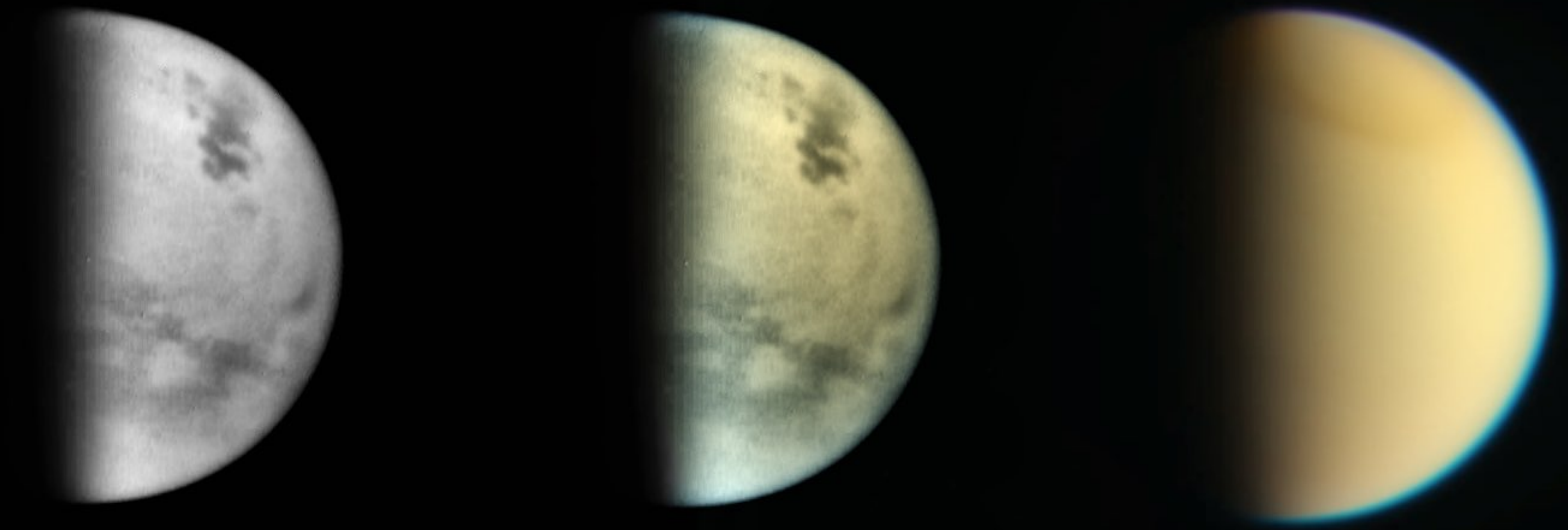
THUNDER

Titan's Hydrocarbons: Uncovering New Dimensions of Evolutionary Processes



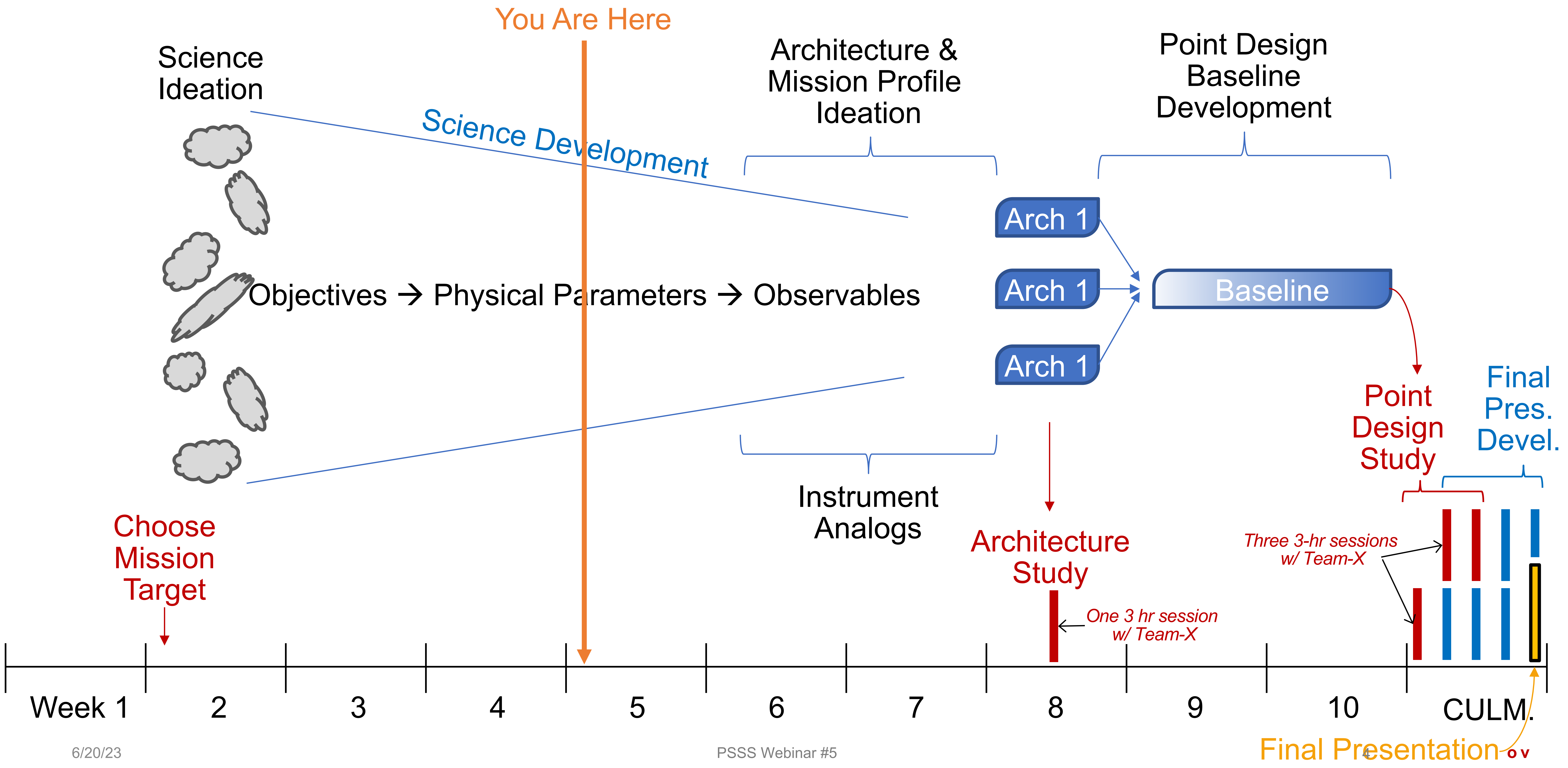
Nicholas Montiel, Planetary Science Summer School 2023 Session 2

