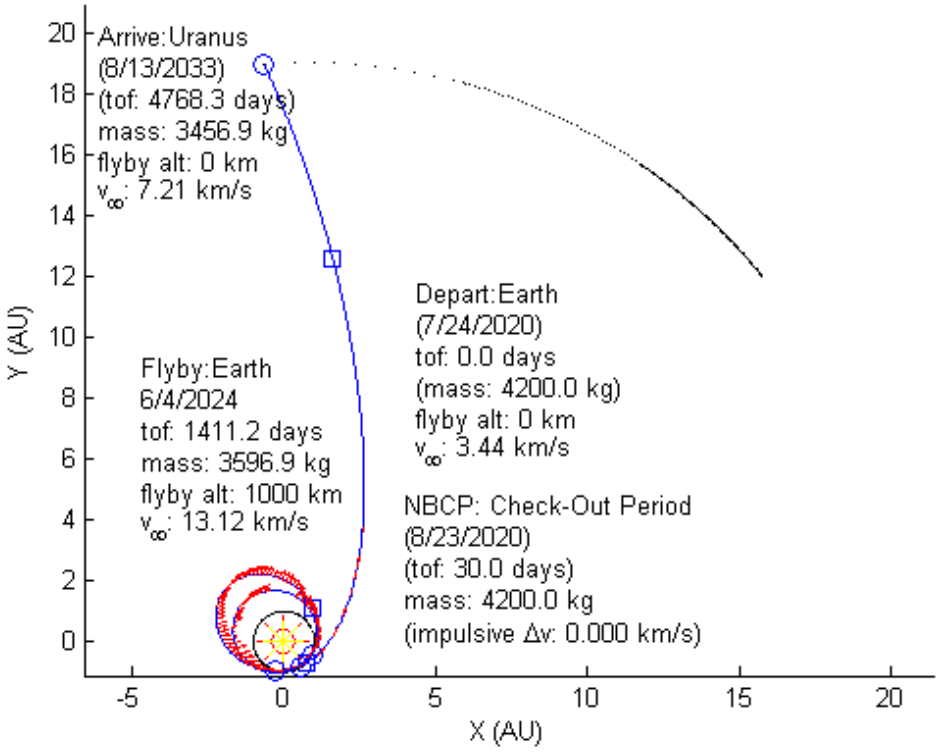
Mission Design Overview

- Baseline mission:
  - Launch: 2020 with 21 day launch period on Atlas V (531)
  - Cruise to Uranus: 13 years, SEP with one Earth flyby
  - Uranus arrival: 2033
  - Uranus atmosphere probe: released in a hyperbolic trajectory upon Uranus arrival, 29 days before Uranus orbit insertion
  - Uranus Orbiter: inserted into Uranus orbit after probe descent completion
  - Primary science orbit: 20 high inclined elliptic orbits around Uranus (431 days)
  - Secondary Uranus satellite tour: 10 targeted flybys of 5 major Uranus satellites (424 days)
  - Total Uranus orbit phase: 2.4 years (28.7 months)
  - Total baseline mission duration: 15.4 years
- Back launch: repeatable launch opportunities every year (2021-2023)



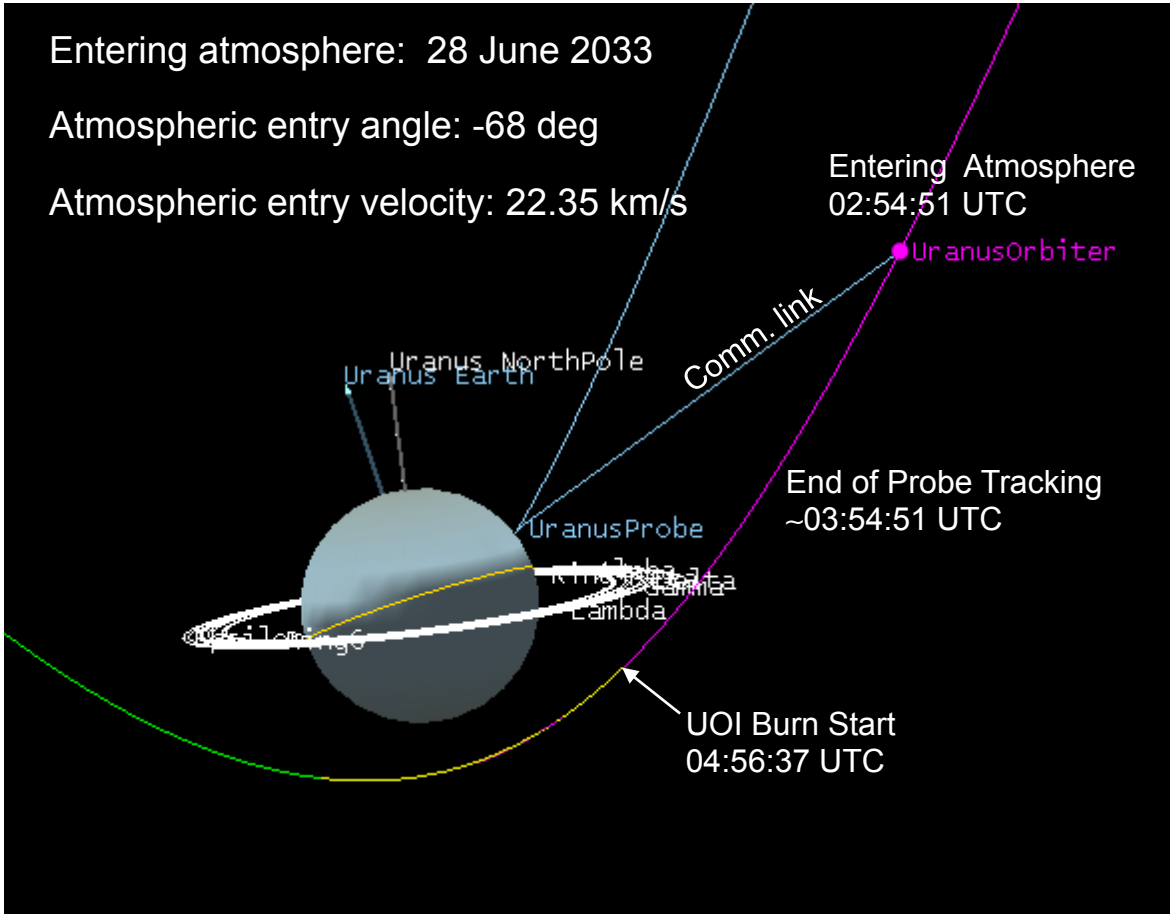
Interplanetary Trajectory

- **Solar electric propulsion trajectory with an Earth gravity assist**
  - 2 NEXT Engines
  - 20 kW Power (1 AU)
- **Assumed launch date of August 2020**
  - 20 day window
  - Launch C3 ≤ 11.83 km^2/s^2
  - Repeatable opportunities every yea
  - Atlas V 551 Launch Vehicle
- **7 Coast Periods**
  - 30 day checkout
  - 42 day prep for EGA
  - 5 other coast periods (20-30 days)
- **13 year cruise period**
  - SEP stage released after 5 years

