Design of a Smallsat for Uranus

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- Attitude Determination and Control: Brent Faller
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- Propulsion: Jim Fittje
- Structures: John Gyekenyesi
- Cost Estimating: Natalie Weckesser

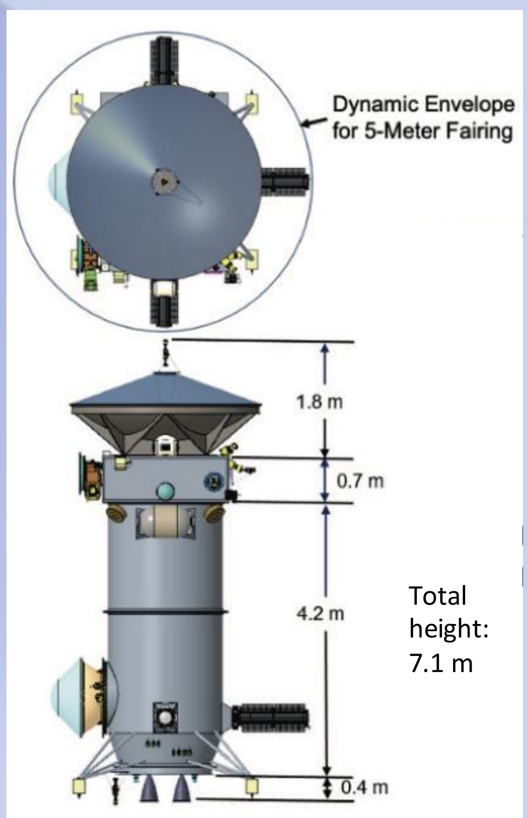
Purpose

- Thermoradiative energy conversion is a new concept for generating electrical power from a thermal source
  - In principle this power generation technology can be smaller, lighter, and more efficient than current radioisotope power sources
  - The technology is still in the early stages of development

- Purpose: Engineering design of a technology demonstrator smallsat using a thermoradiative cell (TRC) radioisotope power system
  - Demonstrates the utility of a smallsat for outer planet science
  - Demonstrates the utility of the thermoradiative conversion system to provide power to a smallsat

- Smallsat to be carried along with NASA's proposed Uranus Orbiter with Probe (UOP), which will serve as its communications relay

- Mission: add significant science to the Uranus Orbiter mission by taking measurements of the Uranus magnetosphere and radiation belts



NASA's proposed Planetary Flagship mission Uranus Orbiter with Probe

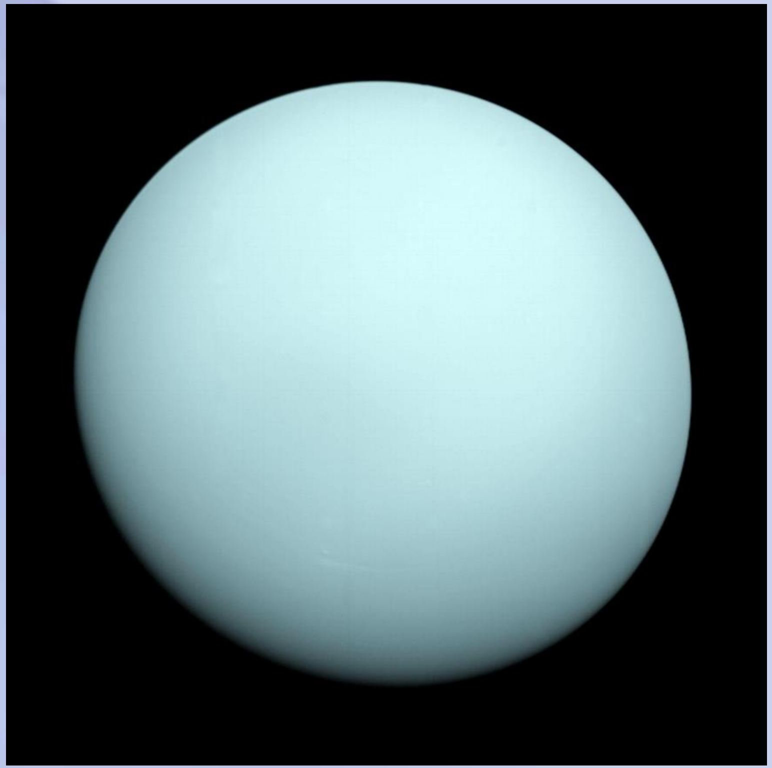
Science at Uranus

Uranus has only been visited by a spacecraft once: Voyager-II in 1986

- Flyby mission spent only a few hours inside Uranus' magnetosphere
- Many science questions remain unanswered

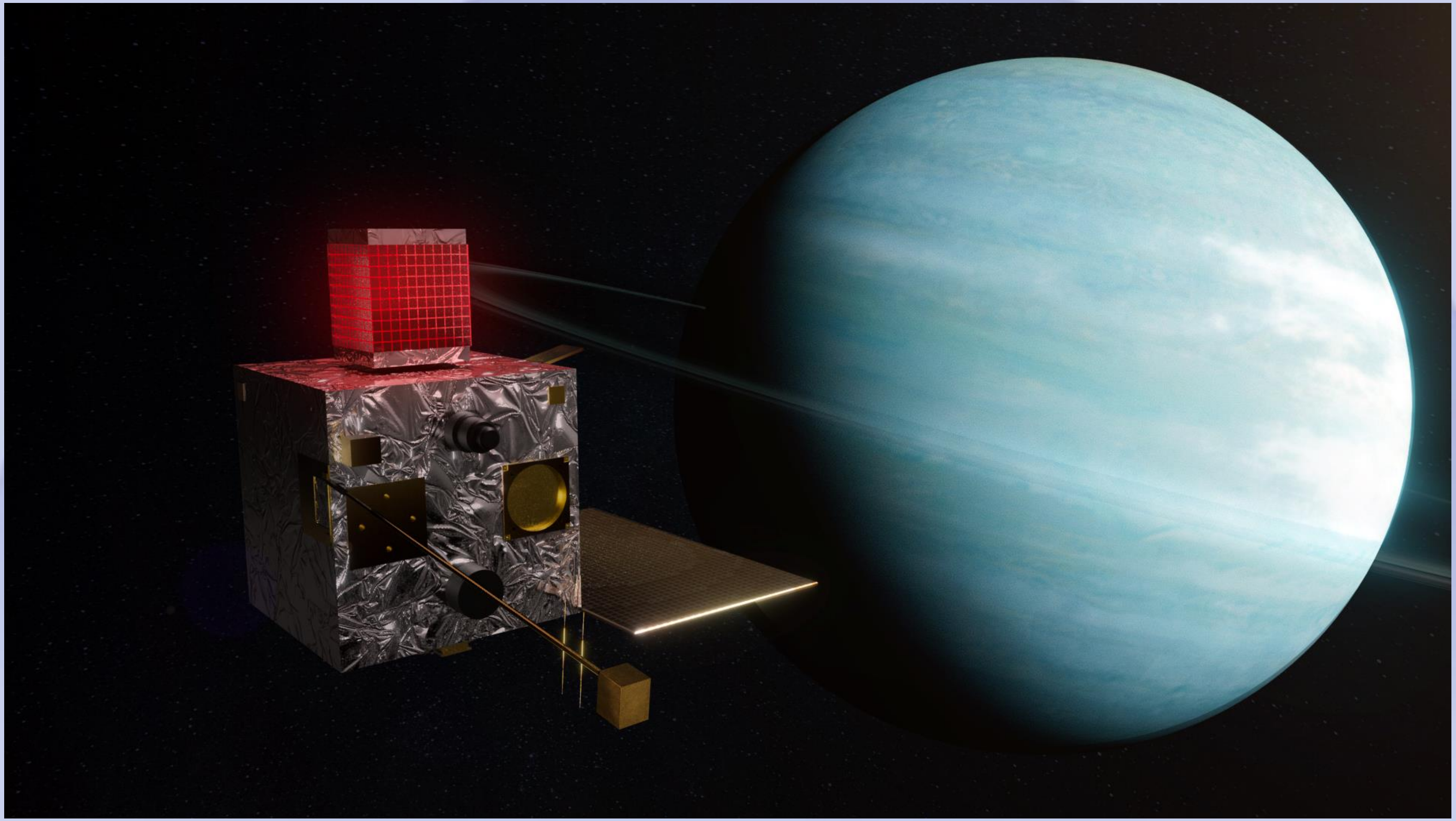
NASA Decadal Survey for Planetary Science named a mission to Uranus as the **highest priority new Flagship mission** for the decade 2023-2032