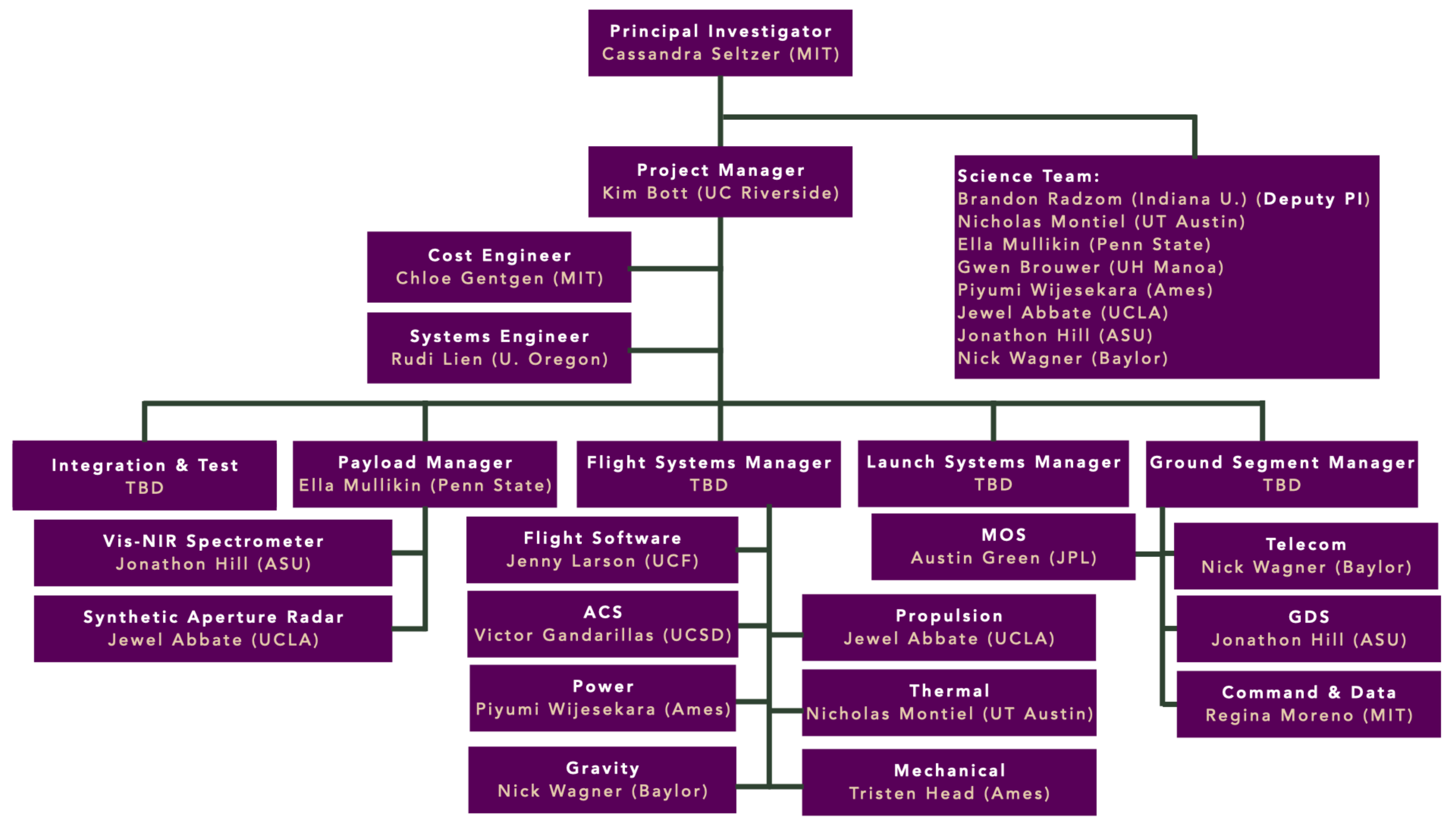

Titan
Orbiter
THUNDER


THUNDER
TITAN ORBITER
PSSS 2023


CHARLES ELACHI MISSION CONTROL CENTER

PSSS Schedule at a Glance





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GDS
Jonathon Hill (ASU)
Command & Data
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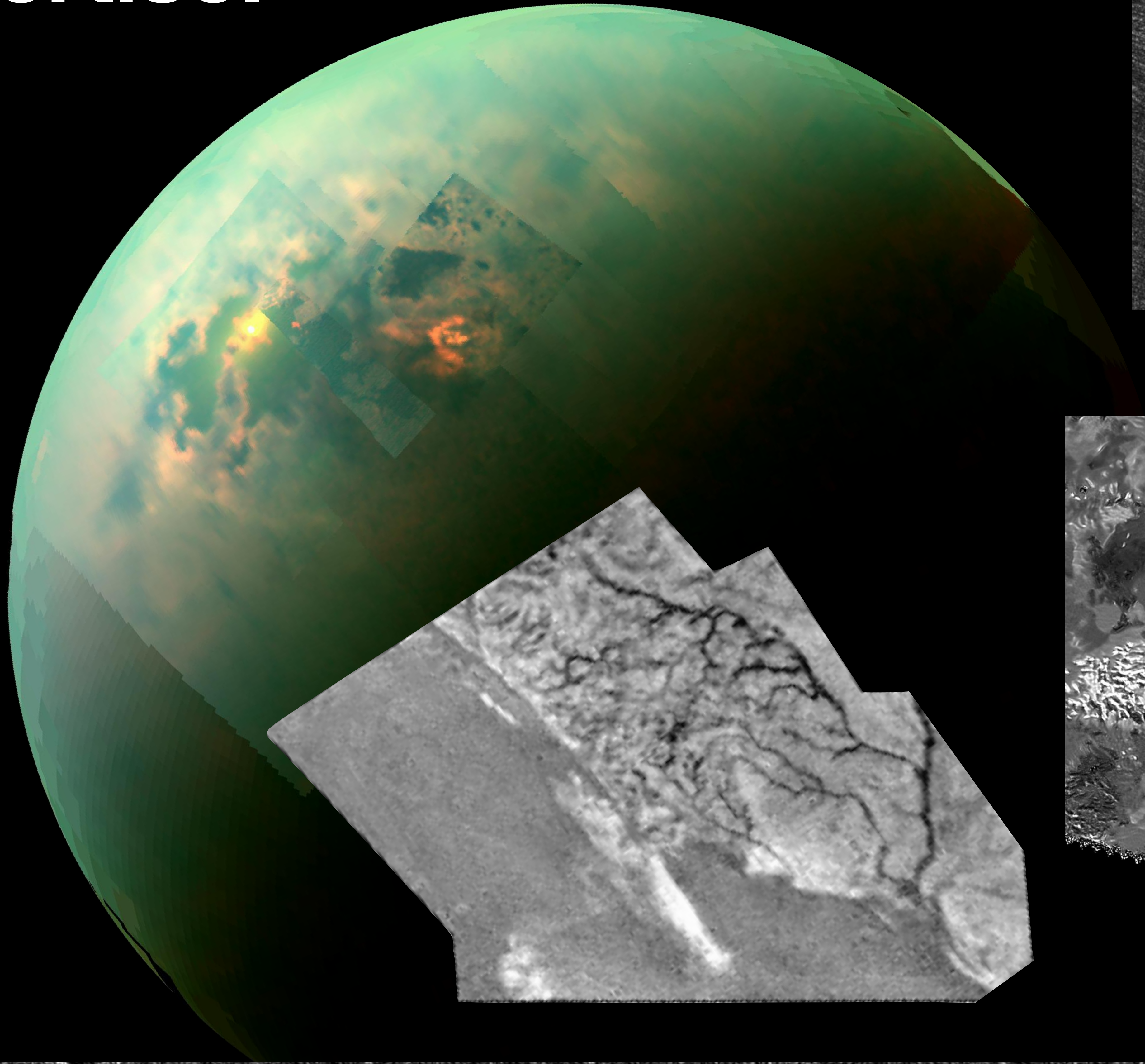
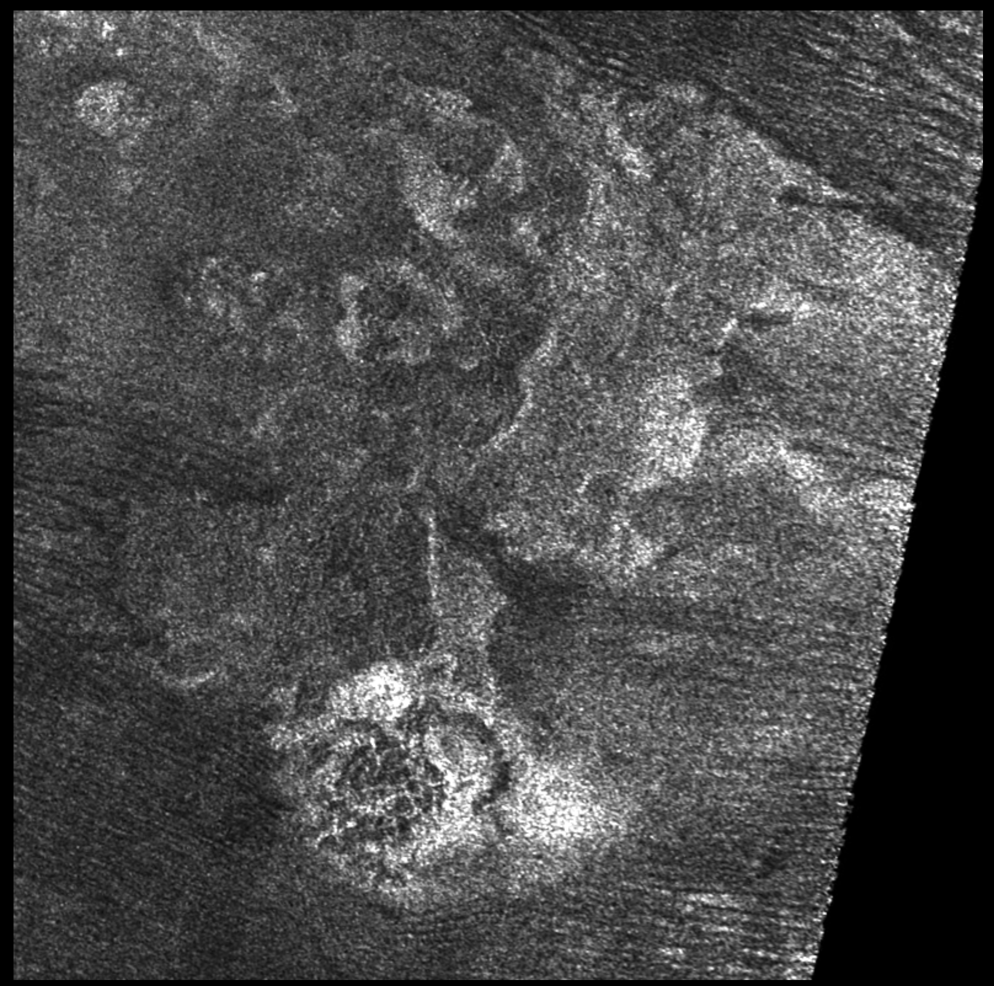
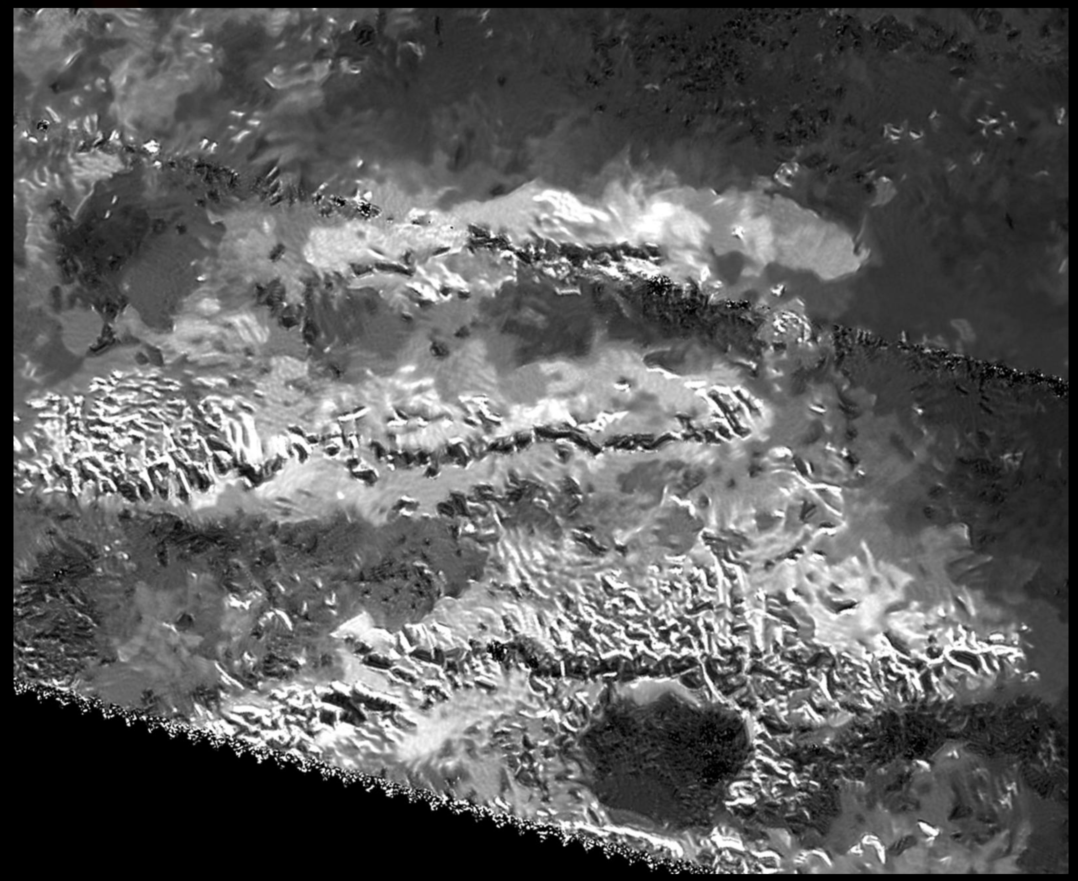
Titan Background

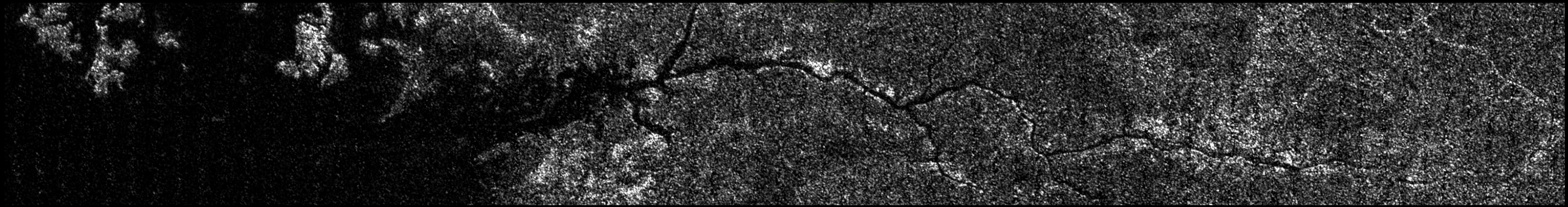
"Just to the left of all our expertise."

- Rivers, lakes, seas, O my!
- Unstable, massive atmosphere.
- Interior water ocean.
- Dynamic surface geology.
- Global tectonics, contraction?
- Cryovolcanoes?









2023 Decadal Survey on Titan

New Frontiers Mission - $1650M Cost Cap

Titan Orbiter globally characterizes Titan's dense N_2 atmosphere that harbors prebiotic molecules, its Earth-like methane hydrological cycle and seas, and its subsurface liquid water ocean, including how they evolve over time, in order to assess Titan's potential habitability. Cassini flybys revealed complex organic chemistry, methane-ethane lakes and seas, and meteorology on Titan, however these processes could not be thoroughly studied due to instrumentation and flyby coverage limitations. Titan orbiter will investigate how the organic chemical factory on Titan works both in the atmosphere and on the surface, providing important context for data from Dragonfly and complementary global measurements.[29]

Science Objectives:

- Determine Titan's internal structure, the depth and thickness of the ice shell and subsurface ocean, and whether the former is convecting; and determine rates of interior-surface solid or gas interchange
- Characterize Titan's global geology and its landscape-shaping processes
- Characterize Titan's global methane hydrological and sedimentological system, including surface transport/flow rates and cloud distributions
- Quantify the production, transport and fate of organic molecules in Titan's upper atmosphere and atmospheric and climate evolution in general

The mission shall address all four objectives.

Science Traceability Matrix

- Government funded, answerable to the public.
- ***Must show concrete success.***
- Hypothesis-driven, deductive science.

Goal	Objective	Physical Parameter	Observables	Instrument	Requirements
Decadal Question	Science Closure	System being investigated.	Actual measurement (usually photons)	Method to get measurement.	Resolution, range, etc.
"Characterize Titan's global geology."	"Determine if Titan has a convecting ice shell."	"Tectonic mode - Stratigraphically young folds and thrusts."	"Radar backscatter."	"Synthetic Aperture Radar"	"~125 m horizontal"

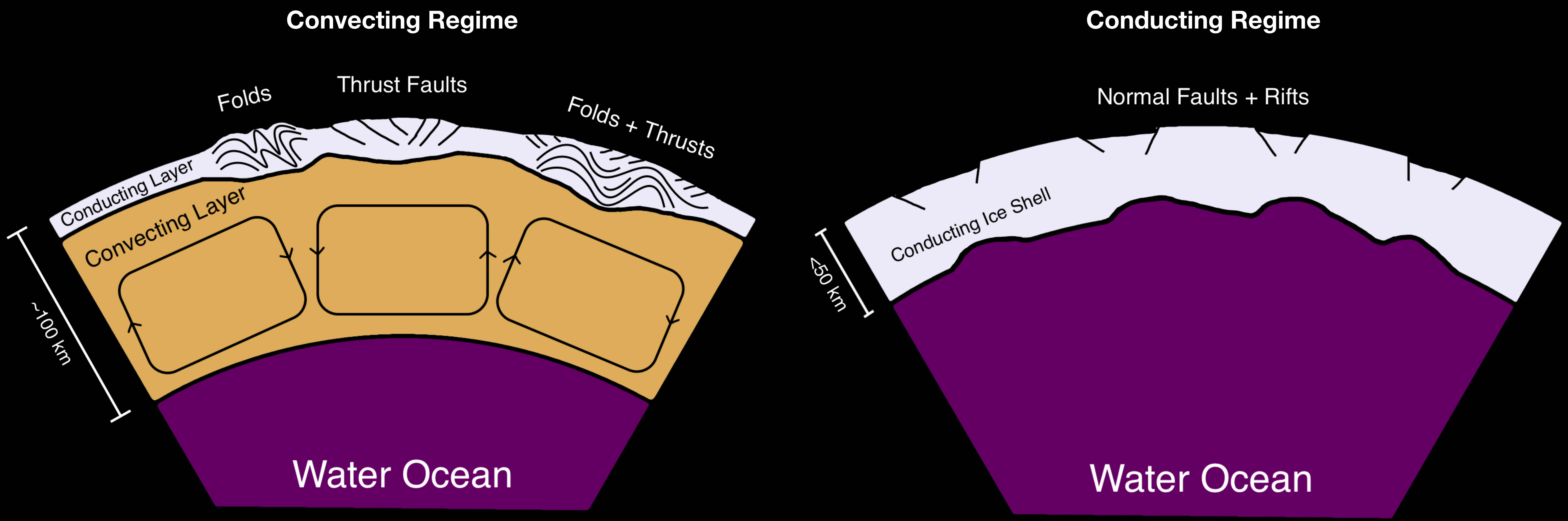
			SCIENCE			ENGINEERING				
						INSTRUMENTATION			MISSION REQUIREMENTS	
Goal	Domain	Objective	Physical parameters		Observables	instrument	Requirements for polar orbit at 1300 km	Capabilities at 1300 km orbit	Spatial	
			Description	End members					geographic	% surface coverage (minimum)
							OBJECTIVE 1		OBJECTIVE 1	
Goal: Understand how Titan's hydrocarbon cycle has shaped its evolution	Interior + Ice Shell	**Determine if Titan has a convective ice shell which can facilitate material transport between the surface and ocean**	**Admittance at spherical harmonic degree >15**	Precision of ±2.5 mGal/km for n≤15	Radar two-way travel time	Radar: altimetry	horizontal resolution: ≤ 400 km vertical resolution: ≤ 10 m	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm	Global 100% coverage	100
					Acceleration as measured by Doppler shift of spacecraft	Gravity science	≤ 0.03 mm/s over 60s integration	0.01 mm/s over 60s integration		
			Tectonic Style	IF CONVECTING: Stratigraphically young, tall (2 – 5 km) ridge features which are randomly oriented across Titan's surface. IF NOT: Short (<2km), extensional features concentrated in regions of high stresses from despinning and global expansion).	Radar backscatter	Radar: SAR	horizontal resolution: ≤ 125 m *driving requirement for SAR* swath width: ≥ 10 km *driving requirement for vis-IR*	horizontal resolution: 100 m swath width: 31.0 km	mid-latitudes that are largely unobscured by the mare, lakes, or dune seas; mountainous regions; lake regions; transects through distinct geological provinces to determine stratigraphic relations; 78% coverage	78.59
					Radar two-way travel time	Radar: altimetry	horizontal resolution (along track): ≤ 500 m *driving requirement for altimetry* vertical resolution: ≤ 30 m	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm		
			Re(k2)	Precision of ±0.01	Acceleration of the spacecraft as measured by Doppler shift of spacecraft	Gravity science	≤ 0.03 mm/s over 60s integration	0.01 mm/s over 60s integration	Global 100% coverage 7.5 day measurement spacing btwn Titan's apoapsis and periapsis	100
							OBJECTIVE 2		OBJECTIVE 2	
	Surface	**Determine whether Titan's major liquid hydrocarbon bodies, are connected and exchanging material with one another through a subsurface reservoir**	**Lake/paleolake elevations and depths**	IF CONNECTED: Neighboring (paleo)lakes have elevations within ±10 m of each other, negative elevation gradients towards the paleoseas/mare IF NOT: Neighboring (paleo)lakes have no statistically significant similar relative elevation nor a gradient towards the paleoseas/mare	Radar backscatter	Radar: SAR	horizontal resolution (along track): ≤ 500 m swath width: ≥ 10 km	horizontal resolution: 100 m swath width: 31.0 km	**North pole**: 3 broad patches covering the lakes and mare regions **South pole**: 4 patches covering filled or empty lakes 6.5% coverage SAR and altimetry acquired within 1 Earth month of each other VIS-IR acquired minimum 1.5 months ahead of SAR/altimetry, to control for transient precipitation events	6.53
					Radar pulse two-way travel time	Radar: altimetry	horizontal resolution (along track): ≤ 500m swath width (cross track): ≥ 10 km	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm		
					Microwave emissions from surface	Radar: radiometry	horizontal resolution: ≤ 149 km *driving requirement for radiometry* antenna temperature precision: ≤ 0.75 K *driving requirement for radiometry*	horizontal resolution: 124 km temperature precision: 0.6 K		
					IR reflectance	vis-IR	horizontal resolution: ≤ 10 km *driving requirement for vis-IR* spectral resolution: ≤ 25 nm *driving requirement for vis-IR* spectral bandwidth: 1.22–1.32, 1.5–1.62,	horizontal resolution: 5 km spectral resolution: 10 nm spectral bandwidth: 0.4 – 4.3 μm		
			Lake and mare composition	IF CONNECTED: Compositional gradient will be consistent in ~100 km radius of a lake, skew more methane-rich towards maria IF NOT: No significant statistical compositional gradient should exist as a function of distance between lakes or maria	Radar backscatter	Radar: SAR	horizontal resolution (along track): ≤ 500 m swath width: ≥ 10 km	horizontal resolution: 100 m swath width: 31.0 km	**North pole**: 3 broad patches covering the lakes and mare regions SAR and altimetry acquired within 1 Earth month of each other VIS-IR acquired minimum 1.5 months ahead of SAR/altimetry to control for transient precipitation events	4.47
					Radar pulse two-way travel time	Radar: altimetry	≤ 500 m horizontal (along-track) ≤ -20 dB sensitivity	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm		
					Microwave emissions from surface	Radar: radiometry	horizontal resolution: ≤ 149 km antenna temperature precision: ≤ 0.75 K	horizontal resolution: 124 km temperature precision: 0.6 K		
					IR reflectance	vis-IR	horizontal resolution: ≤ 10 km spectral resolution: ≤ 25 nm spectral bandwidth: 1.22–1.32, 1.5–1.62, 1.96–2.09, 2.65–3.1 μm	horizontal resolution: 5 km spectral resolution: 10 nm spectral bandwidth: 0.4 – 4.3 μm		
		OBJECTIVE 3					OBJECTIVE 3		OBJECTIVE 3	
	Surface/atmosphere exchange	**Determine if Titan is losing its atmosphere and surface liquids through time.**	**Relative crater age of highlands and lowlands**	IF LOSING MATERIAL: Significantly lower crater counts at poles and equatorial topographic lows (not bounded by highs) compared to highs. IF NOT: Uniform crater distribution across poles and equatorial topographic highs and lows.	IR reflectance	vis-IR	horizontal resolution: ≤ 10 km spectral resolution: ≤ 25 nm spectral bandwidth: 0.94 – 3.2 μm *driving requirement for vis-IR*	horizontal resolution: 5 km spectral resolution: 10 nm spectral bandwidth: 0.4 – 4.3 μm	**Equatorial region** 45 to −45° latitude; 0°–90° and 225°–315° longitude bands **North pole (surrounding lakes)** 60° to 90° latitude, all longitudes	42.42
					Microwave emissions from surface	Radar: radiometry	horizontal resolution: ≤ 149 km antenna temperature precision: ≤ 0.75 K	horizontal resolution: 124 km temperature precision: 0.6 K		
					Radar backscatter	Radar: SAR	horizontal resolution: ≤ 500 m swath width: ≥ 20 km *driving requirement for SAR*	horizontal resolution: 100 m swath width: 31.0 km		77.4
					Radar pulse two-way travel time	Radar: altimetry	along track resolution: ≤ 500 m swath width: ≥ 10 km vertical resolution: ≤ 10 m	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm		
			Extreme lake level loss	IF LOSING MATERIAL: Significant shoreline retreat (> 10 km) at Ontario Lacus and/or level loss (> 5 km) compared to Cassini obs and/or over course of mission. IF NOT: No significant shoreline retreat (> 10 km) or level loss (> 5 m) compared to Cassini obs or over course of mission.	Radar backscatter	Radar: SAR	horizontal resolution: ≤ 1 km swath width: ≥ 2.5 km	horizontal resolution: 100 m swath width: 31.0 km	**North pole** 55° to 90° latitude, 30 to 180° longitude **South pole** Ontario Lacus two observations, at beginning and end of mission, at least 2 years apart	3.952
					Radar pulse two-way travel time	Radar: altimetry	along track resolution: ≤ 1 km swath width: ≤ 10 km *driving requirement for altimetry* vertical resolution: ≤ 1 m *driving requirement for altimetry*	along track resolution: 300 m swath width: 6.0 km vertical resolution: 20 cm		