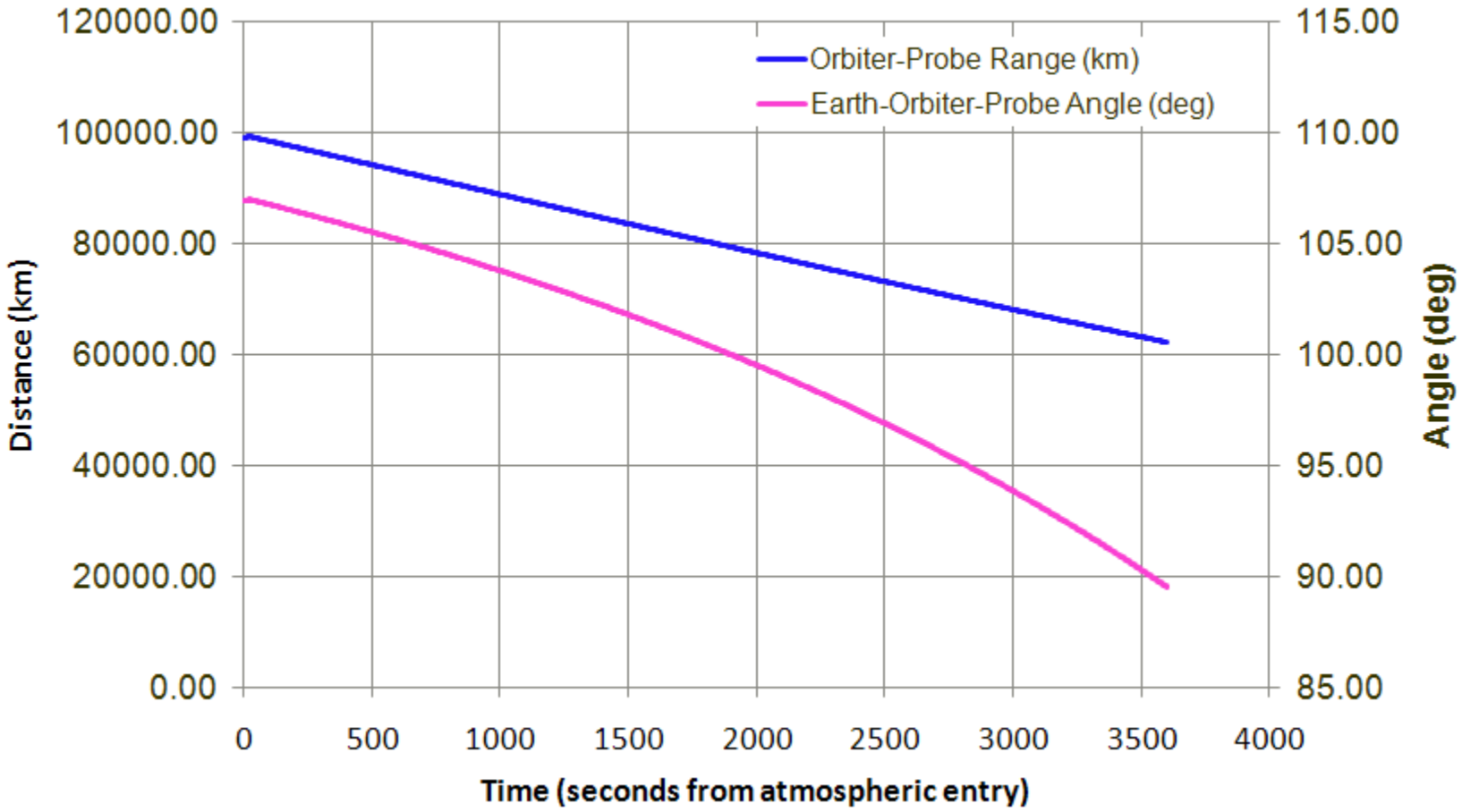


Uranus Capture and Probe Delivery

- **Probe is release 29 days prior to UOI**
  - Spin stabilized
- **One day after probe release, the orbiter will perform a deflection maneuver**
- **Probe is tracked by orbiter during entry and data is relayed to orbiter**
- **Probe collects data from 0.1-5 bars pressure for 1 hr**
- **UOI burn is conducted 1 hr after probe entry phase is completed**
  - 66.7 min burn
  - Delta-V = 1660.8 m/s
  - Contact with Earth is not possible during the burn



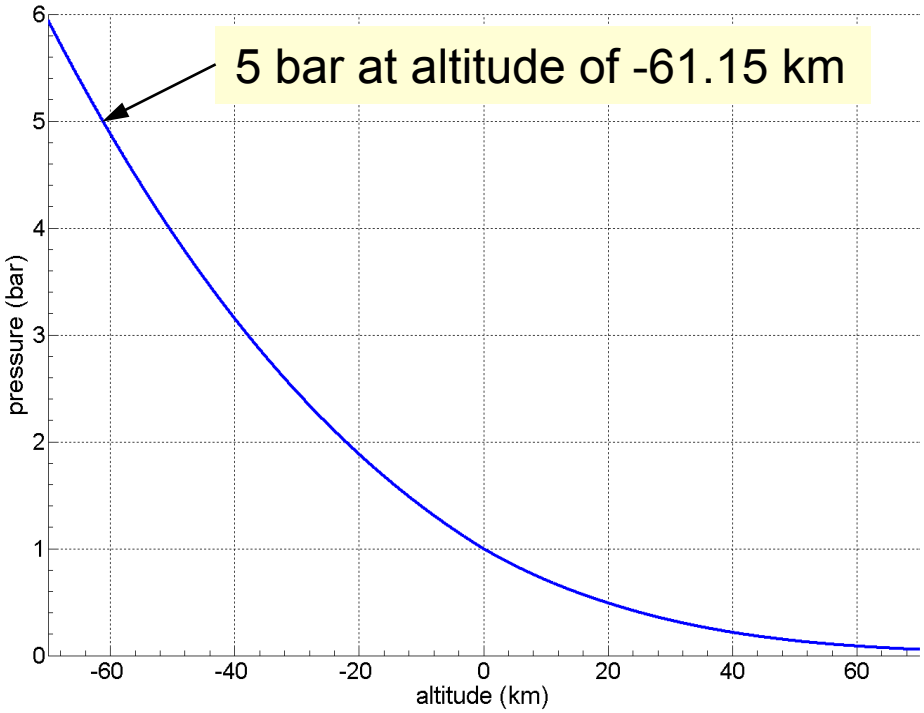
Probe-Orbiter Range During Atmospheric Descent



Probe Atmospheric Entry Modeling

- Probe mass: 127 kg
- Drag coefficient: 1.05
- Area: 0.45 m^2
- Atmosphere model provided by Brigette
  - Model starts at ~550 km altitude
  - Assumed to rotate with planet
  - Other assumptions
    - γ=1.3846
    - R=3,614.91 J/(kg K)

    (Planetary Data System)



$$\mathbf{a}_D = -\frac{1}{2}\frac{c_D A}{m}\rho v_{rel}\mathbf{v}_{rel} = -\frac{1}{2}\frac{\rho}{B}v_{rel}\mathbf{v}_{rel}$$

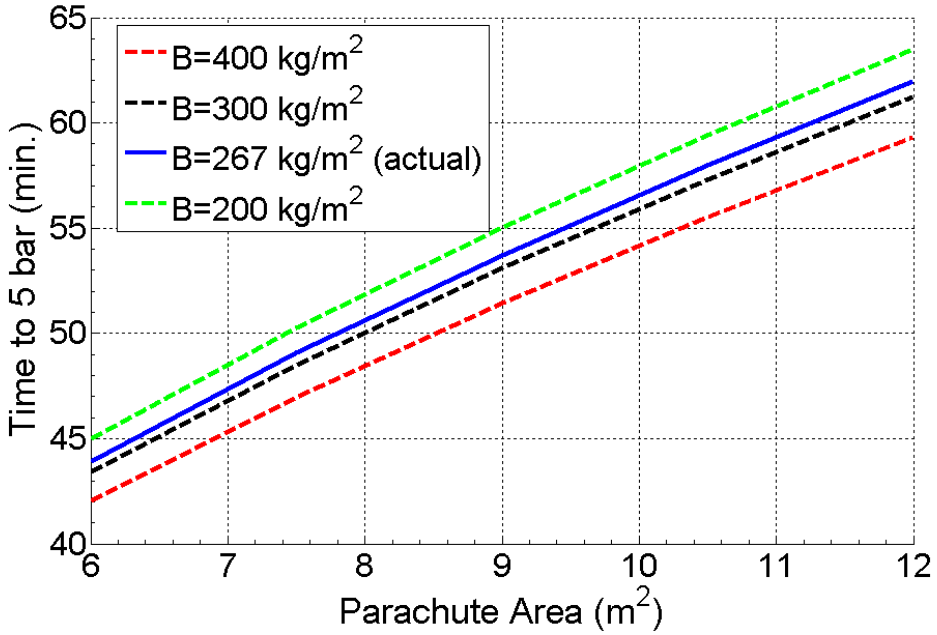
Parachute Area Selection Trade

- Total probe descent duration: ~60 min
- Uncertainty/margin: ~10 min
- Parachute area selected to obtain a nominal probe descent duration at ~50 min