- Uranus Orbiter and Probe mission



Uranus viewed from Voyager II

TITUS: Technology Innovation Thermoradiative Uranus Smallsat

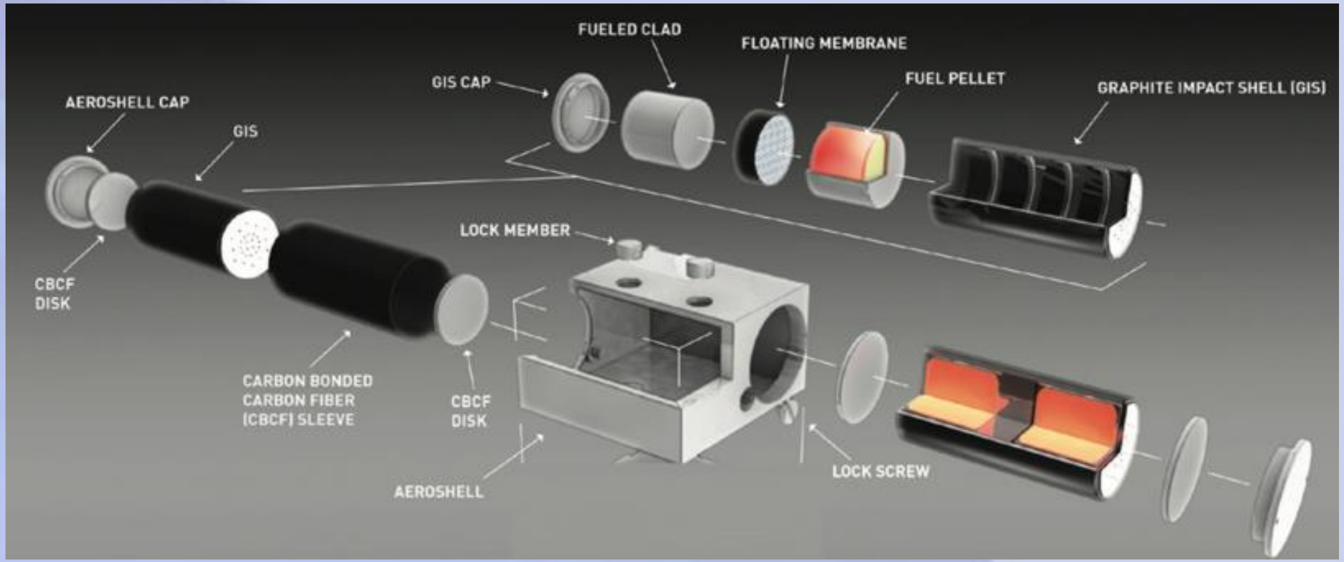


Artist's conception of TITUS around Uranus

Note:
This is the view you would get if your eyes could see infrared! The actual visible glow from the thermoradiative cells would actually be too far in the infrared to see.

General Purpose Heat Source (GPHS)

- **Space-qualified plutonium source producing heat**
  - Used for radioisotope power generators (RTG) for planetary missions
  - Long history of spaceflight
  - Alpha emitter: very easy to shield the radiation from the source
  - Pu-238 half-life = 87.7 years
  - We use this as a heat source, using the TRC to convert the heat to electrical power



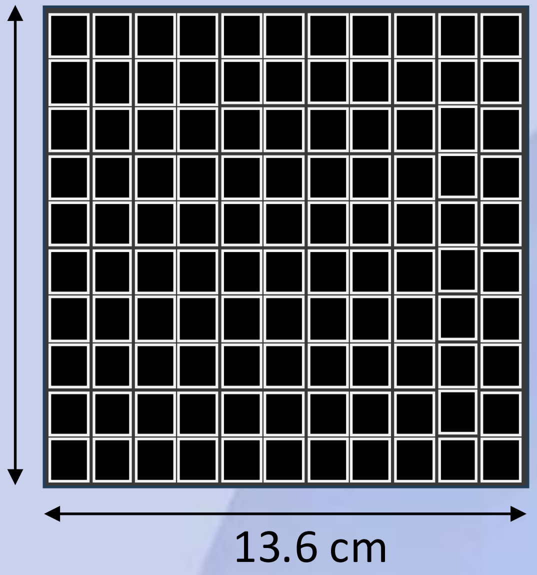
Standard size:

- Each fueled-clad pellet assembly puts out 62.5 watts of heat. 4 are put together into a 250-watt heat source
- A 250 (thermal) watt unit has size ~ 9.3cm x 9.3 cm x 5.3 cm
- Mass – 1.61 kg; contains ~ 0.6 kg Pu-238
- Current RTG power supplies used in space use 8 GPHS units. Our (much smaller) power supply uses only a single unit.

Reference

Gary L. Bennett *et al.*, "Mission of Daring: The General-Purpose Heat Source Radioisotope Thermoelectric Generator," AIAA 2006-4096, 4th IECEC, 26-29 June 2006, San Diego, CA

Power Source: Technology

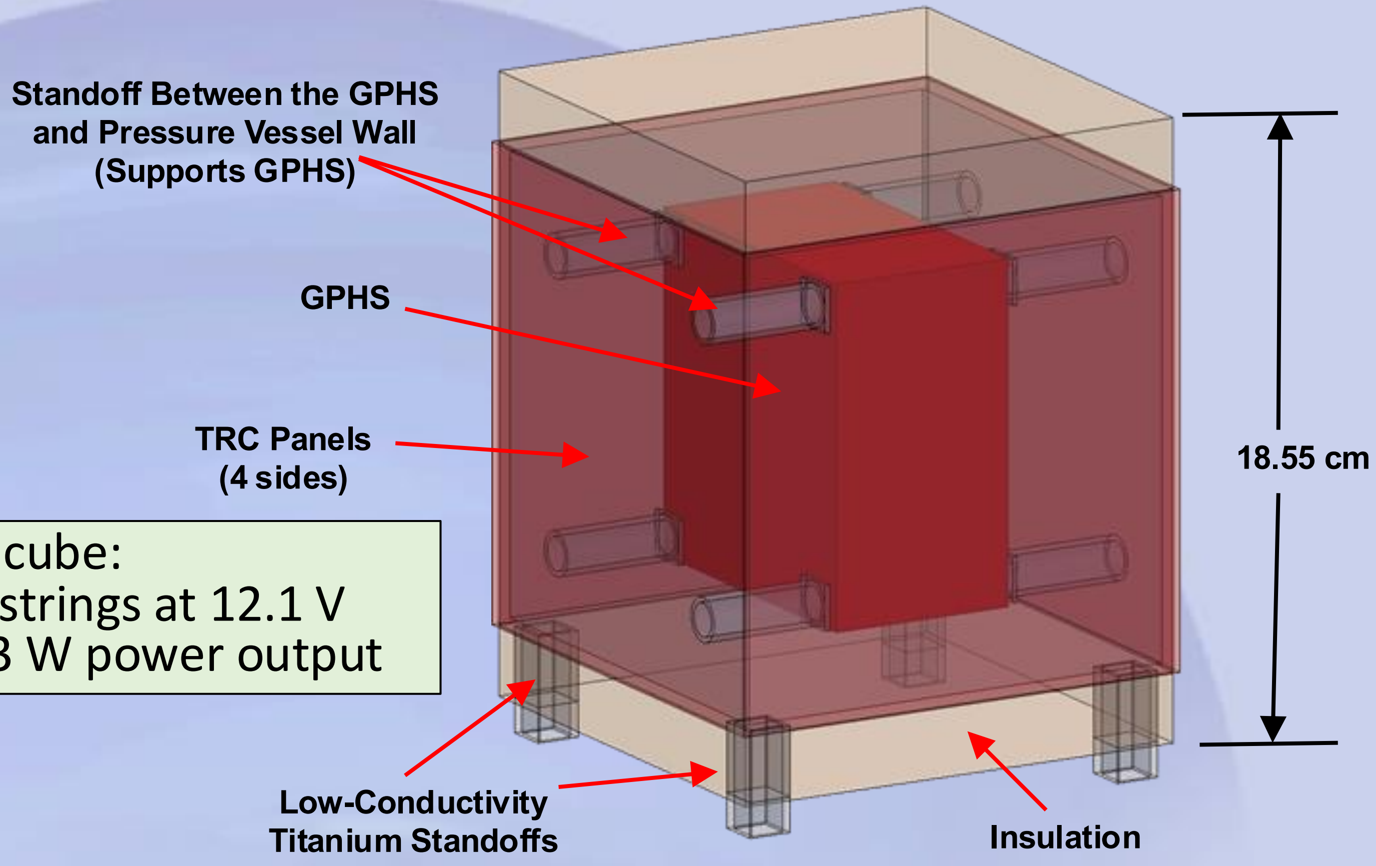


Panel of Thermoradiative Cells (TRC)

1.18 cm x 1.3 cm cell size 169 cm² total emitter area

One panel is on four sides of the power cube, with the GPHS thermal source in the center

Power cube:
- 2 strings at 12.1 V
- 33 W power output

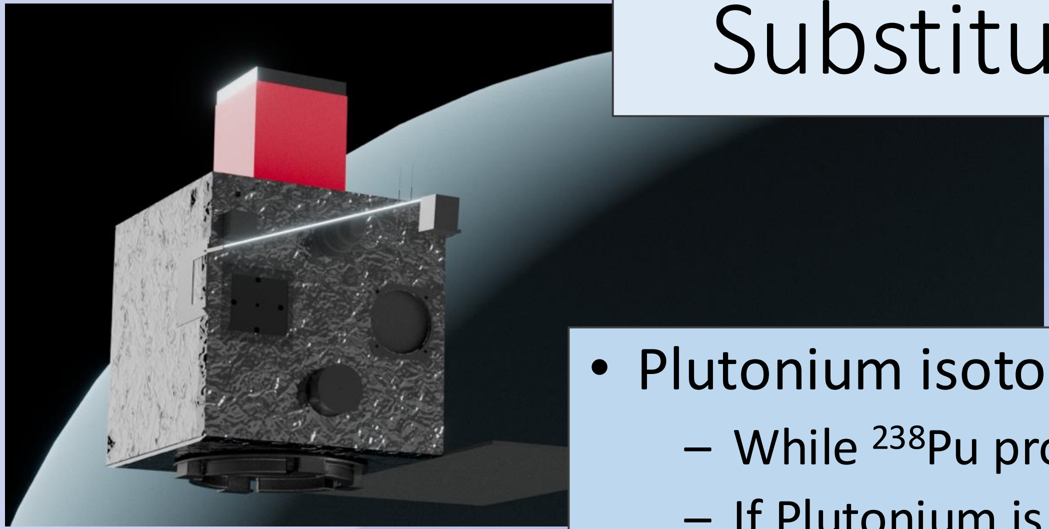


Thermoradiative energy conversion is a new method to generate electrical power from a thermal source

- A solid-state conversion element radiates waste heat directly, without a separate radiator.
  - Individual thermoradiative cells are put together in series to produce required voltage
  - Operating temperature 650K
  - Think of it as a radiator that also converts some of the radiated energy to electrical power
- Thermoradiative conversion element requires a view to deep space to radiate waste heat

