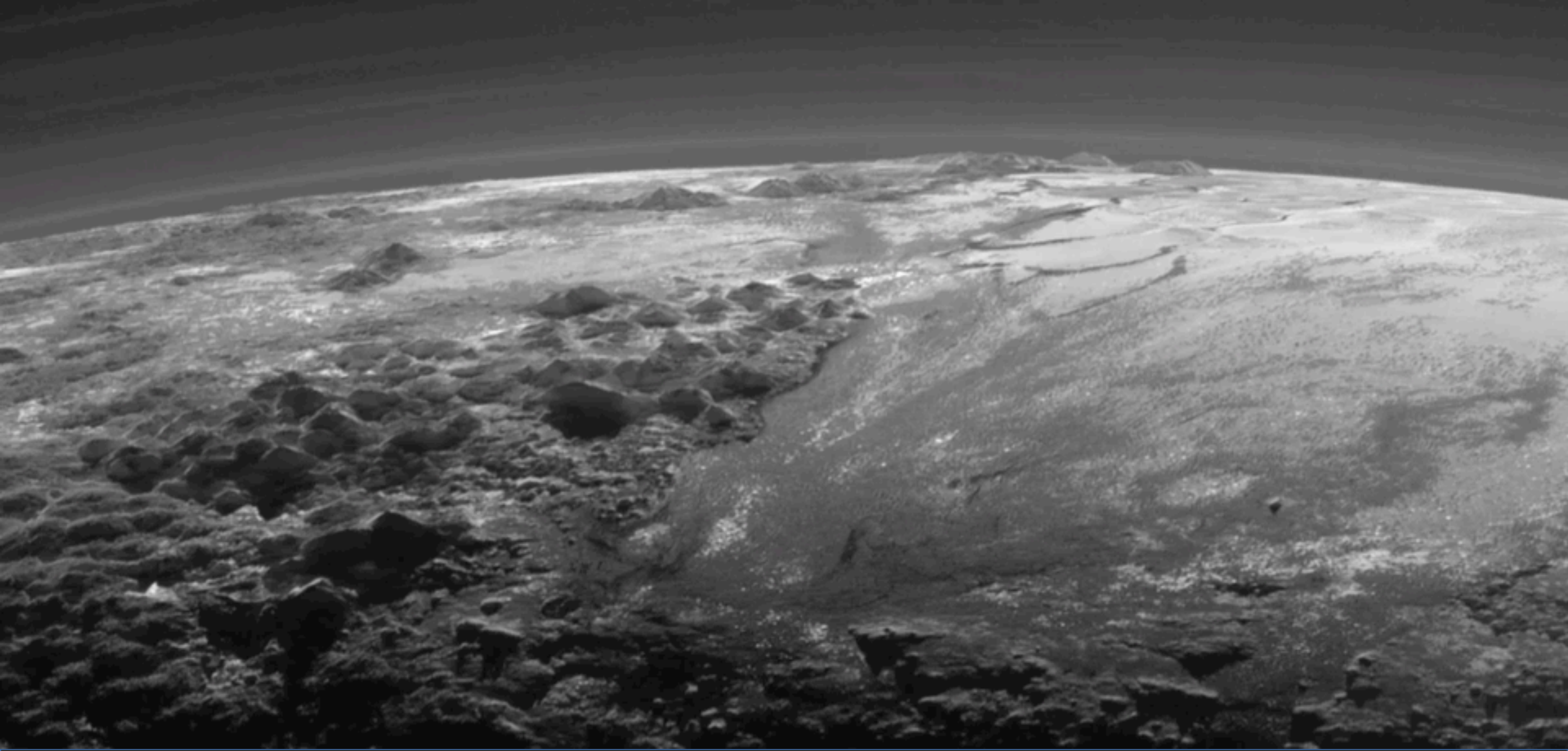


Persephone: A Pluto-System Orbiter & Kuiper Belt Explorer

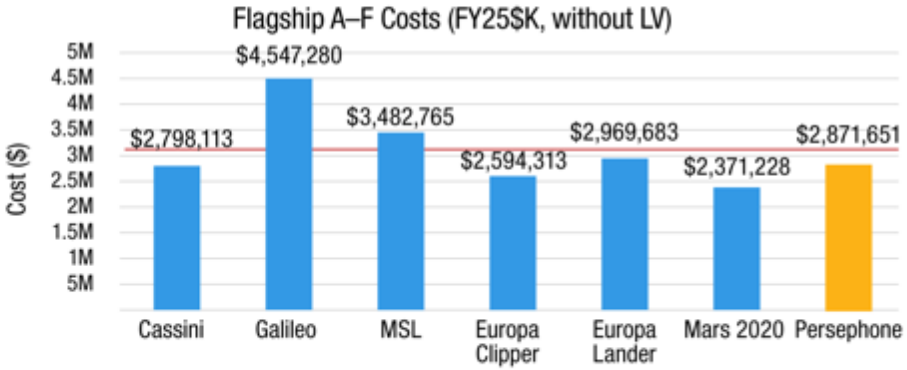
A Planetary Mission Concept Study

PI: Dr. Carly Howett (SwRI)

PERSEPHONE

Conclusion

- We have closed (CML4) on a spacecraft and tour design that would provide up to 8 different KBOs:
  - A pre-Pluto KBO encounter
  - A 3.1 (Earth) year tour of the Pluto-system
  - An extended mission to another KBO
- Unprecedented KBO science
  - Three Level 1 Science Questions:
    - *What is the internal structure of Pluto and Charon?*
    - *How have the surfaces and atmospheres in the Pluto-system evolved?*
    - *How has the KBO population evolved?*
  - Two Level 2 Science Questions:
    - *What is Pluto's internal heat budget?*
    - *What is the structure of magnetic fields in the outer solar system?*
- Nominally a payload of 11 instruments
- Cost: $3.0B FY$25 (excluding all LV costs)
  - Extended mission is an additional $237M



Our Team

- PI: Carly Howett (SwRI)
- DPI: Stuart Robbins (SwRI)
- APL Lead: Karl Fielhauer
- Science Team:
    - Anne Verbiscer (University of Virginia)
    - Bill McKinnon (Wash U)
    - Bryan Holler (STScI)
    - Kelsi Singer (SwRI)
    - Amanda Hendrix (SwRI)
    - Heather Elliott (SwRI)
    - Jani Radebaugh (BYU)
    - Carolyn Ernest (APL)
    - Leslie Young (SwRI)
    - JJ Kavelaars (CADC)
    - Robert Wilson (CU Boulder)
    - Alan Stern (SwRI)
    - Orenthal Tucker (GSFC)
    - Silvia Protopapa (SwRI)
    - John Spencer (SwRI)
    - Francis Nimmo (UCSC)
    - Adam Thodey
    - Simon Porter (SwRI)
    - Jon Pineau (Stellar Solutions)
- APL Support Team:
    - Mark Perry
    - Fazle Siddique
    - Clint Edwards
    - Clint Apland
    - Rachel Sholder
    - James Leary

Kuiper Belt

Mission Overview

- Aim: To explore the Pluto-System and Kuiper Belt
- Overarching Science Questions:
  - What are the internal structures of Pluto and Charon?
  - How have the surfaces and atmospheres in the Pluto-system evolved?
  - How has the KBO population evolved?