Parachute coefficient of drag: 0.55

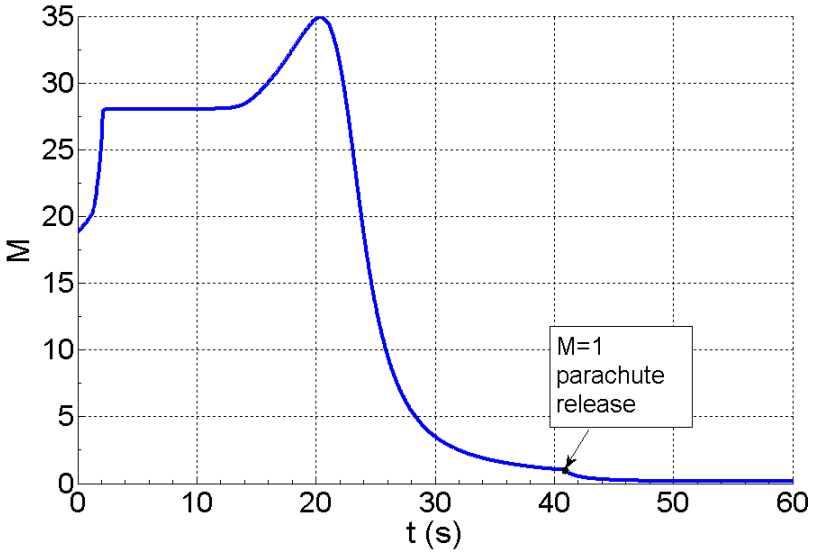
Area of parachute selected: 8.13 m^2

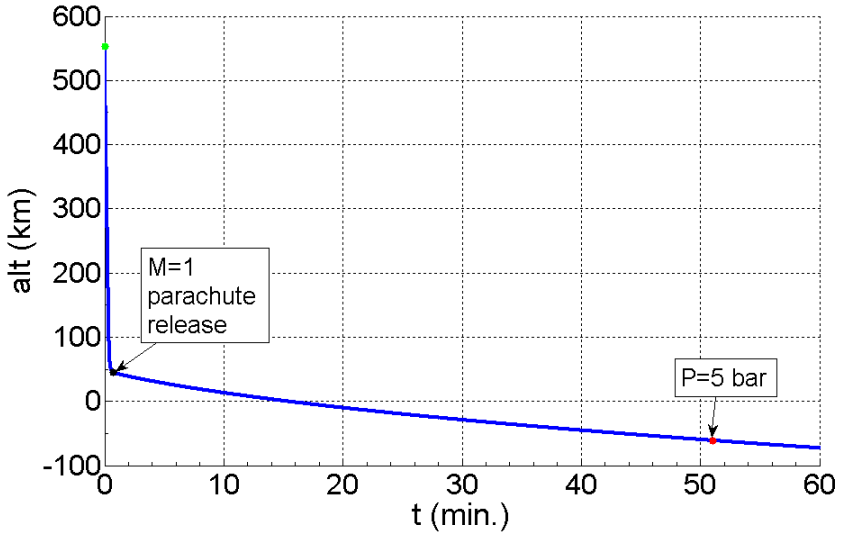
B is the ballistic coefficient



Probe Atmospheric Entry Timeline

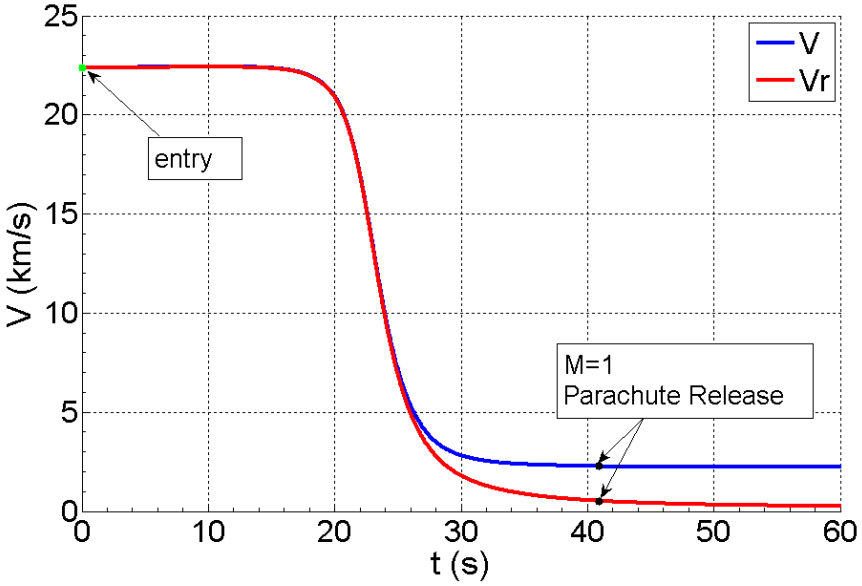
- Time from entry to M=1: ~41 s
- Time from entry to 5 bar: ~51 min
- Drogue parachute opens: <1 min. after entry (not modeled)
- Main parachute opens extending descent to ~1 hr
- (Reference: Galileo's probe descent ~60 min)
- Release parachute at ~45.5 km