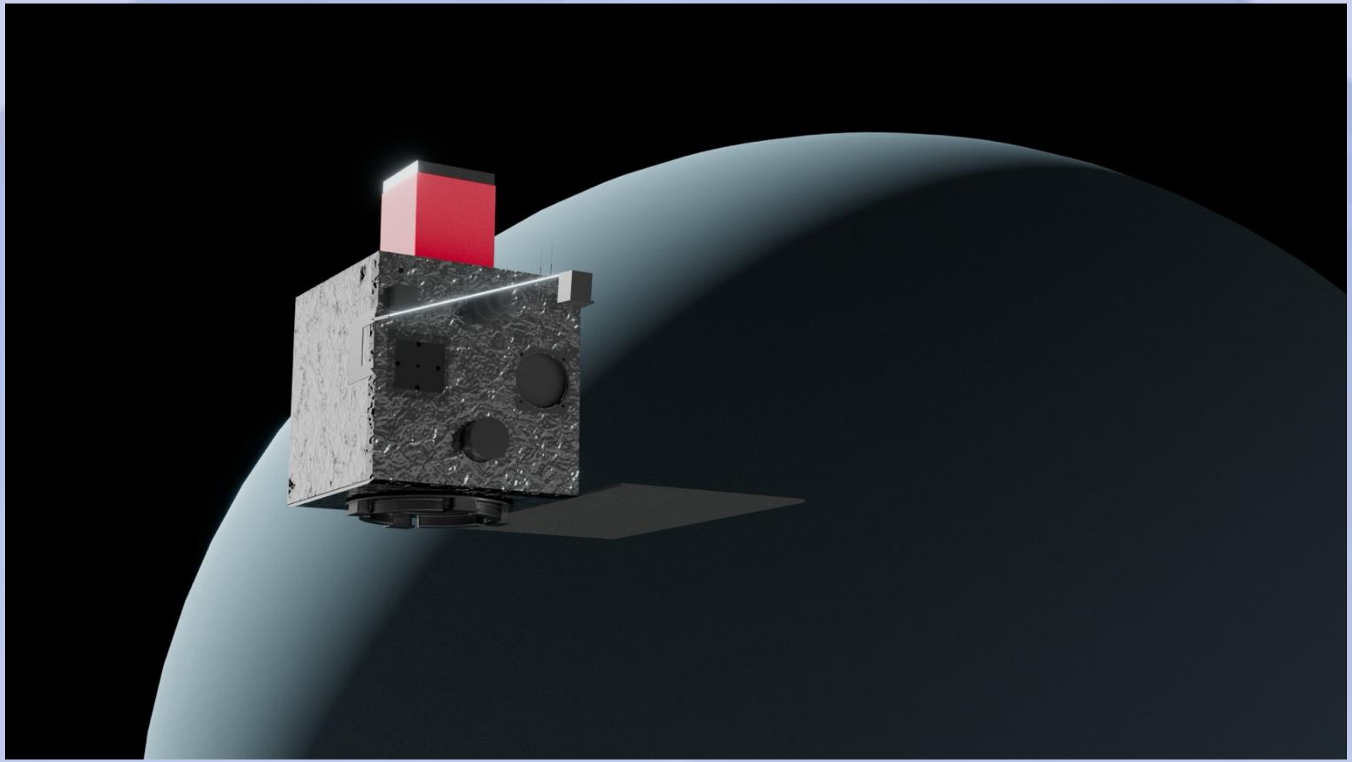
Alternate Isotope

Substituting ^{241}Am for ^{238}Pu



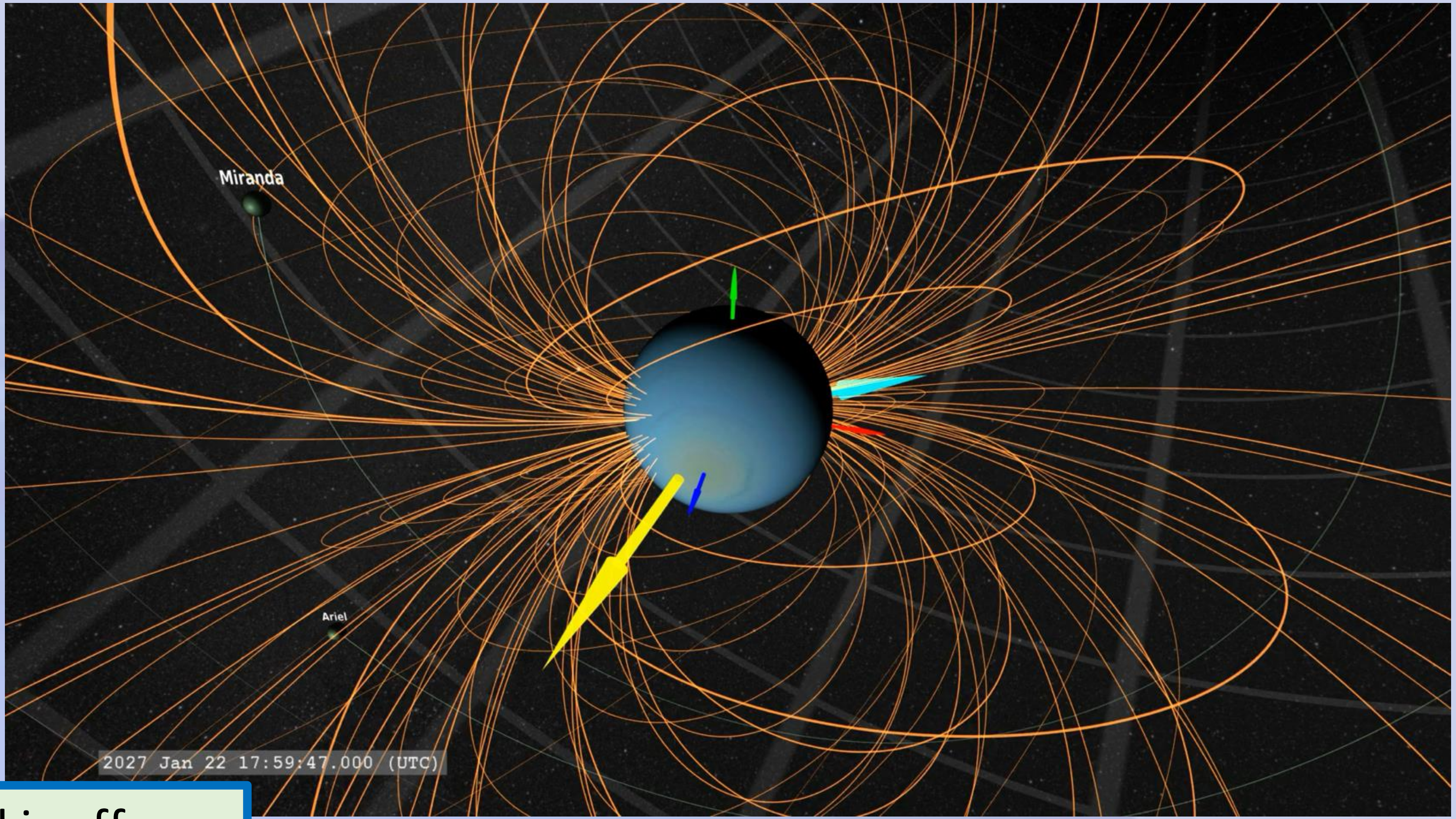
- Plutonium isotope availability is limited.
  - While ^{238}Pu production has been restarted, availability may still limited
  - If Plutonium is not available, we looked at a substitute isotope, Americium 241
  - ^{241}Am has a lower thermal output but longer half life (432.6 years)
  - Volume specific power is 1.17 W/cm^3 for AmO_2, compared to 5.66 for PuO_2
- Design would be identical, except for slightly larger power cube
  - if we substitute AmO_2 pellets for PuO_2 but keeping everything else the same, to produce the same power, the power cube would be a 16.5 cm cube (instead of 14 cm)
  - Adds ~6 kg to mass of TITUS

Spacecraft Subsystem Details



TITUS

Science at Uranus



Uranus' tilted magnetic field (Image courtesy NASA's Scientific Visualization Studio)

Uranus' magnetic field is weird, and not well understood

- Unlike every other planet, the magnetic field is off center and tilted 50° tilted from the rotational axis
- Interactions with the solar wind (the "magnetopause") are different from any other planet

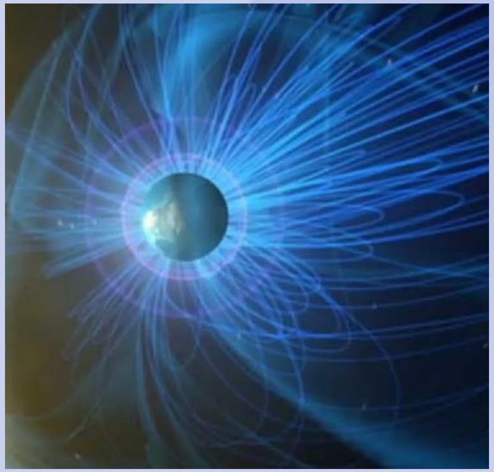
Uranus' radiation belts are not understood

- Proton radiation belts are weaker than expected
- Electron radiation belts are stronger than expected

Mission:
Measure Uranus' magnetic field, radiation belts, and plasma environment

- simultaneous observations from UOP and from our smallsat shows variations in time and space
- Requirement: UOP and smallsat in different orbits to make measurements at different places in magnetosphere