- Answerable to Decadal Survey without overlapping with *Dragonfly*.
  - Geology and geophysics focused.
  - No atmospheric science or prebiotic chemistry experiments
- "He put the fear of Cost into us."

THUNDER	Science Objectives: Decadal Titan Orbiter
✓	**Determine Titan’s internal structure, the depth and thickness of the ice shell and subsurface ocean, and whether the former is convecting**; and determine rates of interior-surface solid or gas interchange.
✓	**Characterize Titan’s global geology and its landscape-shaping processes.**
✓	**Characterize Titan’s global methane hydrological** and sedimentological **system**, including surface transport/flow rates and cloud distributions.
✓	**Quantify the** production, transport and fate of organic molecules in Titan’s upper atmosphere and **atmospheric and climate evolution in general.**

Is Titan's ice shell convecting?

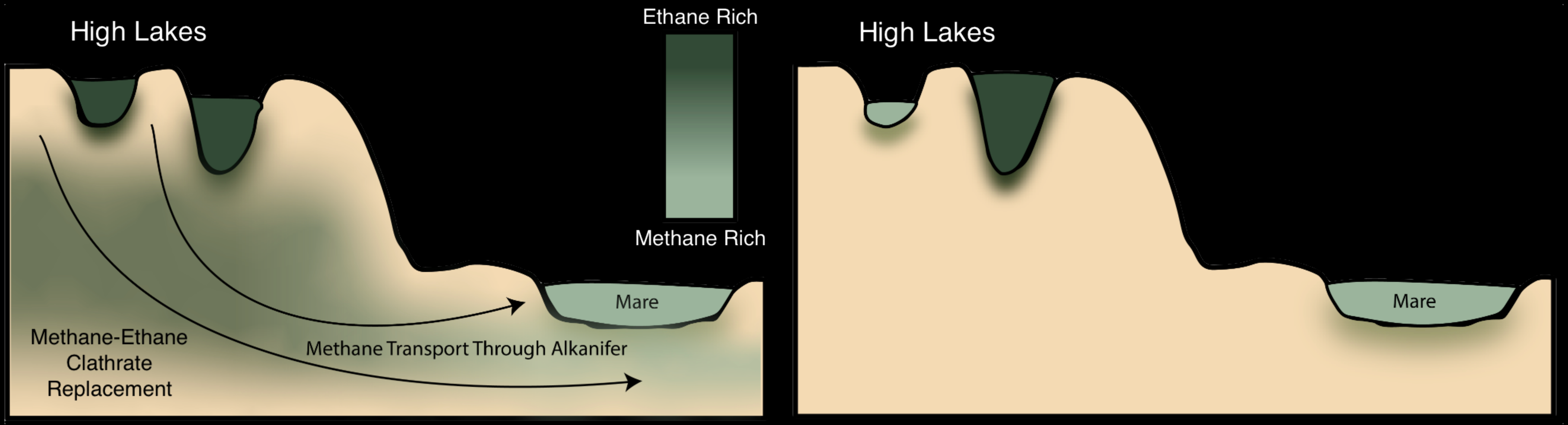
Objective 1



A convecting ice-shell efficiently dissipates heat from the deep interior, enhancing the formation of high-pressure ice phases.

Are Titan's lakes connected by an alkanifer?

Objective 2

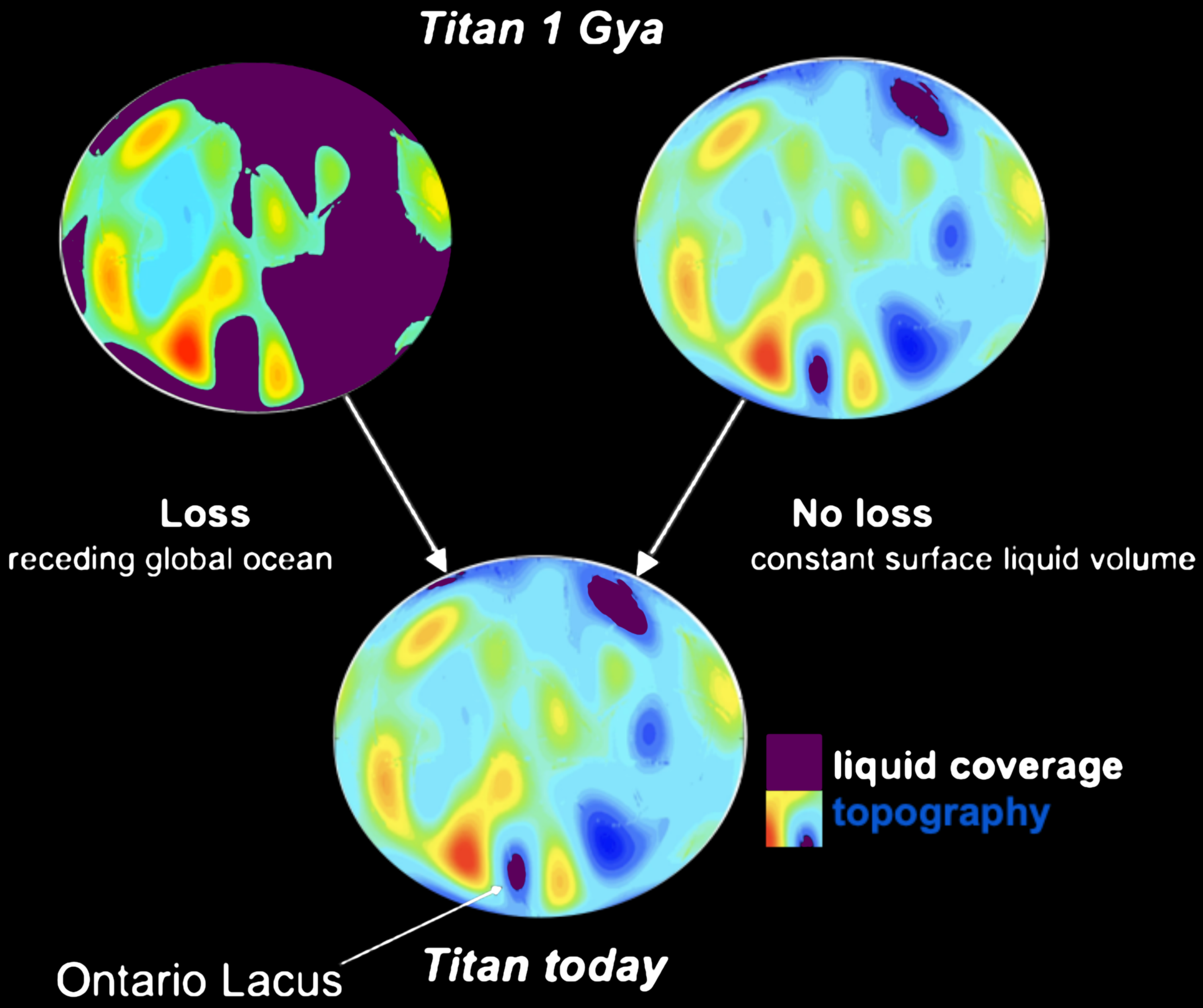


If true, this may be a major geological source of methane to sustain the atmosphere.

Is Titan losing atmospheric and marine methane?

Objective 3

- Crater counting.
  - Fewer, smaller craters at low altitude is evidence of a global ocean.
  - Constrains atmospheric evolution.
- Changes in lake volume between *Cassini* and *THUNDER*
  - Sensitive to medium-scale climate variations.
  - Constrains exchange between N and S poles.



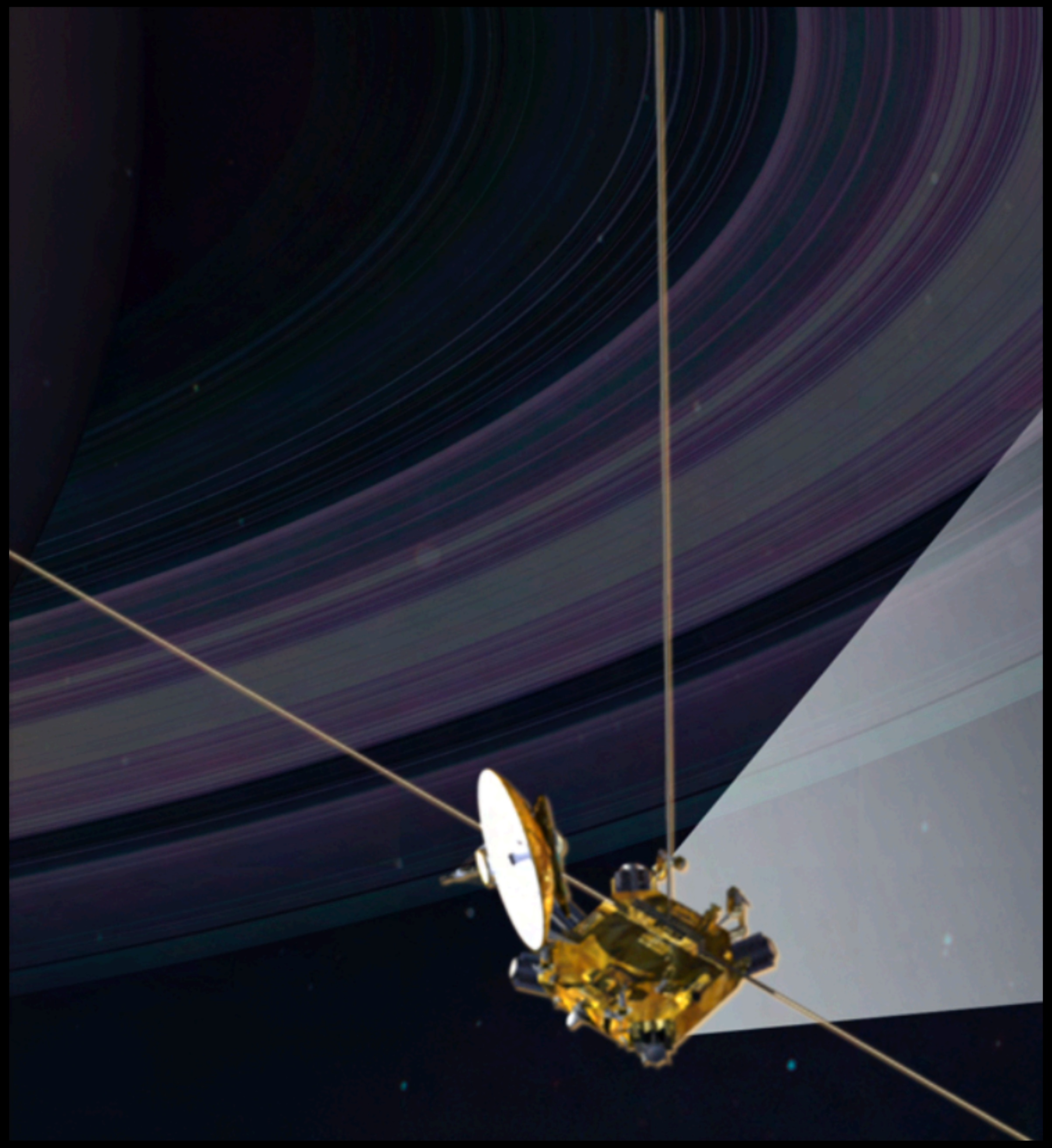
“Taking the pulse of Titan’s hydrocarbon circulatory system.”