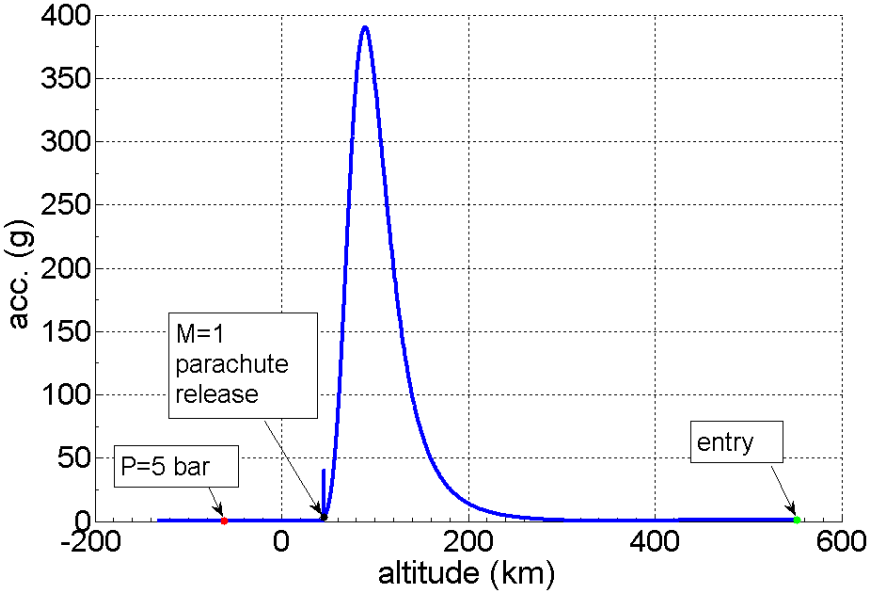
Probe Velocity and Deceleration

Probe Velocity



Blue line: inertial velocity
Red line: velocity wrt atmosphere

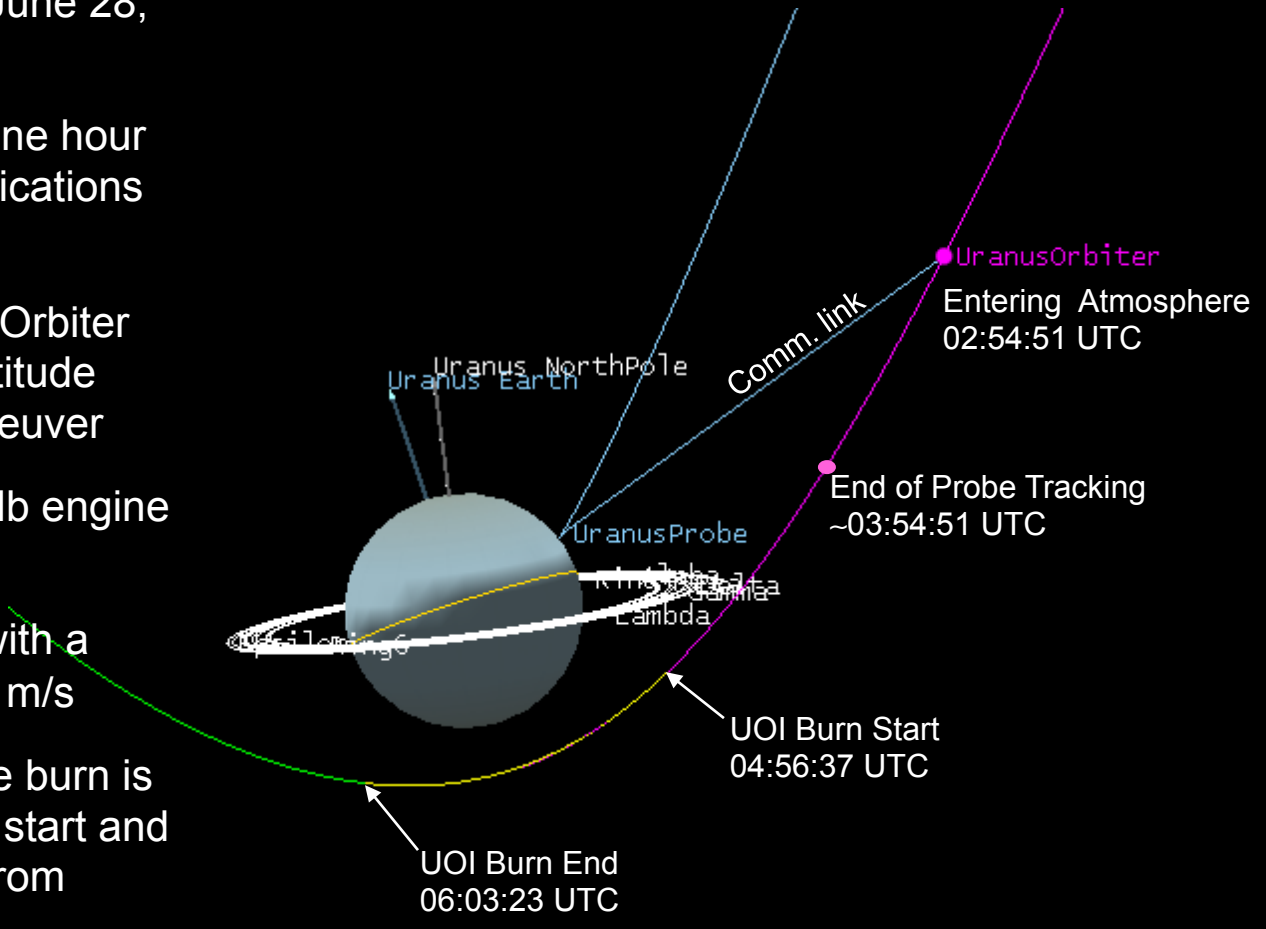
Probe Deceleration



Maximum deceleration likely an overestimate due to drag model

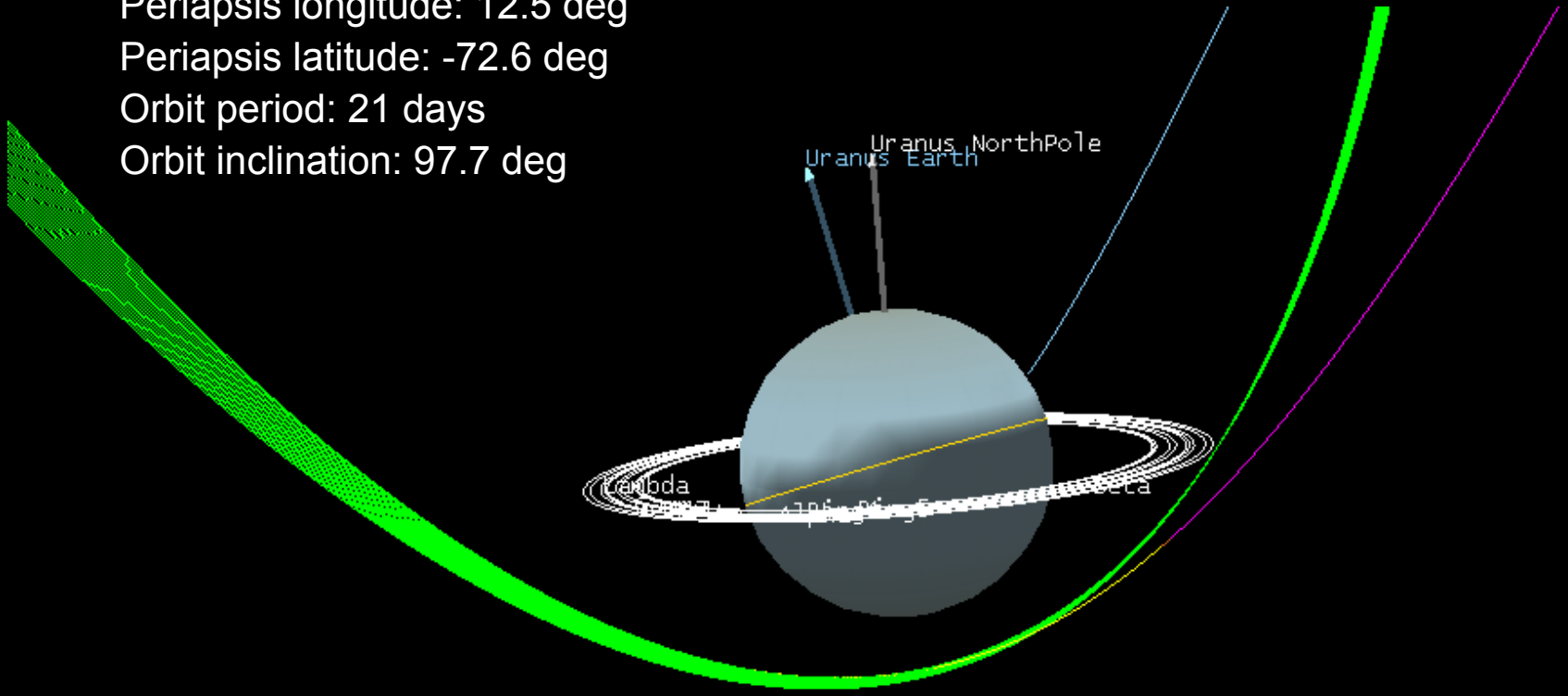
Uranus Orbit Insertion

- Uranus orbit insertion on June 28, 2033
- UOI burn will start about one hour after Probe relay communications completion
- The one-hour time allows Orbiter to slew to the UOI burn attitude and get ready for the maneuver
- UOI burn assumes a 150-lb engine of Isp=332 s
- UOI burn lasts 4006 sec with a burn magnitude of 1660.8 m/s
- Most of the time during the burn is not visible from Earth, but start and end of the burn is visible from Earth



Primary Science Orbit Phase (431 Days)

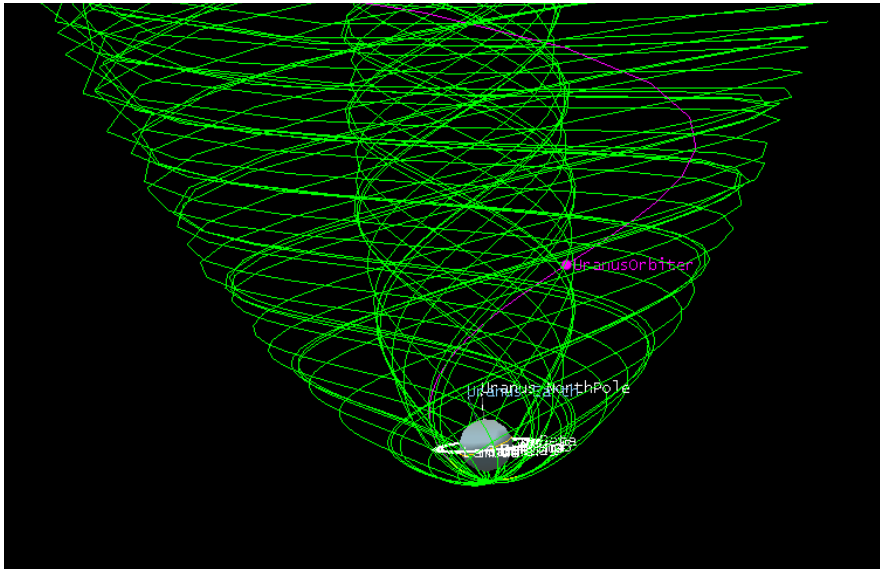
Periapsis radius: 33424.5 km (1.3 Ru)
Periapsis longitude: 12.5 deg
Periapsis latitude: -72.6 deg
Orbit period: 21 days
Orbit inclination: 97.7 deg



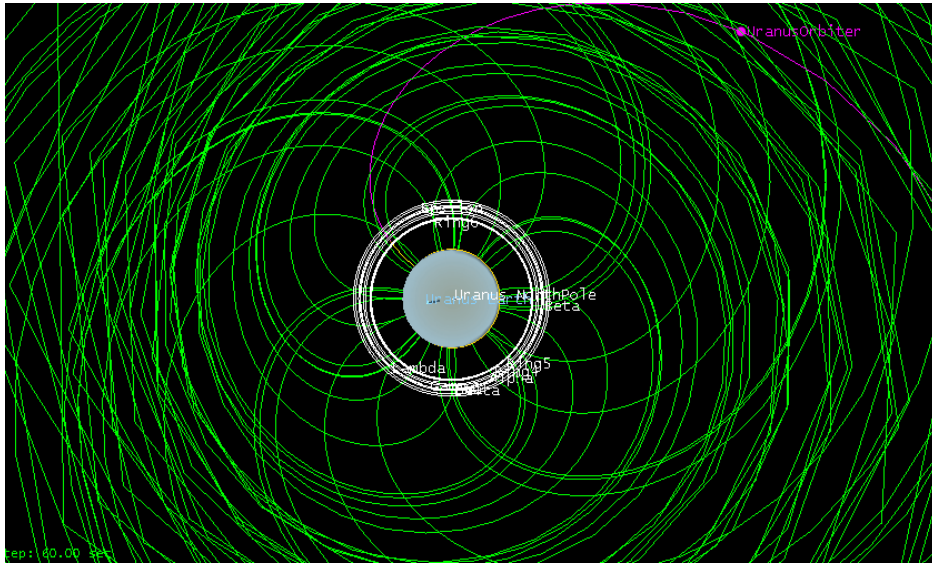
20 highly inclined elliptical orbits providing the desired science measurements (atmosphere, magnetic field, gravity field)

Uranus Observation Coverage

20 Science Orbits Plotted in Uranus Fixed Coordinate System
(purple line: incoming trajectory, green line: science orbits)



