NEP Capabilities for Uranus and the Outer Planets: Power, Maneuverability and Faster Transit Times

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ANALYTICAL MECHANICS ASSOCIATES

Outline

- Overall NEP Capability to Outer Planets
- Uranus Study Goals
- Uranus Mission Options
- NEP Vehicle

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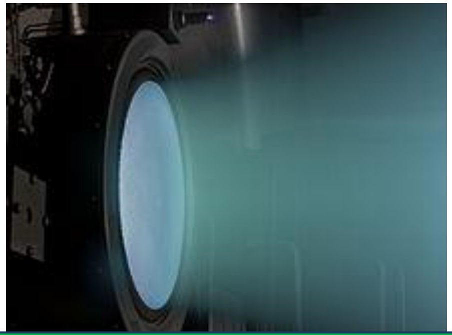
Analytical Mechanics Associates, Inc. was funded for this effort under Contract No. 80LARC23DA003.

10-40 kW Electric Propulsion in Outer Solar System

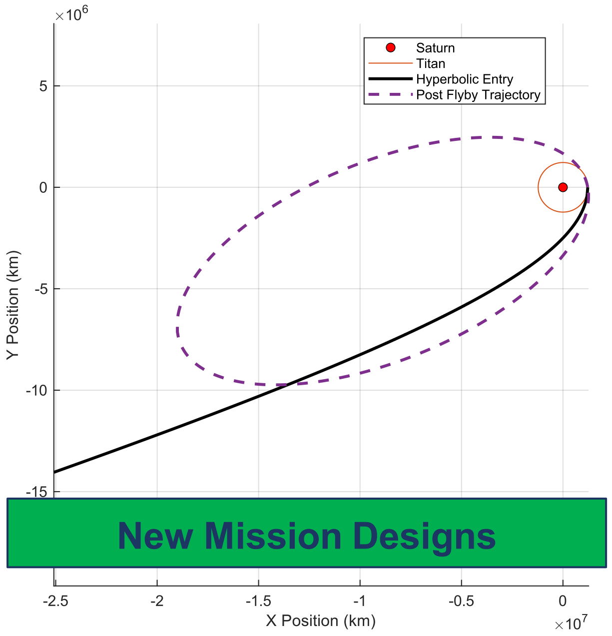
- Expanded possibilities for mission design
  - Optimize for trip time, payload, thruster life, or launch window flexibility
  - Design maneuvers for plane changes, moon tours, icy moon orbit insertion, non-Keplerian orbits



Electric Propulsion everywhere in the solar system

Examples:

- Outer planet arrival V_∞ can be reduced compared to a ballistic trajectory
  - Optimize a chemical orbit-insertion burn to reduce system mass
  - Capture into orbit by an unpowered moon flyby gravity assist
- Moon tour V_∞-leveraging trajectories can be executed
  - With much less propellant mass
  - With fewer flybys, thus faster
- Departure from outer planets and moons for sample return



New Mission Designs

Electric Power at Destination

- Science campaign CONOPS no longer power-limited
  - Instruments can all operate simultaneously
  - Data collection campaign not limited by power budgeting
- Kilowatts are available for high data rate downlink
- Together, these two capabilities mean:
  - Instruments can collect data more continuously and simultaneously, not limited by downlink capacity
  - A larger data volume can be returned to Earth
- New high-power (and higher mass) instrument types possible

What will you do with more power?

Nep-Enabled Time of Flight to Outer Planets

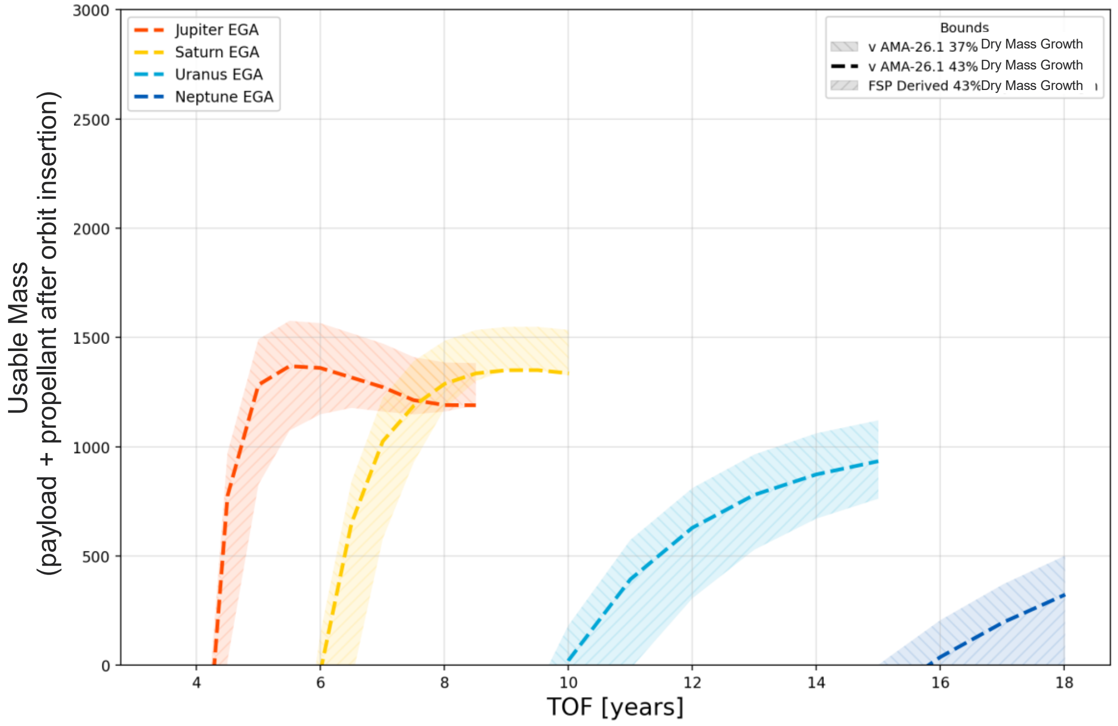
Fastest TOF to each planet with 300 kg payload and corresponding NEP system power

	Jupiter	Saturn	Uranus	Neptune
Falcon Heavy Expendable	4.5 years (33 kWe)	4.5 years (30 kWe)	11 years (25 kWe)	17 years (26 kWe)
New Glenn 9x4	4.5 years (25 kWe)	4.5 years (45 kWe)	9.5 years (30 kWe)	14.5 years (35 kWe)
Starship Partially Refueled	3.5 years (120 kWe)	4.5 years (60 kWe)	9 years (150 kWe)	12 years (80 kWe)
SLS B1B	4 years (140 kWe)	4 years (110 kWe)	8 years (120 kWe)	11.5 years (80 kWe)
SLS Block 2	2.5 years (165 kWe)	4 years (115 kWe)	9 years (170 kWe)	11 years (118 kWe)

Color Key:
Direct
One EGA

Preliminary Estimate of Useful Mass Deliverable
as a Function of Time of Flight

Outer Planets Usable Mass
4000 s I_{sp} NEP, Optimal Power,
Falcon Heavy Expendable Launch, One EGA



Outer Planets Usable Mass
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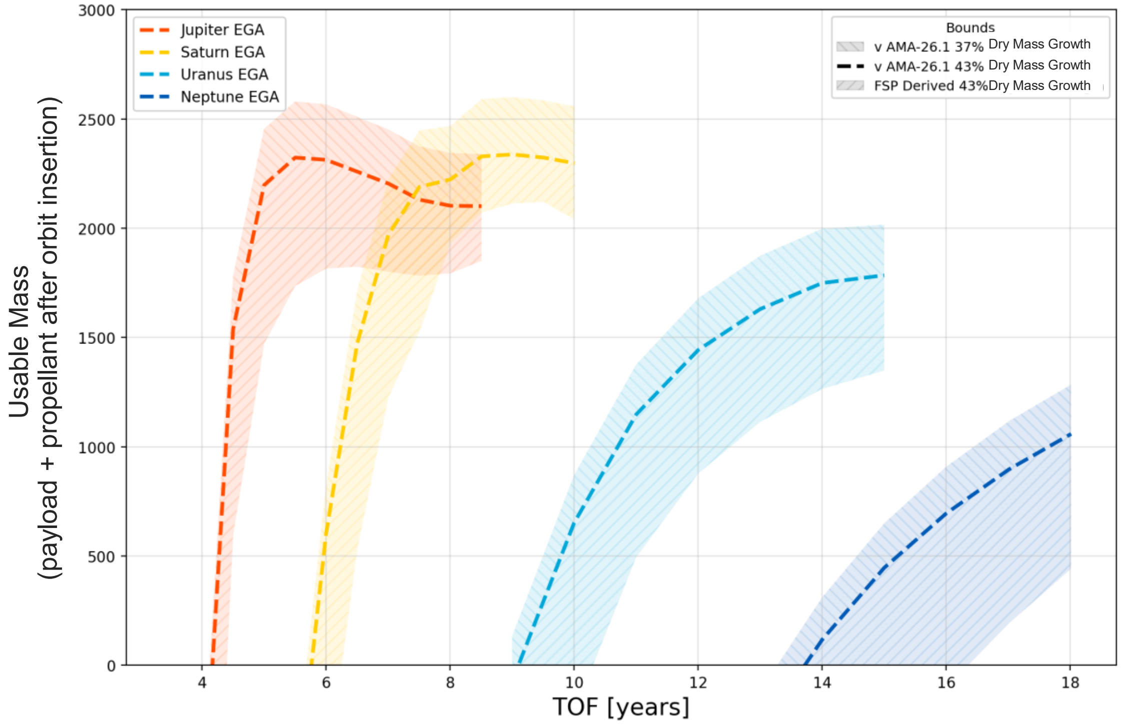
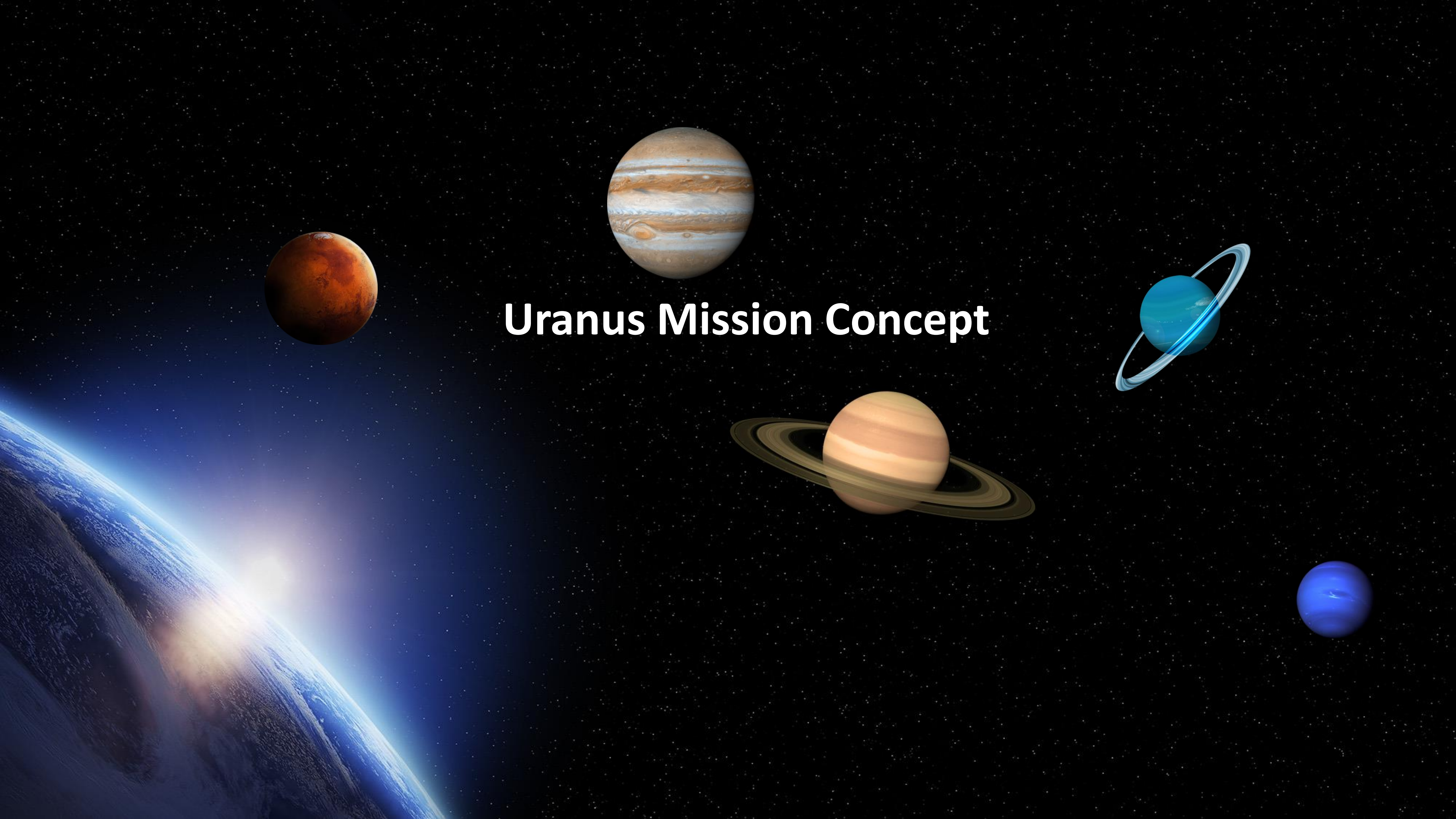


Note: For any given point design, the available usable mass may differ due to the spacecraft design details, power system design, trajectory design, margin policy. This chart reflects trajectories with one Earth flyby about two years after launch and a power system sized for the optimal power level for a given trajectory.

Uranus Mission Concept

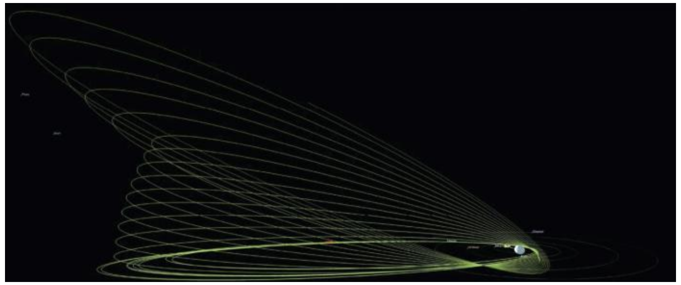


Roster of our Team & SMEs

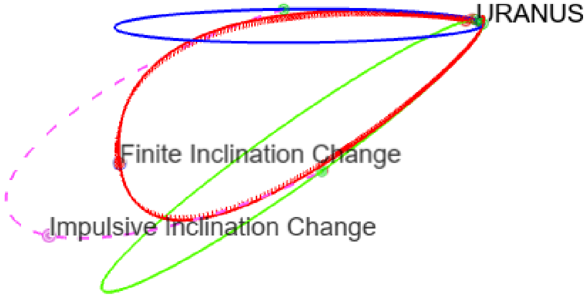
Team Member	Organization	Role
Matthew Duchek	AMA	Lead/PI
Adam Boylston	AMA	Mission Modeler & Spacecraft
Sean Greenhalge	AMA	Mission Modeler
Emanuel Grella	AMA	PMAD & Communications Design
Chris Harnack	AMA	Power Conversion System Design
Will Machemer	AMA	Radiator Design
Regan O’Neill	AMA	Instrumentation & Spacecraft CAD – Intern
Bella Shaffer	AMA	Mission Modeler – Uranus Sphere of Influence
Corey Smith	AMA	Reactor Design
Jason Hofgartner	SWRI	Moon Science SME
Alexander Hayes	Cornell	Moon Science SME
Carol Paty	University of Oregon	Magnetosphere science SME
Roger Myers	R Myers Consulting	Advisory SME
DV	INL	Nuclear Reactor SME

Study Goal:
Illustrate a NEP-enabled mission to engage the science community

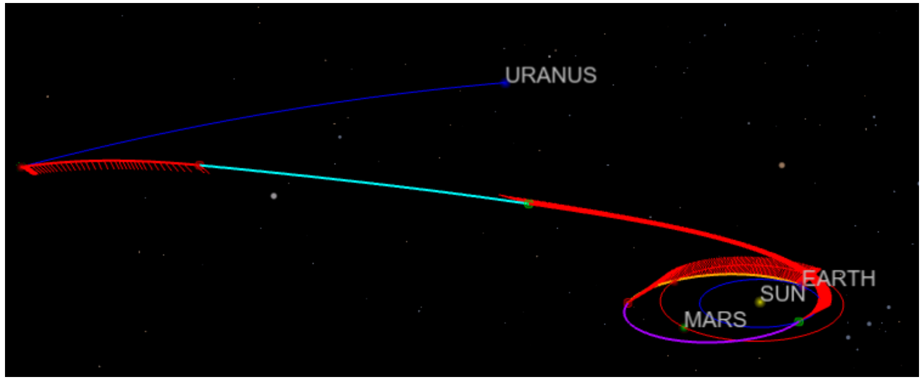
1. Illustrate the NEP system
2. Interplanetary transit responsive to feedback from first workshop (more focus on trip time and propulsion at destination)
3. NEP-enabled propulsion at destination
4. NEP-enabled data budget & instrument CONOPS