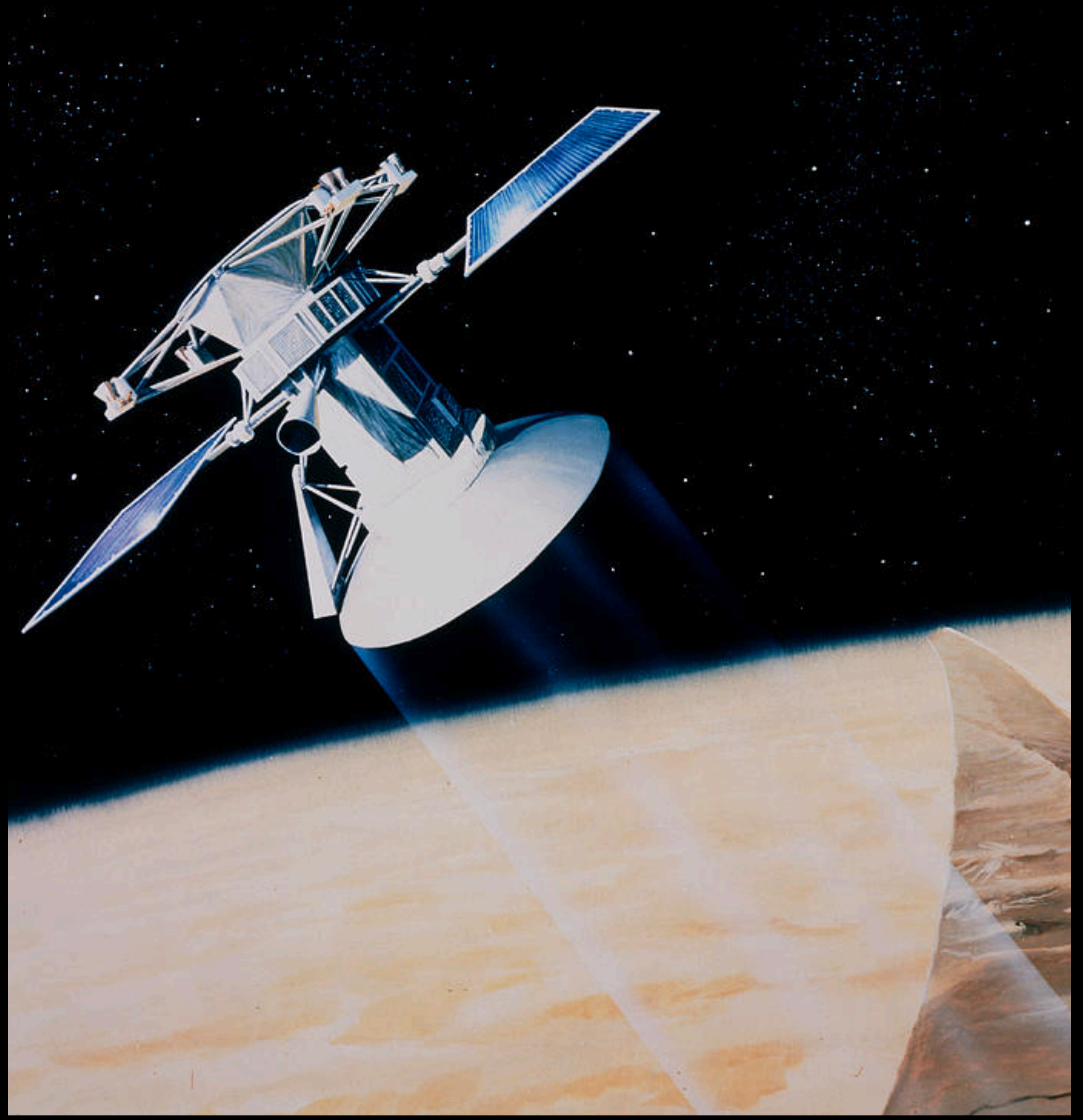
“Is Titan dying?”

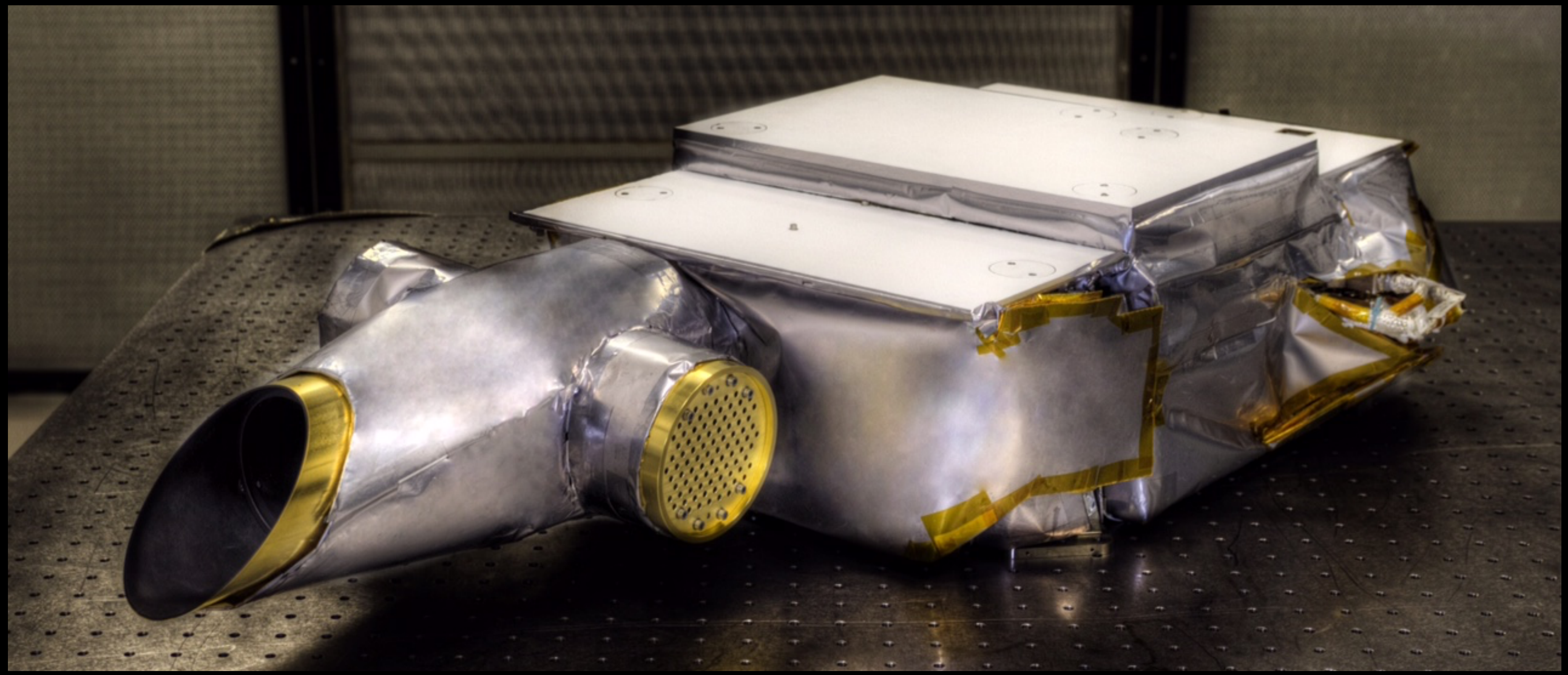
Instruments

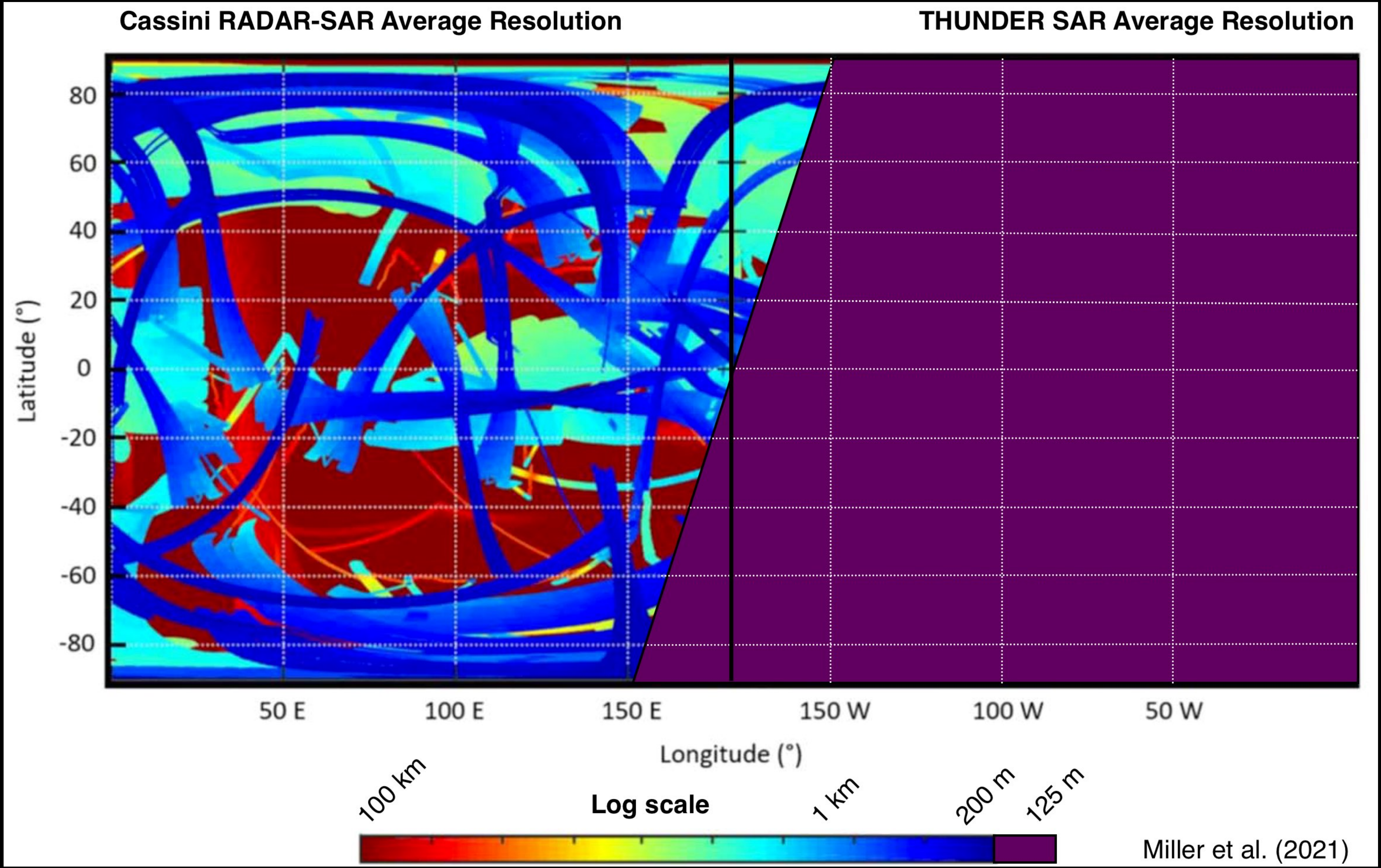
Driven by Science Traceability

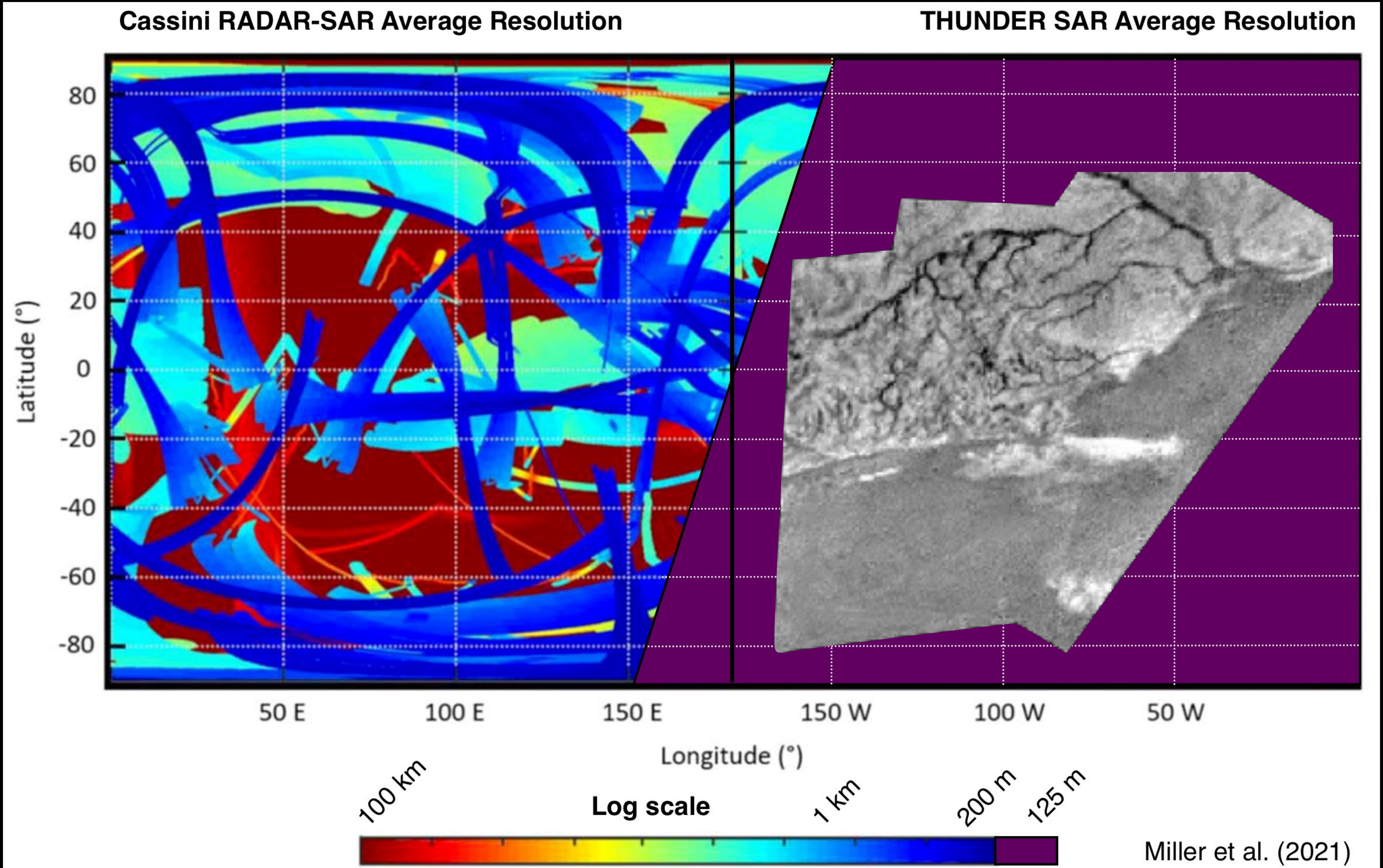
- Radar (*Magellan* RDRS/ *TitanExplorer* radar analog)
    - Synthetic aperture radar
    - Radar altimeter
    - Radiometry
- Vis/IR spectrometer (*OSIRIS-REx* OVIRS analog)
- Gravity science (X & S band)