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  - XR-5 electric propulsion system
  - 5 Next Gen RTGs

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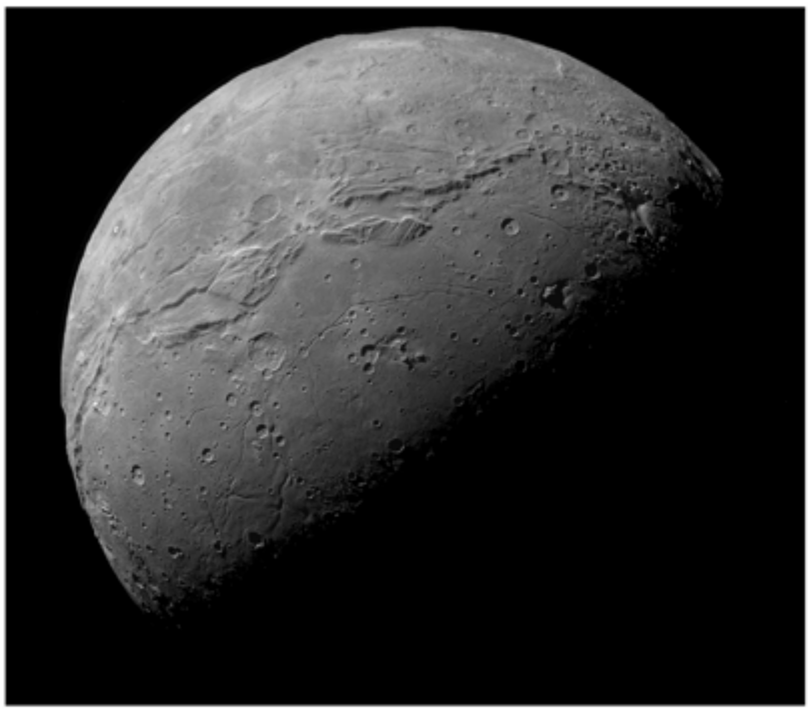
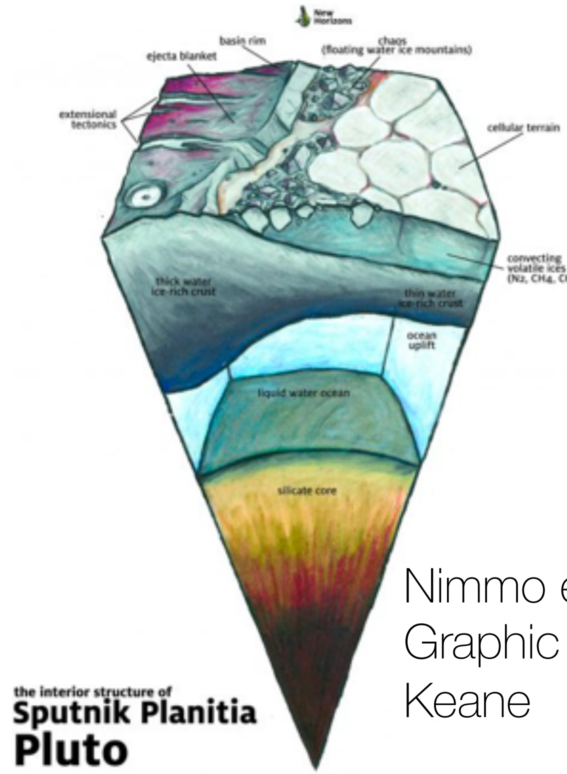
- Launch:
  - SLS Block 2 with Centaur
  - XR-5 electric propulsion system
  - 5 Next Gen RTGs
- Mission phases:
  - Cruise to Pluto, featuring a Kuiper Belt Object (KBO) flyby
  - 3.1 Earth-year tour of the Pluto system
  - Extended mission to explore another post-Pluto KBO

Science Goals – Level 1

- **What are the internal structures of Pluto and Charon?**
  - What is the evidence for a sub-surface ocean on Pluto?
  - Are Pluto (and Charon) fully differentiated?
  - Does Pluto have any magnetic field: induced or intrinsic?



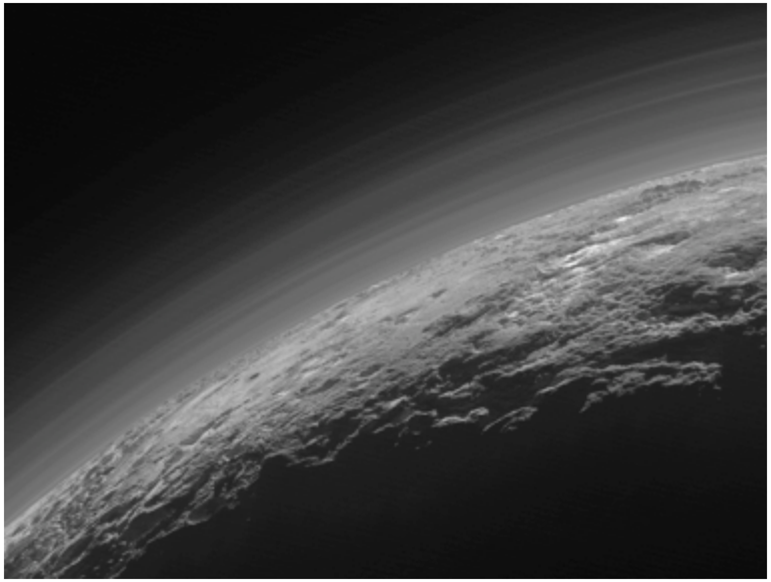
Beyer et al. (2019)



Nimmo et al. (2016) Graphic by James Keane

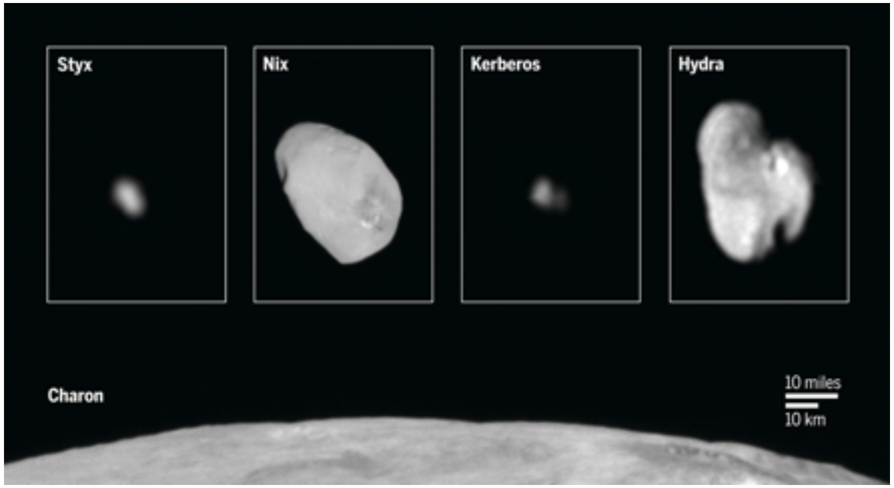
Science Goals – Level 1

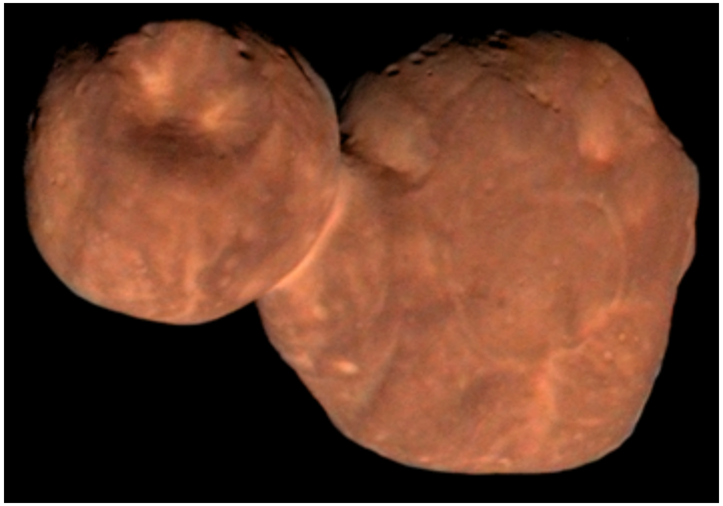
- **How have the surfaces and atmospheres in the Pluto-system evolved?**
  - What are the relative ages and geologic processes (including current and internally-driven activity) acting on different terrains globally on Pluto and Charon?
  - What is the origin and evolution of Pluto's volatiles (surface and atmospheric)?
  - What ate the chemical composition and thermal structure of Pluto/Charon atmosphere, hazes and exospheres?
  - What is the composition and escape rate of heavy and light ion species?