Uranus Orbiter & Probe Titania Flybys Major Moons



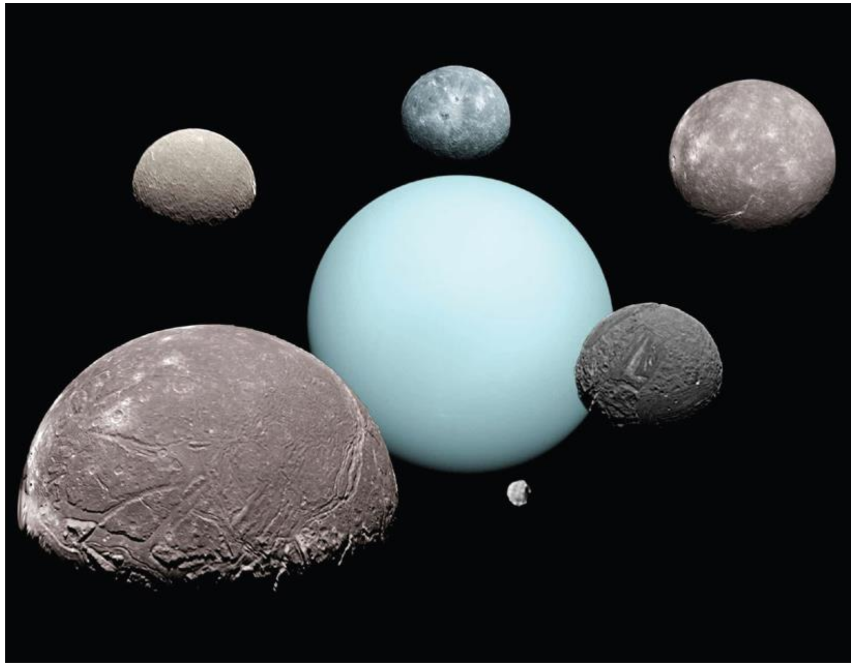
NEP-Enabled inclination change in much less time



Uranus Flagship Mission Context

- Uranus Orbiter and Probe Flagship Mission was prioritized in the most recent decadal study.
  - Uses a Jupiter gravity assist and FHe launching in ideally 2032, later dates possible with inner solar system cruise
  - 13- to 14-year cruise
  - Ideally arrives by 2050 to take observations at the moment of equinox
  - Highly elliptical Uranus orbits and flybys of major moons
- Can NEP avoid Jupiter gravity assist and enable a similar, but enhanced mission?
  - Launch 2038 with 12-year cruise arrives in 2050 for the equinox
  - Cassini-type mission at Uranus (many flybys of many objects)

Regardless of the arrival date and schedule feasibility, UOP comparison point is valuable to understand capability.



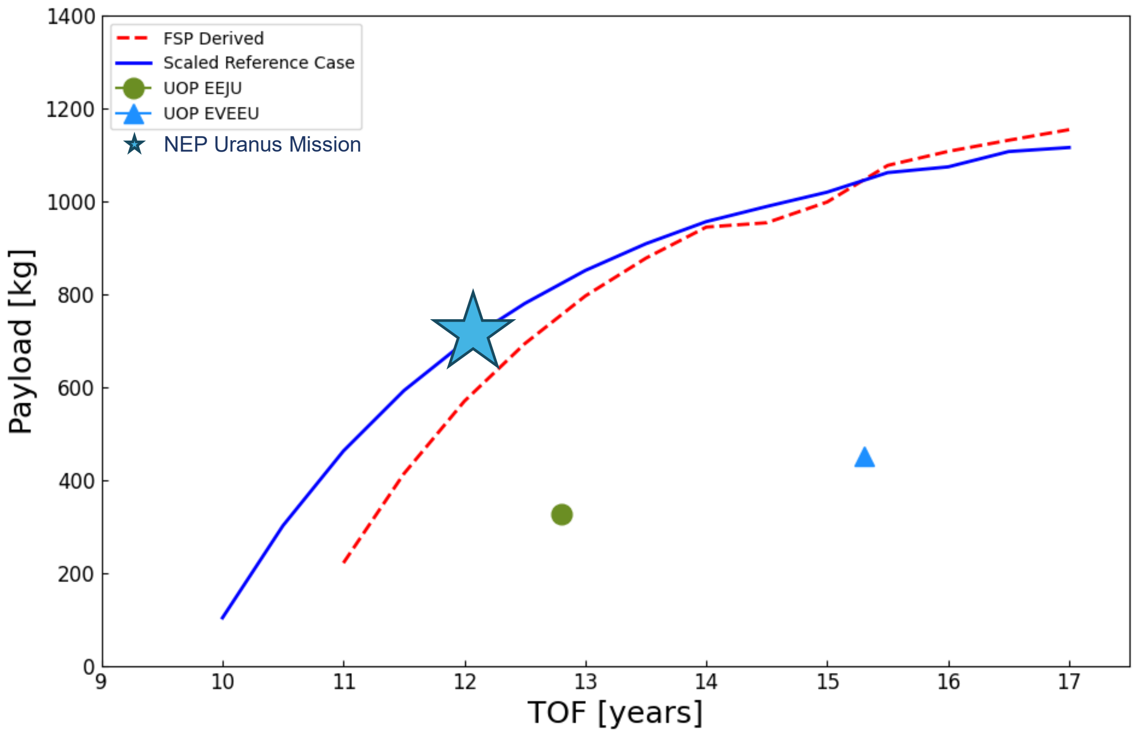
Mission Goals

Informed by science input at Accelerating Space Science Workshop and subsequent meetings with planetary scientists

- Shorter time of flight (TOF) to planet → 12 years
- Launch window flexibility → 1 per year, no Jupiter flyby
- Maneuvering capability in orbit of target planet → NEP to equatorialize, speed up moon tour, orbit a moon
- Small amount of more instrument/probe payload → This iteration assumes the UOP payload
- Higher data return by higher data rate → 2 kWe comm
- Analysis covers a wide trade space of mission parameters
- We maximize usable delivered mass over a range of TOF from minimum TOF to maximum usable mass

NEP Uranus Trade Space and Design Point Selection

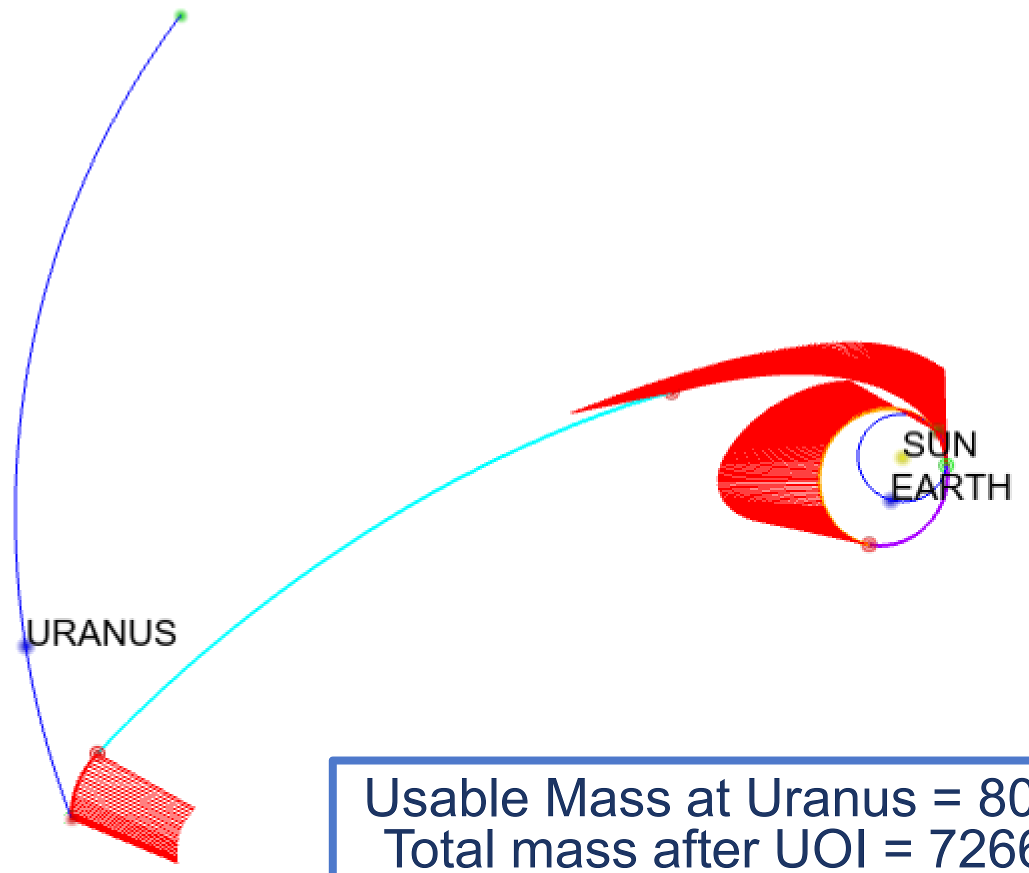
- Trade space for capability as a function of time of flight
  - Chosen point determines NEP power required
- "Payload" represents:
  - science instruments
  - probes
  - maneuvering propellant available after Uranus orbit insertion (UOI)
- UOP chemical propulsion reference point: 12 - 15 years Earth-Uranus
- NEP chosen point: 12 years Earth-Uranus, 20kW$_e$



Point Design Interplanetary Trajectory

Design Point:

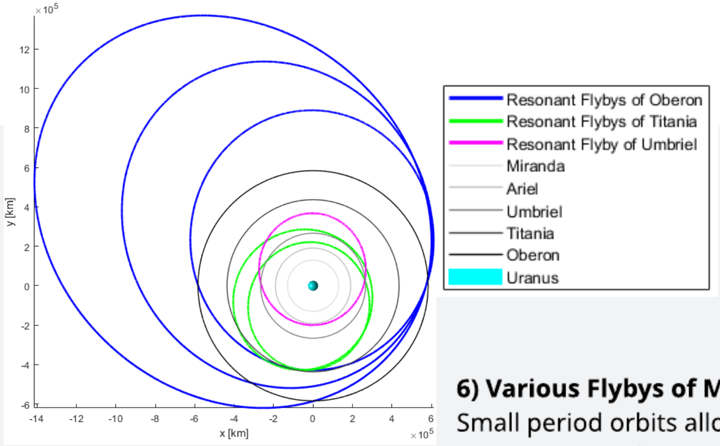
- 20 kW_e power system
- 12-year TOF
- Launch optimized to C_3 = 17 km^2/s^2 (no spiral up to Earth escape)
- Required interplanetary EP ΔV = 11 km/
    - 2605 kg Xenon used by three NEXT-C thr
- 2.5 km/s V_∞ at Uranus arrival, followec
- Begin Uranus operations with 804 kg u
    - Infinite mission design possibilities!



Usable Mass at Uranus = 804 kg
Total mass after UOI = 7266 kg

ConOps Option 1 (12-year to Uranus) – Moon Tour & Capture

Science Package: Core 100 kg



EEU Transfer
12 years

Uranus Arrival
UOP Capture Orbit

~180 days

2) PRM
Raise Rp to Oberon altitude using NEP.

3) NEP 15° Inclination Change
113 days

1) Probe Release
Highly elliptical orbit brings spacecraft close to Uranus for probe release

4) Equatorializing Flyby Sequence
15 deg inc change in 7-8 flybys similar to UOP equatorializing flyby sequence. ~250 days

5) Orbit Lowering Flyby Sequence
Representative ballistic flyby sequence to lower orbit 655 days

UOP equatorialized over 882 days – but includes lowering apoapsis

6) Various Flybys of Moons - ~1100 days
Small period orbits allow for targetting of several balistic flyby sequences, with close flybys for science objectives. Specific flyby sequence not planned, but period of orbit about Uranus is <15 days

7) Capture at Major Moon
NEP enables capture at a major moon. Sprial down to 100km orbit is on the order of 10-40 days.

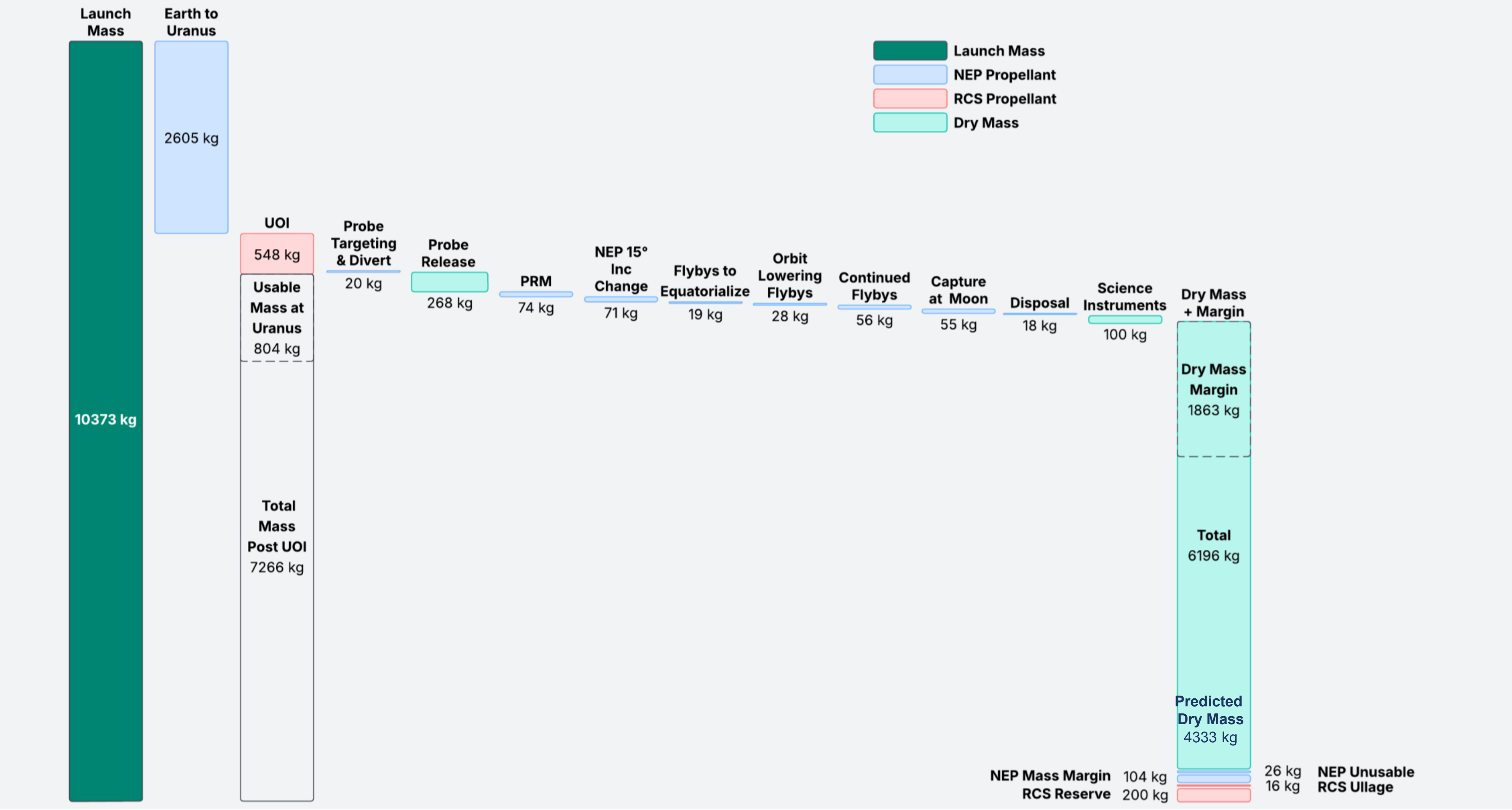
8) Disposal at moon
Total Mission Time 18.5 years, matches UOP