Cassini RADAR-SAR Average Resolution
THUNDER SAR Average Resolution
80
60
40
20
0
-20
-40
-60
-80
Latitude (°)
50 E
100 E
150 E
150 W
100 W
50 W
Longitude (°)
100 km
Log scale
1 km
200 m
125 m
Miller et al. (2021)



Cassini RADAR-SAR Average Resolution
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80
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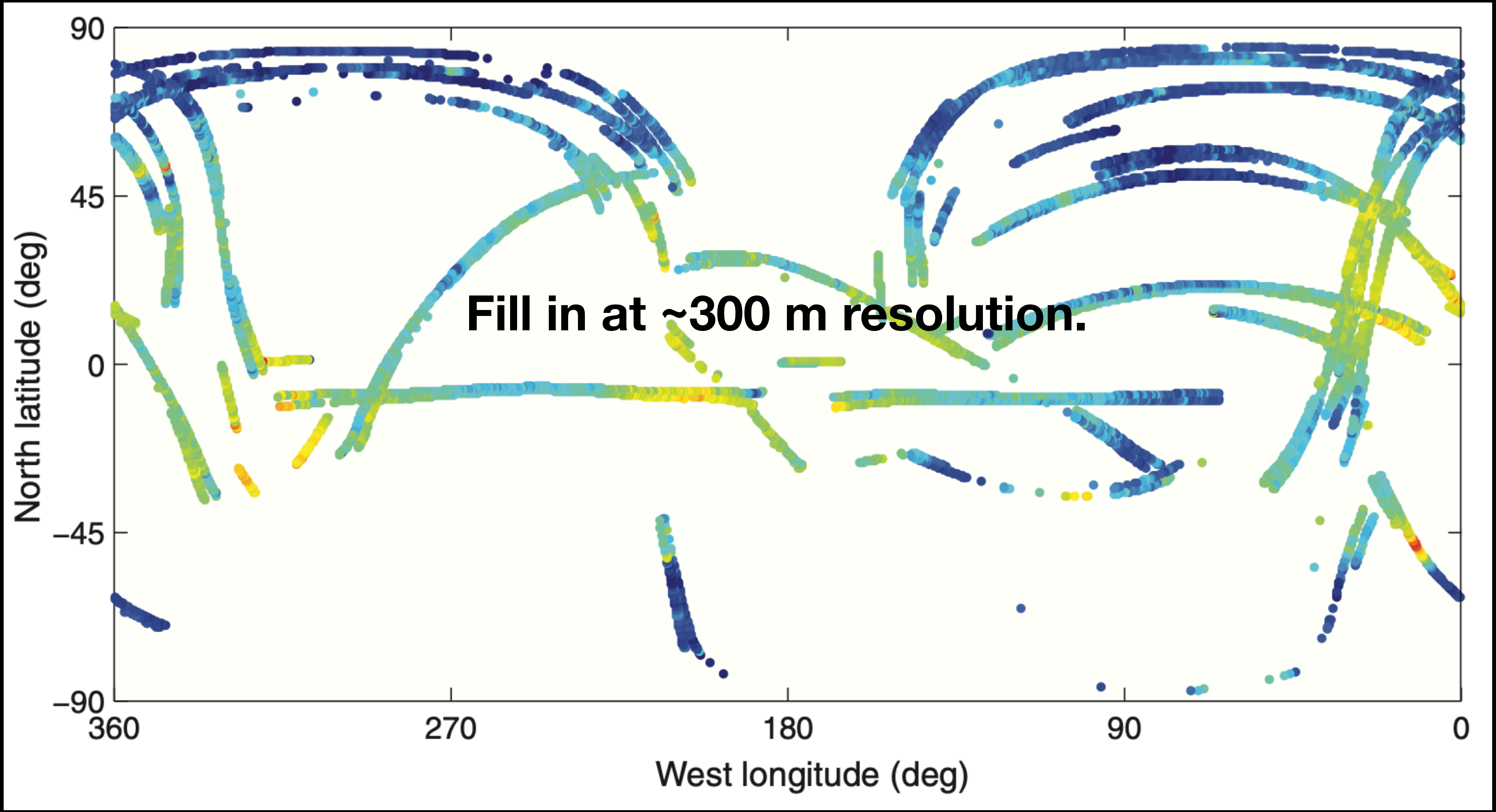
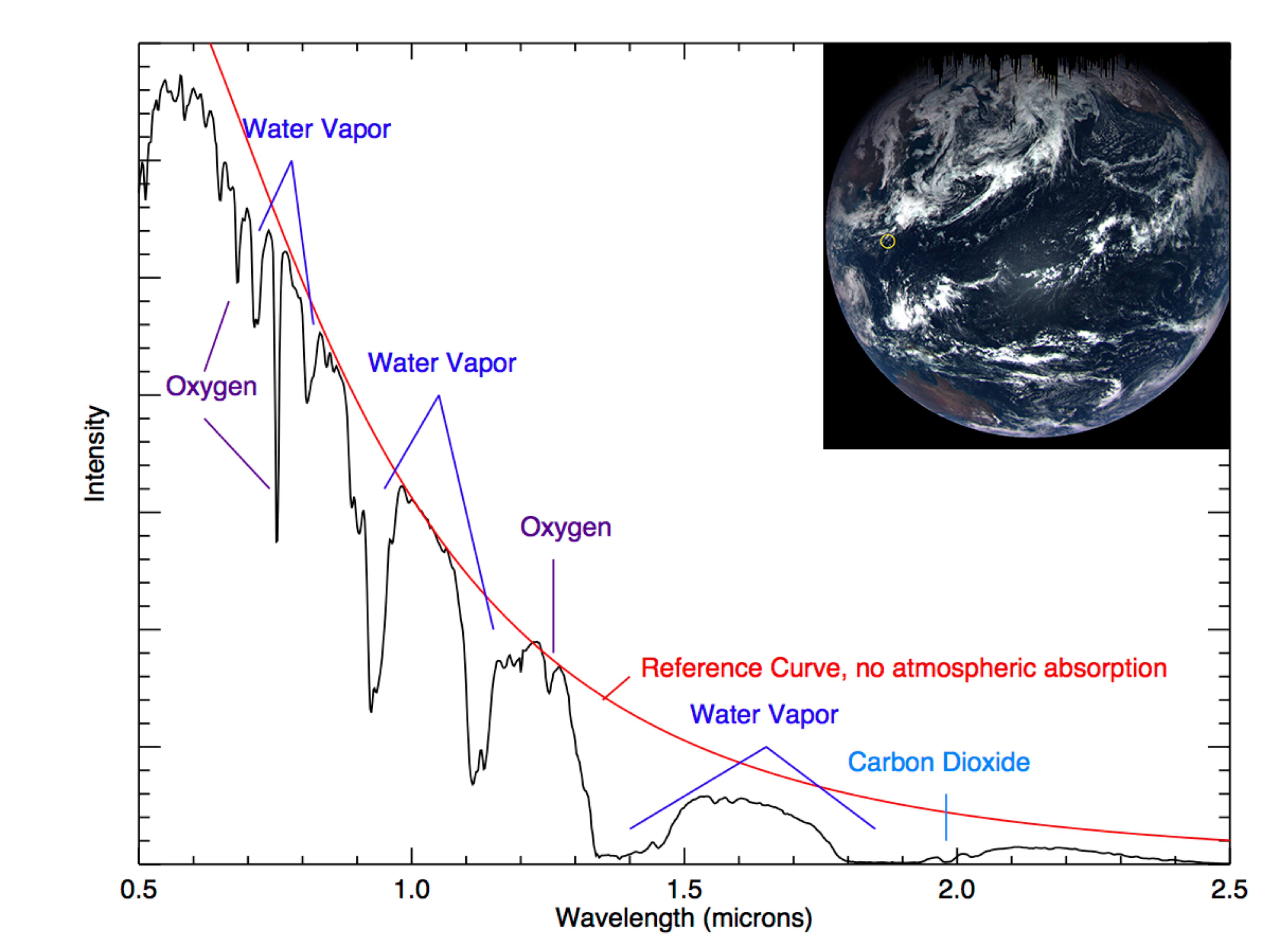
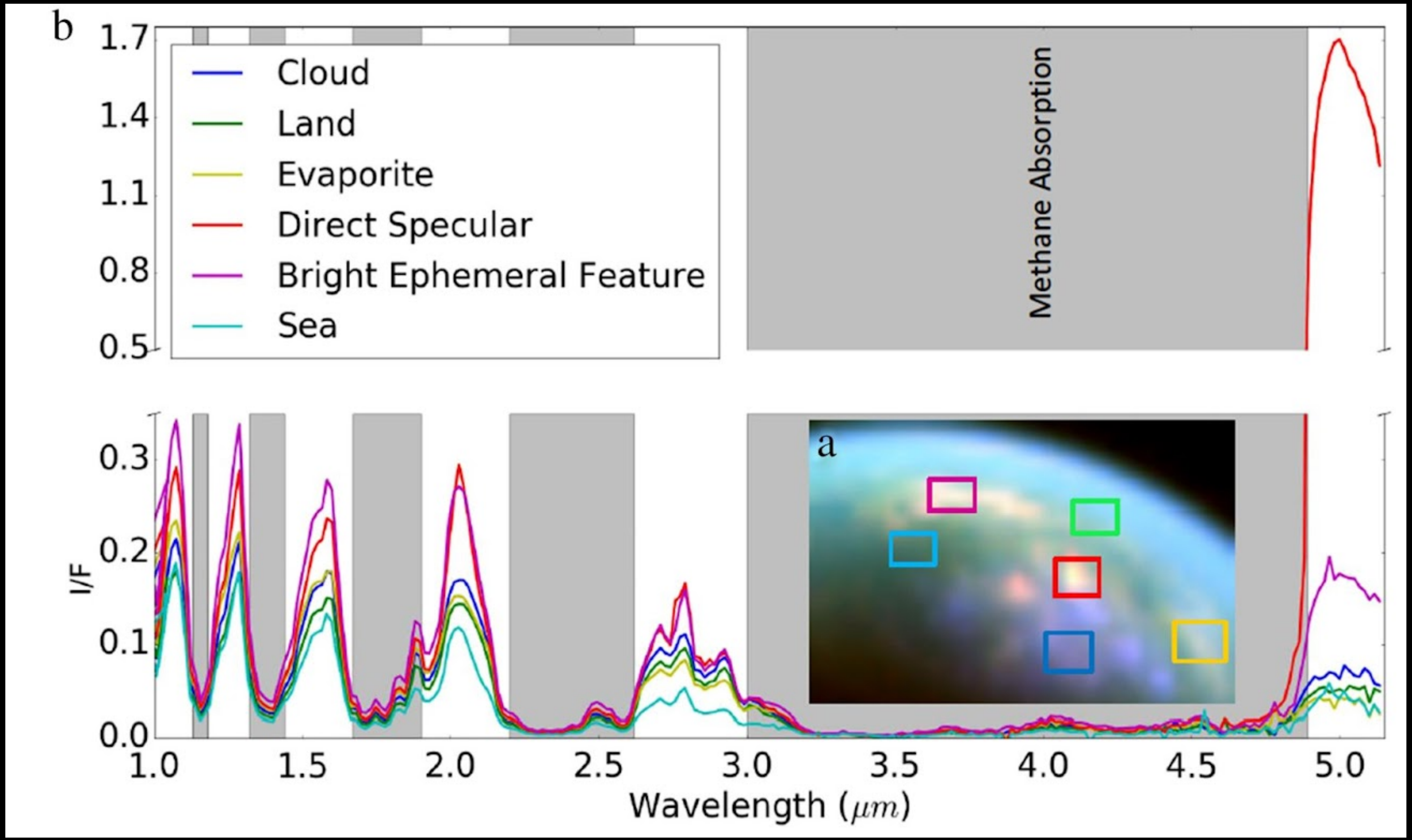


Zebker et al (2013)