Science Goals – Level 1

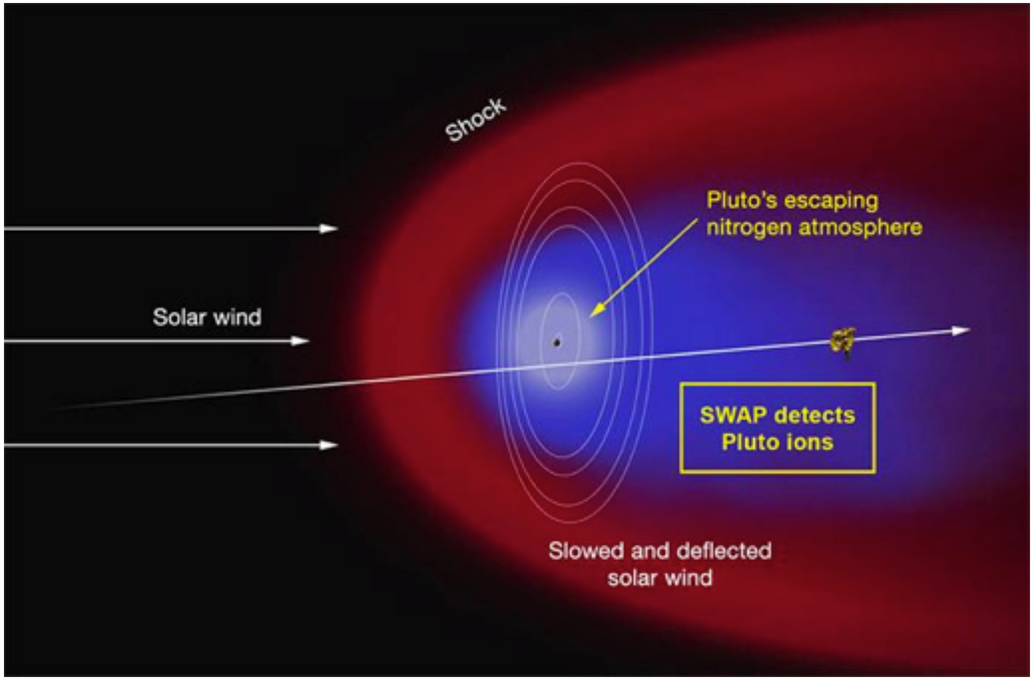
- **How has the KBO population evolved?**
  - What constraints do the small satellites in the Pluto-system place on its evolution?
  - How do the detailed surface properties, composition, volatiles and atmospheres of KBOs vary?
  - What do the surface features (incl. cratering records) of encountered KBOs reveal about the origin, evolution and geologic history of KBOs?
  - What can binary fraction, density, and shapes of KBOs tell us about their formation and the collisional environment in the primordial Kuiper Belt? Do they support current streaming instability models?





Science Goals – Level 2

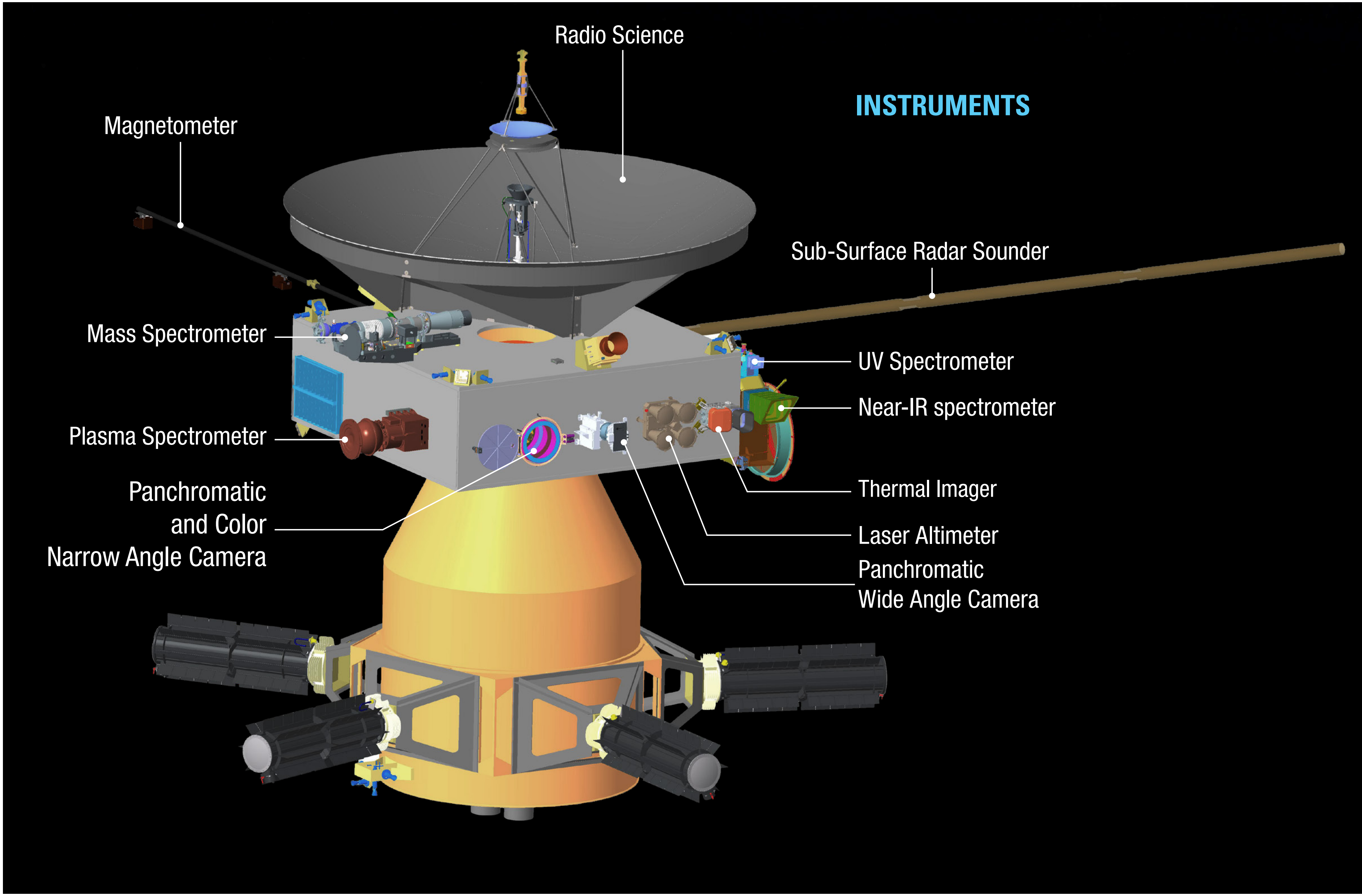
- What is Pluto's internal heat budget?
- What is the structure of magnetic fields in the outer solar system?
  - Is there a Plutopause, tail, bow shock or interaction region, and if so, what are their shapes and motions?
  - How do pick up ions affect shocks throughout the heliosphere and at solar system objects?