Probe: 268 kg

Usable Mass at Uranus = 804 kg
Total mass after UOI = 7266 kg

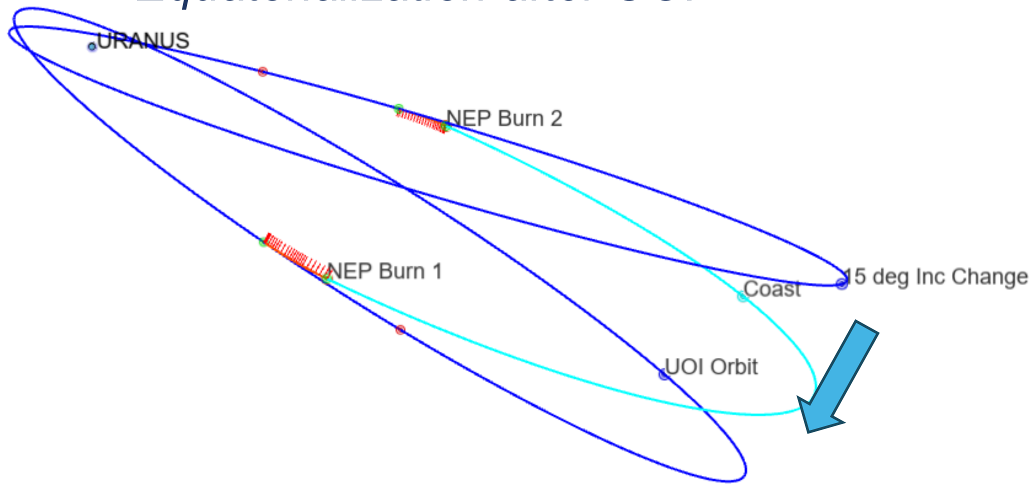
Segment	1	2	3	4	5	6	7	8	Total
ΔV (m/s)	~100	375	375	<100	<150	~300	~500	<100	2000

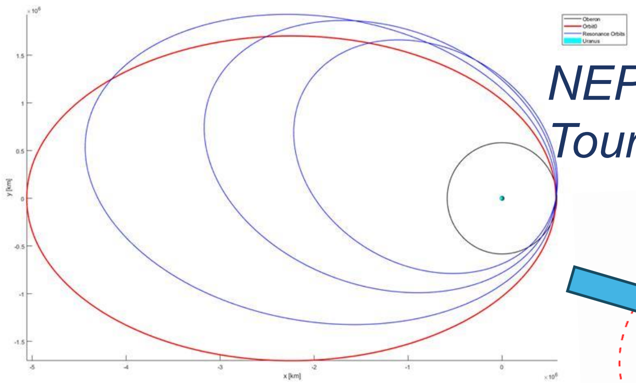
Mass Budget for Point Design ConOps 1



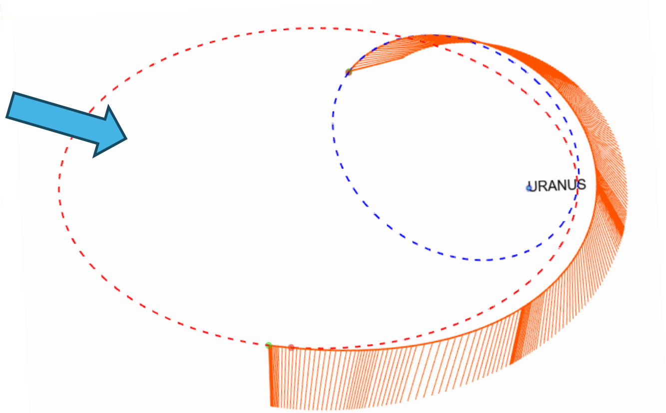
Exemplary Maneuvers Diagrams

Equatorialization after UOI

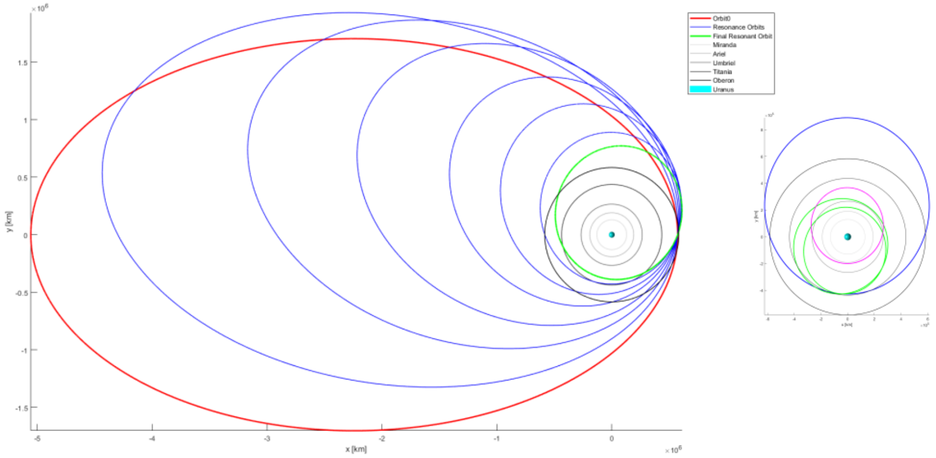




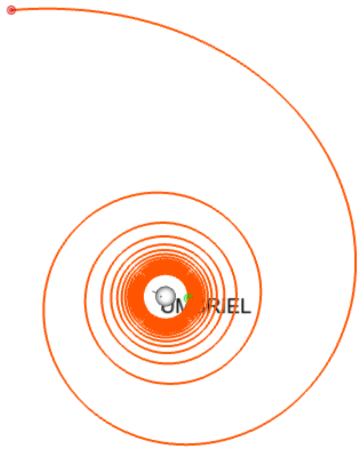
NEP Burn to Speed Up Moon Tour



Example flyby Moon Tours



Spiral into a moon orbit



ConOps Option 2 (13-year to Uranus) – UOP + Magnetotail

Science Package: Enhanced 178 kg

EEU Transfer
13 years

Uranus Arrival
UOP Capture Orbit

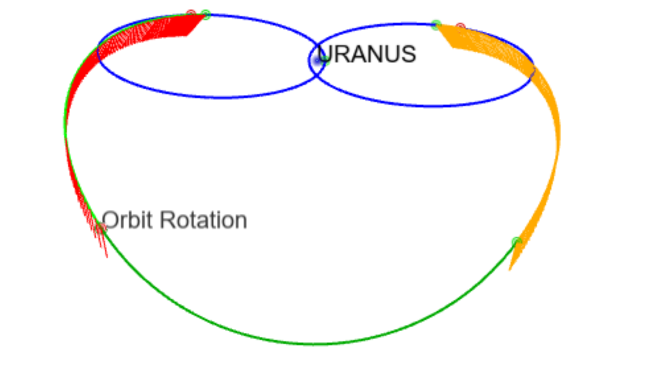
~180 days

2) PRM
Matches
UOP PRM
Maneuver

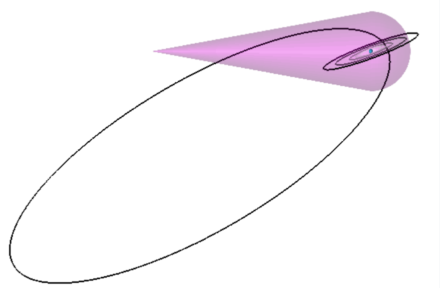
Orbit: 5,040,000
x 183,950km

1) Probe Release
Highly elliptical orbit brings spacecraft close to Uranus for probe release

3) NEP used to spin AOP of orbit into magnetotail
~230 days, depending on specific AOP that can be targetted based on arrival time.



4) Orbit within Magnetotail
~700 days can be spent in orbit doing science in magnetotail



5) Equatorializing Flyby Sequence
880 days, resulting in approximately ~30 deg inc change, includes lowering apoapsis. Assume matching performance of UOP

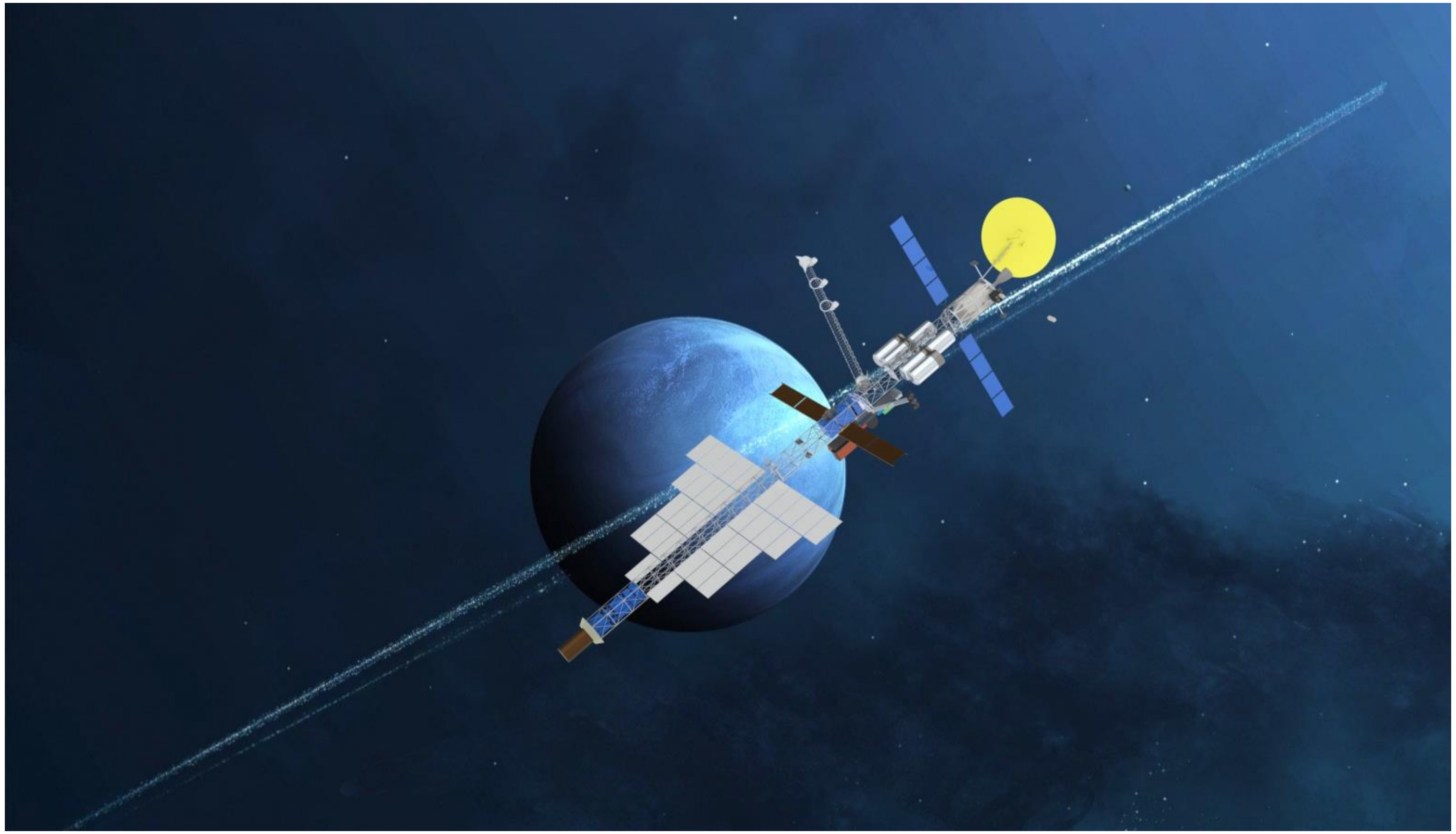
6) Disposal into Uranus
Total Mission Time 18.5 years, matches UOP

Usable Mass at Uranus = 1042 kg
Total mass after UOI = 8014 kg

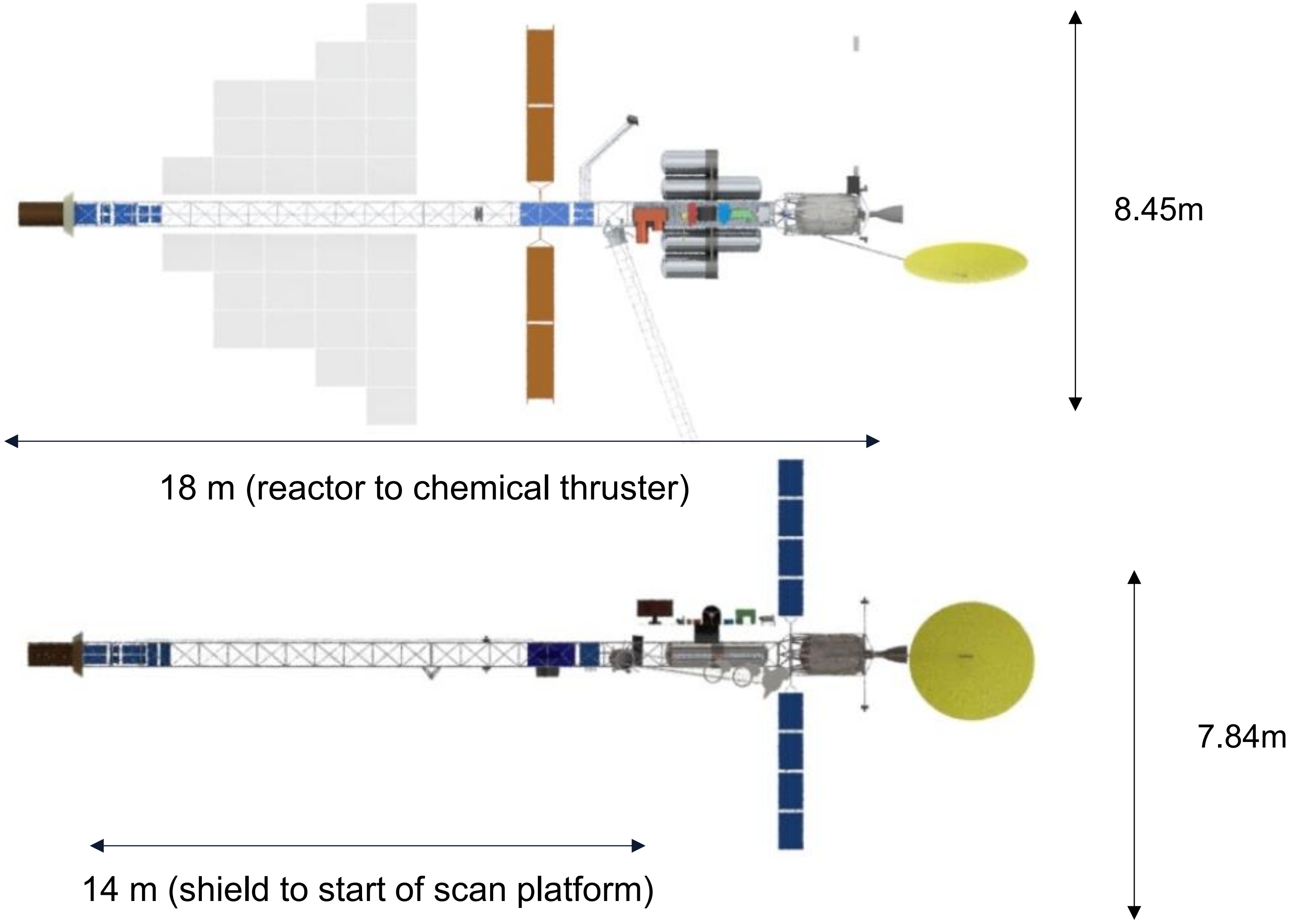
Segment #	1	2	3	4	5	6	Total
ΔV (m/s)	~100	178	~1750	<100	<100	~300	2528