Science Questions and Instrument Selection



Science Question	Measurement	Requirements	Selected Instrument
1. What dynamo process produces Uranus's complex magnetic field?	Internal magnetic field structure	Close Passes	Digital Fluxgate Magnetometer (DFGM)
2. What are the plasma sources & dynamics of Uranus's magnetosphere and how does it interact with the solar wind?	Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)	Multiple Passes	Suprathermal Ion Spectograph (SIS), Multi-needle Langmuir probe (m-NLP), Low energy module (LEM)
3. How does the magnetosphere interact with Uranus's upper atmosphere and satellite surfaces?	Energetic particle fluxes at satellite orbital ranges	Magnetic fields and particle flux densities	
4. How do internal and external sources and drivers shape particle populations and enable particle transport within Uranus's magnetosphere?	3D vector magnetic field	Range: ±20,000 nT; Resolution ≤ 0.1 nT; Temporal Res: 10 s	Digital Fluxgate Magnetometer (DFGM)
	Plasma energy, angular, and distributions	Range: ~10 eV – 30 keV; Species: e^-; temporal Res: 10 s	Multi-needle Langmuir probe (m-NLP)
	Suprathermal ion energy, angular, and compositional distributions	Range: ~1-200 keV/Q; Species: H, He; temporal Res: 10 s	Suprathermal Ion Spectograph (SIS)
	Energetic particle energy, angular, and compositional distributions	Range: 30 keV - 10 MeV; Species: e^-, H, He, C, O; Temporal Res: 10 s	Low energy module (LEM)
5. Contribute to: What does Uranus's global current system look like and how does this couple to upper atmospheric dynamics?	3D vector magnetic field	Same as Science Question 4	Digital Fluxgate Magnetometer (DFGM)
6. Contribute to: Which processes source and shape Uranus's radiation belts?	Same as SQ 4	Same as Science Question 4	Same as Science Question 4

Mission: it's all about the Science

Science Instrumentation Mass Equipment List

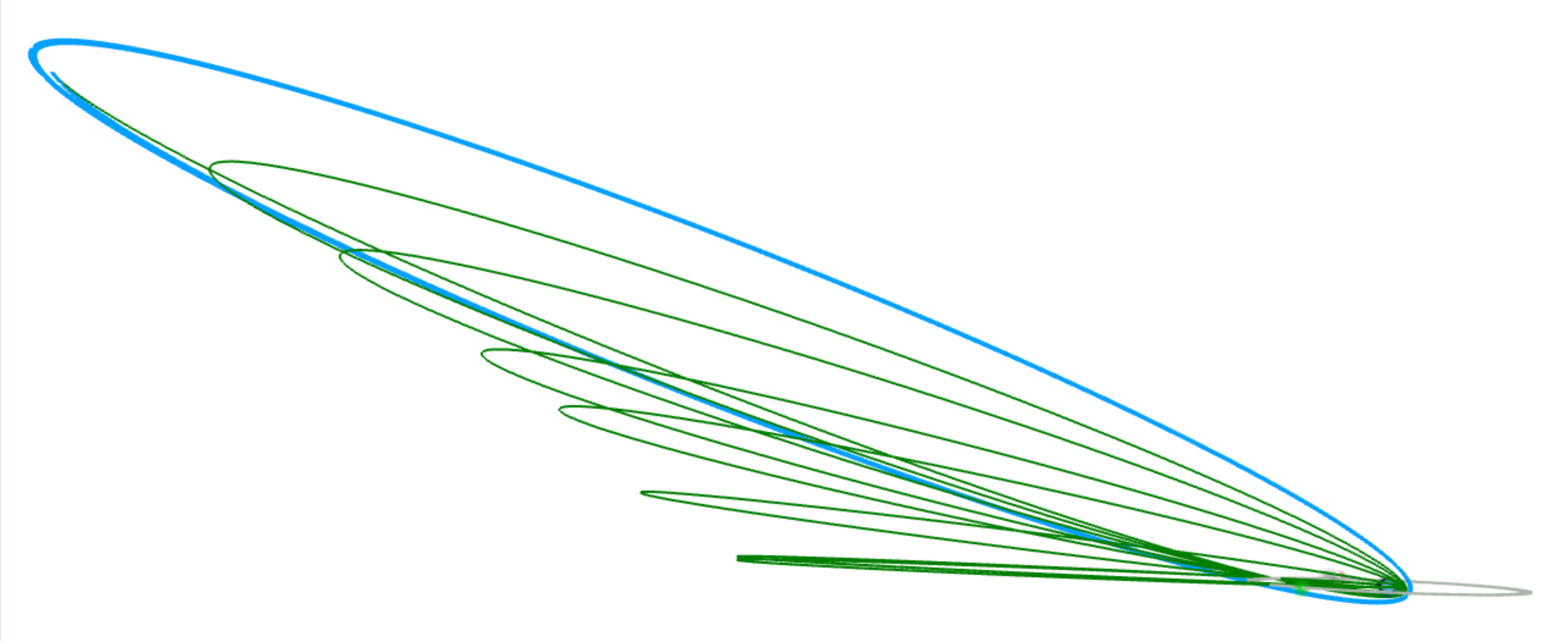
Description Case 1_TITUS CD-2025-225	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
		(kg)	(kg)	(%)	(kg)	(kg)
Science			**4.32**	**30%**	**1.30**	**5.61**
Science Package Group One			**4.32**	**30%**	**1.30**	**5.61**
Digital Fluxgate Magnetometer boom	1	0.07	0.07	30%	0.02	0.10
Multi-needle Langmuir probe	1	0.22	0.22	30%	0.07	0.29
Suprathermal Ion Spectrograph	1	1.37	1.37	30%	0.41	1.78
Low energy module	1	2.00	2.00	30%	0.60	2.60
Wide Angle Camera	1	0.50	0.50	30%	0.15	0.65
Magnetometer electronics	1	0.07	0.07	30%	0.02	0.08
Magnetometer sensors	2	0.05	0.09	30%	0.03	0.12

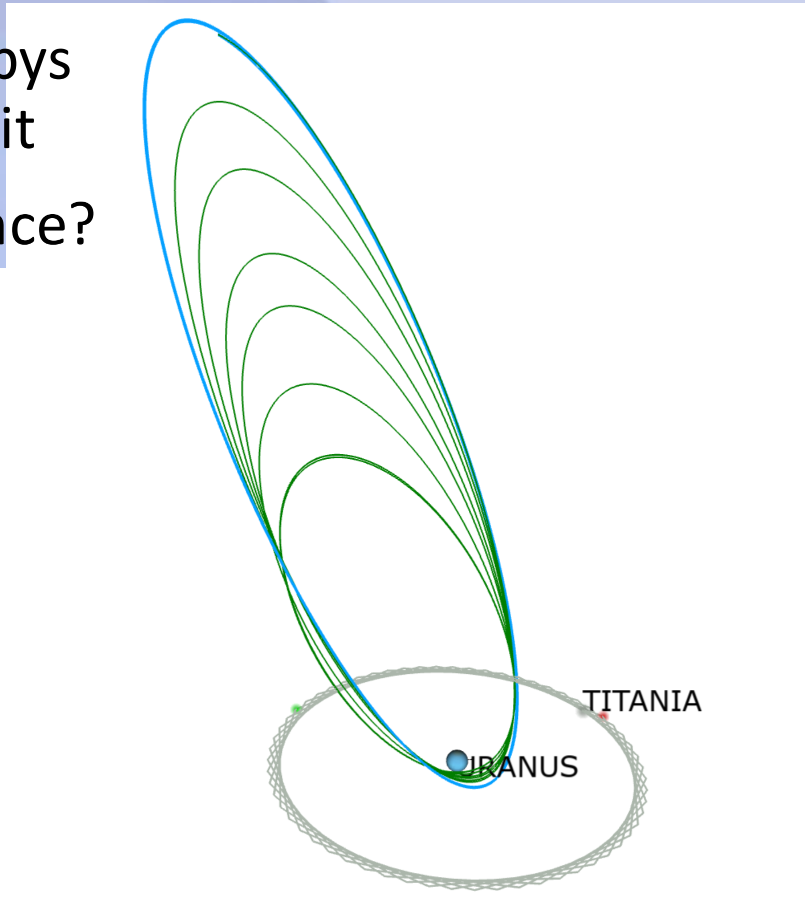
Mass growth allowance is per recommendations of AIAA Standard ANSI/AIAA S-120A-2015.

Science instruments are compact versions of instrumentation on UOP, based on instruments flown on other smallsat missions

Uranus Orbiter with Probe:
Uranus orbital insertion and orbits

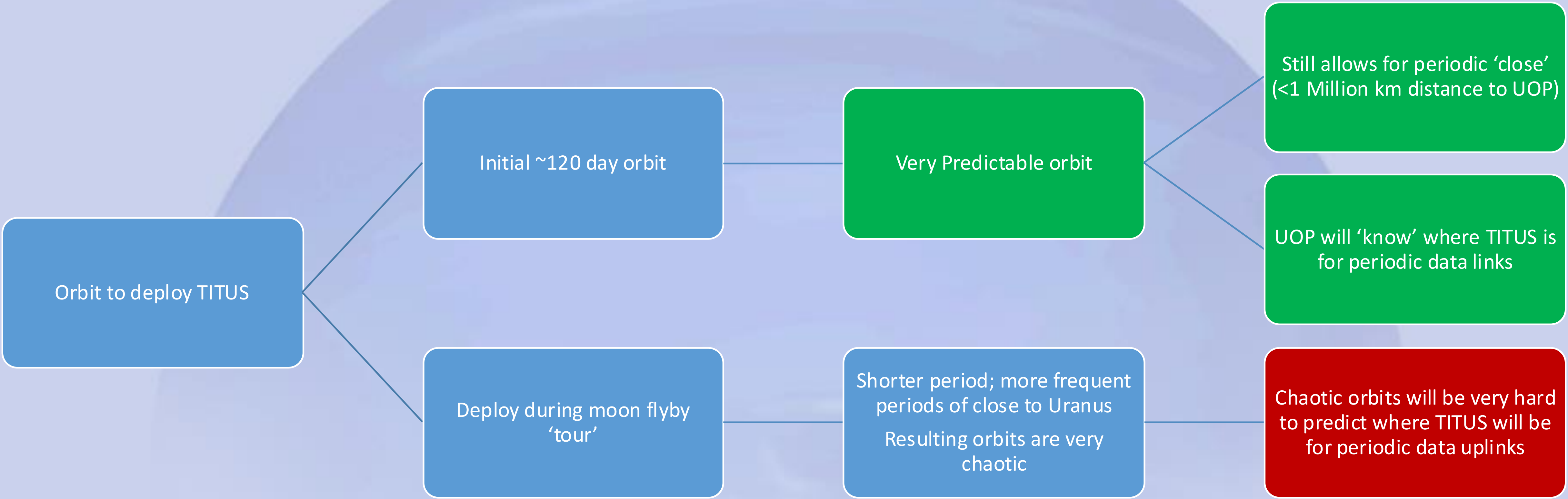
- UOP enters Uranus system and captures into a highly elliptical, highly inclined orbit
- Atmospheric probe is released from this orbit to impact Uranus
- UOP divert maneuver then raises periapsis to ~120-day orbital period
- Over the course of three years UOP uses multiple moon fly-bys to reduce its apoapsis and transition toward an equatorial orbit
- Where should we release the TITUS probe to maximize science?