Spacecraft: Payload

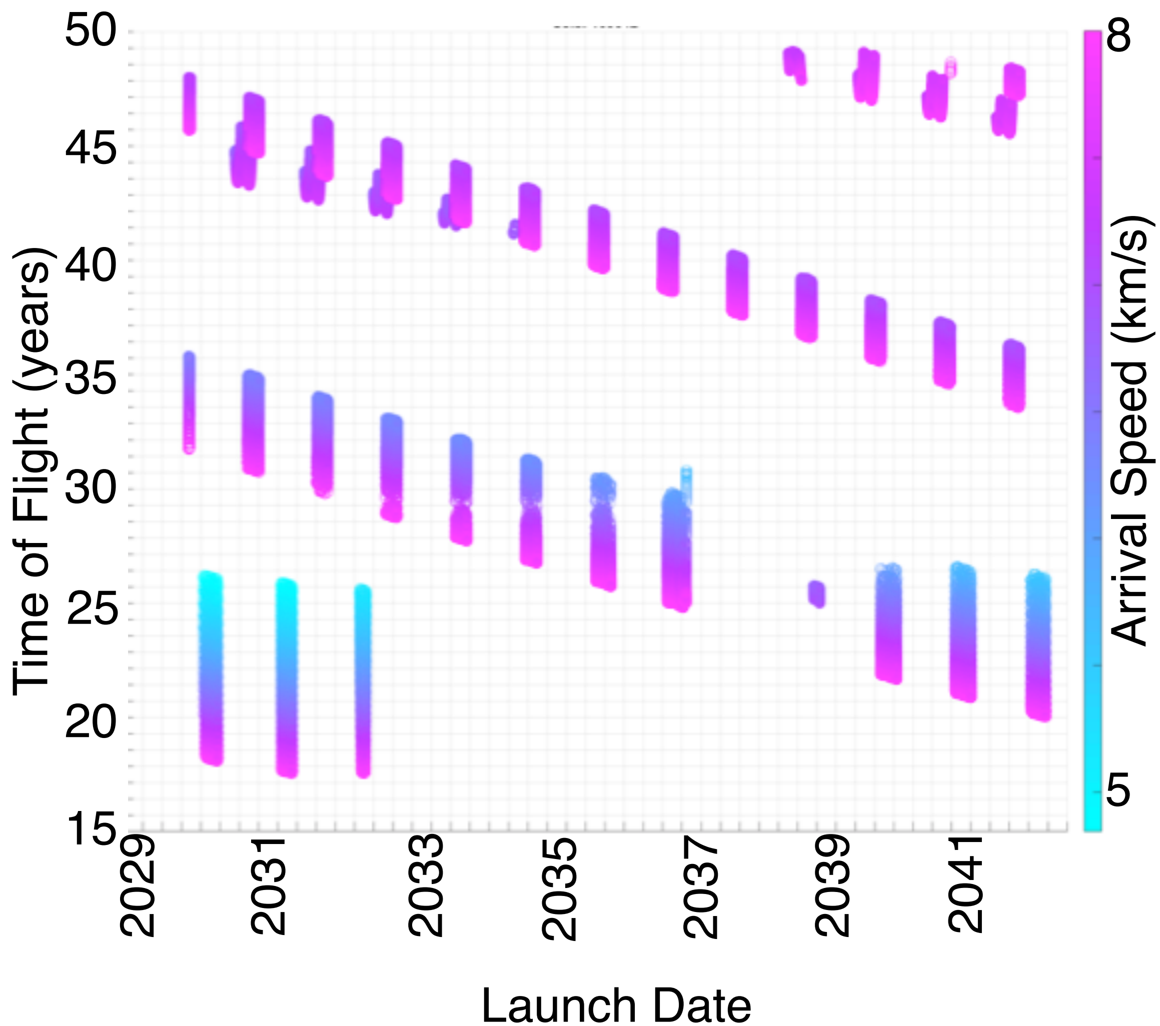
1. Panchromatic and Color High Resolution Imager (ex. Europa Clipper/EIS-NAC)
2. Low-light Camera (ex. Europa Clipper/EIS-WAC)
3. UV Spectrometer (ex. New Horizons/Alice)
4. Near IR Spectrometer (ex. Lucy/LEISA)
5. Thermal-IR (ex. Mars Odyssey/THEMIS)
6. RF Spectrometer (ex. New Horizons/REX)
7. Mass Spectrometer (ex. Europa Clipper/MASPEX)
8. Altimeter (ex. MESSENGER/MLA)
9. Ice Penetrating Radar (ex. Mars Express/MARSIS)
10. 3-axis Fluxgate Magnetometer (ex. IMAP/MAG)
11. Plasma - Solar Wind Ions and Electrons (ex. IMAP/CoDICE-Lo)

INSTRUMENTS



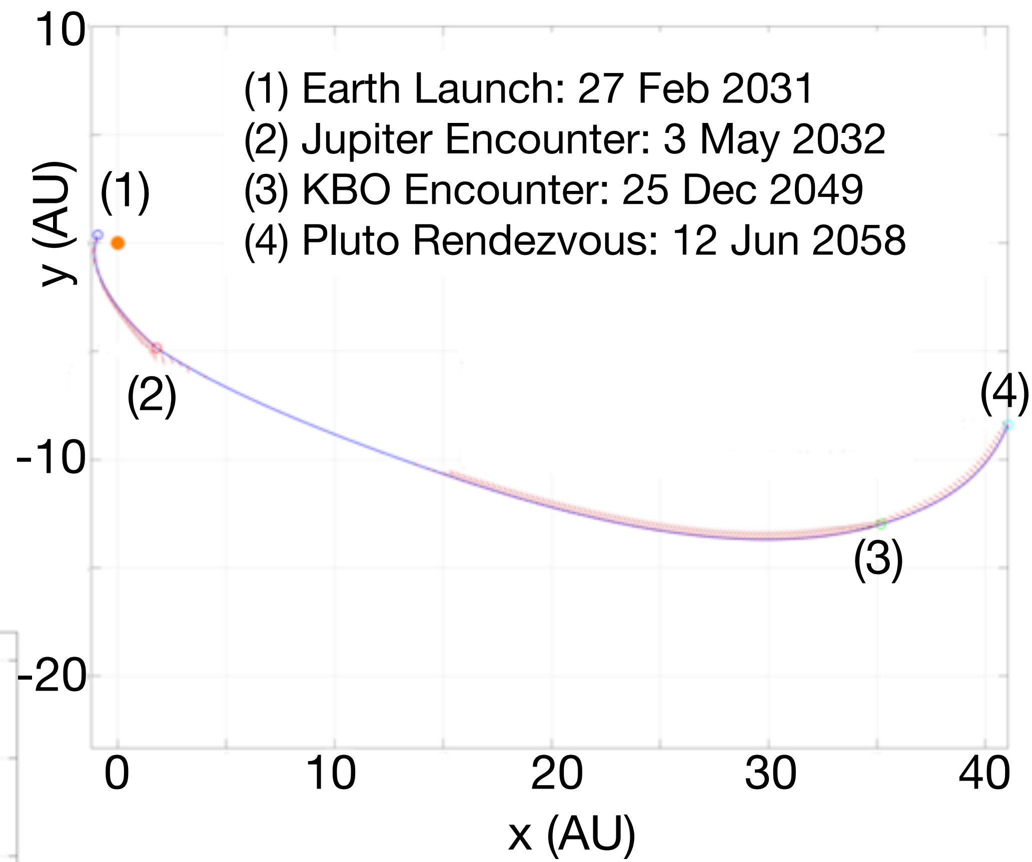
Launch Windows

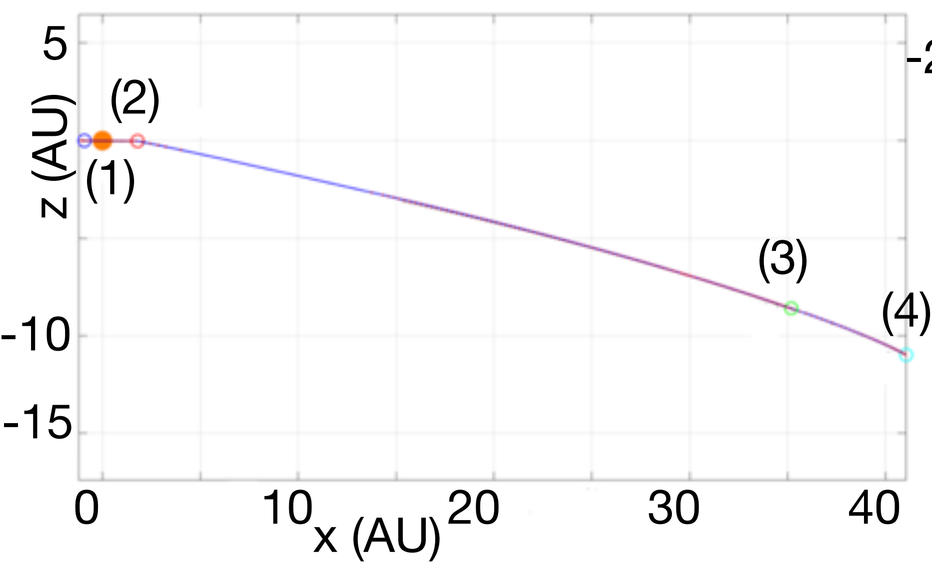
- Direct to Jupiter transfers heavily reliant on Jupiter being in phase en route to Pluto
  - Optimal phasing ends is early 2032
  - After 2032, ~10 year transfer time penalties
  - Jupiter does not come back in phase until 2042
- Pluto arrival speeds <8 km/s puts us in the feasibility space of current propulsion technology
  - Transfers times bottom out at ~18 years



Trajectory

- Launch on SLS Block 2 with Centaur
- XR-5 electric propulsion system
  - High thrust mode
  - 85% duty cycle, 1 thruster
- 5 Next Gen RTGs
  - 1925 W at launch (assume 2yr pre-fuel)