Uranus Mission Vehicle

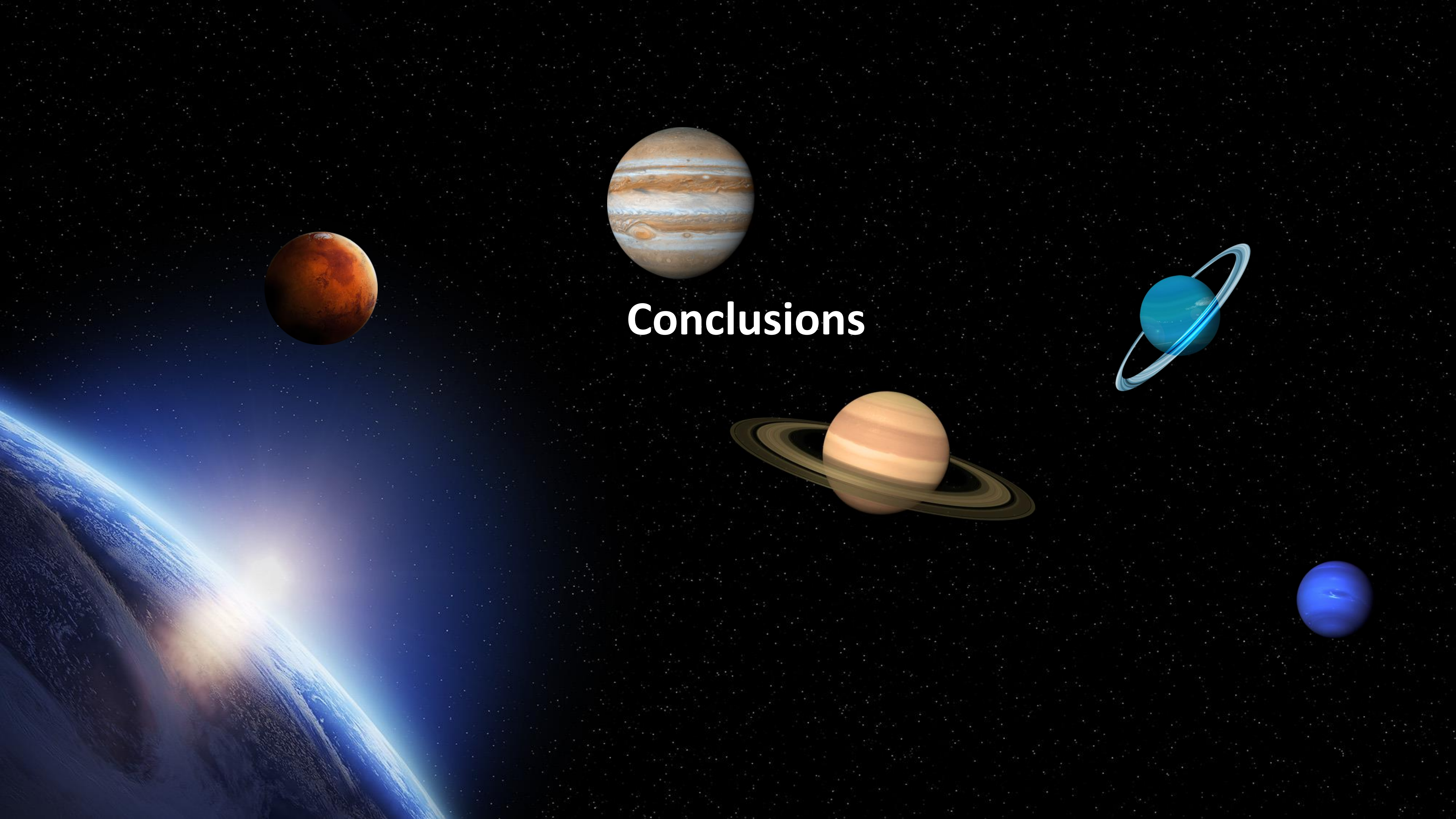
- 20 kW electric power
- 40 m^2 primary heat rejection system
- 2,300 kg of Xe (~10 km/s ΔV)
  - Cryogenic storage (170 K)
  - NEXT-C thruster
  - 4000s I_{sp}
- 700 kg of chemical propellant (350 m/s ΔV)
  - R-4D-15 HiPAT
  - MON and MMH propellants
  - 325 I_{sp}
- 6500 kg dry mass
- 12 Year time of flight to Uranus



Notional Uranus Mission Vehicle



Conclusions



Conclusions

- NEP enables a high-value Uranus mission – "Cassini at Uranus"
- NEP enables a mission that is fundamentally more capable than the comparable chemical mission (UOP)
  - More ΔV for maneuvers and flexible ConOps, moon orbiting possible
  - Data rate limitation is lifted, mass available for instruments
- NEP system defined in this study represents a candidate target for SNP technology development – ***need feedback from this workshop to confirm the usefulness of this performance!***
- Workshop participants, provide your feedback on:
  - The relative attractiveness of trip time, propulsion, launch vehicle options
  - Opportunities for further engagement with science in new instrument concepts, mission design, ConOps

Acknowledgement

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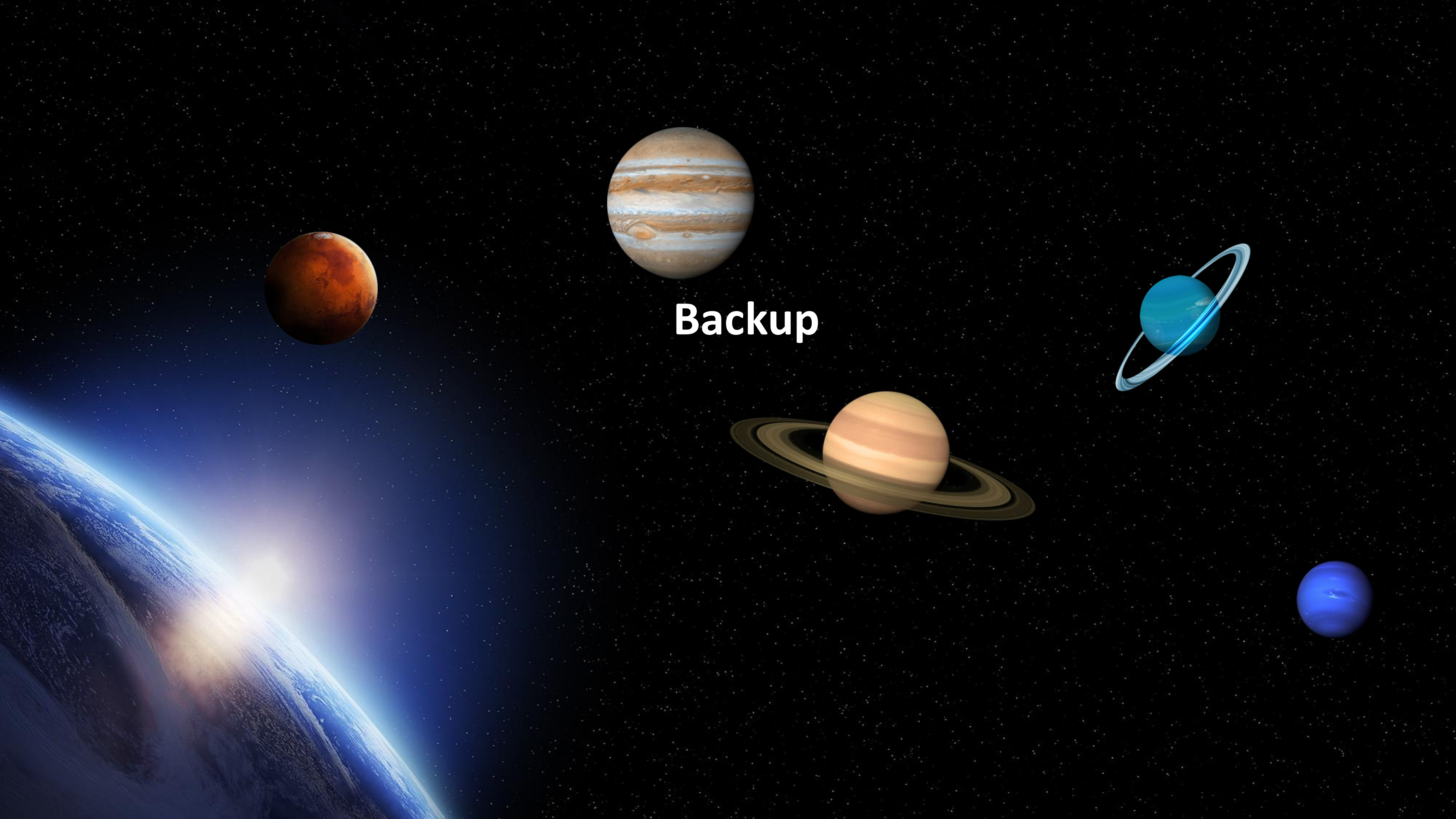
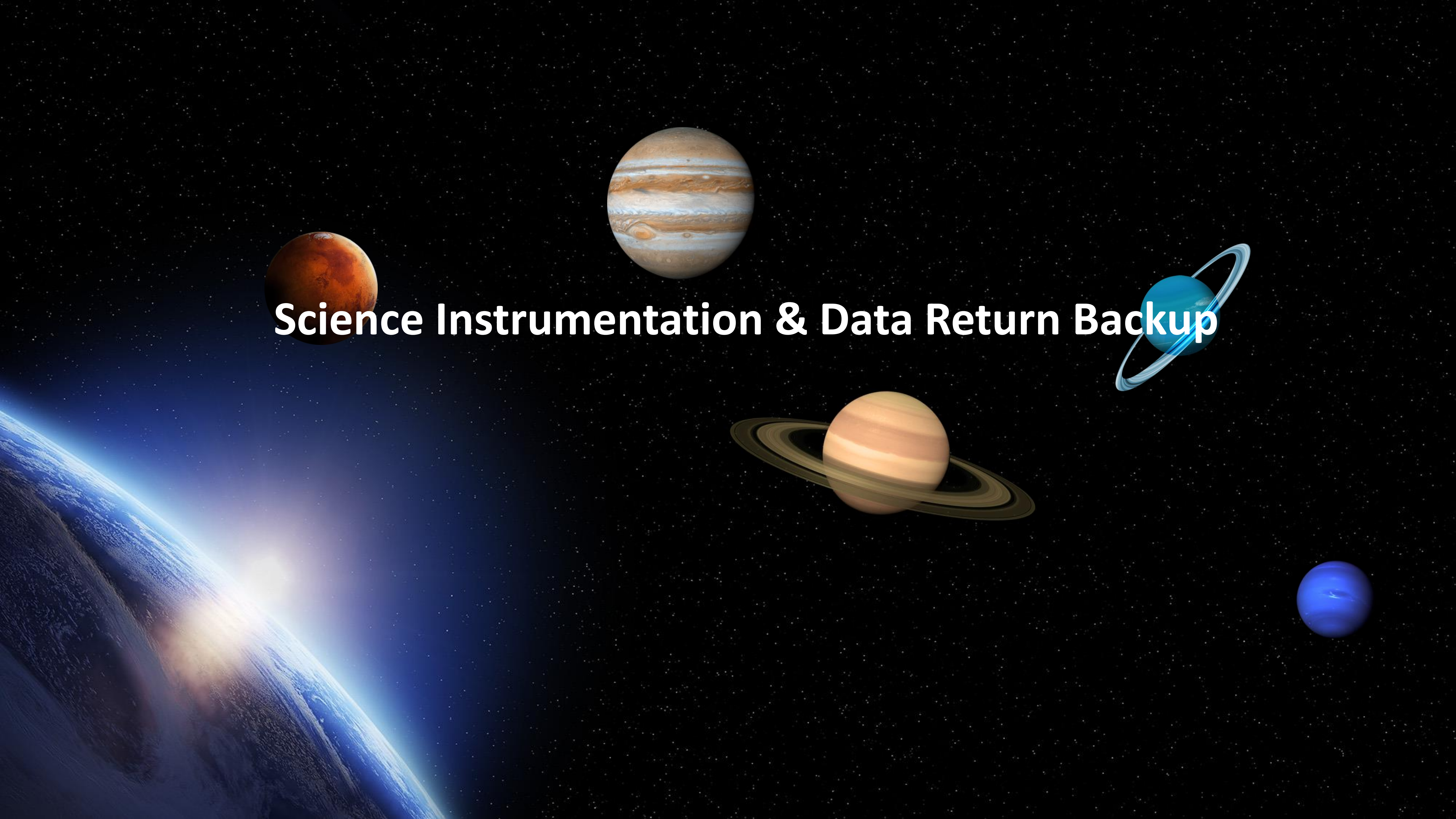
Contract No. 80LARC23DA003

Backup

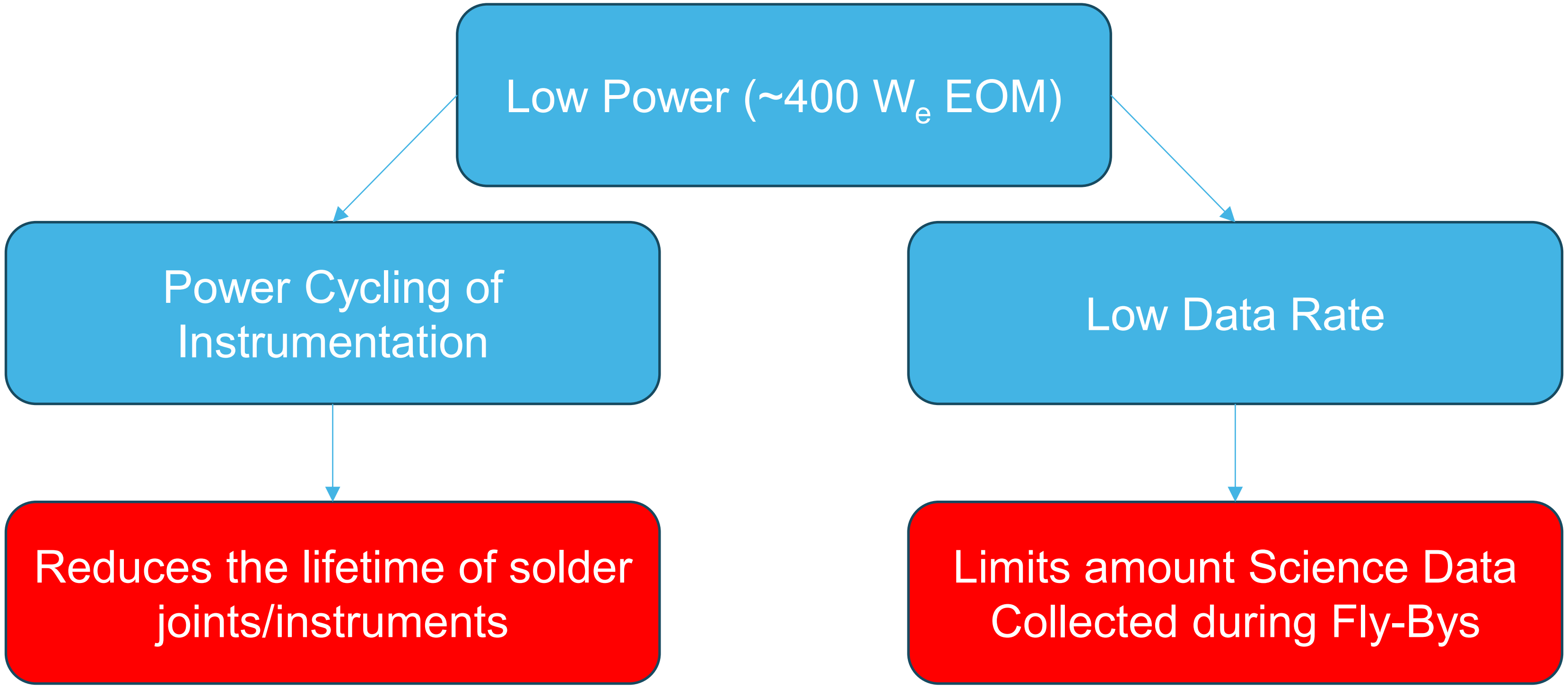


Science Instrumentation & Data Return Backup



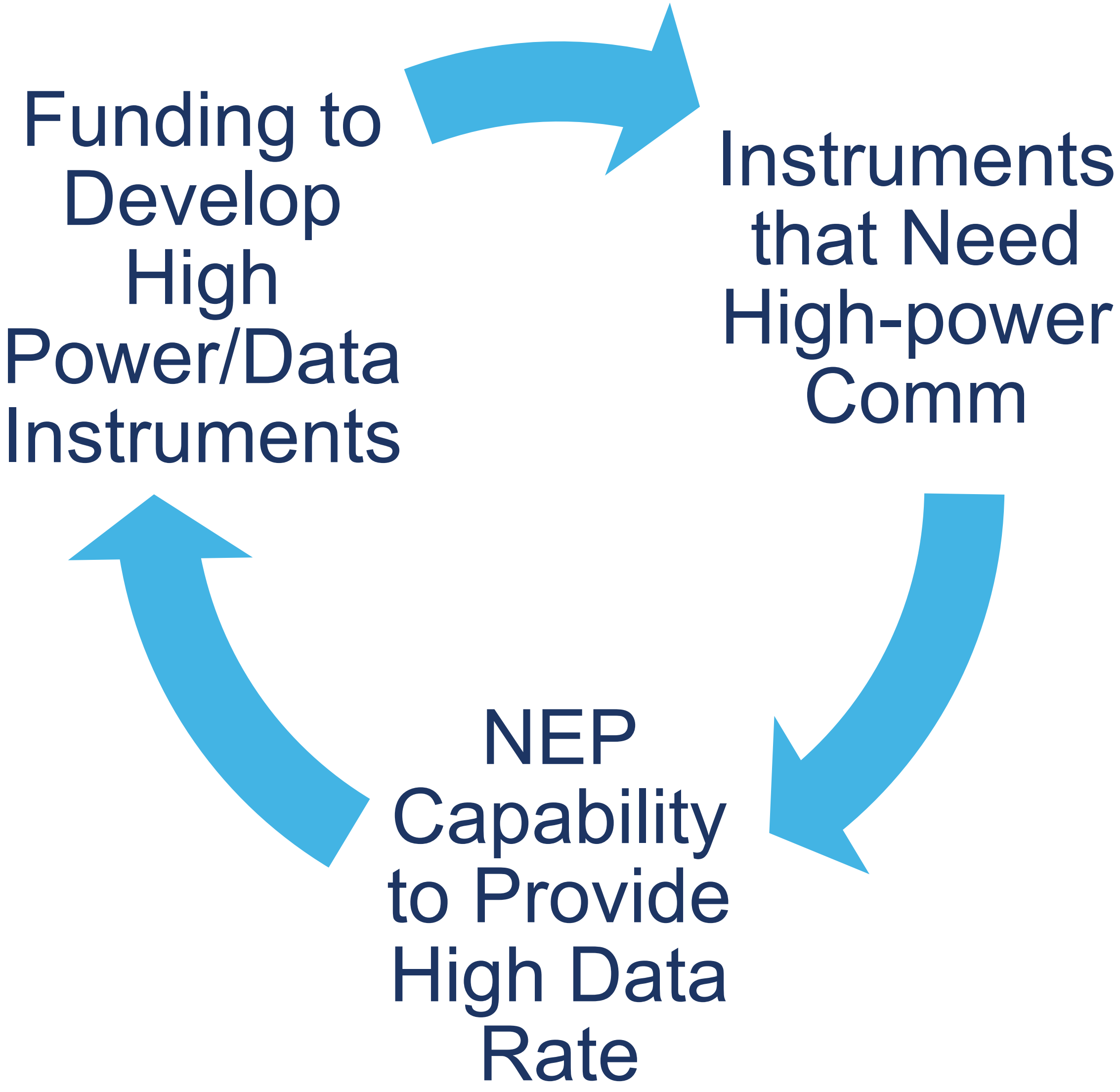
Ice Giants Study Limited Power Effect On Instrumentation