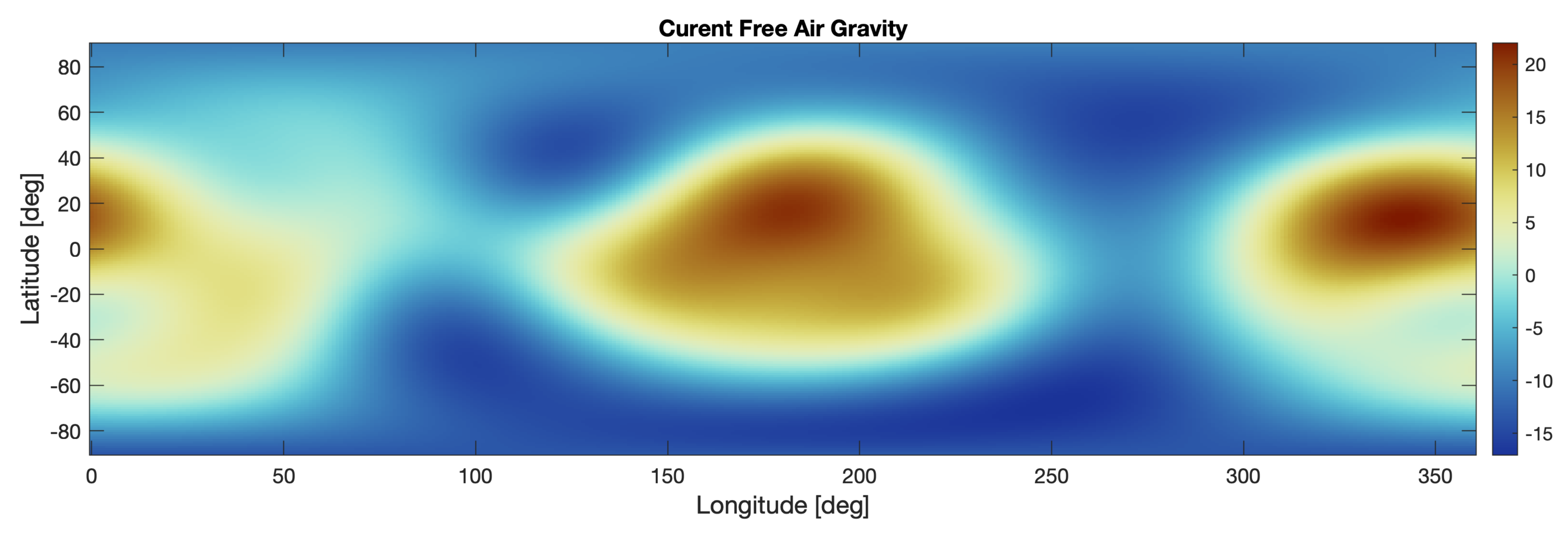
IR spectrometer (don't ask me, please)

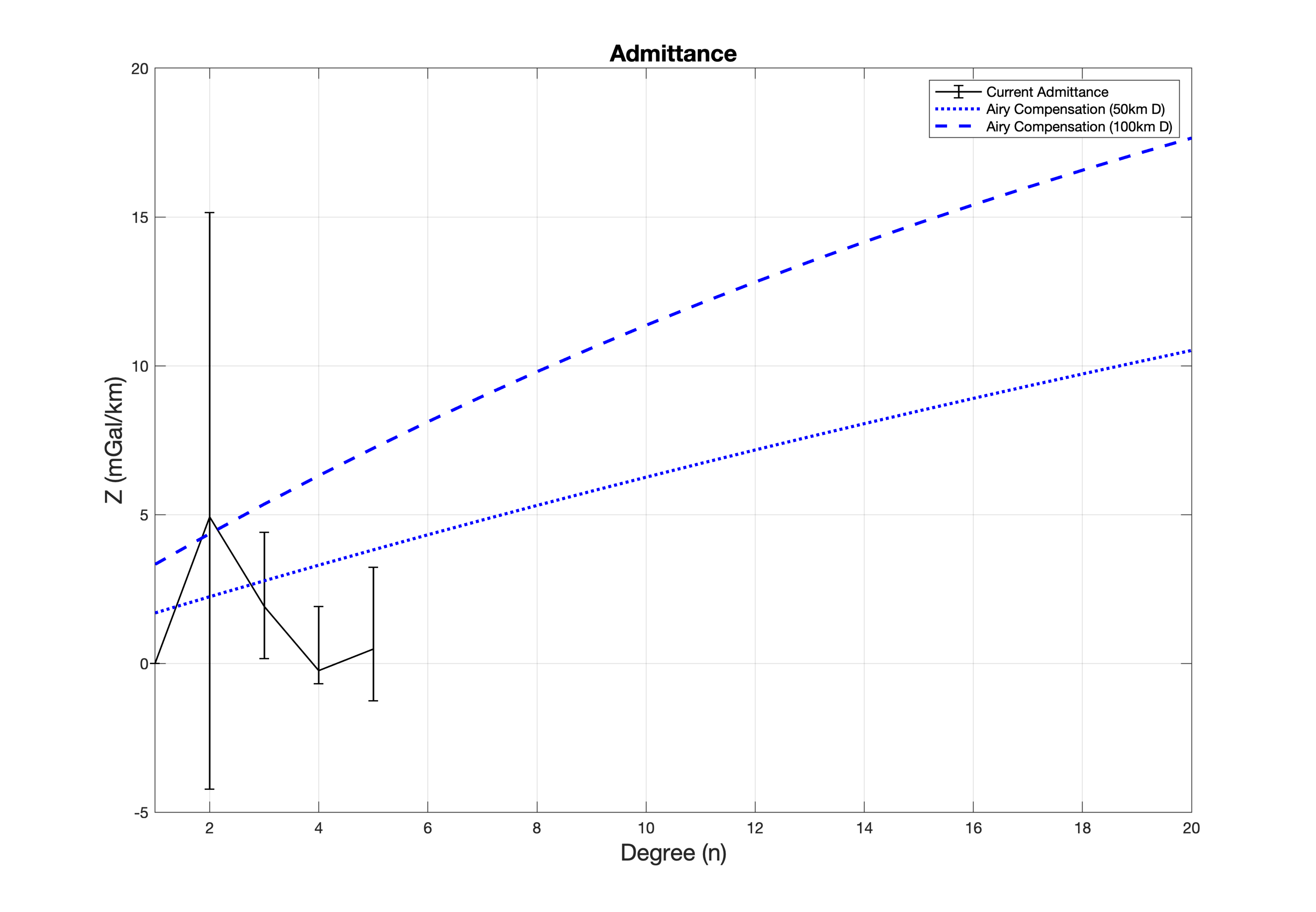


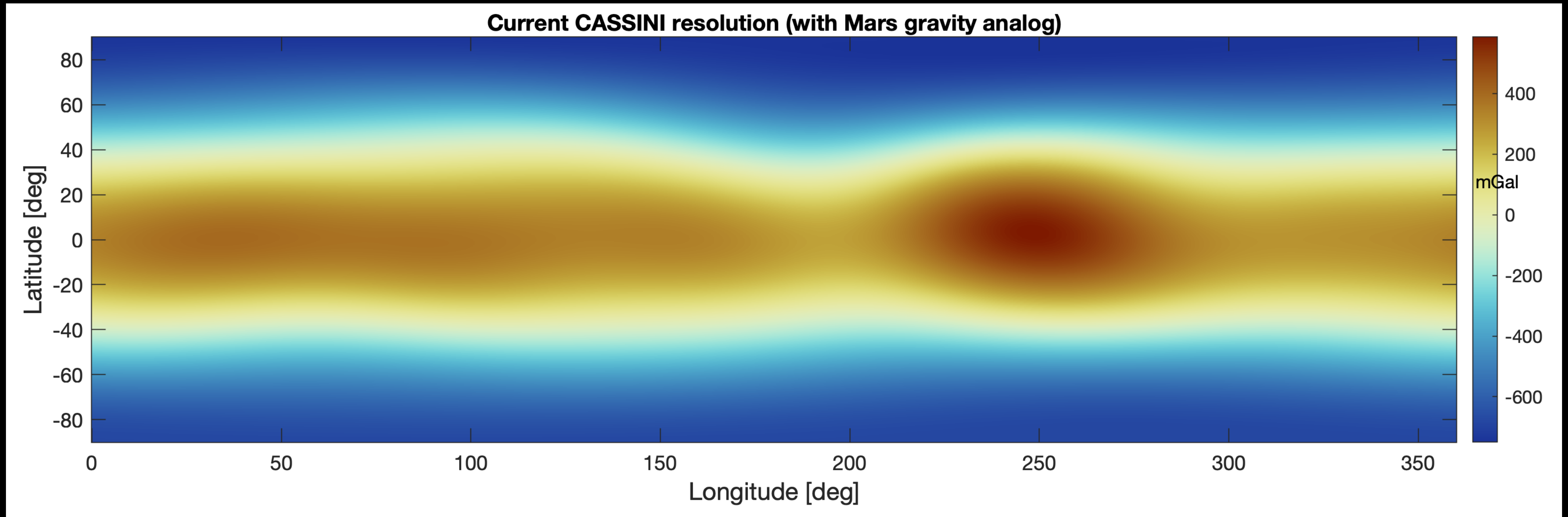


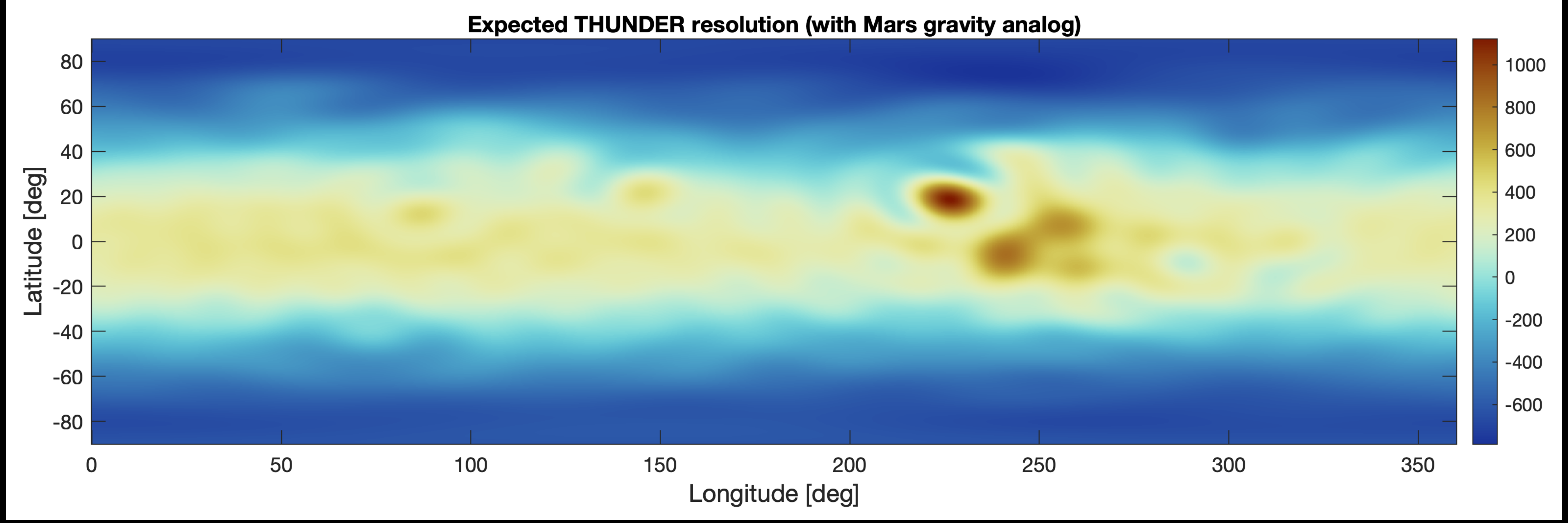
[Dhingra et al. 2019]()