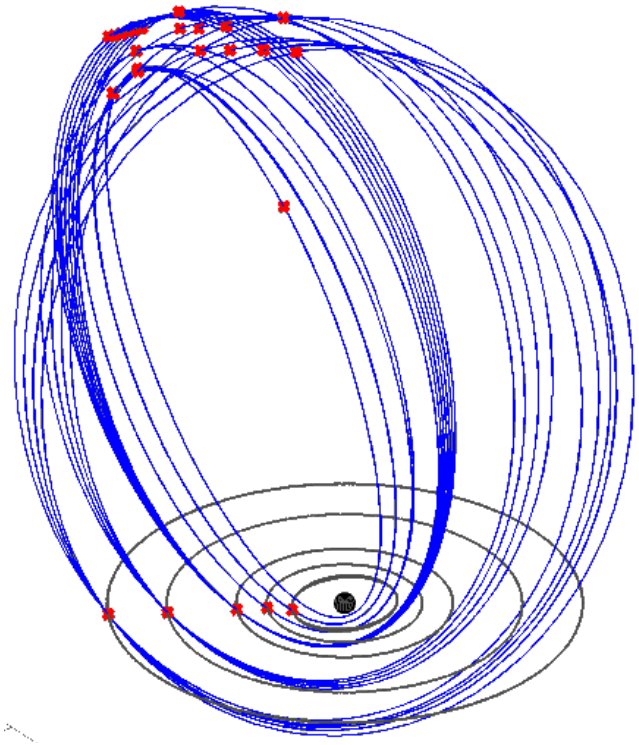
Side view



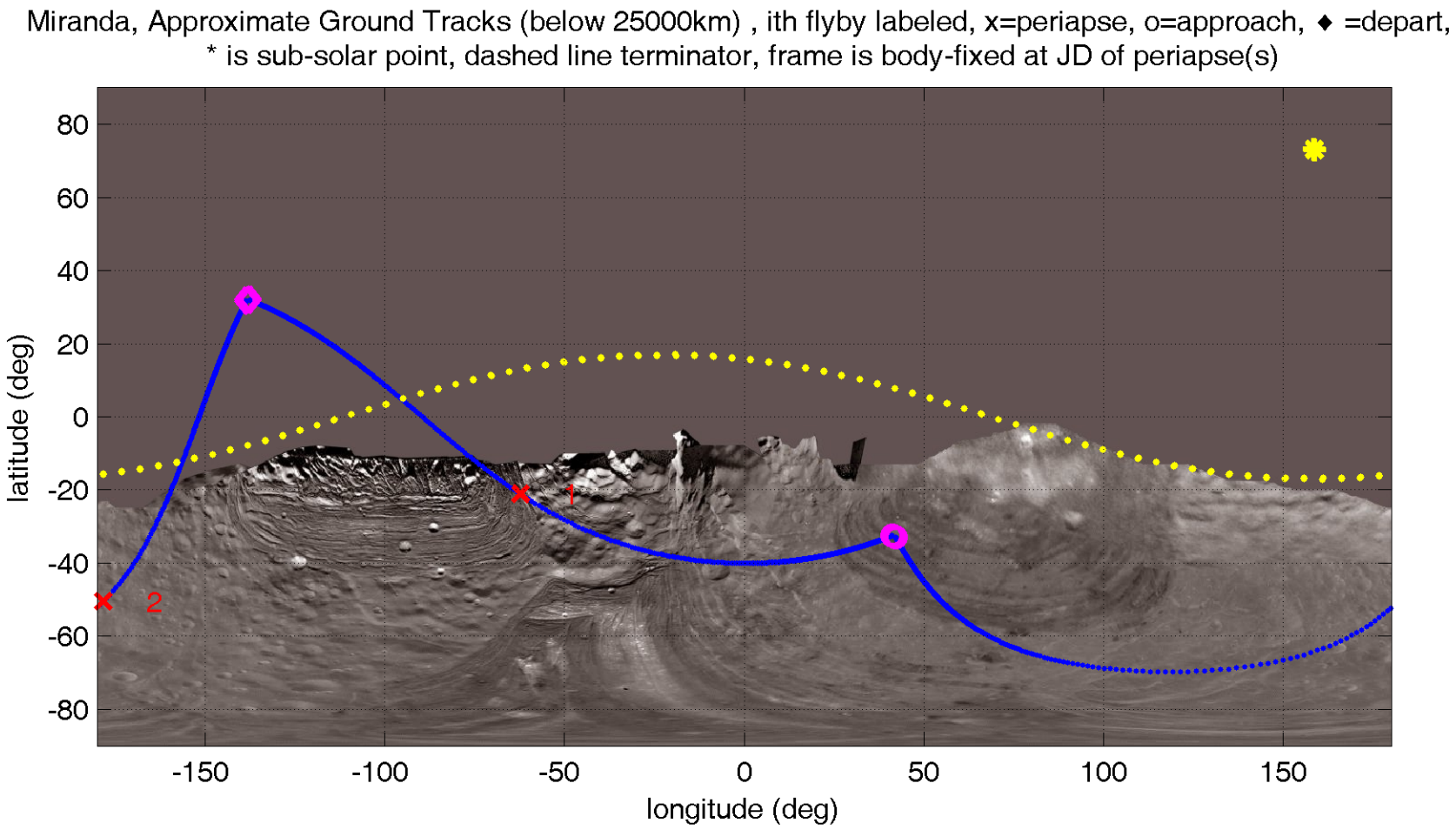
View above the equatorial plane

Satellite Tour

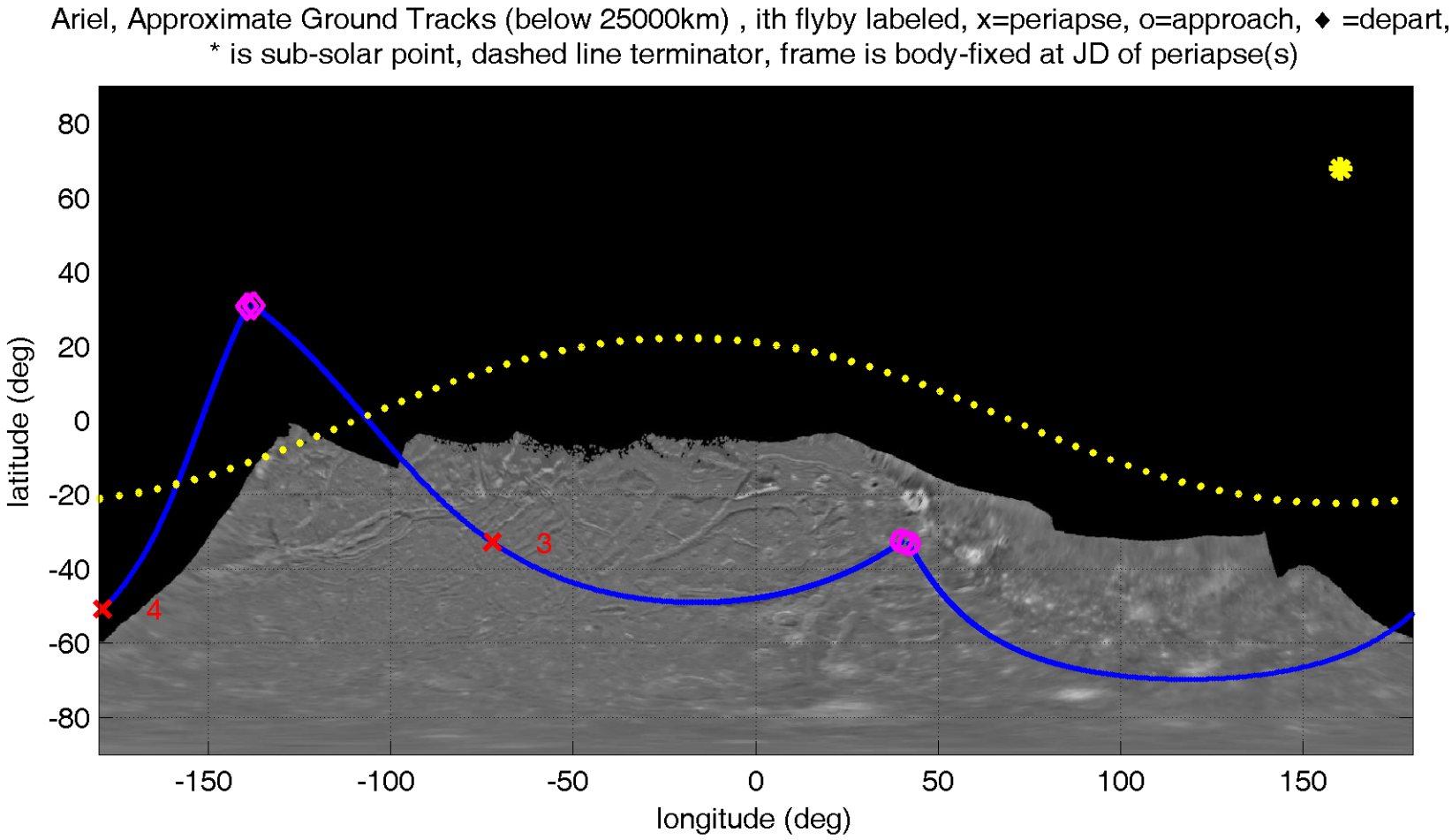
- **Tour Duration = 424 days**
- **Total Delta-V = 619 m/s**
- **10 total targeted flybys + 4 close untargeted flybys**
  - 2 Miranda (16:1)
  - 2 Ariel (10:1)
  - 2 Umbriel (6:1) + 4 close untargeted
  - 2 Titania (3:1)
  - 2 Oberon (2:1)
- **Closest approach for targeted flybys is 50 km altitude**