- In the Ice Giants Study **power and data rate limit the instrumentation**:



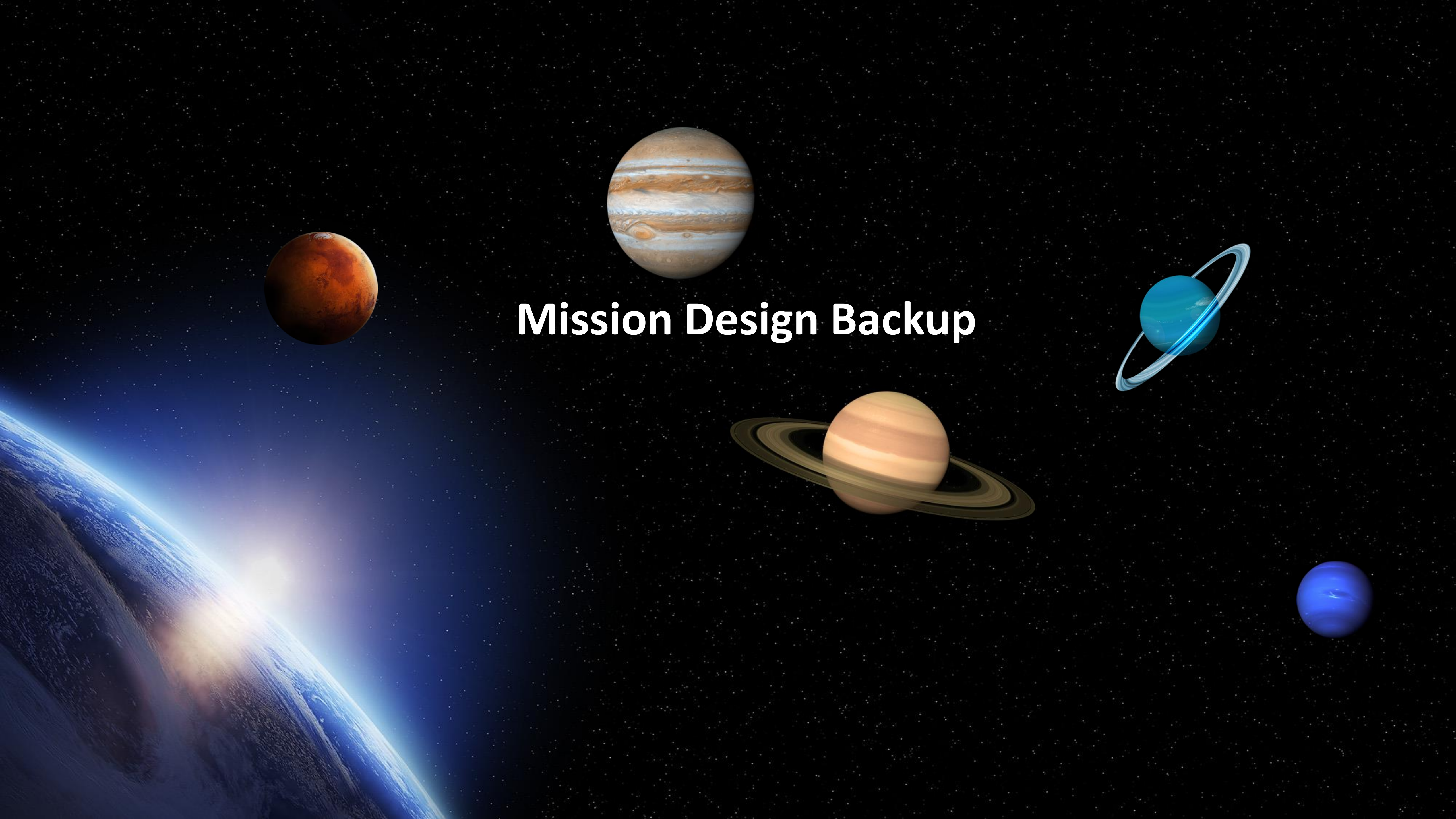
NEP enables more useable mass at Uranus (payload), less to no power cycling, and removes limitations on the amount of science data that can be collected.

Development of High Data Rate Instruments



- Camera resolution of existing instruments produces low data volume
- High-power/data RADAR instruments only applicable in certain environments

Mission Design Backup

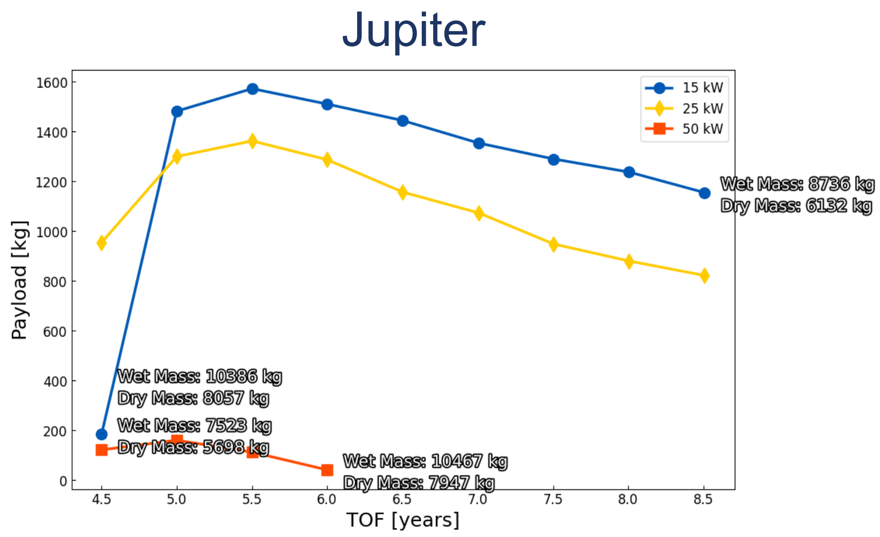


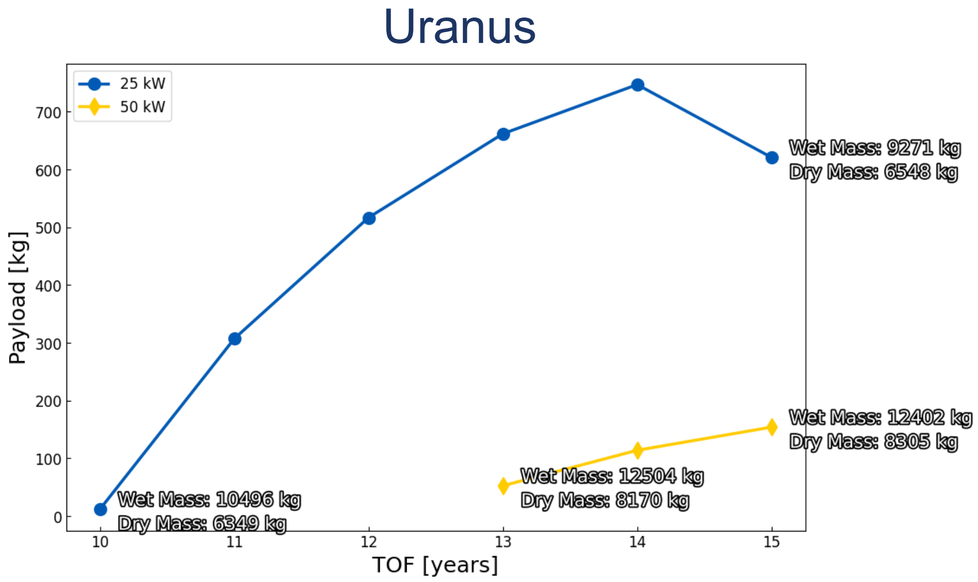
Mass & Propellant Margins Policy Summary

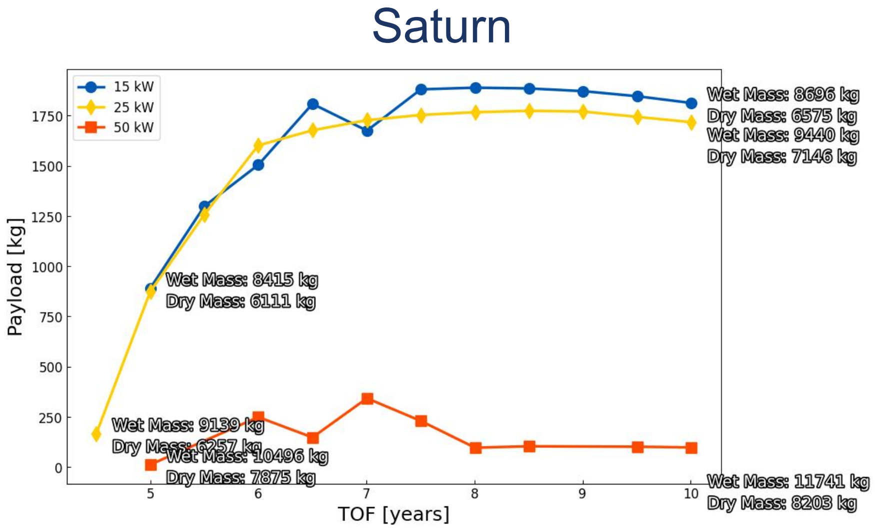
- EP and RCS margins are applied in post-processing of trajectories (parametric sweep) or in plugins (point design)
- Subsystem MGA follows the ANSI/AIAA Mass Properties Control Standard S-120A-2014
- Total dry mass margin 43% is greater than required by AIAA standard, chosen to compare with the decadal survey studies

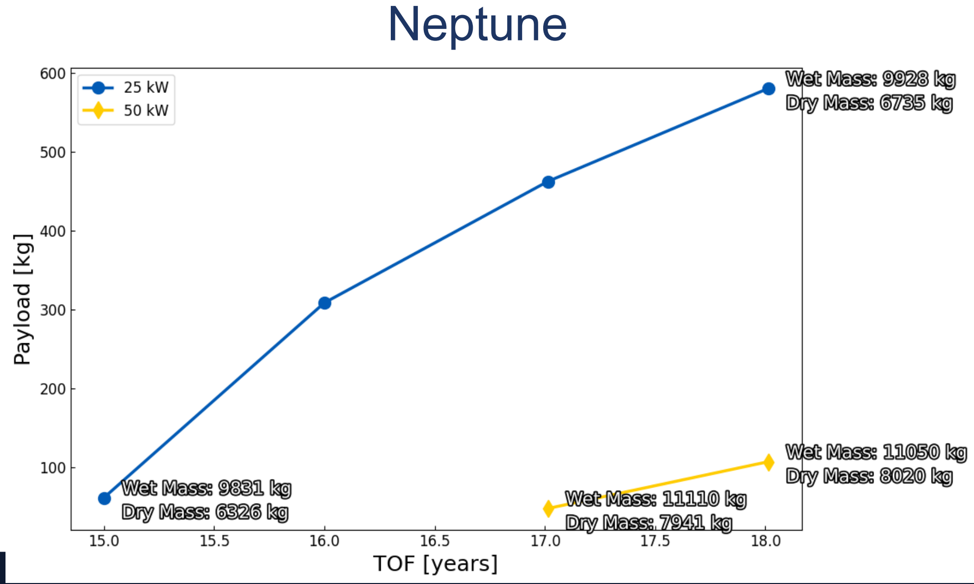
Margin Description	Value
EP Mass Margin	4%
EP Unusable Residual	1%
EP Thruster Performance Margin	5% applied to I_{SP}
RCS ΔV Reserve	75 m/s ΔV, prop mass calculated at destination
RCS Ullage	3%
Total Dry Mass growth (MGA + system level growth)	43%

Time of Flight and Usable Mass to the Outer Planets
Falcon Heavy Expendable Launch