Where to Deploy TITUS?

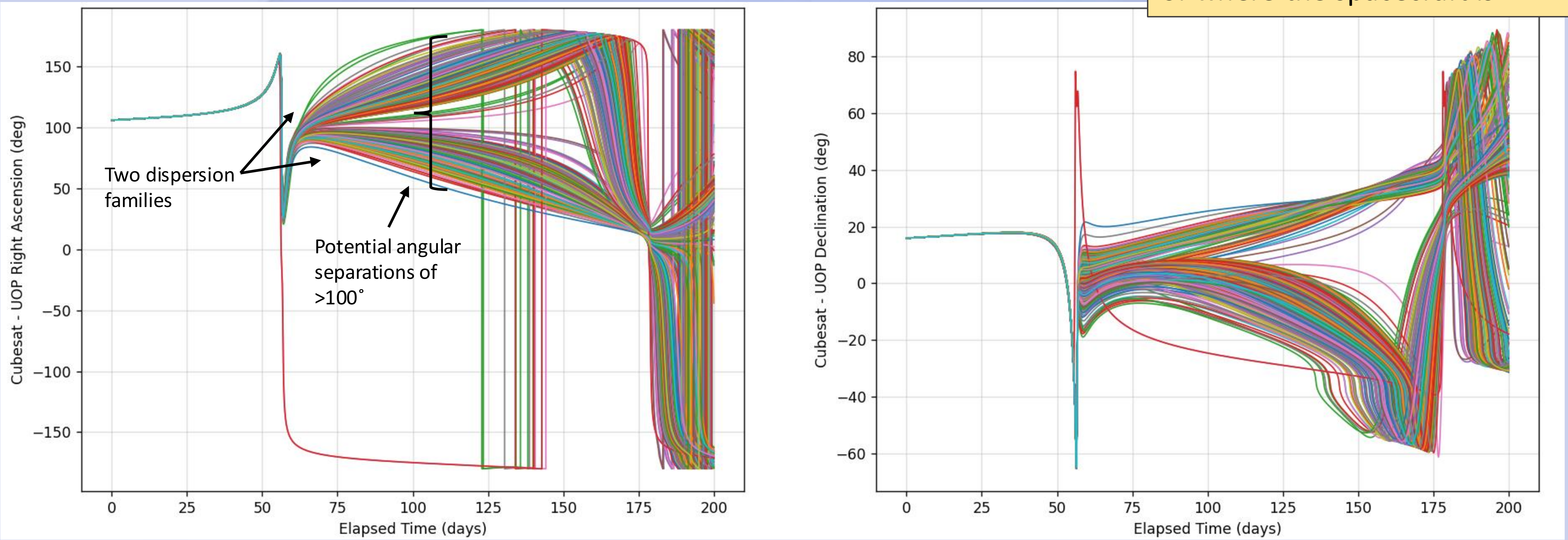
- The TITUS smallsat does not have propulsion capable of making significant change to its orbit; it will remain in the orbit that the UOP deploys it into.



Lower deployment results in chaotic orbit

- Deploying during moon-tour carries significant risk of introducing uncertainty into Titania fly-by sequence
- Gravity assists due to close passage by Titania will magnify state uncertainties, a problem that is amplified by the lack of a maneuvering capability
- Trajectories modeled with Copernicus (NASA JSC developed high-fidelity modeling software)
- Conducted 500-sample analysis against random state dispersions to observe impact on cubesat position
- Trajectory begins at post-PRM apoapsis state and ballistically moves through 2x Titania fly-bys
- 42/500 samples (8%) impacted Titania (cubesat carries no ability to execute trajectory correction)

Conclusion: we do not want to wait and deploy into a lower orbit, because we will lose track of where the spacecraft is



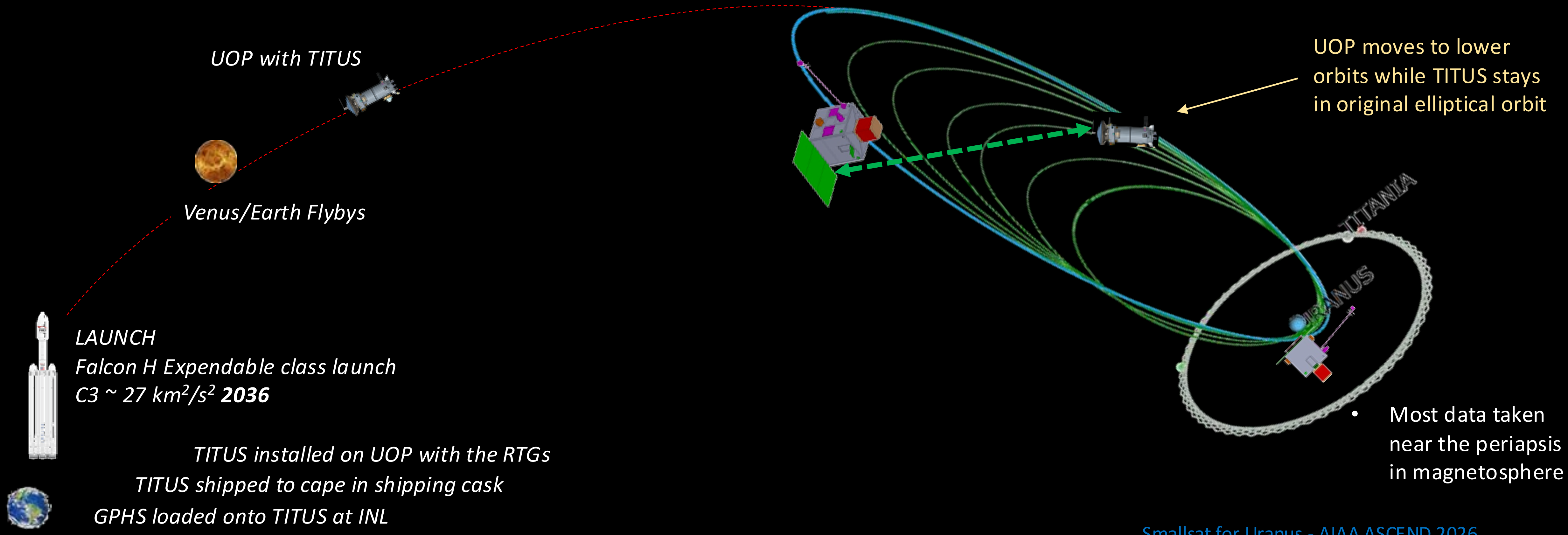
TITUS Overall Mission Conops

Capture at Uranus w UOP in 2049

- Separate from UOP after probe separation into 120-day stable orbit
- Remain in 120-day orbit for rest of 5 yr mission

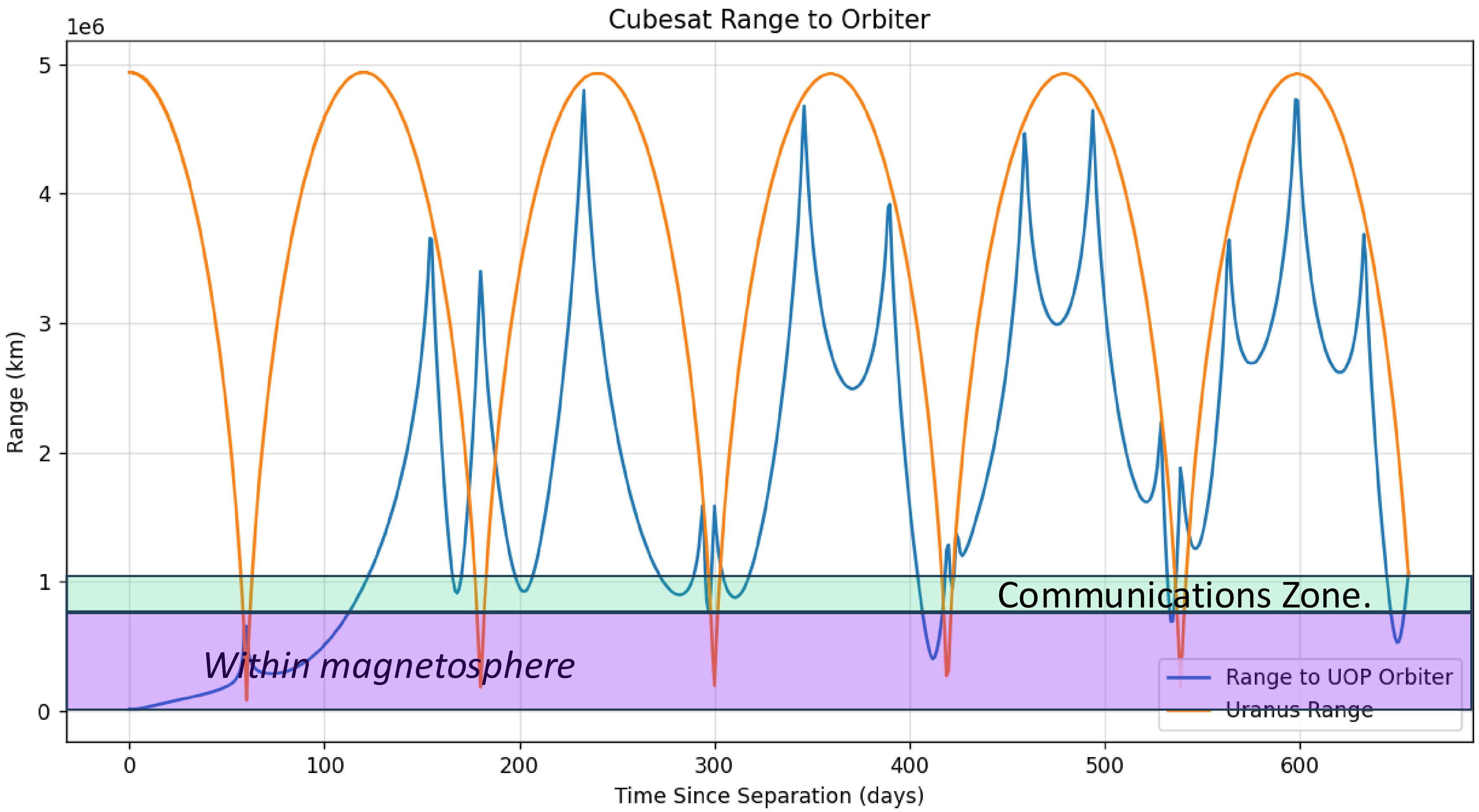
Data Relay:

- Relay data to UOP every 120 days (not at periapsis)
- TITUS uploads 120 d of data 400 Mb over~ 3 hrs
- 3- 5 days later repeat acquisition

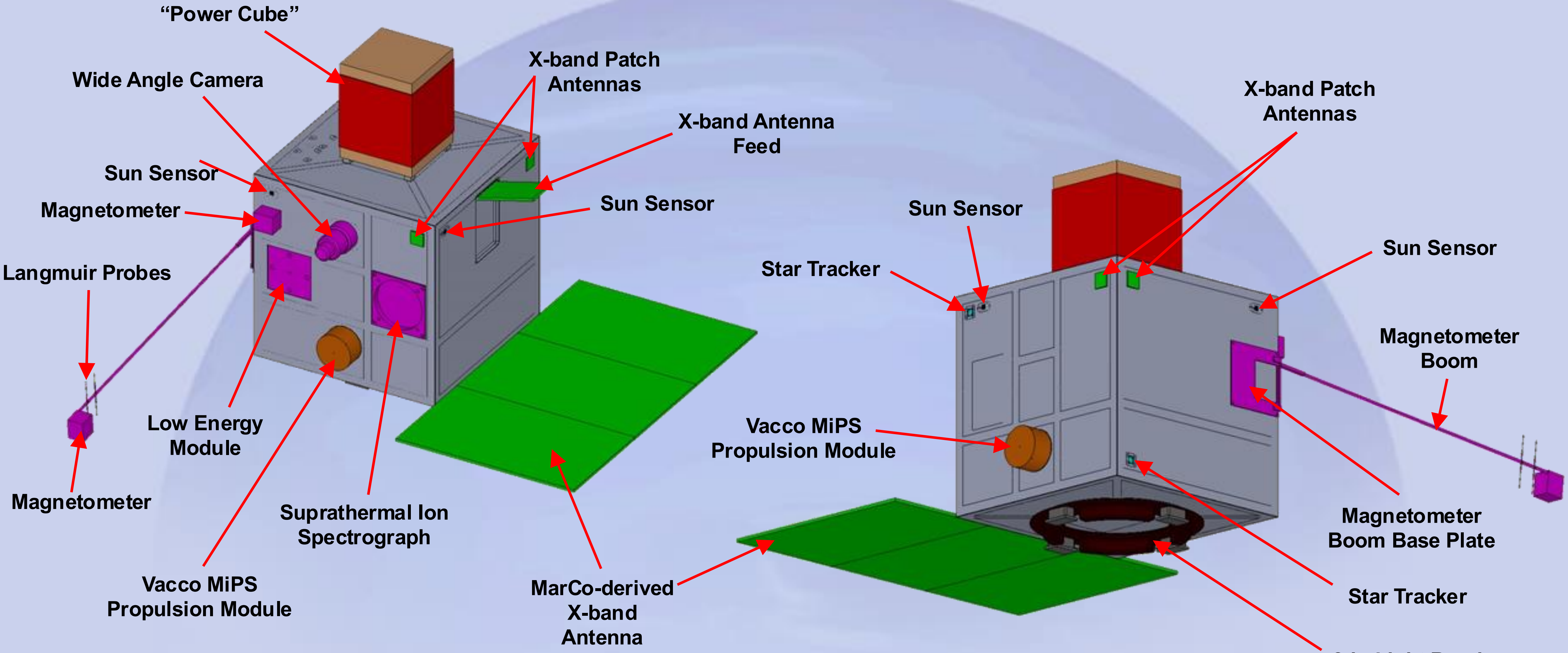


TITUS range to orbiter and to Uranus

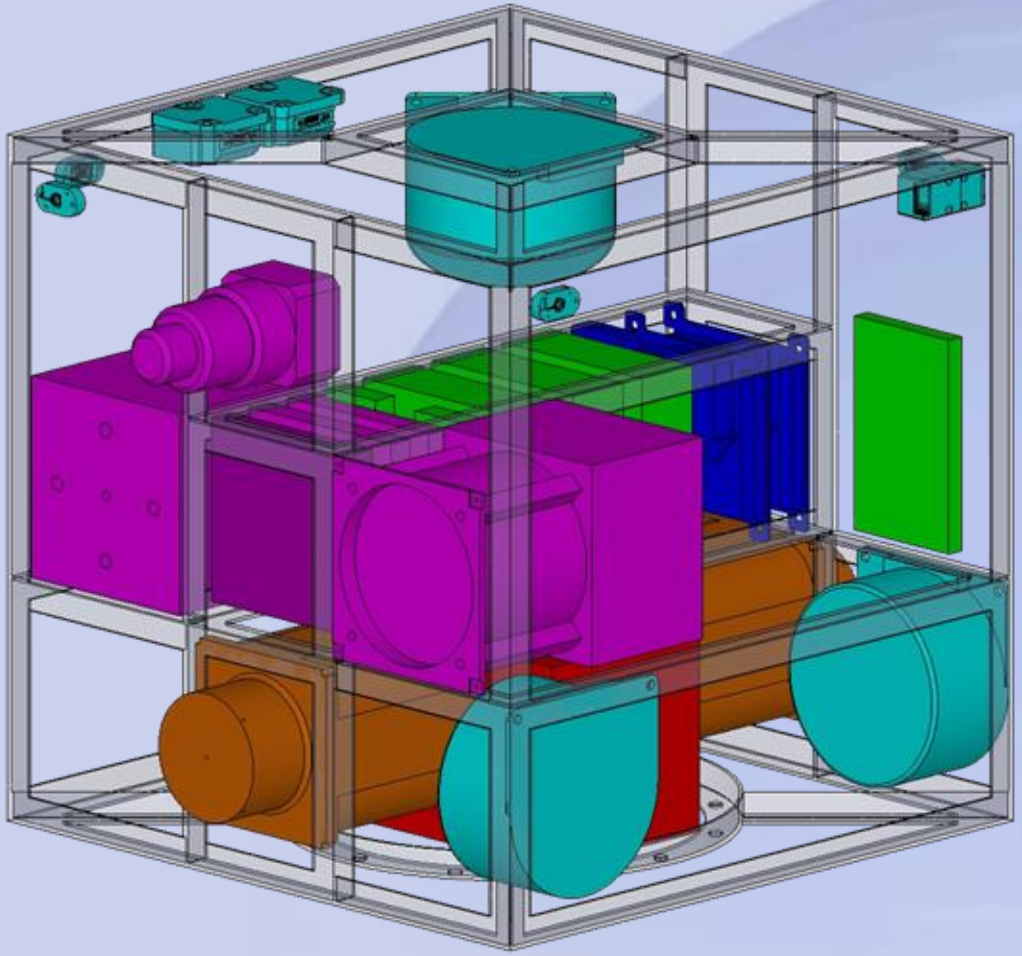
High data-rate communications to orbiter occurs when TITUS is within 1 million km of the UOP (blue), roughly once every hundred days