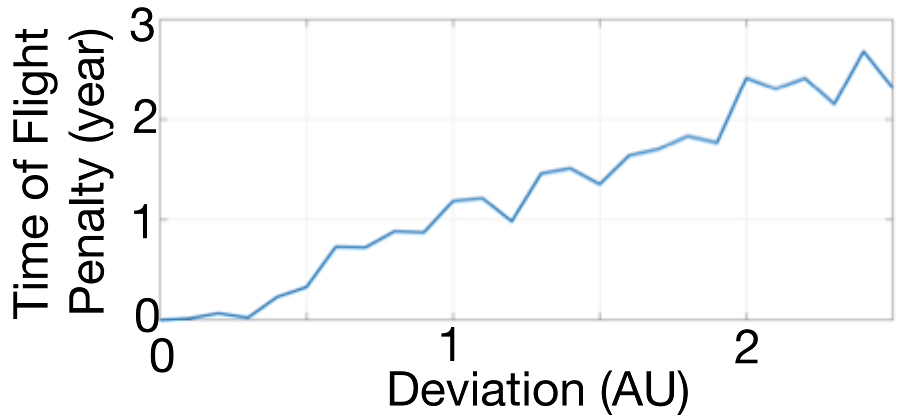


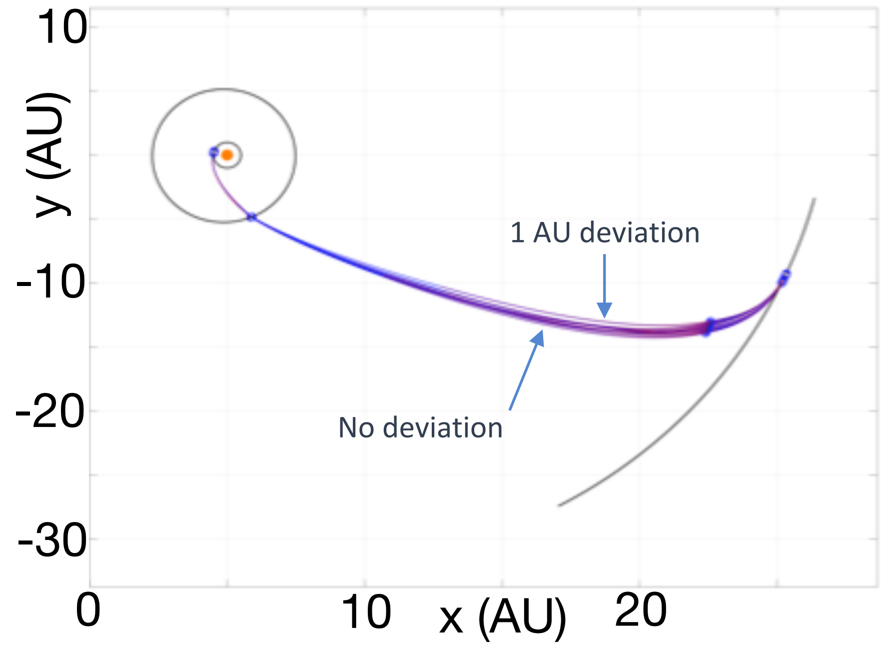


- Time of flight to Pluto: 27.3 years
  - 1 AU deviation for pre Pluto KBO flyby in 2049
- Delivered mass to Pluto: 2627 kg

Pre-Pluto KBO Statistical Model

- Statistical modeling identified locations in inertial space where KBOs would exist along the nominal trajectory to Pluto
- 0.2 AU to visit ~30 km (Arrokoth sized)
- >0.5 AU to visit larger target
- Selected a 1 AU deviation





Pluto tour

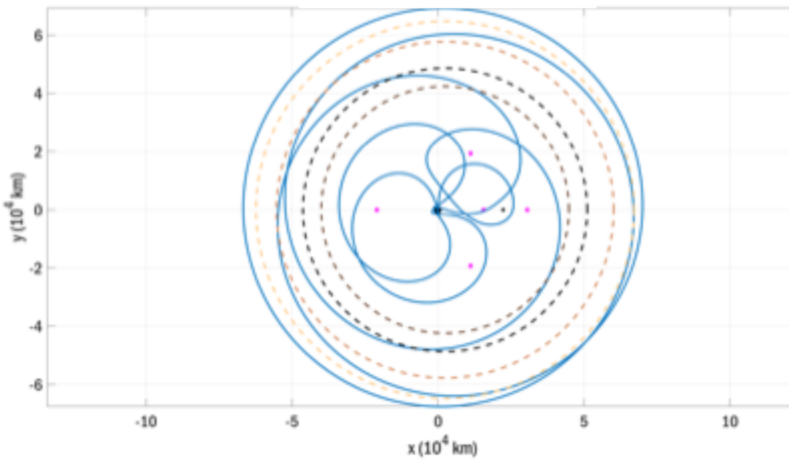
- Considered innovative ways to accomplish science goals within a small DV budget
  - Leverage Charon perturbations vs fight them
  - Tidally locked primaries allows for repeat groundtracks

- Several periodic orbits identified in 2 categories:
  - High latitude access for global coverage
  - Low altitude access for in situ measurements

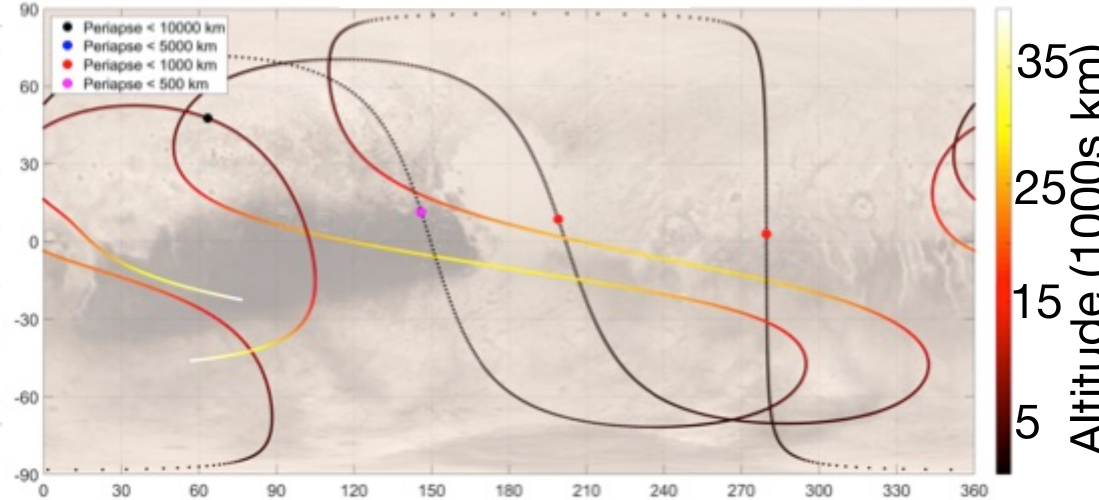
- Use of EP enables transitions between orbits

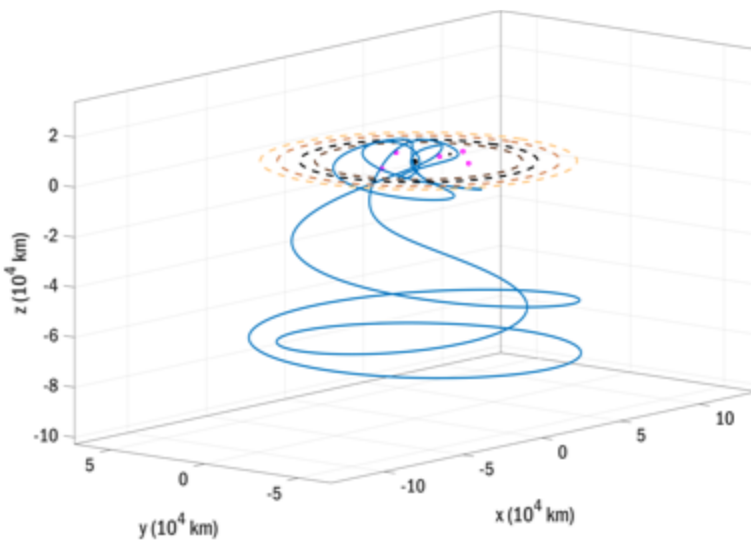
- Science team selected four periodic orbits