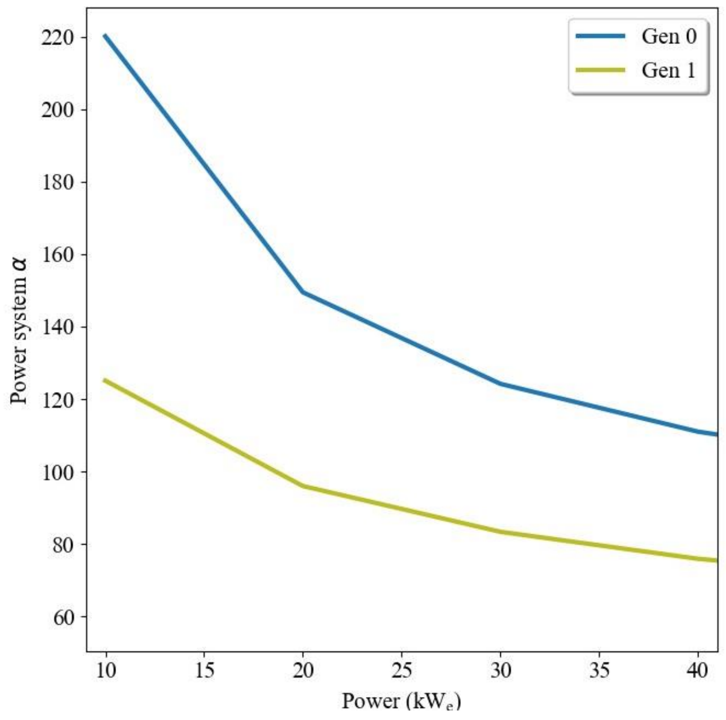


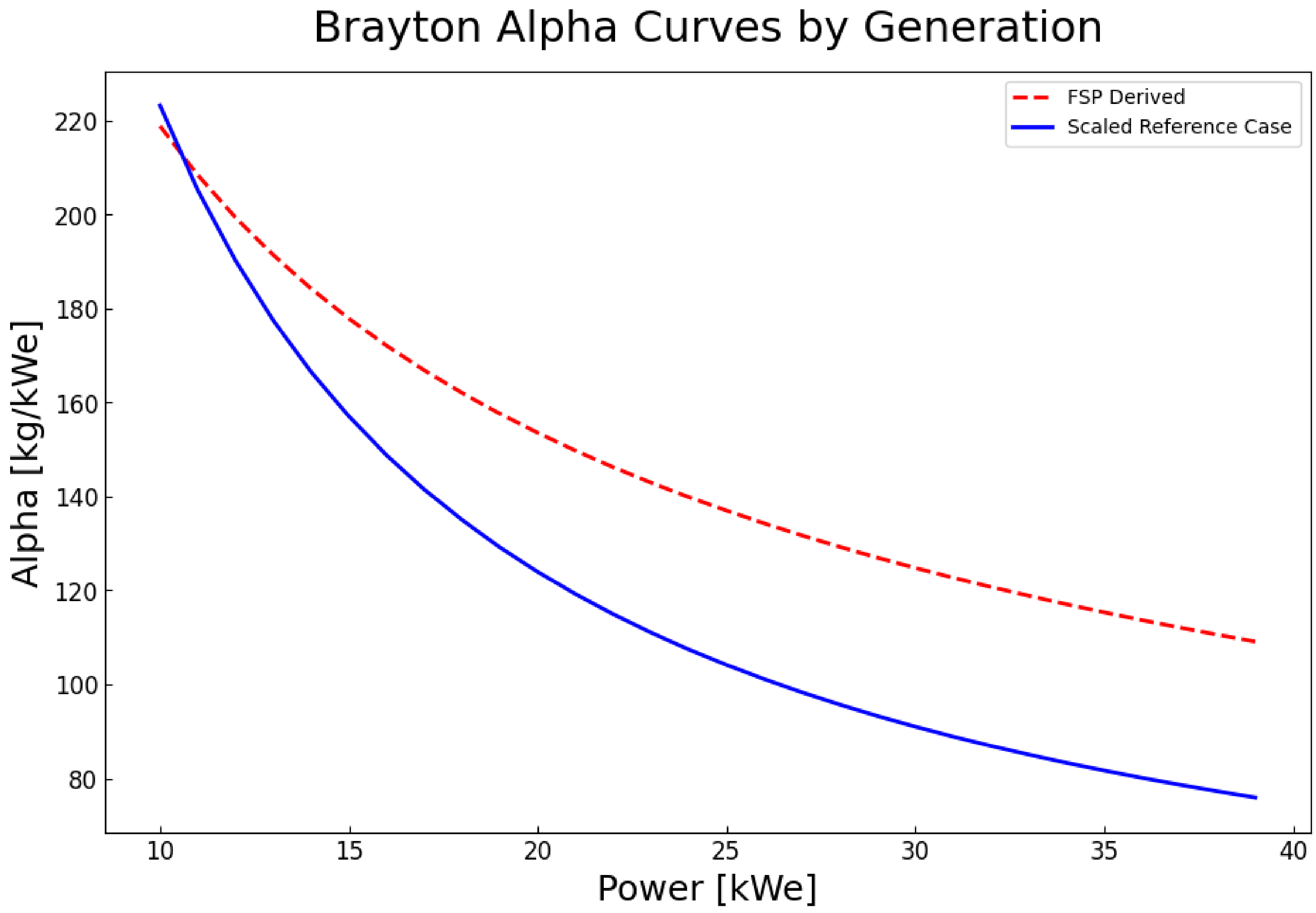






Power System Specific Mass

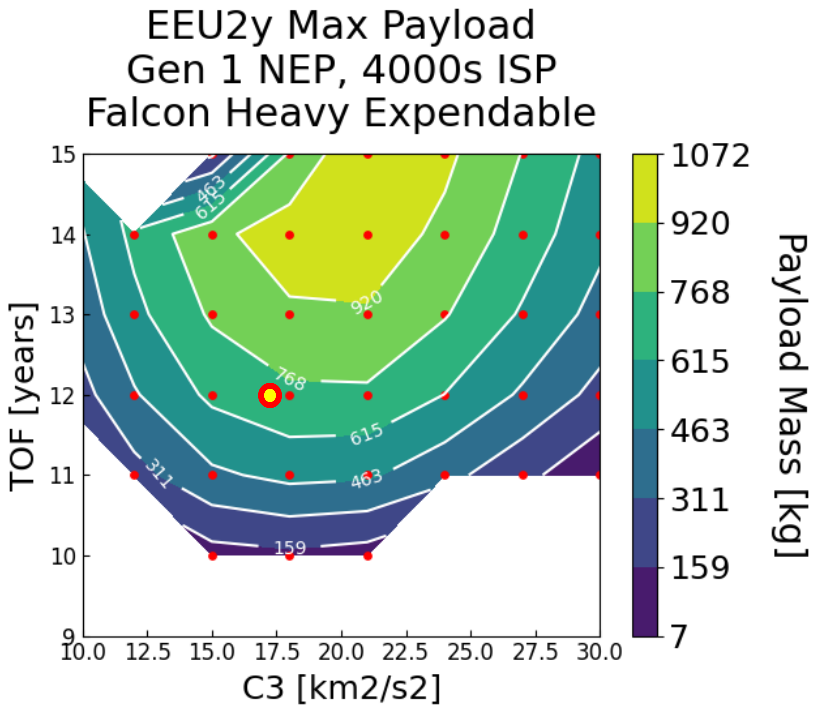


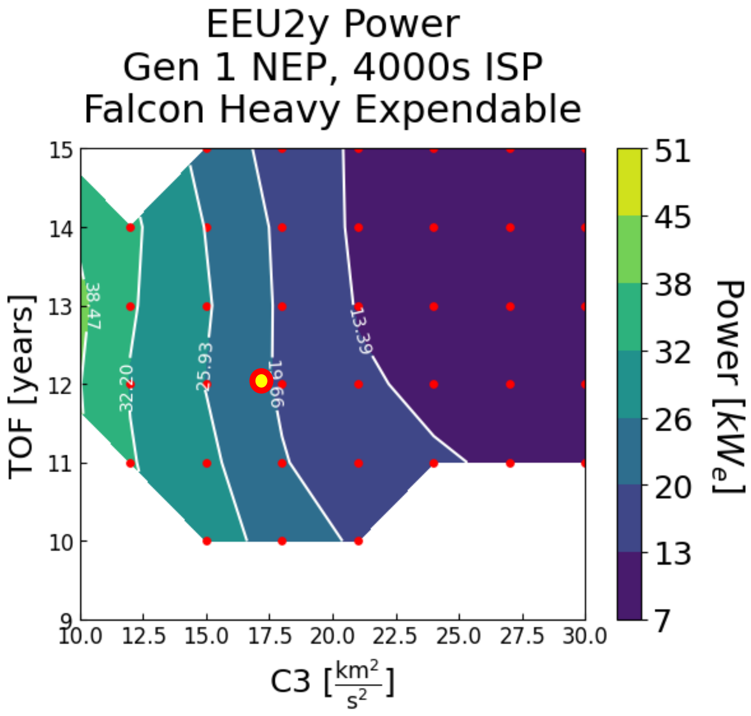


NEP Uranus Trade Space and Design Point Selection

- Trade space sweep results for EEU mission shown below
- "Payload" represents science instruments, probes, or additional propellant for maneuvering after Uranus orbit insertion (UOI)
- "Power" represents power to the thruster PPUs
- Chemical UOP reference point: 12 - 13 years Earth-Uranus
- NEP chosen point: 12 years Earth-Uranus, 20kW$_e$

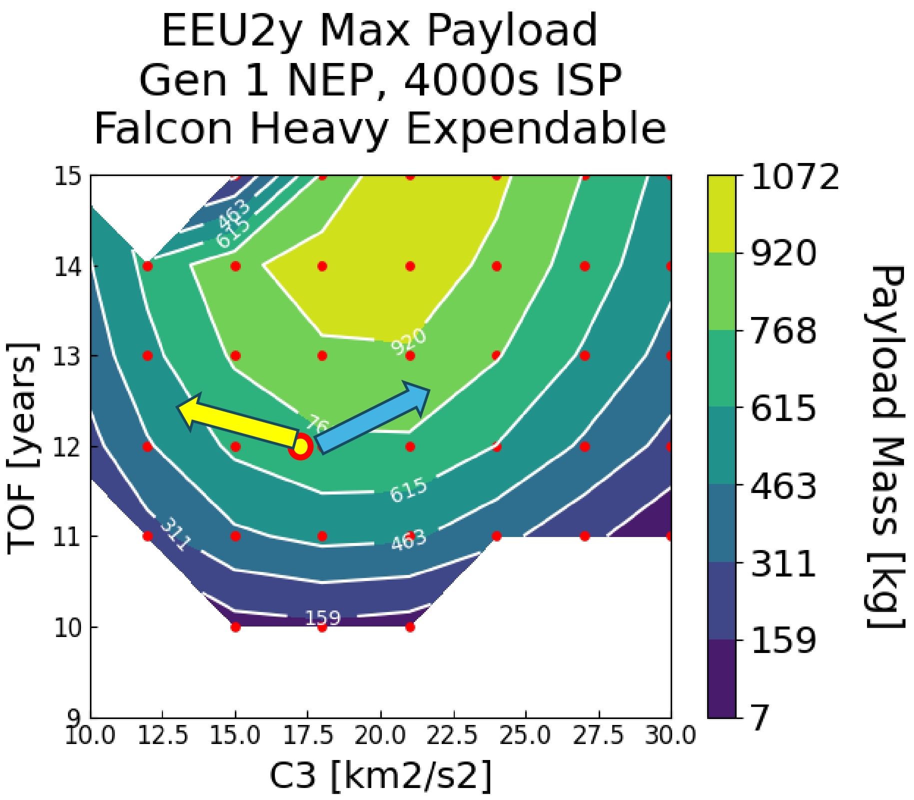
Parameter	Value	Note
v_∞ at Uranus	2.5 km/s	Roughly Optimized
Chem UOI Burn	210 m/s	Bi-propellant
RCS Reserve	75 m/s	Carried to Mission End

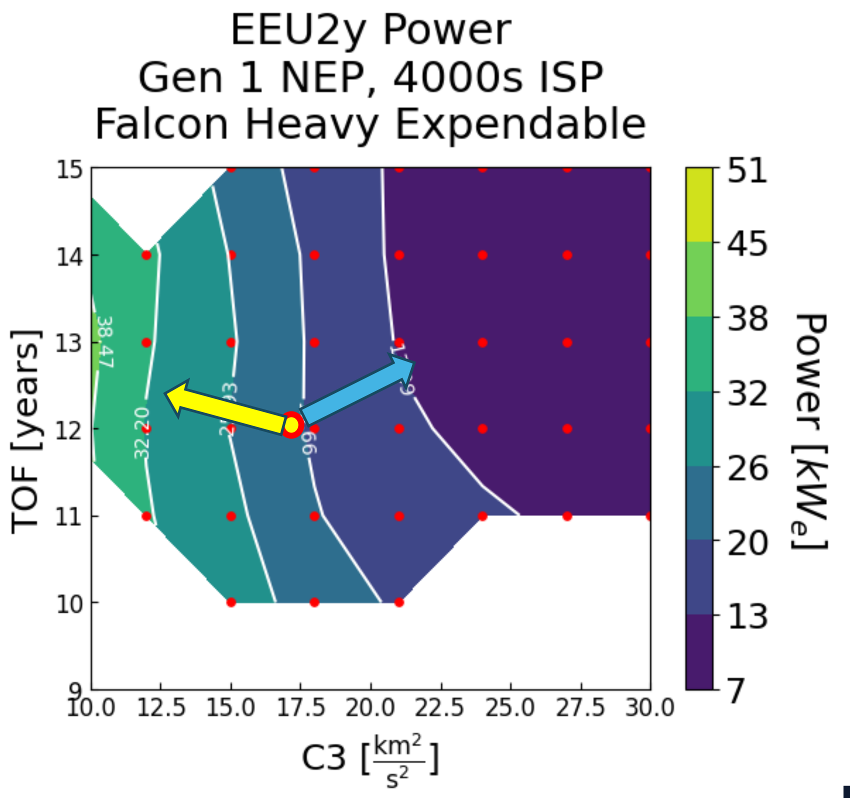




NEP Uranus Trade Space on Falcon Heavy expendable launch

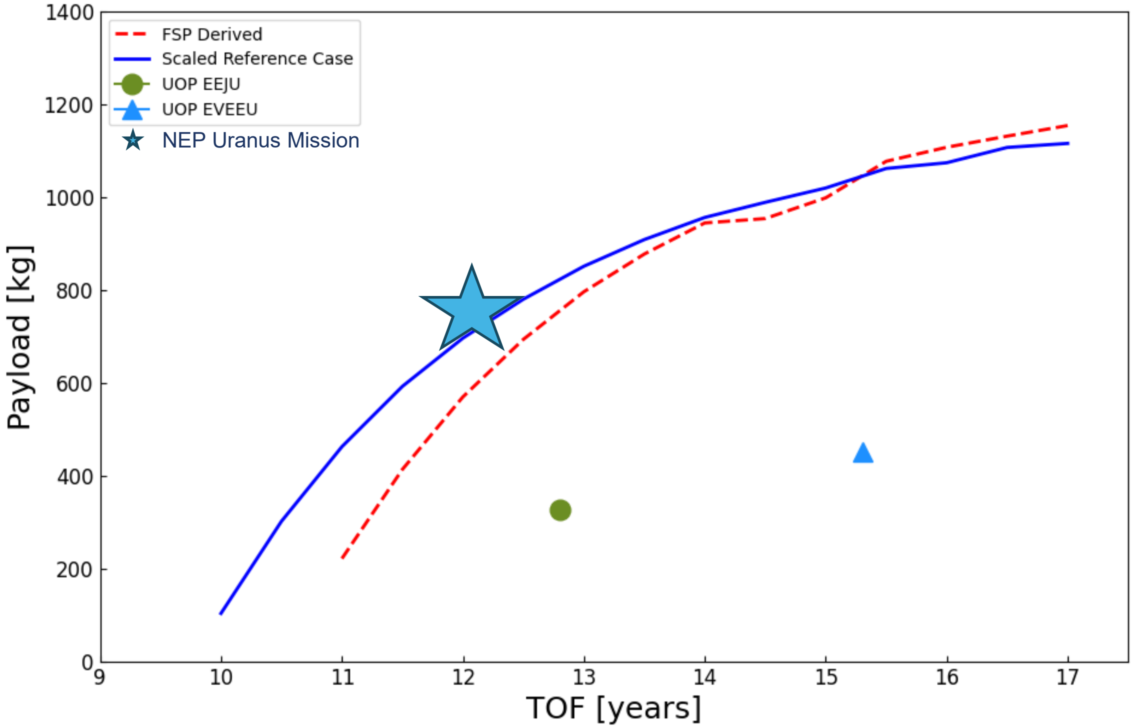
- Lower power system takes longer to deliver the same payload
  - Despite lower-mass NEP, the added ΔV of a less-efficient trajectory results in either less payload or longer trip time
- Higher-power system devotes more dry mass to NEP
  - Despite ΔV efficiency of higher power, either payload goes down or trip time goes up