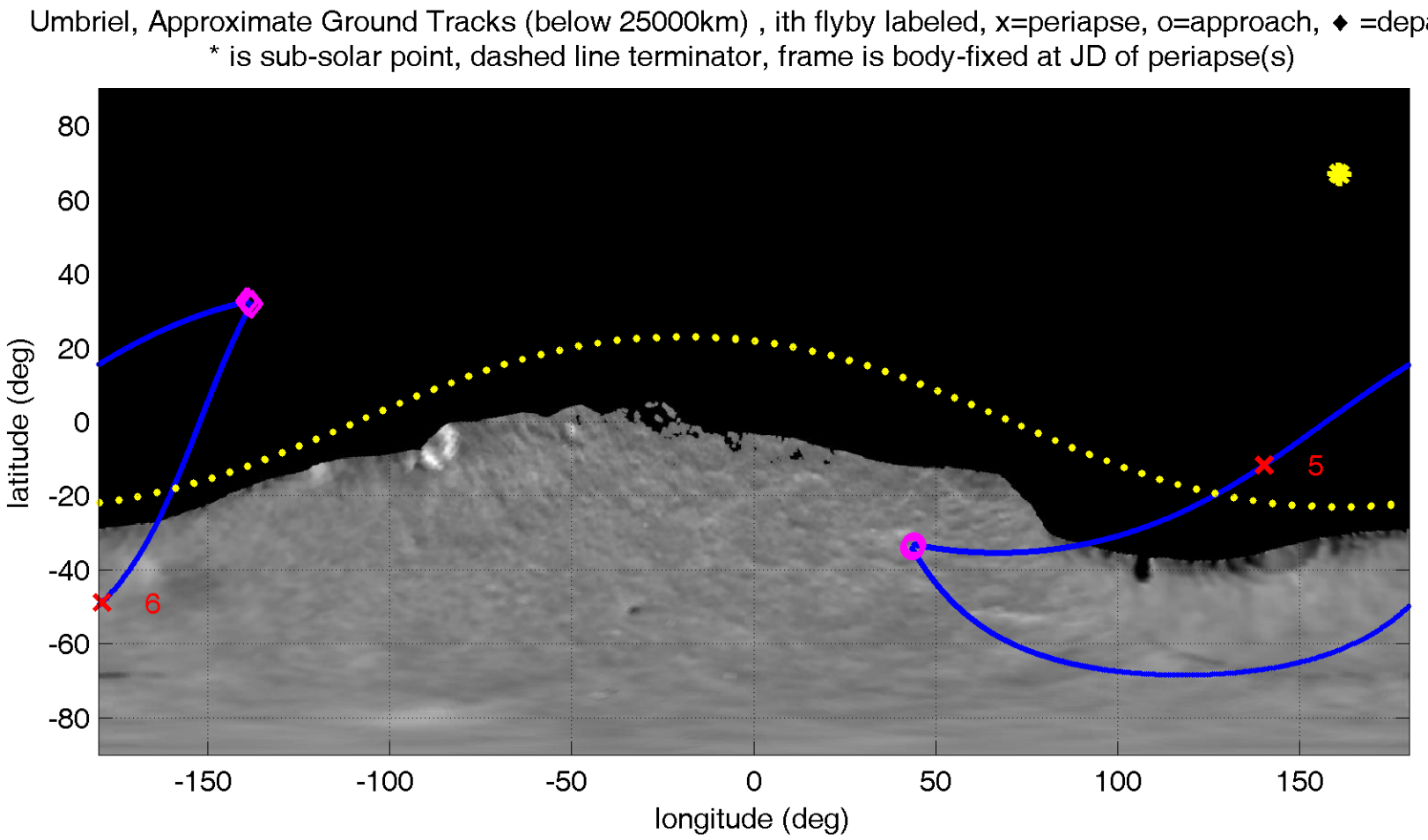
Baseline Tour: Miranda Ground Track



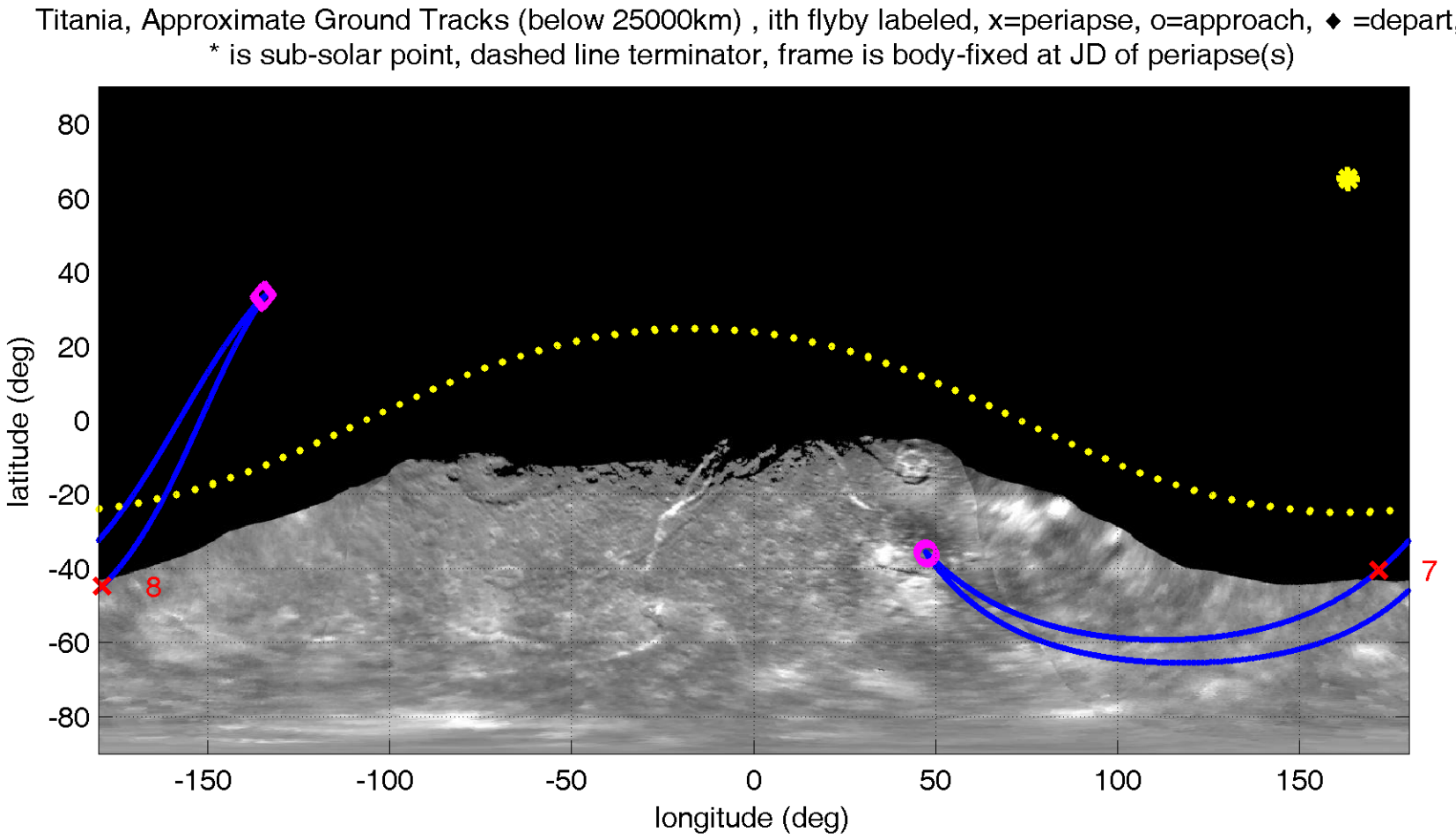
Baseline Tour: Ariel Ground Track



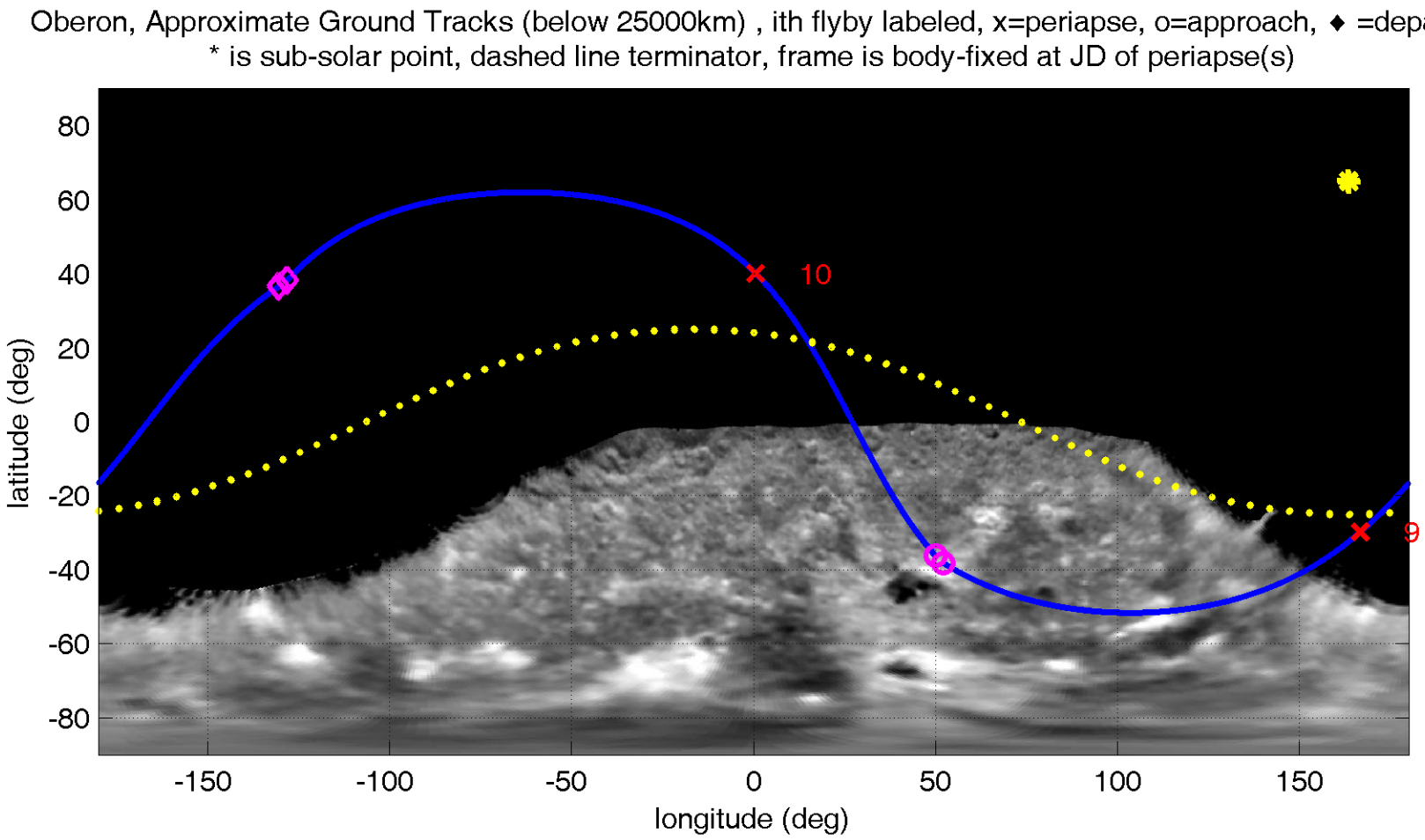
Baseline Tour: Umbriel Ground Track



Baseline Tour: Titania Ground Track



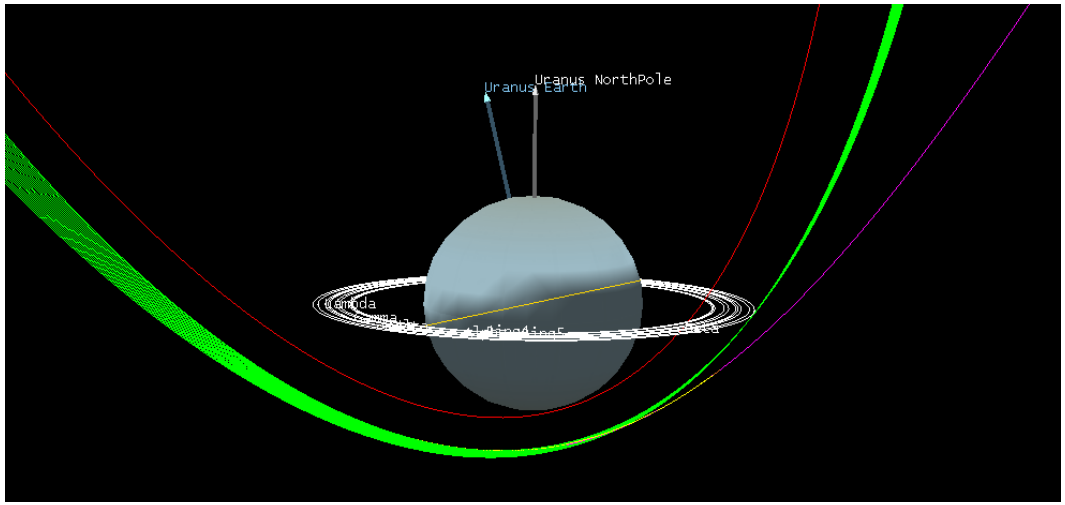
Baseline Tour: Oberon Ground Track



Option to Lower Periapse at the End of Science Orbit Phase

- Periapse closer to Uranus is desired for measuring gravity field J6 term
- Due to the ring crossing constraint, the achievable minimum periapsis radius is 1.3 Ru for the science orbit
- Periapse altitude can be lowered near the end of science orbit phase if desired, after assessment in the early part of the mission of the hazard posted by the environment inside the rings
- The closest periapsis distance possible is limited by the spacecraft heating rate, which is estimated in the range between 25,600 km and 26,000 km