Science Orbit #1 – High Latitude

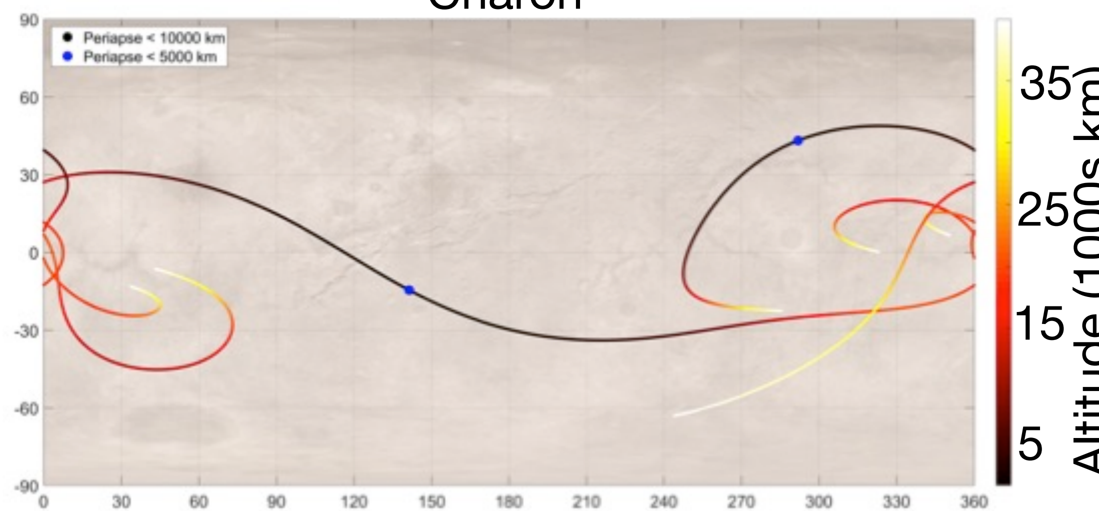


Pluto

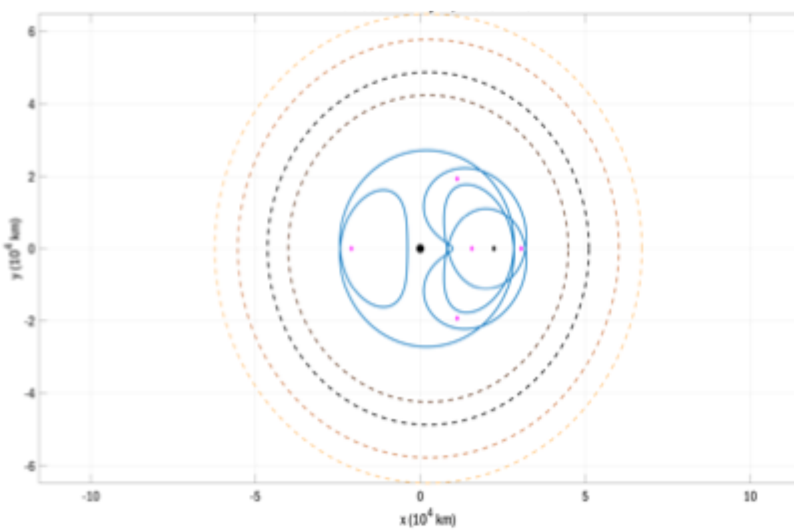




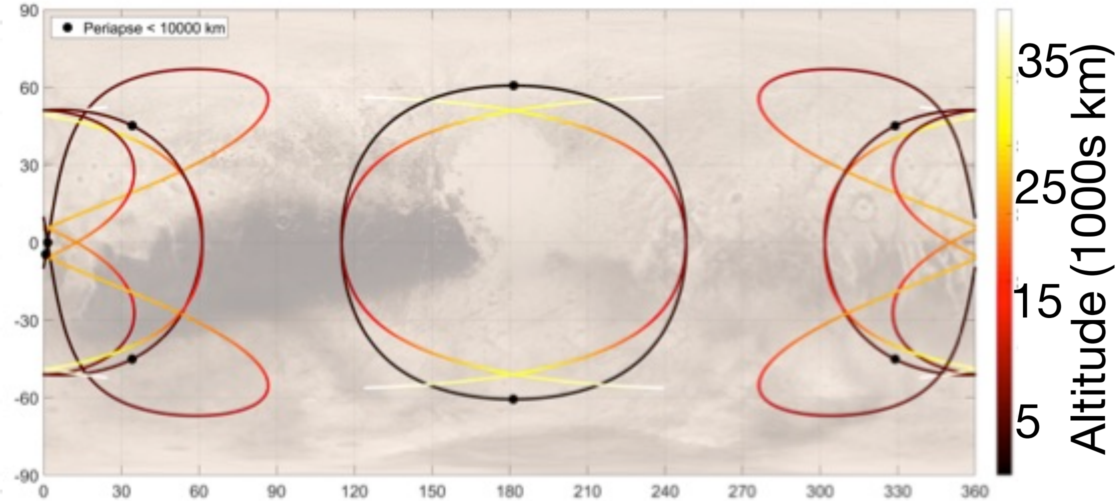
Charon

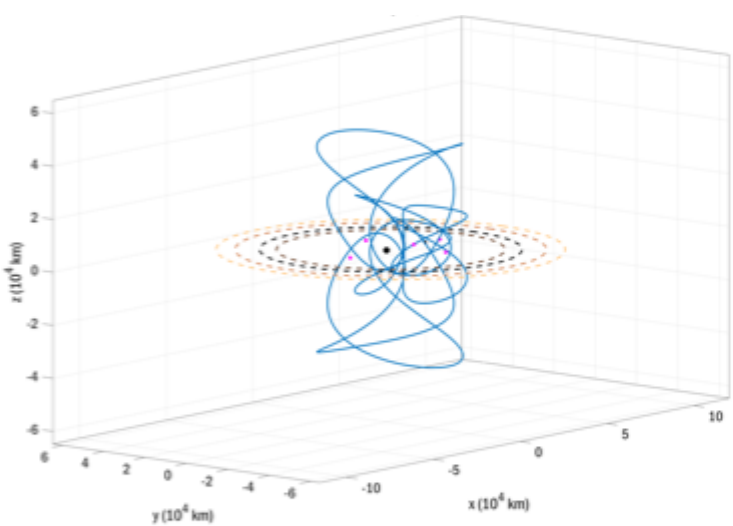


Science Orbit #2 – High Latitude