Gravity Science





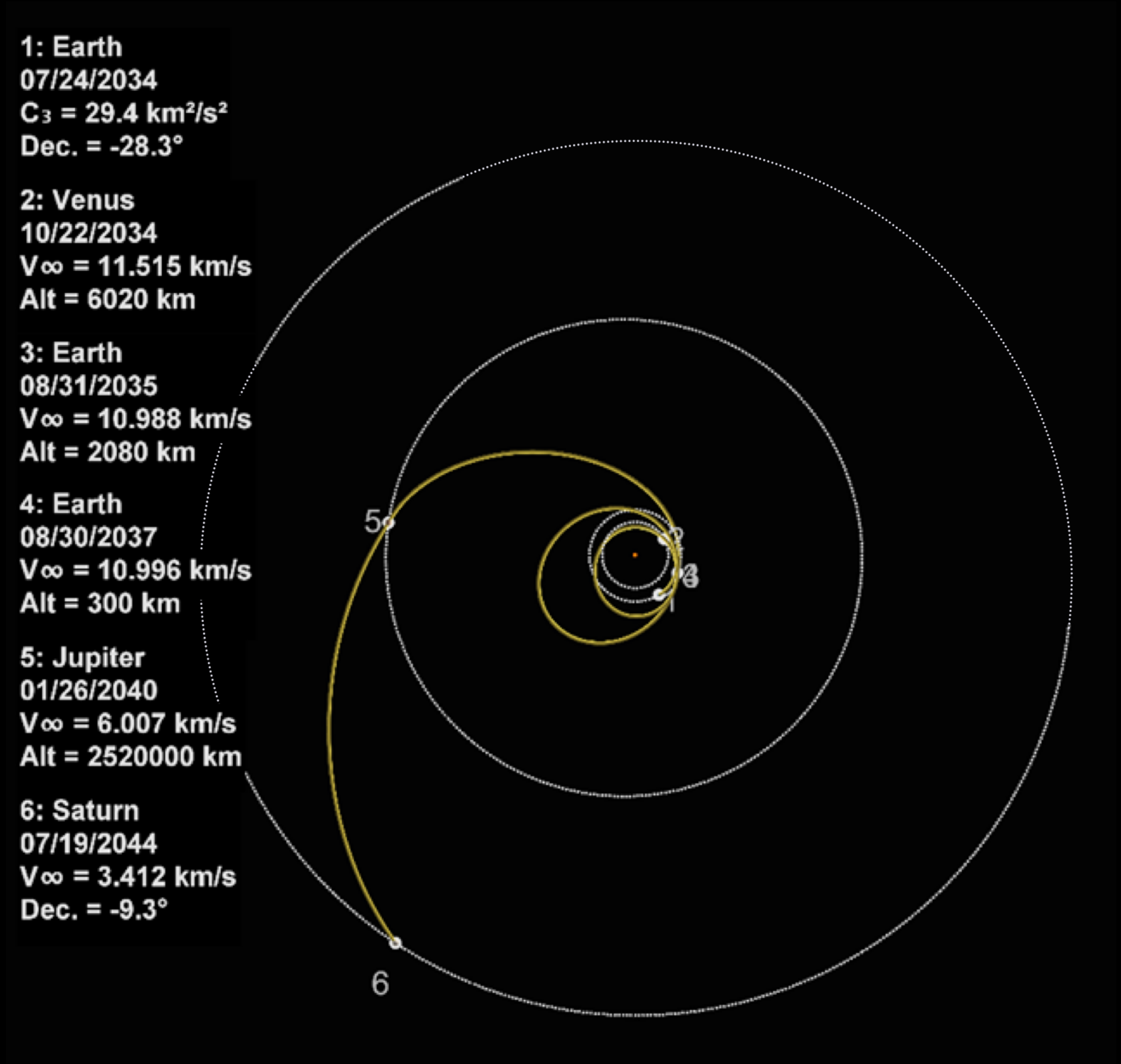


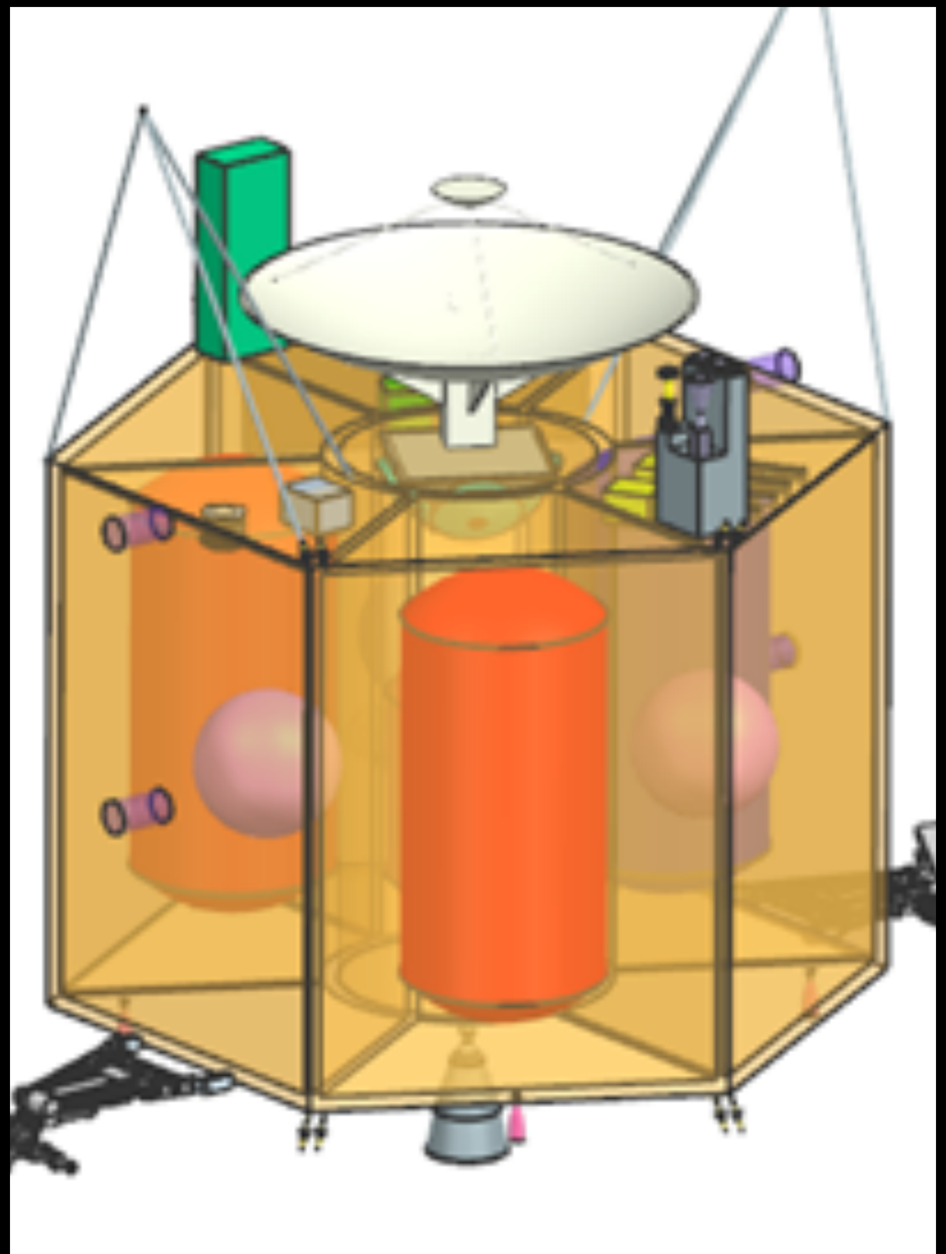


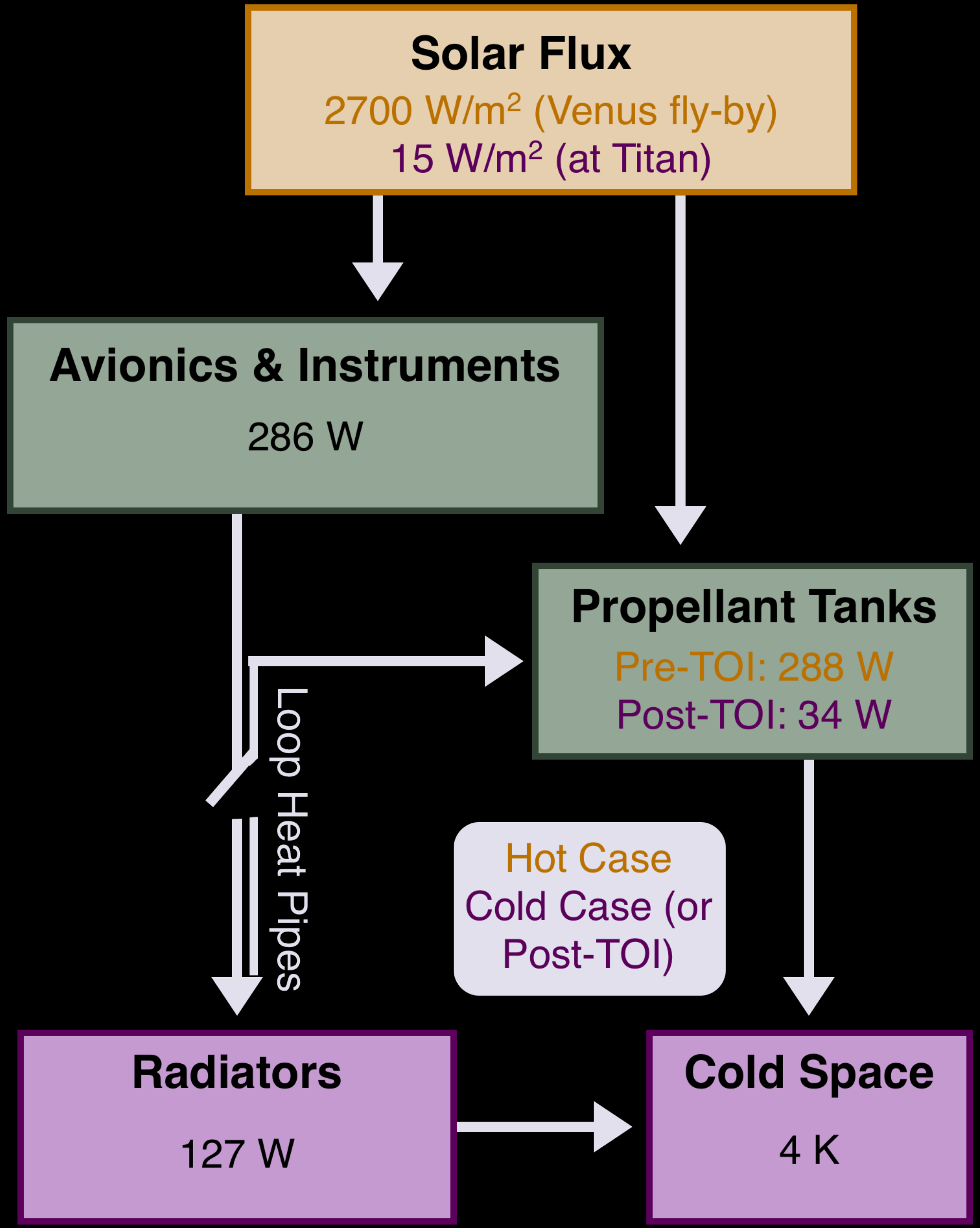
Courtesy of Nick Wagner at Baylor

Getting to Titan

Cold bias at Venus, warm bias at Saturn.



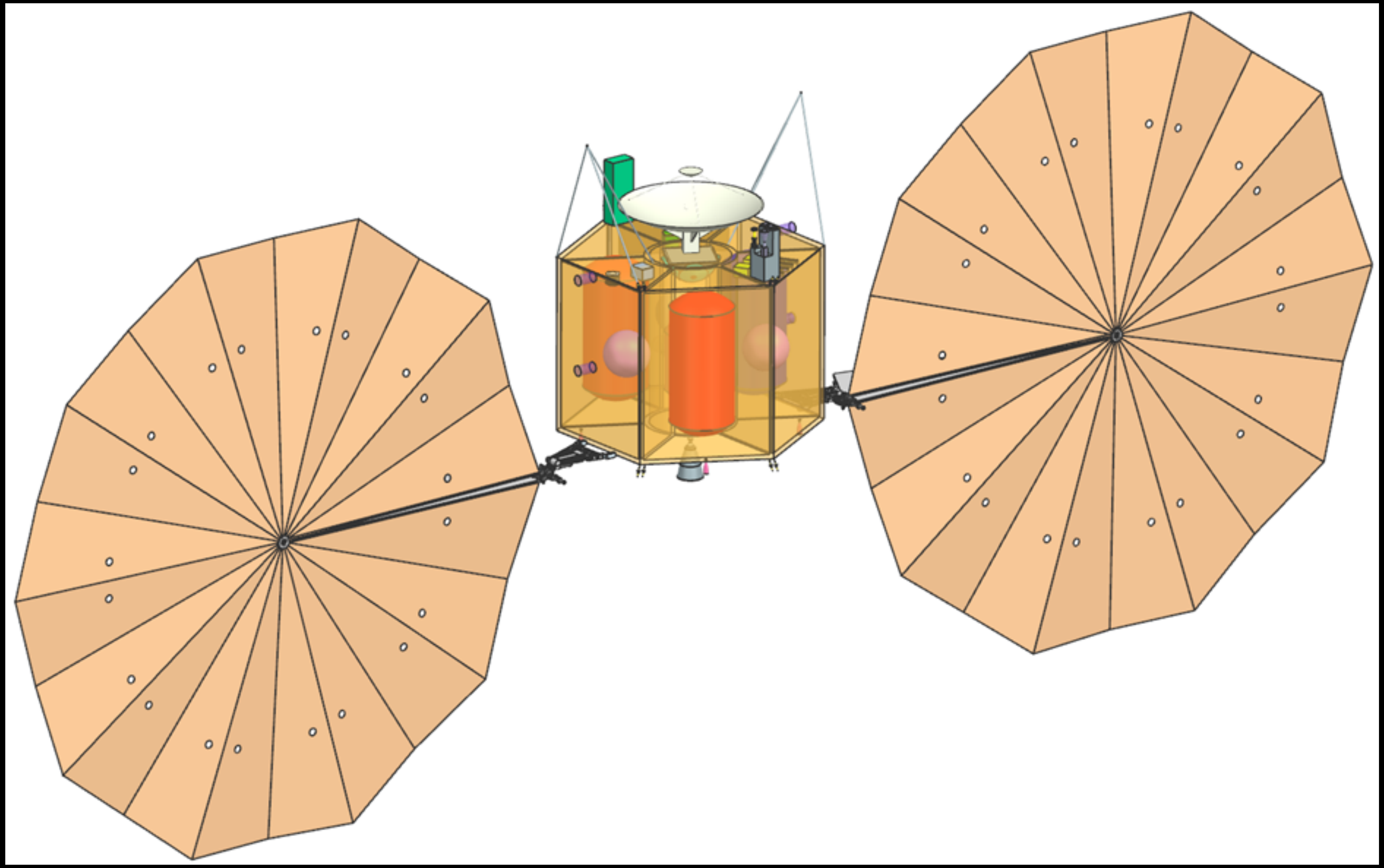




10 year cruise phase, 2 year pump down phase, 5 year science phase.