- Delta-V required for periapse change: 56 m/s
- For periapse of 25,600 km, the min altitudes before and post Earth occultation are:
  - Ingress altitude: 6961 km
  - Egress altitude: 6170 km
  - Occultation duration: 2623.3 s



Mission Drivers

#	Driver	Mission Concept Impacts
1	Flexible launch year	SEP stage with Earth Flyby
2	Distance for communications	3 ASRGs to accommodate 40 W RF TWTA
3	Shallow Entry Probe	Conduct probe science up to 1 hour prior to UOI
		Communications system that requires mono-pulse tracking of the probe
4	Limited launch capacity	Maximum mission duration of 15.5 years
5	Chemical propulsion for UOI	
6	Avoiding rings	Initial periapse of 1.3 AU
		Earth occulted at periapse
		Steep entry angle for probe and higher g loading
7	Satellite Tour	Adds significantly to Delta-V budget and propellant load

Major Mission Trade Studies

Area	Trade Options	Results
Destination	Uranus or Neptune	• Uranus cruise time is 13 years with chemical capture and no JGA • Neptune requires aerocapture or >15 year cruise • Panel selected Uranus as destination
Capture Approach	Chemical vs Aerocapture	• Aerocapture begins to offer mass advantages if capture delta-V is over 2 km/s • For Uranus mission capture delta-V is 1660 m/s • Spacecraft packaging and probe accommodations are much more more challenging with aerocapture • Aerocapture would require $150-$200 M of technology investment to be ready for flight including a previous flight demonstration
Uranus Periapse	Altitude, Viewing Geometry	• Due to ring crossing constraints periapse cannot be below 1.3 Ru and cannot be in view of Earth. • A periapse of 1.1 Ru can be achieved if the trajectory is allowed to come inside of the rings. This is something that could be evaluated during the mission for safety and performed if the risk was deemed acceptable
Data Return	Dish size, power, array ground stations, others	• Basic science can be met with data return capability established in previous study (7.5 kbps, single 34 m ground station, 8 hour per day contacts) • ASRG architecture cannot support higher power TWTA • Dish is sized to 2.5 m to balance pointing requirements, cost, and RF performance • Adequate science can be returned without arraying DSN antennas
Instruments and Satellite Tour	Full Enhanced Mission with Tour Remove Tour Remove Probe Floor Instruments Only	• The full enhanced mission with tour can be achieved from a technical perspective within the cost cap ($1,894M) • Removing probe reduces cost by $310M • Removing the tour reduces cost by $26 • Removing Enhanced Instruments reduces cost by $120M

Significant Flight Element Trades

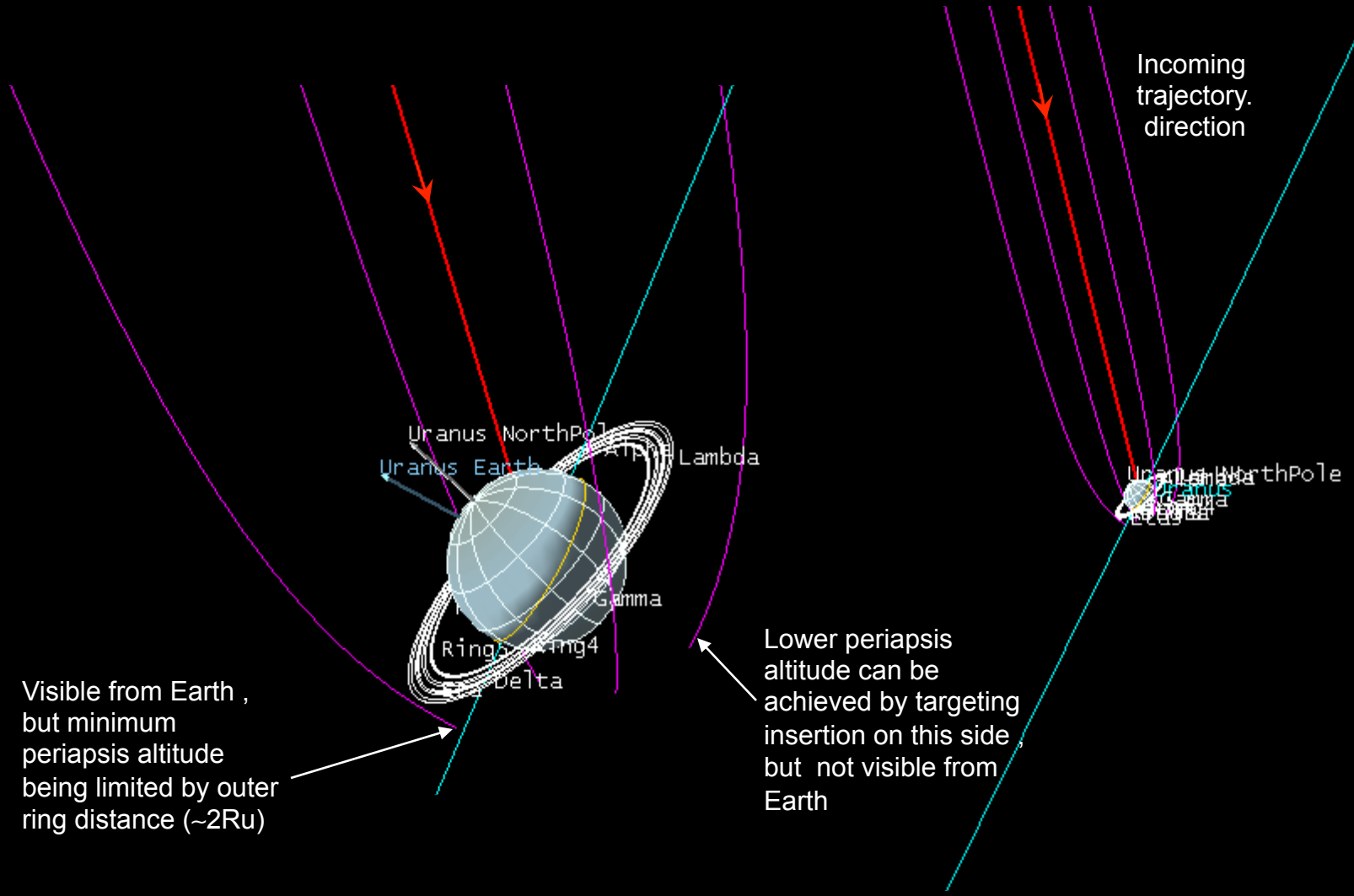
Area	Trade Options	Results
SEP Power Trades	1-3 NEXT Engines, 15-25 kW	• Full mission can be accomplished with 2 NEXT engines and 20 kW of power • More power does provided modest increase in delivered payload performance
Probe Accommodation with Spacecraft	Spin stabilize with spacecraft rotation or spin table, probe placement	• Probe was placed on the bottom and the spacecraft will spin up to release
Probe Power, Activation, and Thermal Control	Activate on timer or command RHU vs battery power	• Use 4 RHUs to minimize power during probe free flight • Checkout probe 2 times prior to entry • Activate probe based on timer
Attitude Control	Wheels vs thruster control on orbiter, SEP stage or both.	• Wheels will meet science requirements • Thrusters provided no advantage in power • Wheels should be able to last 16 years • Orbiter wheels sufficient to control SEP stage