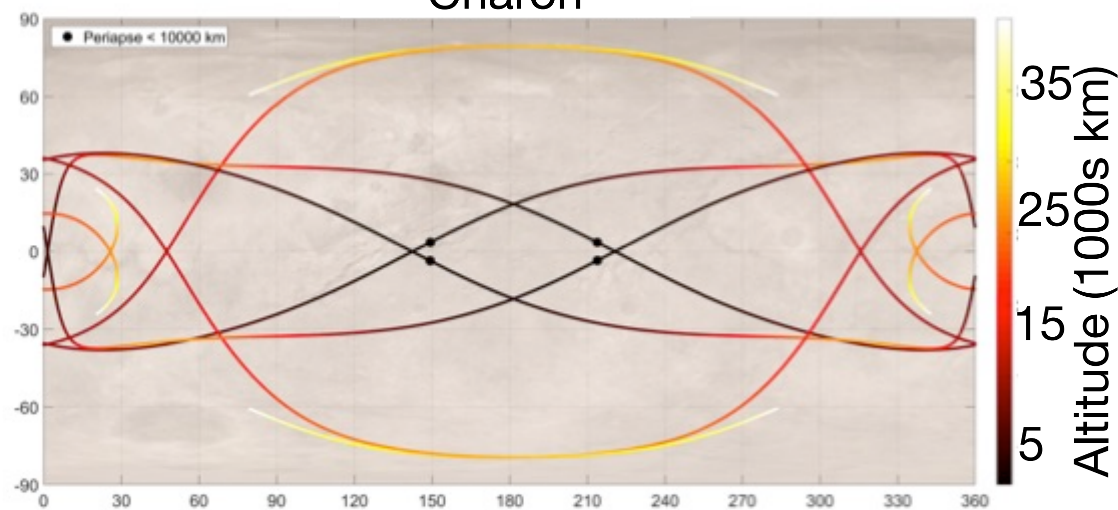


Pluto

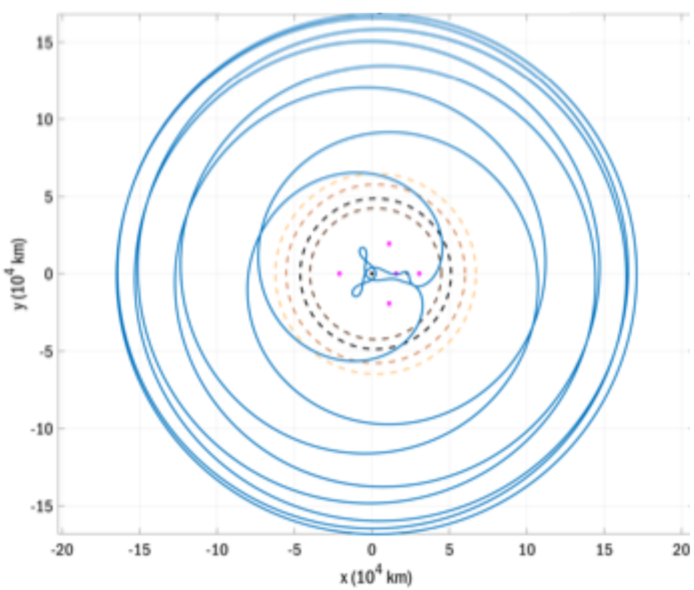


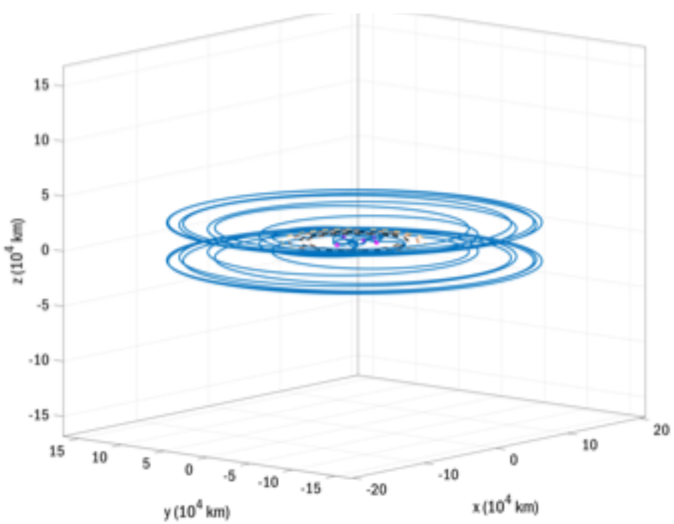


Charon

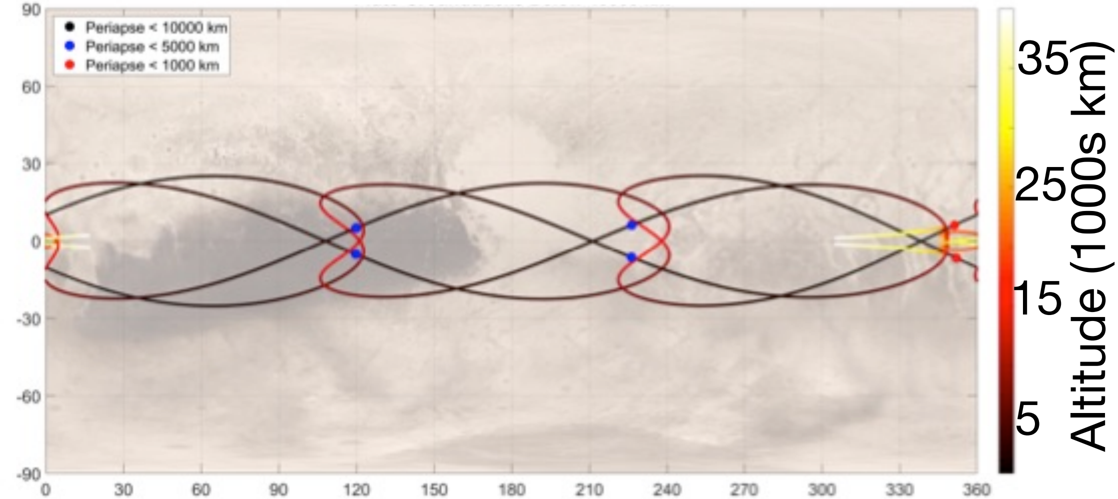


Science Orbit #3 – Low Latitude

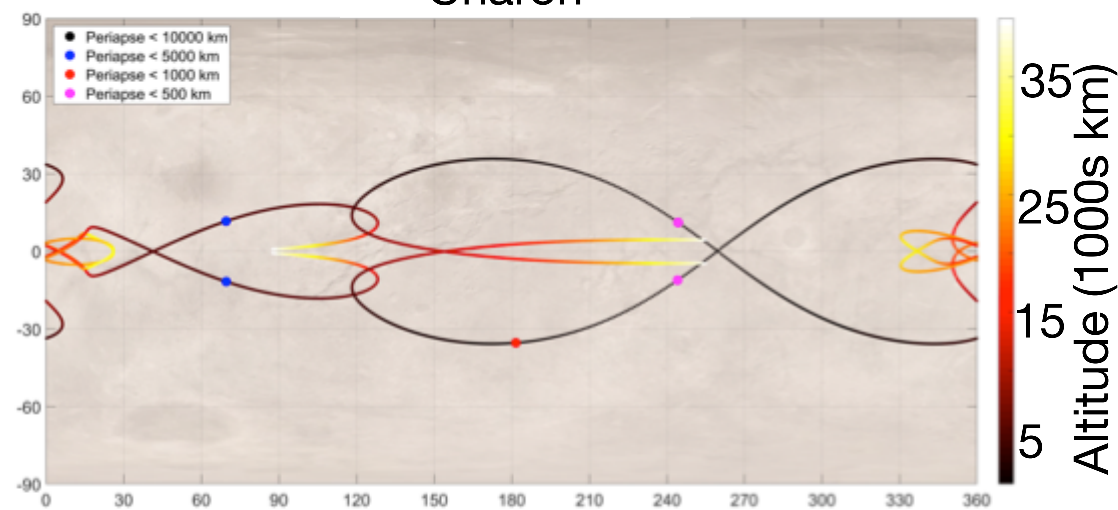