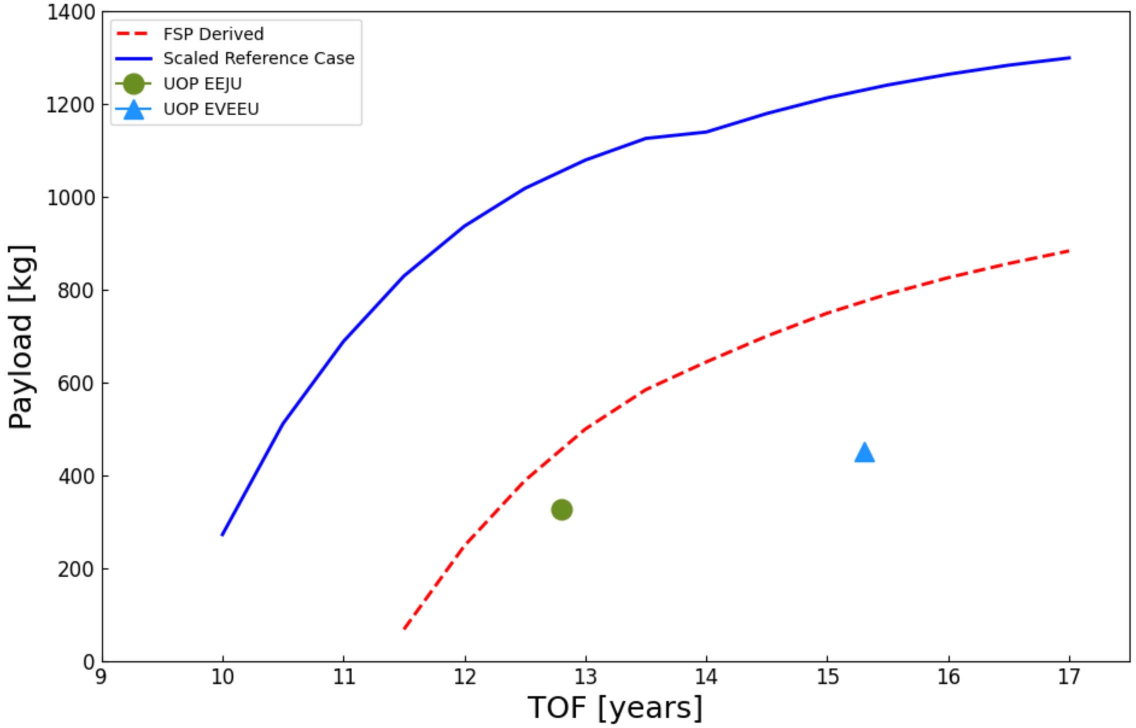


Maximum Payload for E(2y)EU Mission

4000 s I_{sp}



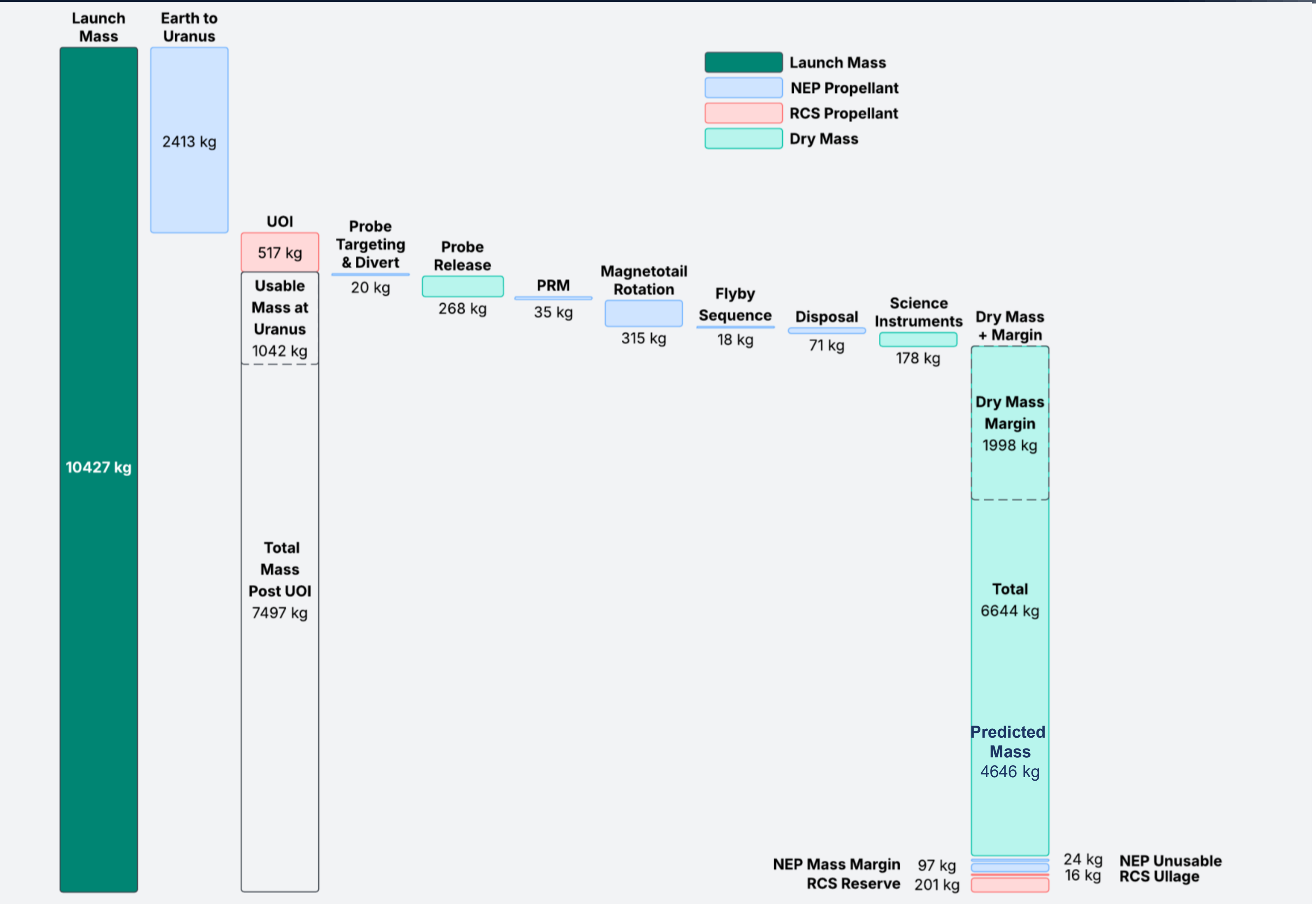
8000 s I_{sp}



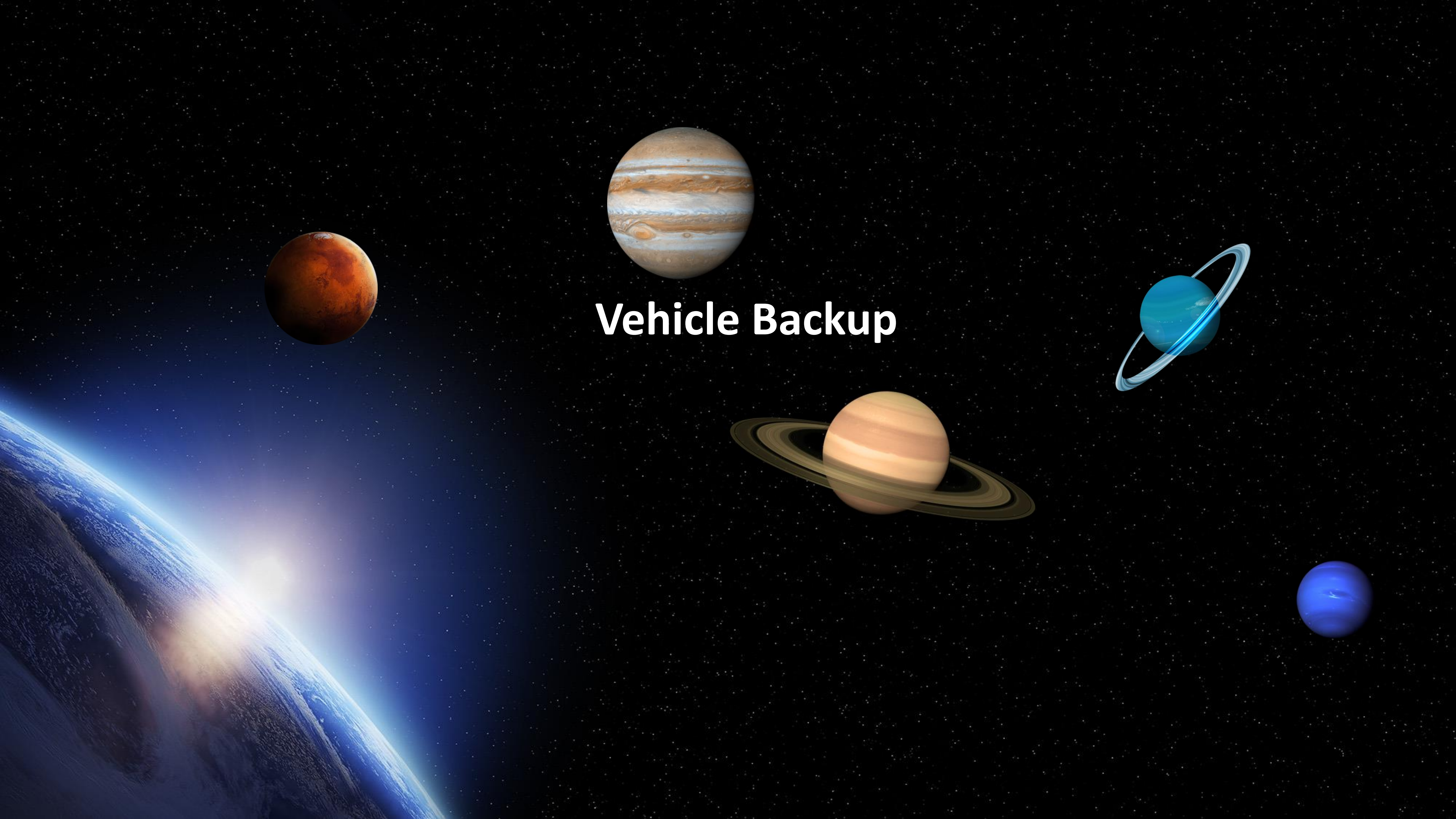
Mission Design Possibilities for Segment at Uranus

- Probe release targeting
- Periapsis raise
- Inclined orbit observations
- Magnetotail fly-throughs
- Equatorialize orbit (plane change) to target more frequent moon flybys
- Moon flybys to lower orbit, time between flybys reduced by EP (faster time to rapid flyby sequence)
- Various moon tours possible, lower velocity flyby possible
- Orbit one moon
- Orbit more than one moon