Top Mission Risk Table

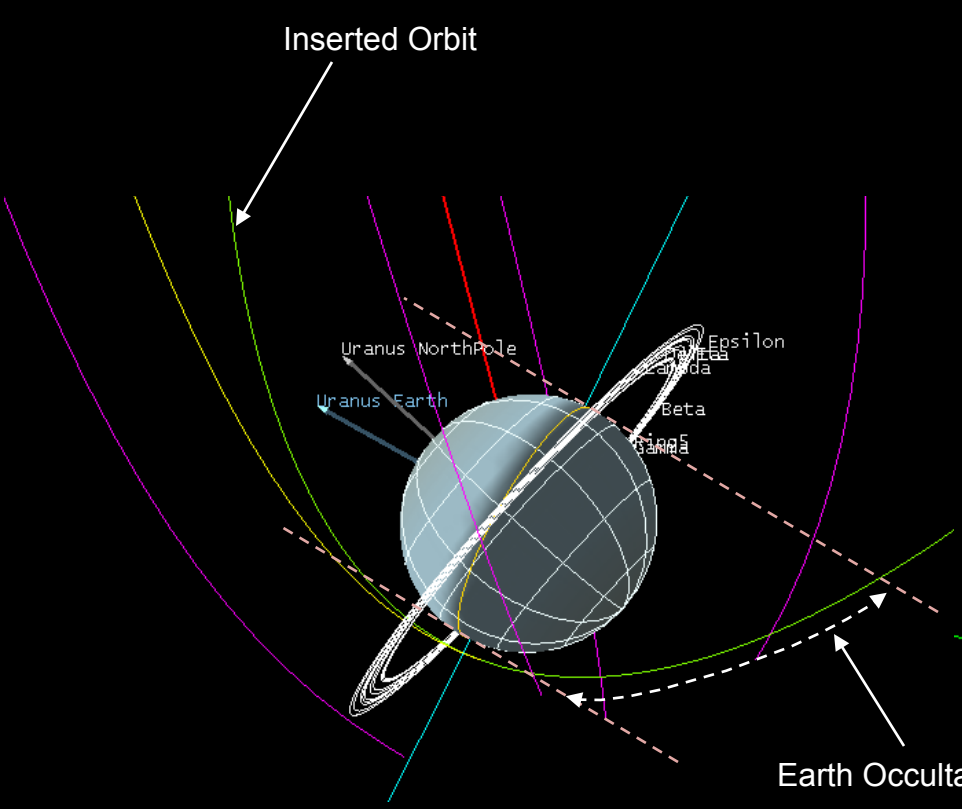
#	Risk	Type	L	C	Mitigation
1	**If the complexity of conducting the probe science prior to UOI is too high, the probe science would be descoped**	Technical	2	4	• Comprehensive analysis and test program • More rehearsals prior to event
2	**If there are problems in the development of a new SEP stage then the schedule could be impacted**	Schedule	2	3	• Develop a SEP stage demonstrator as a technology risk reduction
3	If mass spectrometer has development problems, then schedule will be impacted	Schedule	2	3	• Mass spectrometers are complex instruments and development will need to begin early
4	If significant issues with an Earth flyby develop, then mission schedule could be impacted.	Schedule	1	4	• Keep flyby distance ≥1000 km altitude • Begin approval process as early as possible • Jupiter or Saturn gravity assisted trajectory mitigates Earth flyby
5	**If UOI becomes technically complex due to no contact, then mission schedule will be impacted**	Schedule	1	4	• Assess UOI approach early • Assess required autonomy and associated cost and schedule to develop and test
6	**If there is difficulty developing a large (20 kW) array, then schedule could be impacted**	Schedule	1	3	• Develop and demonstrate a large parasol array as part of a technology risk reduction effort
7	If the orbiter cannot track the probe, then mission performance will be impacted	Technical	1	3	• Develop and test tracking system early • Plan for significant modeling and analysis of probe entry and tracking problem
8	If an ASRG fails, the mission will be degraded	Technical	1	3	• Qualify ASRG for longer life • Limit storage time prior to launch with fueled ASRG to 1 year
9	**If system reliability is not shown to be adequate for long mission, then cost will be impacted**	Cost	1	3	• Perform reliability analysis early to assess weaknesses in system • Assess system architecture options to improve reliability
10	If the peak acceleration loads have a large impact on the probe design, mission cost could be impacted.	Cost	1	3	• Qualify electronics and batteries for environment

Orbit Insertion Constraint: Incoming Asymptote

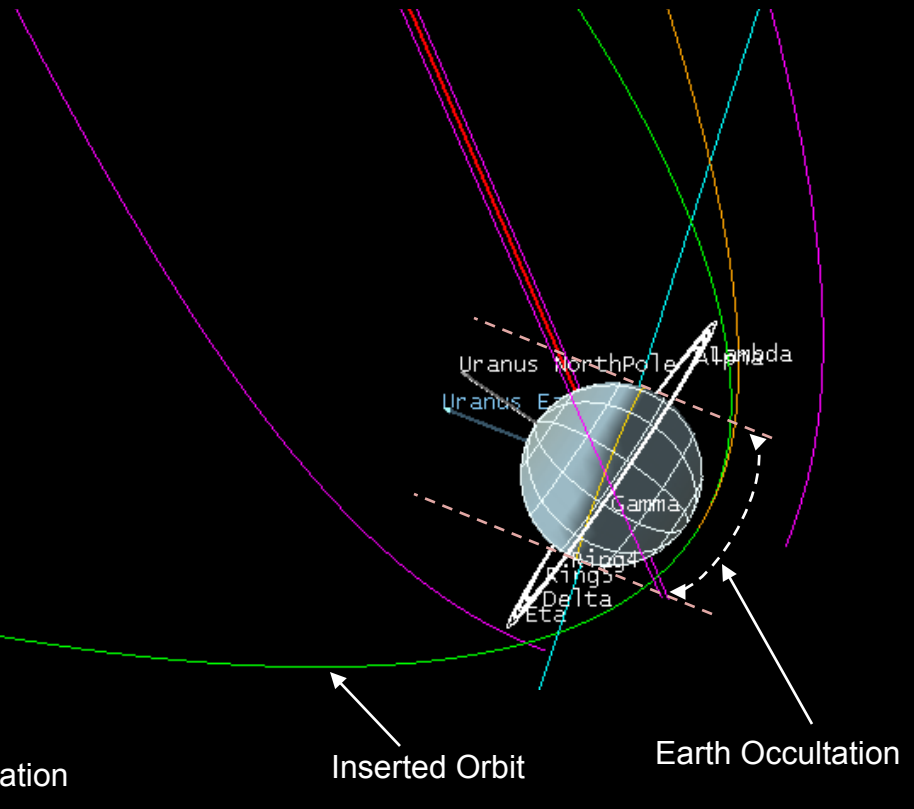
Draft



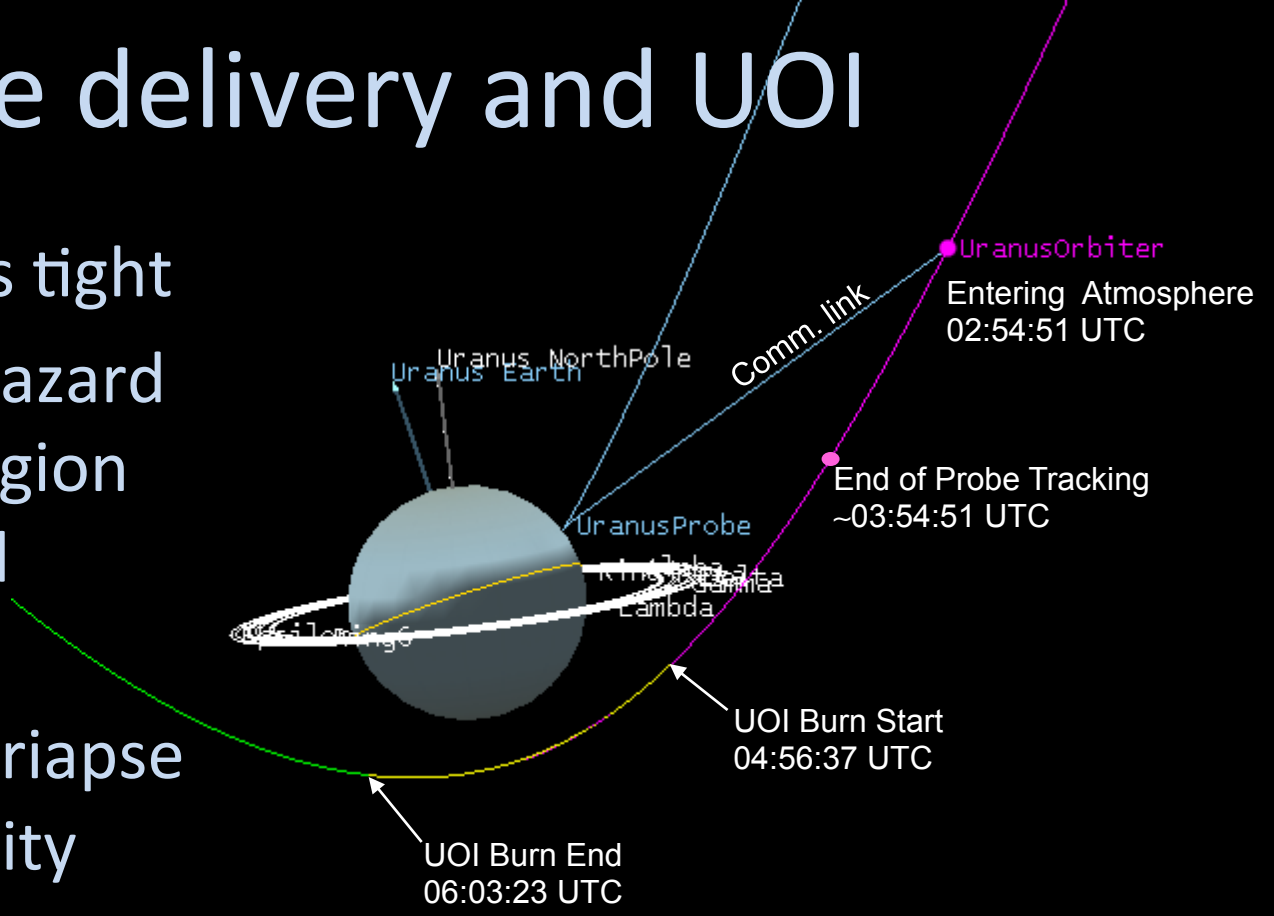
Orbit Insertion Trade



Orbit inserted inside the rings: periapse visible from Earth



Orbit inserted outside the rings: periapse not visible from Earth

Probe delivery and UOI

- Sequence timing is tight
- Avoids rings and hazard associated with region between rings and planet
- Trade between periapse altitude and visibility during UOI burn
- High probe entry angle
- This aspect of a Uranus mission needs particular study – catch-22 of being unable to retire risk in region between rings and planet without a Uranus mission…