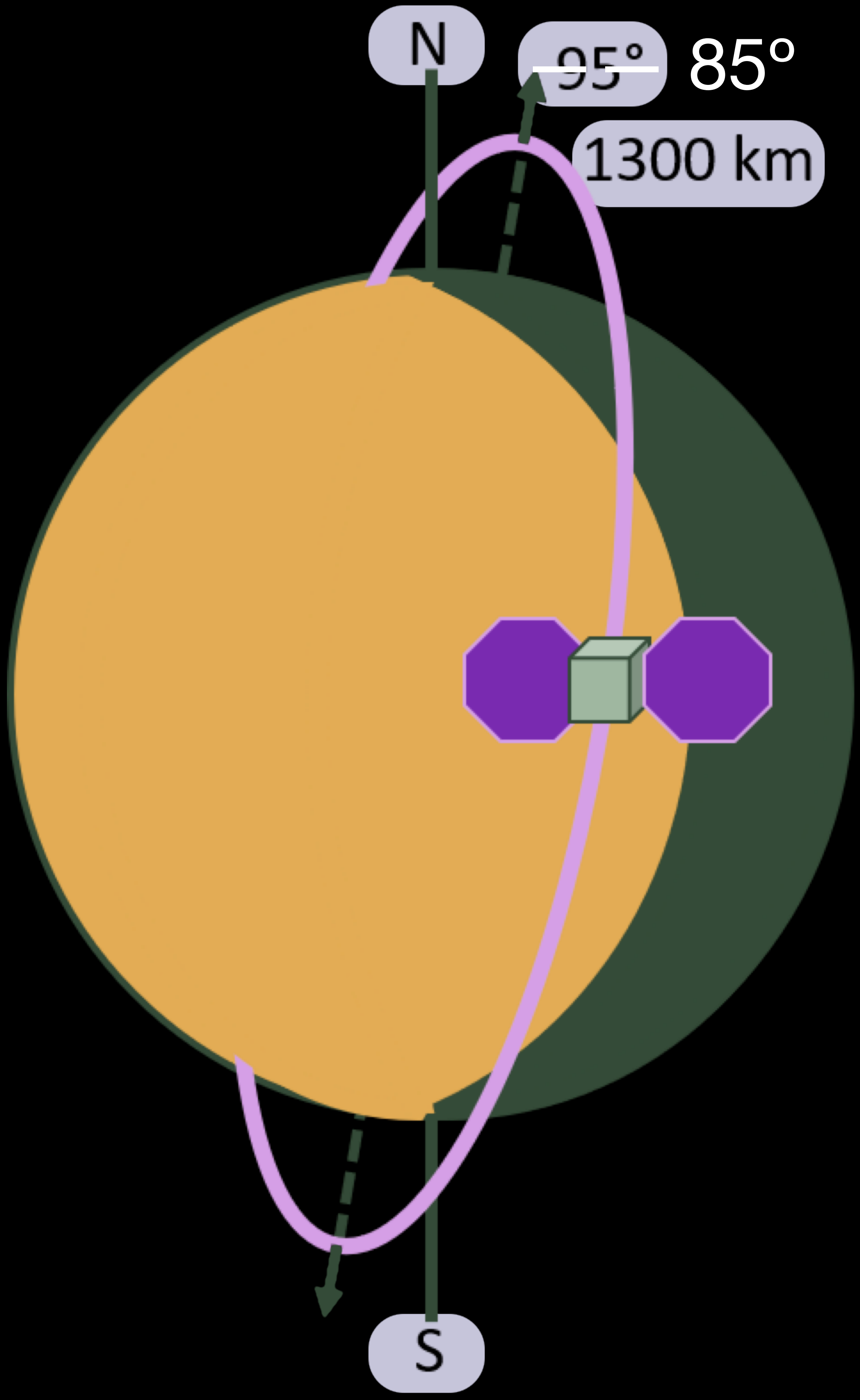
THUNDER

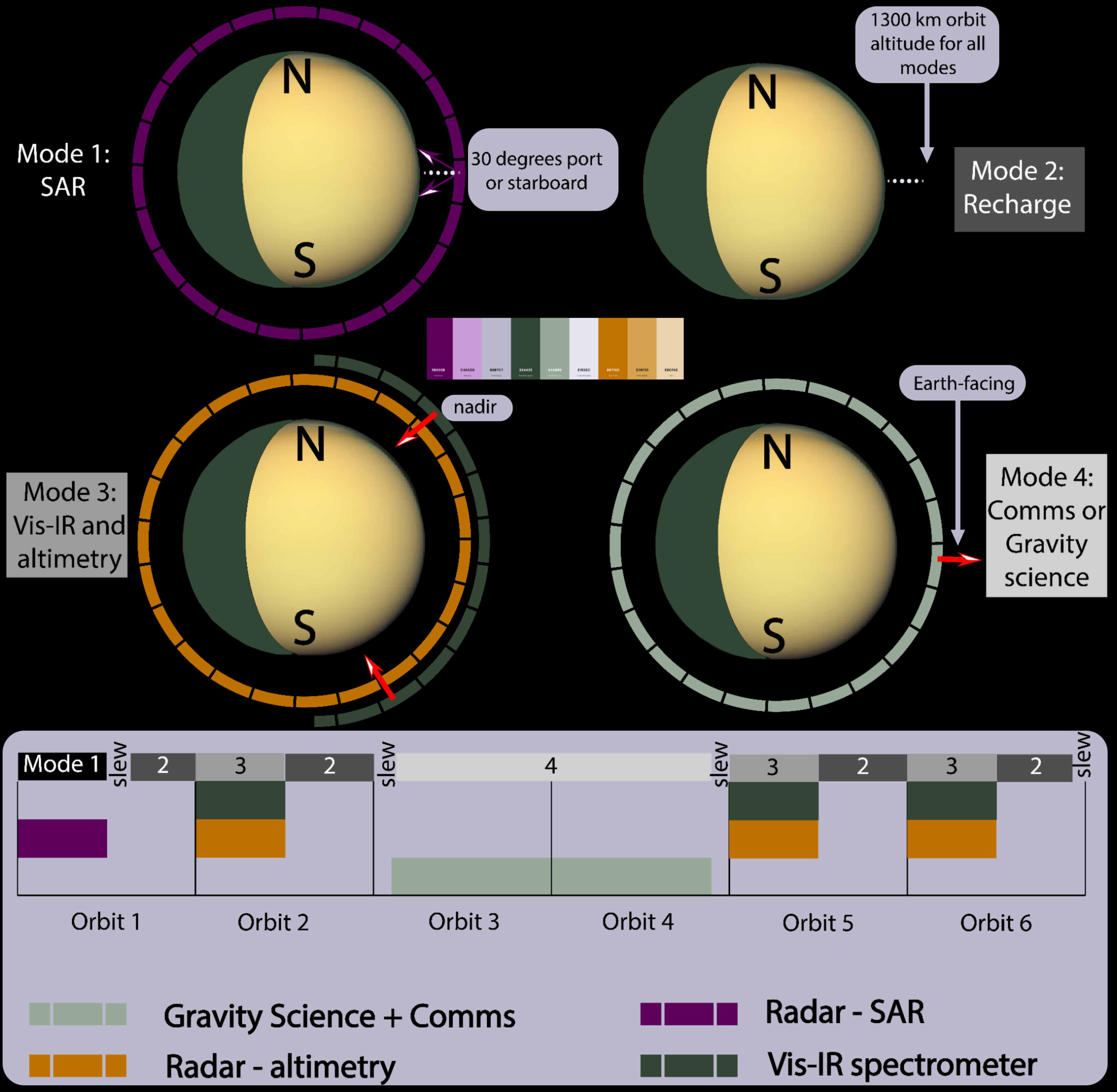
This is the crazy bit.



- Challenges:
  - How do you power a spacecraft in safe mode at both Venus and Saturn?
  - How do you power it for ~17 years?
- Solution:
  - RTGs decay with time.
  - Solar panels don't.
- 129 m^2 UltraFlex solar array.

Science Operations





New Frontiers Mission

$1518.2M FY24 Total Mission Cost ($1650M cost cap)

$1126.5M for Phases A-D with LV ($1240M cost cap)

$ 391.7M for Phases E-F ($ 410M cost cap)

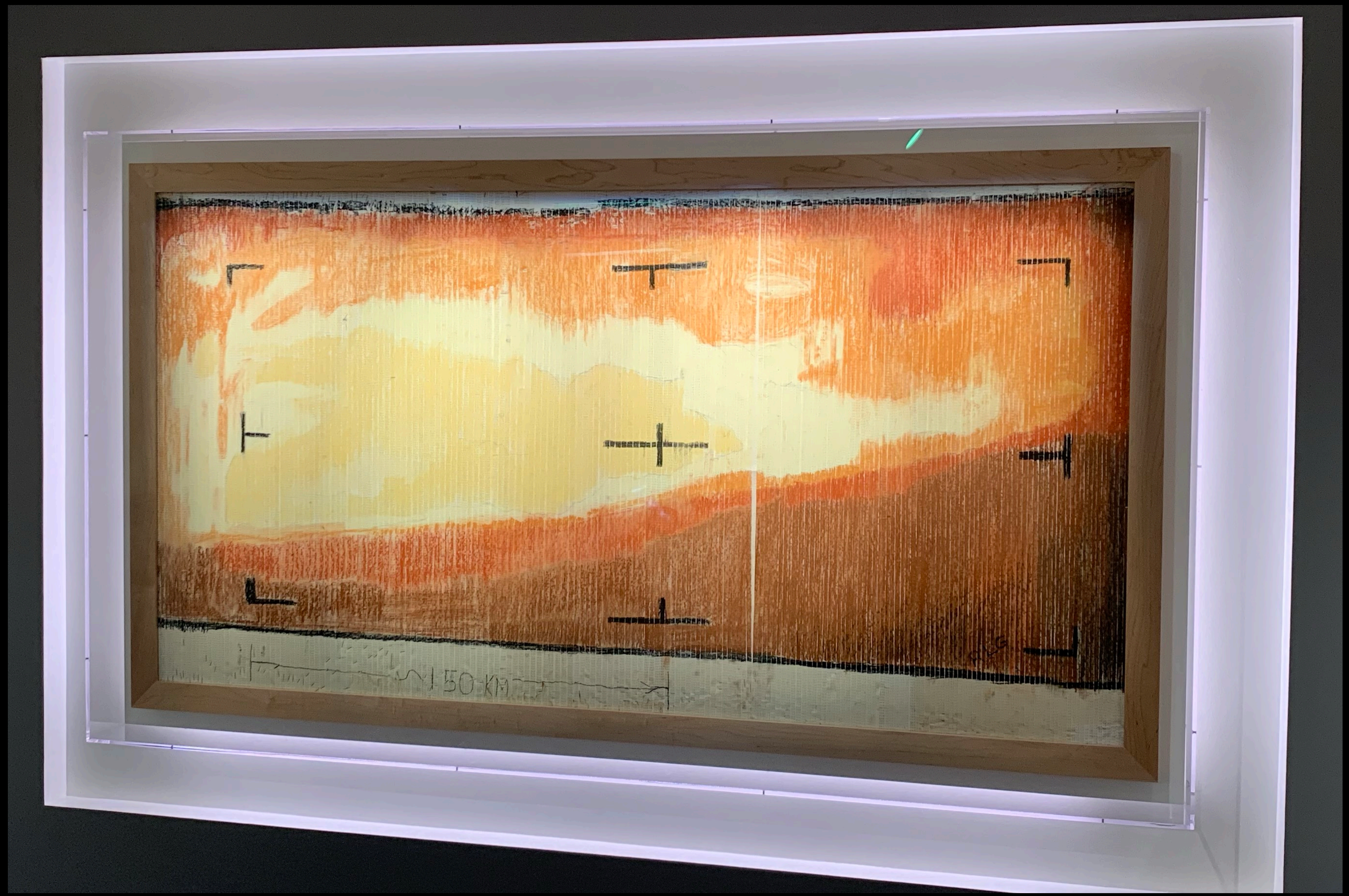
Major Weaknesses

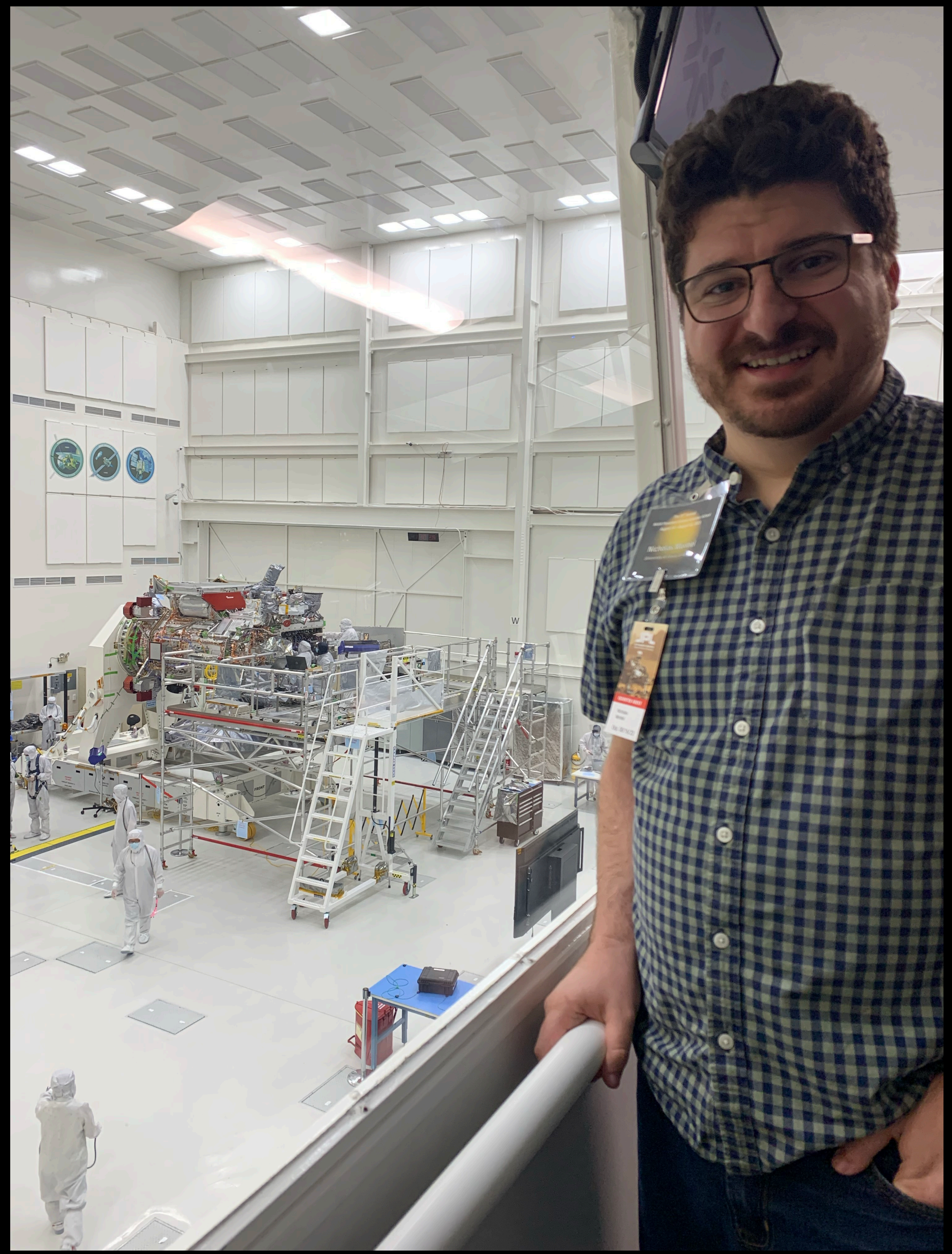
- The decision to use solar panels.
- “Why no mass spec?” (A digression on mission creep.)
- Vis/IR spectrometer is “descope bait.”

WBS Cost Breakdown		Development Cost (Phases B-D)	Operations Cost (Phases E-F)
Total Cost		$1121.5 M	$391.7 M
01.0	Project Management	$17.6 M	$24.6 M
02.0	Project Systems Engineering	$33.6 M	$1.0 M
03.0	Mission Assurance	$37.3 M	$5.6 M
04.0	Science	$14.8 M	$55.6 M
05.0	Payload System	$154.8 M	$0.0 M
06.0	Flight System	$415.9 M	$0.0 M
07.0	Mission Operations Preparation	$31.4 M	$199.2 M
08.0	Launch Vehicle	$77.0 M	$0.0 M
09.0	Ground Data Systems	$22.9 M	$27.9 M
10.0	ATLO	$52.7 M	$0.0 M
11.0	Education and Public Outreach	$0.0 M	$0.0 M
12.0	Mission and Navigation Design	$22.4 M	$0.0 M
	Development Reserves	$240.9 M	$77.7 M

Final thoughts:

- Crash course in NASA priorities, bureaucracy, politics, and mission philosophy.
- Hypothesis-driven, deductive methods for science proposals.
- Collaboration, networking, interdisciplinary education.
- I got to see a bunch of cool stuff, too.






NASA
Jet Propulsion Laboratory