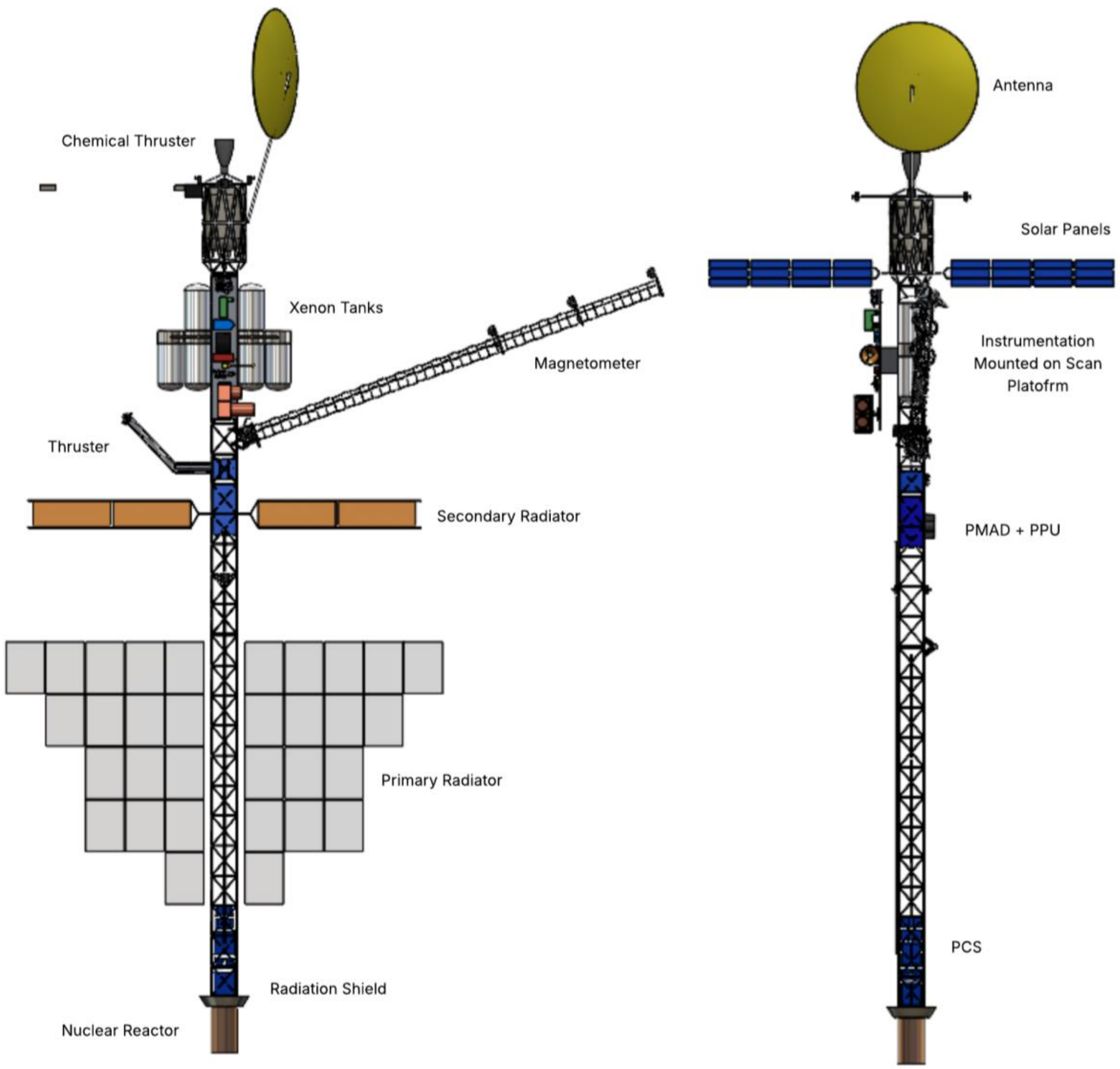
Mass Budget for Point Design ConOps 2



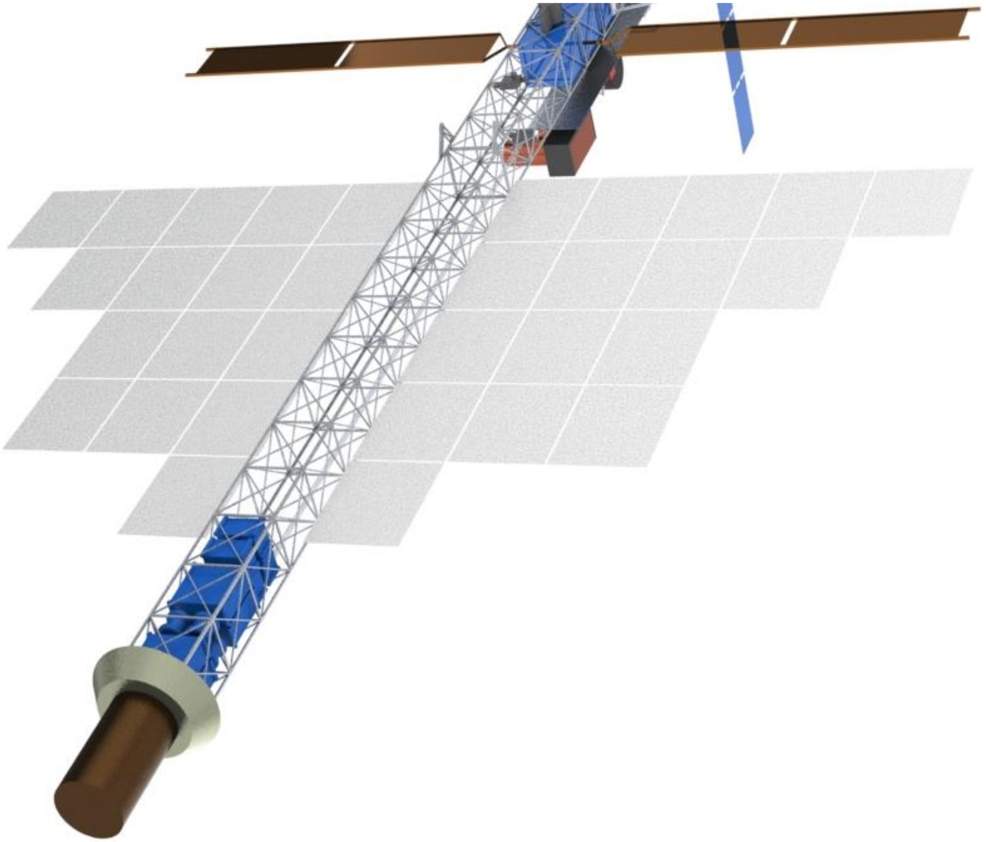
Vehicle Backup

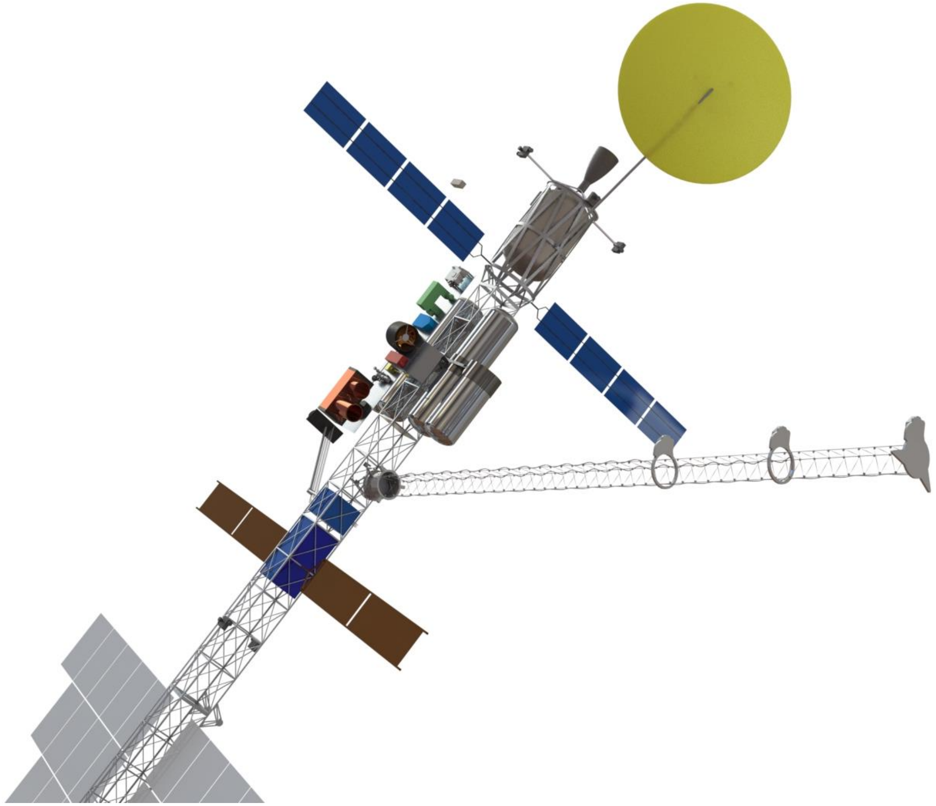


Uranus Mission Vehicle CAD



Notional Uranus Mission Vehicle

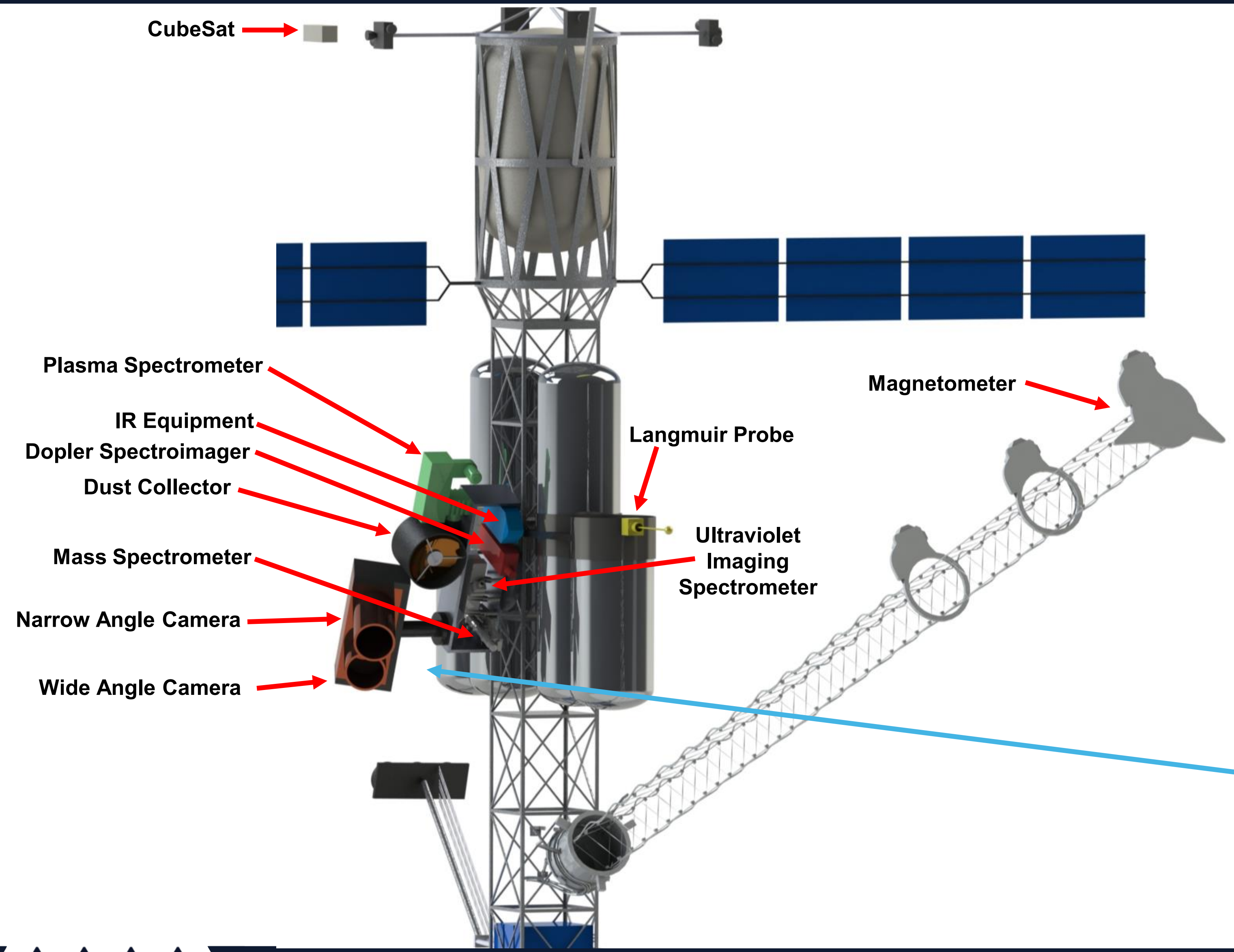




Can Easily Fit in Falcon Extended Fairing

- Boom folds in half at the middle
  - Boom primarily only supports itself during launch
- Spacecraft and NEP system may need structural adapter to interface with stock payload adapter

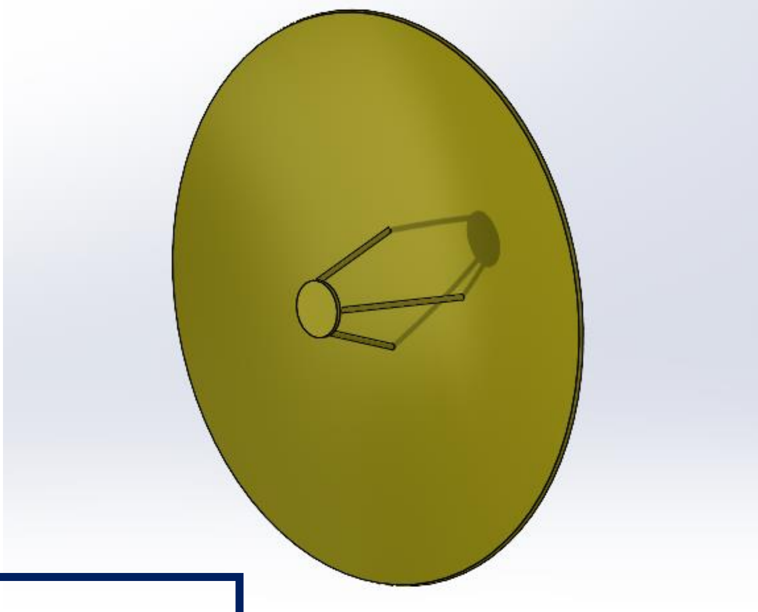
Instrumentation Diagram – Comprehsnive Science Suite



Instrumentation points using scan platform with 1 DOF and additional DOF by rotating spacecraft along axis of boom using reaction wheels

Fly By Data Return & Communication System

- Compared UOP to NEP system high power comms system data rate for moon flybys
- Assumptions
  - 20 AU distance
  - 30 Earth Days per fly by orbital period
  - 8-hour downlink connection per earth day
    - 240 hours of downlink per orbit
  - 5% data margin for dropouts
  - Data is compressed prior to downlink



Point Design

	UOP - 100-Watt comms	NEP - 2 kW_e Comms	NEP - 20 kW_e Comms
Data DL rate	19.5 kbps	390 kbps	3900 kbps
Data Volume Per Orbit	1.9 GB	40 GB	400 GB

High Power enables 20x to 200x more science data transfer than traditional S/C comms systems

NEP System Design Summary

CTE 1 (RXS)

- HALEU SPYDER-derived reactor with Na heat pipes
- PCIT of 1150 K (heat pipes at ~1200 K)

CTE 2 (PCS)

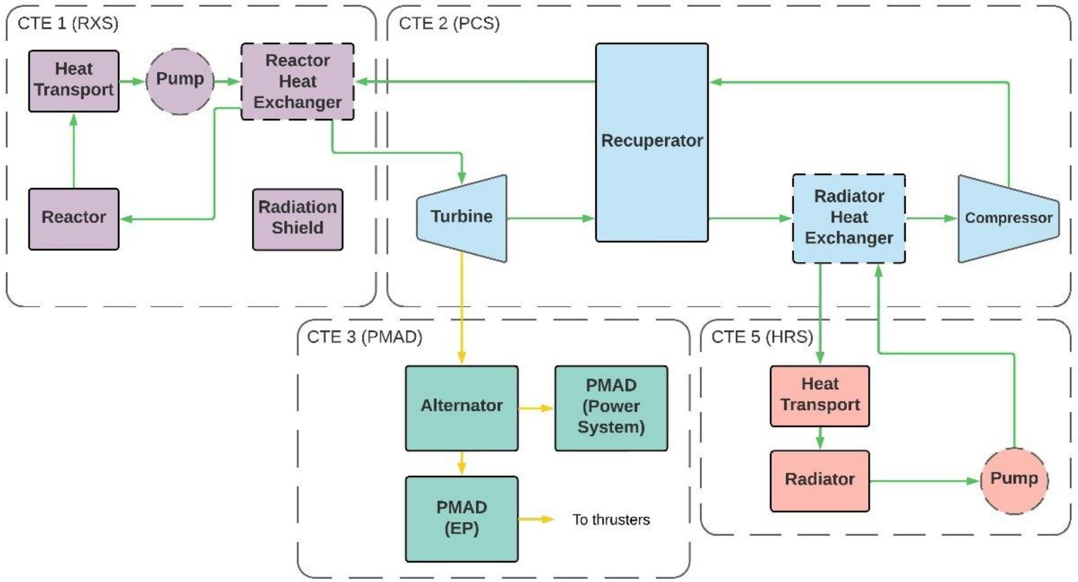
- Four 5.5 kW_e units with He-Xe working fluid
- CIT of 346 K and outlet pressure of 3 MPa

CTE 3 (PMAD)

- Alternator produces a 240 VAC output and the PMAD outputs 240 VDC suitable for the NEXT-C thrusters (requires modification to CTE-5 PPU)

CTE 4 (HRS)

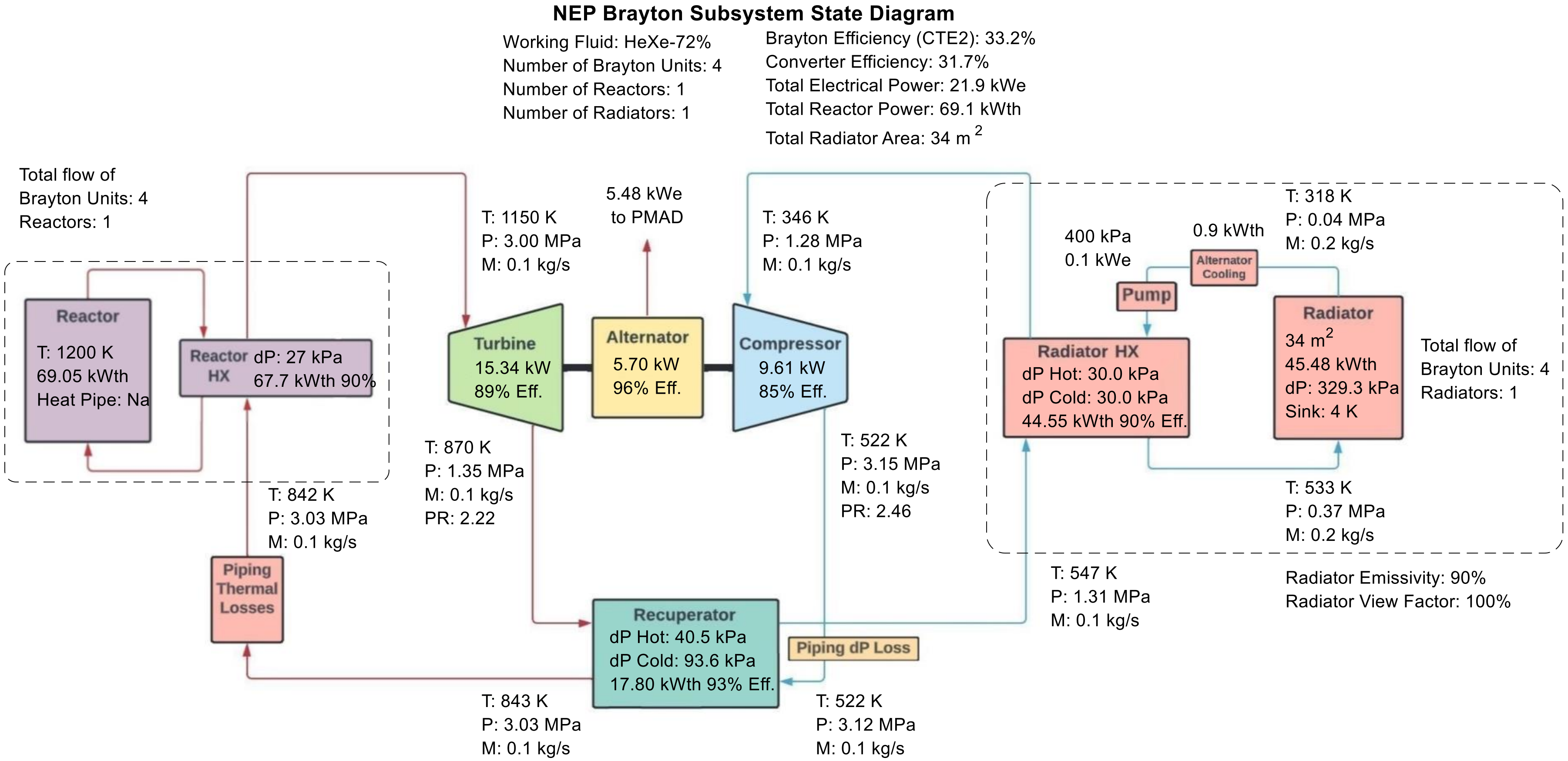
- Ti-water radiator heat pipes with NaK pumped loop (slightly lower mass than water pumped loop)
- Bi-wing design with a 4 K sink temperature



Mass and cycle summary

	Mass (kg)	Alpha (kg/kWe)
'NEP Power System'	**2557**	**128**
'Reactor Total'	1561	78
' Reactor'	822	41
' Shield'	723	36
' Aux'	0	0
' Reactor HX'	16	1
'PCS Total'	326	16
' TAC'	77	4
' Recuperator'	190	10
' Ducting'	5	0
Structure'	54	3
'HRS Total'	176	9
' Piping system'	8	0
' Fluids'	4	0
' Heat Pipes'	62	3
' Panels'	32	2
' Structure'	56	3
' Heat Exchanger'	14	1
'PMAD Total'	494	25
' Electronics'	419	21
' PMAD radiator'	61	3
' Parasitic load radiator'	14	1

(Component details in backup slides)



Converter efficiency of 32% with a 69 kW reactor and ideal radiator area of 34 m^2

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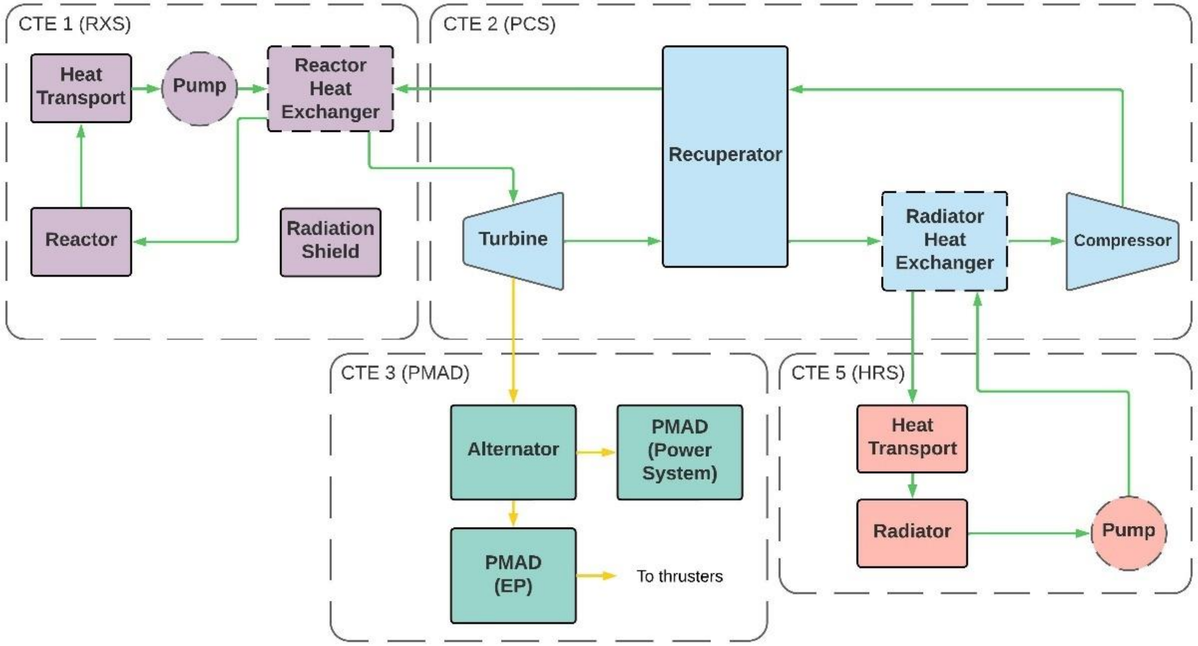

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