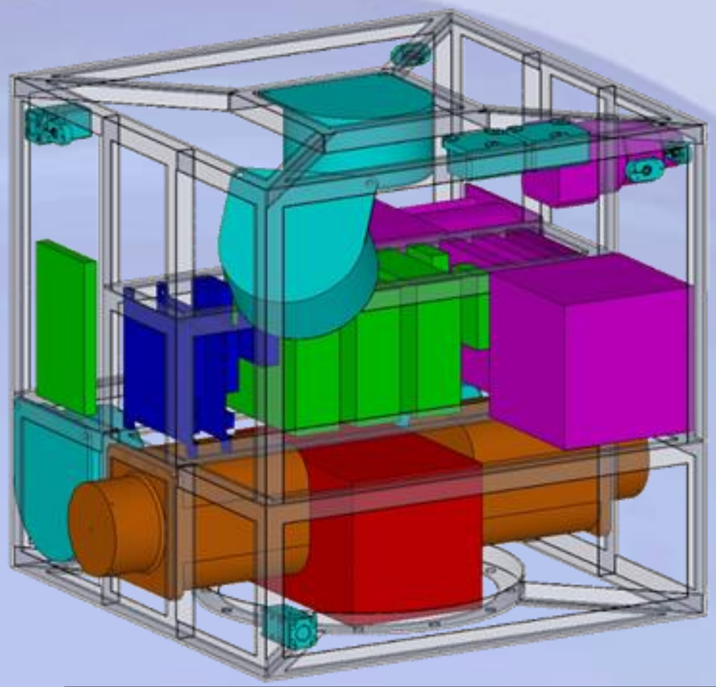


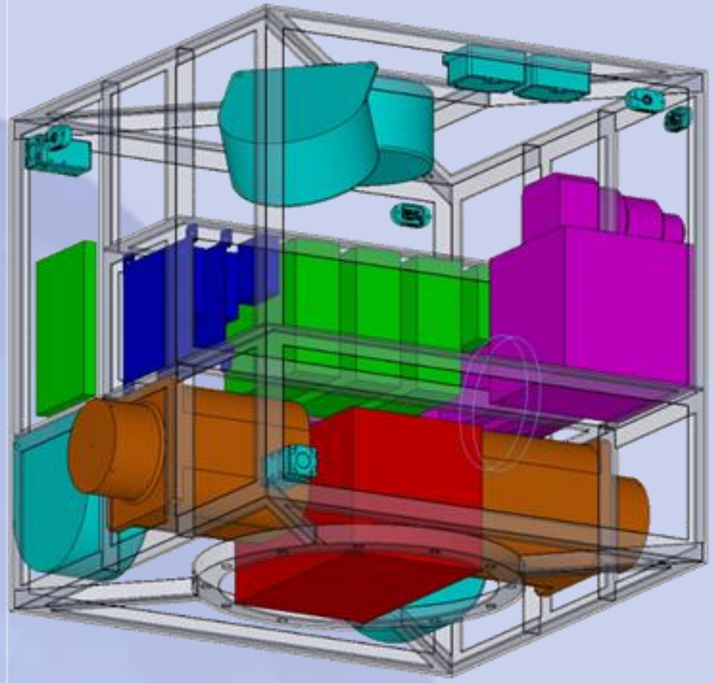
TITUS External Components/Sensors



TITUS Internal Bus Components







Science: Magnetometer Electronics, Camera and Electronics, Langmuir Probe Electronics, Low Energy Module, and Suprathermal Ion Spectrograph

Attitude Determination and Control: 4 Reaction Wheels, 2 IMUs, 4 Sun Sensors, and 2 Star Trackers

Command and Data Handling: Atomic clocks, On-Board Computers, External Storage, and External Watchdog Timers

Communications: All Communication Electronics

Electrical Power: PMADs and Lithium-Ion Batteries (combined into one unit)

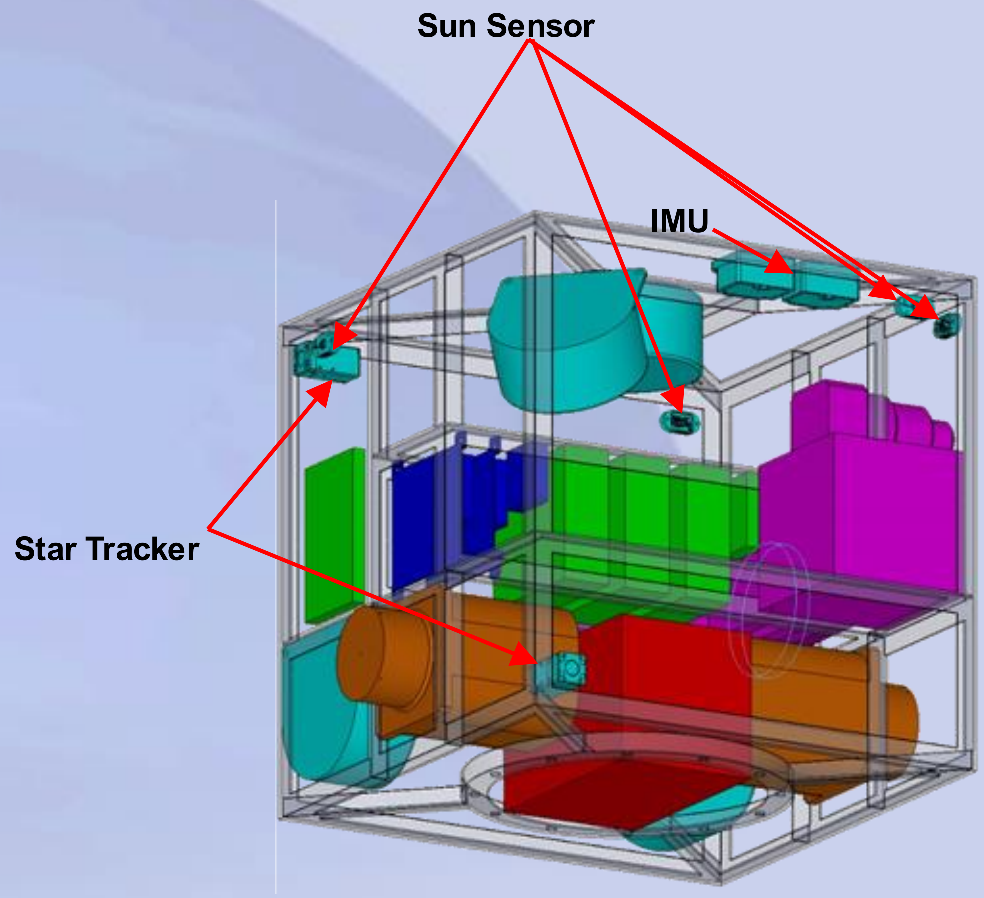
Attitude determination and Control

ADC Sensor Summary

- Inertial Measurement Unit (x2)
- Star Tracker (x2)
- Sun Sensor (x4)

ADC Actuator Summary

- Reaction Wheels (x4)
  - One primary wheel for each body axis with 1 spare
- Reaction Control System (RCS) Thrusters
  - Used to arrest tip-off rates and provide desaturations during high-rate attitude tracking maneuvers



Command and Data Handling

- On-Board Computer (OBC) - RadPC SBC-001
  - RISC-V CPU
  - 64 Bidirectional, General-Purpose I/O Ports
  - 2x UART, 1x SPI, 1x I2C Serial Peripherals

- Atomic clock – CSAC-SA65

- External Storage – PDC 69F12GB NAND Flash Memory
  - 1.5 GB of storage capacity
  - Requires NAND controller, potential custom solution

- External Watchdog Timer – Renesas ISL706ARH IC

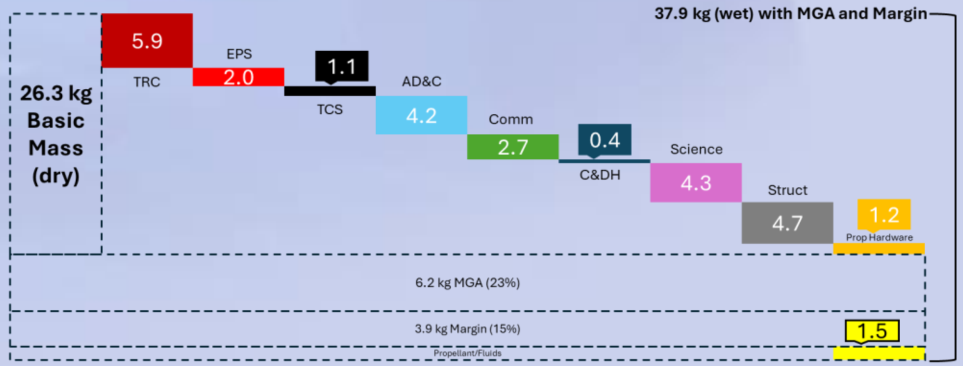
TITUS: Systems Integration

Description Case 1_TITUS CD-2025-225	Basic Mass	Growth	Growth	Total Mass
	(kg)	(%)	(kg)	(kg)
TITUS	27.79	22%	6.16	33.95
Bus	21.88	23%	4.92	26.80
Science	4.32	30%	1.30	5.61
Attitude Determination and Control	4.19	10%	0.43	4.62
Command & Data Handling	0.41	30%	0.12	0.53
Communications and Tracking	2.65	18%	0.47	3.12
Electrical Power Subsystem	2.02	23%	0.47	2.49
Thermal Control (Non-Propellant)	1.11	18%	0.20	1.31
Propulsion (Chemical Hardware)	1.20	5%	0.06	1.26
Propellant (Chemical)	1.52	0%	0.00	1.52
Structures and Mechanisms	4.45	42%	1.88	6.33
TRC	5.91	21%	1.23	7.15
Electrical Power Subsystem	2.01	10%	0.19	2.21
Thermal Control (Non-Propellant)	0.10	18%	0.02	0.12
Fluids	0.00	0%	0.00	0.00
Structures and Mechanisms	3.80	27%	1.02	4.82

Program Milestone	Recommended MGA	Recommended Mass Margin	MGA + Mass Margin	
	%	%	%	Grade
ATP	>15	>15	>30	Green
	9<MGA≤15	10<Mass Margin≤15	19<MGA + Mass Margin≤30	Yellow
	≤9	≤10	≤19	Red

Total accommodation mass is 39 kg to account for the adapter.

MEL Summary: Case 1_TITUS CD-2025-225	Bus	TRC	TOTAL
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Science	4.3	0.0	4.3
Attitude Determination and Control	4.2	0.0	4.2
Command & Data Handling	0.4	0.0	0.4
Communications and Tracking	2.7	0.0	2.7
Electrical Power Subsystem	2.0	2.0	4.0
Thermal Control (Non-Propellant)	1.1	0.1	1.2
Propulsion (Chemical Hardware)	1.2	0.0	1.2
Propellant (Chemical) / Fluids	1.5	0.0	1.5
Structures and Mechanisms	4.5	3.8	8.2
Element Total	*21.9*	*5.9*	*27.8*
Element Dry Mass (no prop,consum)	20.4	5.9	26.3
Element Propellant	1.5	0.0	1.5
Element Mass Growth Allowance (Aggregate)	4.9	1.2	6.2
MGA Percentage	24%	21%	23%
Predicted Mass (Basic + MGA)	25.3	7.1	32.4
System Level Mass Margin	3.1	0.9	3.9
System Level Growth Percentage	15%	15%	15%
Element Dry Mass (Basic+MGA+Margin)	28.3	8.0	36.4
Element Inert Mass (Basic+MGA+Margin)	28.5	8.0	36.5
Total Wet Mass (Allowable Mass)	*29.9*	*8.0*	*37.9*

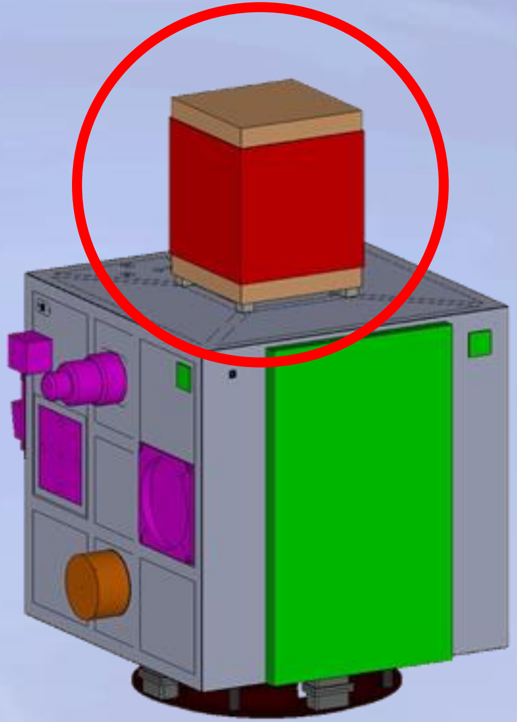


Mass growth allowance is per recommendations of AIAA Standard ANSI/AIAA S-120A-2015.

Size comparison

The entire TITUS smallsat is smaller than a single MMRTG power source, the power system for the parent UOP spacecraft

Current technology
MMRTG: 110 W
45 kg, 64 cm diam, 66 cm height
(three used on Uranus Orbiter and Probe)

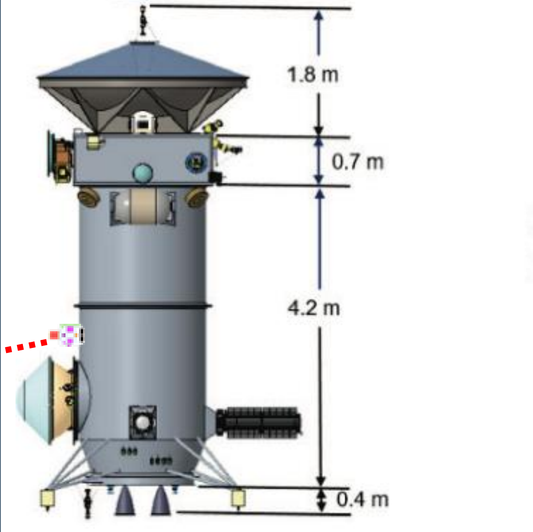


TITUS: 33W
Power supply: 5.9 kg (7.1 including growth)
14 cm square, 18.6 cm height

Acronyms decoded:
MMRPG = Multi-mission Radioisotope Thermoelectric power Generator

Mounting TITUS on the Uranus Orbiter & Probe

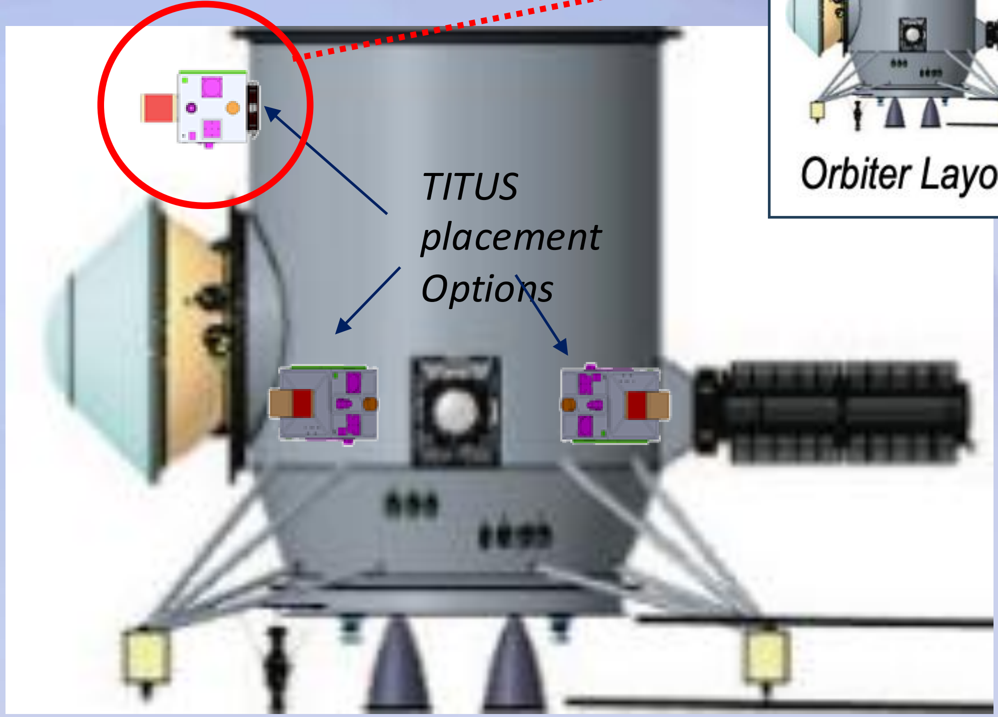
- UOP will already have radioisotope launch approval
- Integration to UOP
  - Notionally place on side next to RTGs and Probe



Orbiter Layout with Dimensions

- Mass of TITUS compared to UOP
  - UOP: wet mass 7235 kg;
  - dry mass: ~ 2500kg
  - Atmospheric Probe: ~270 kg
  - TITUS: ~ 40 kg

TITUS is 0.55% of the wet mass of UOP

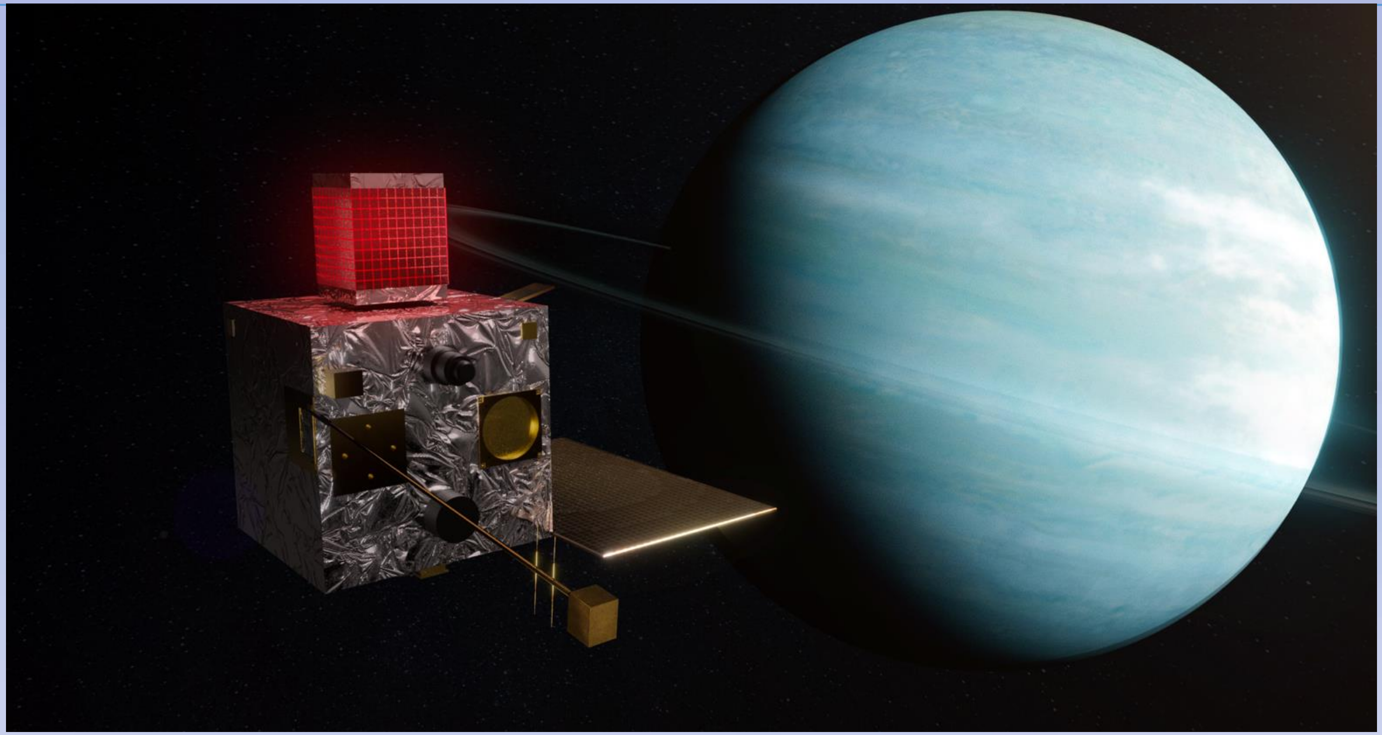


Conclusions

This study did an engineering design of a smallsat to accompany the Uranus Orbiter Probe to Uranus, enabled by a new, lightweight power system currently under development

The project had two significant goals:

- Shows how the thermoradiative conversion power generation could be integrated into a practical mission
- Shows that a ride-along smallsat can contribute valuable science to a proposed Uranus mission



TITUS in orbit around Uranus: artist's conception

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NIAC NASA Innovative Advanced Concepts