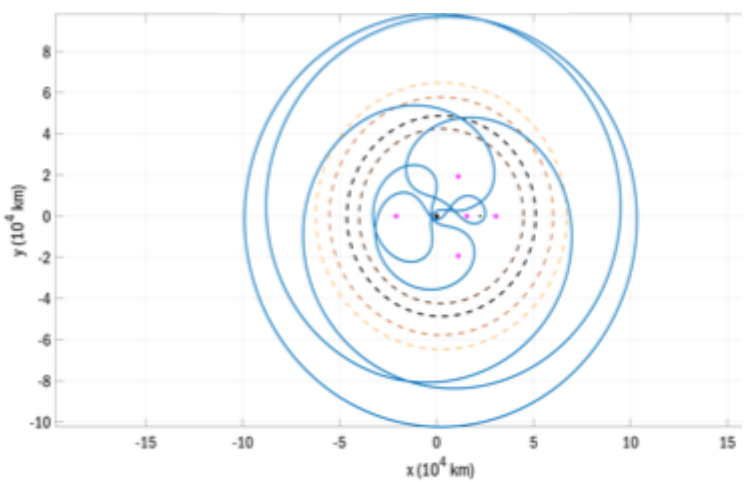
Pluto



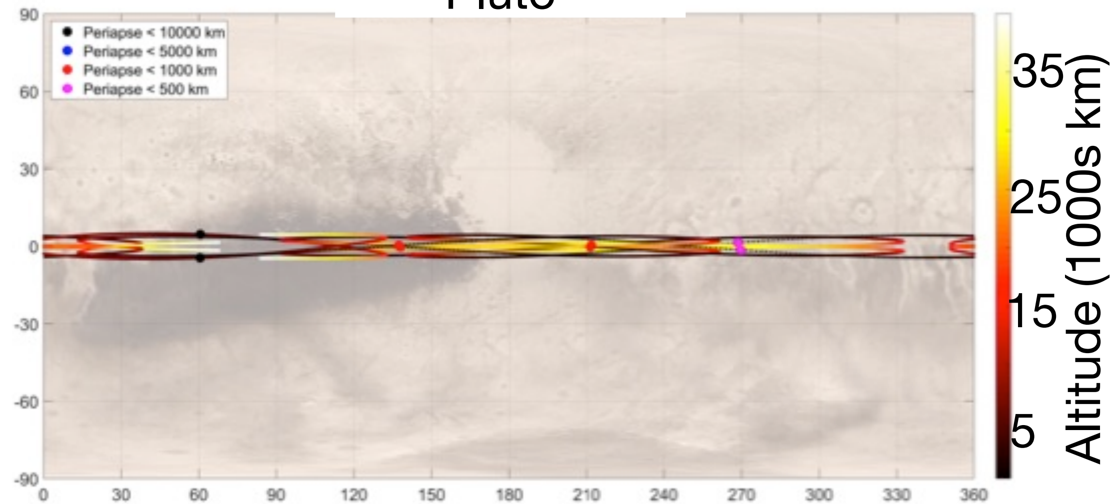
Charon

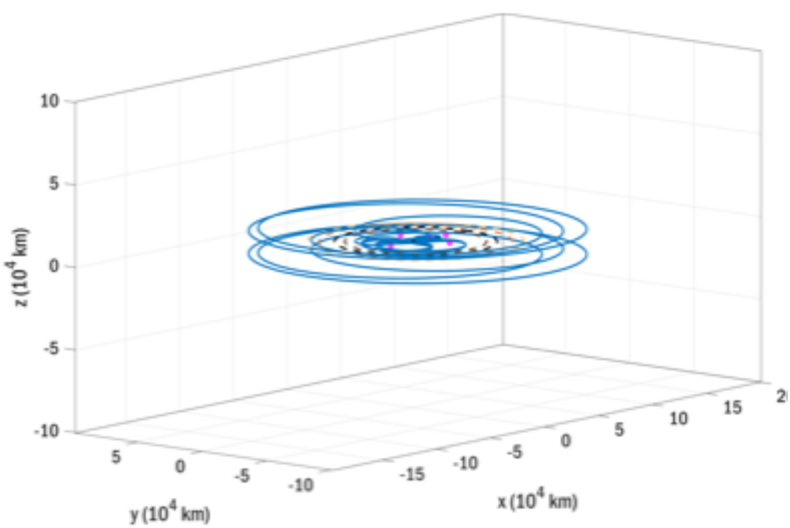


Science Orbit #4 – Low Latitude

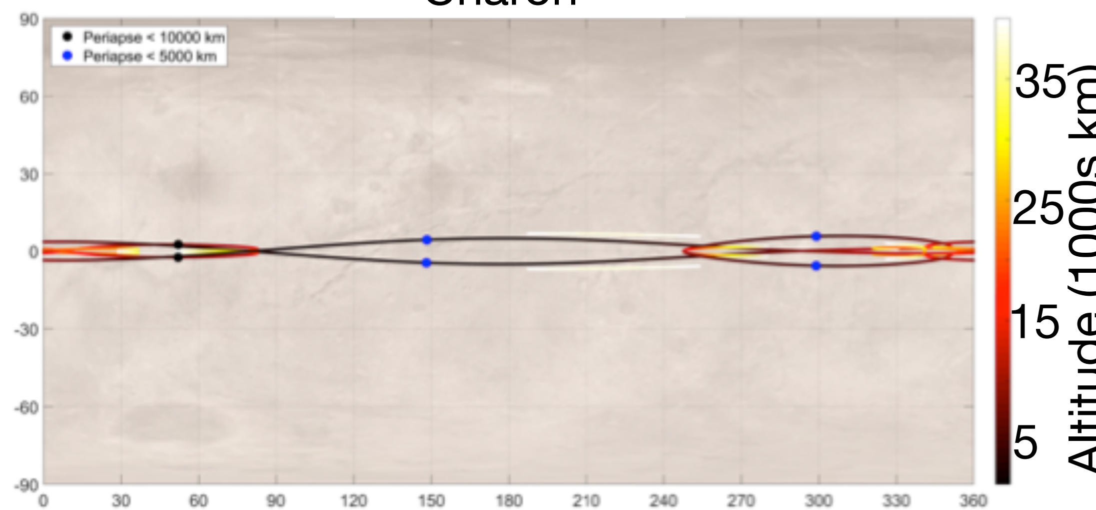


Pluto

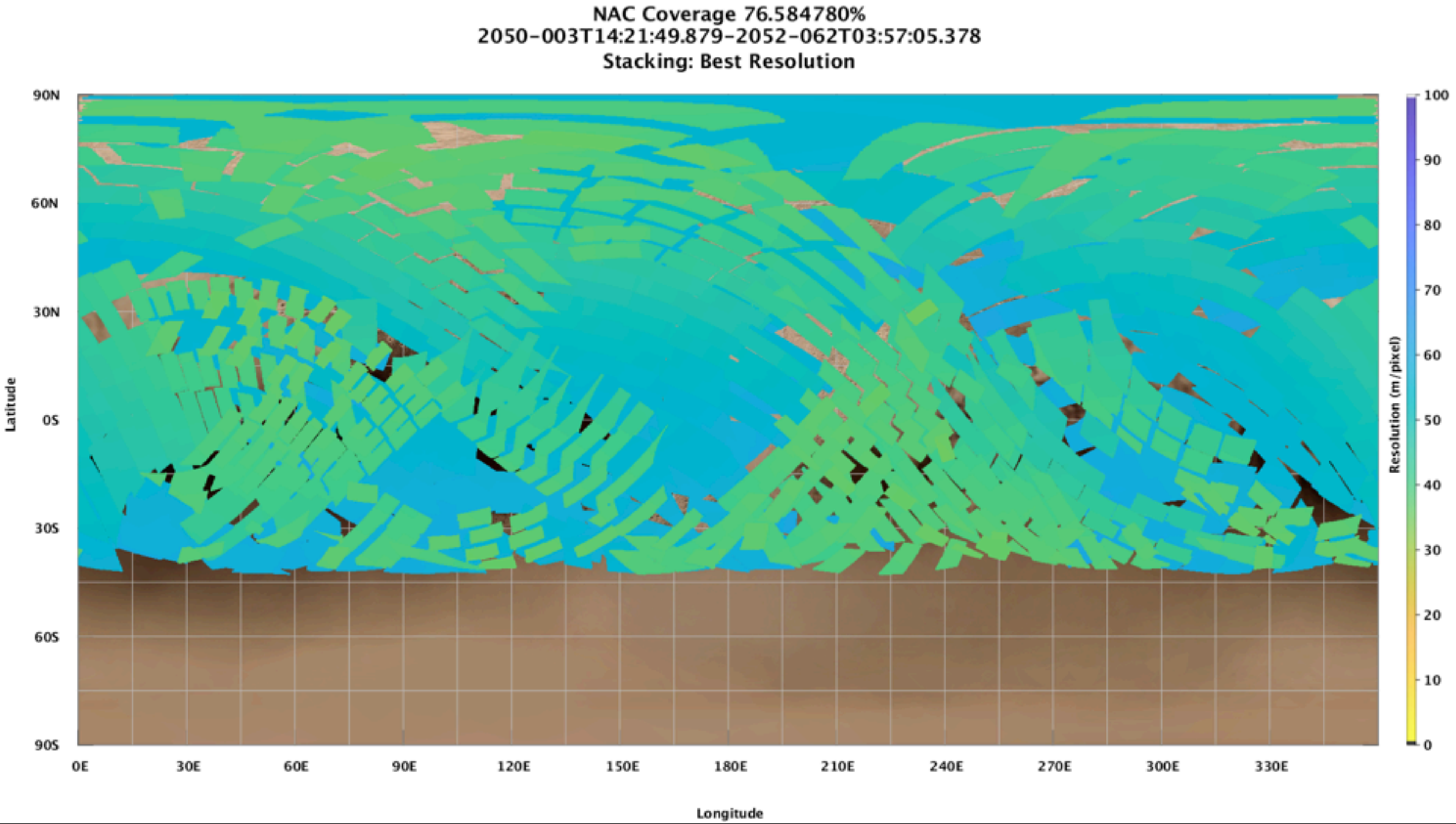




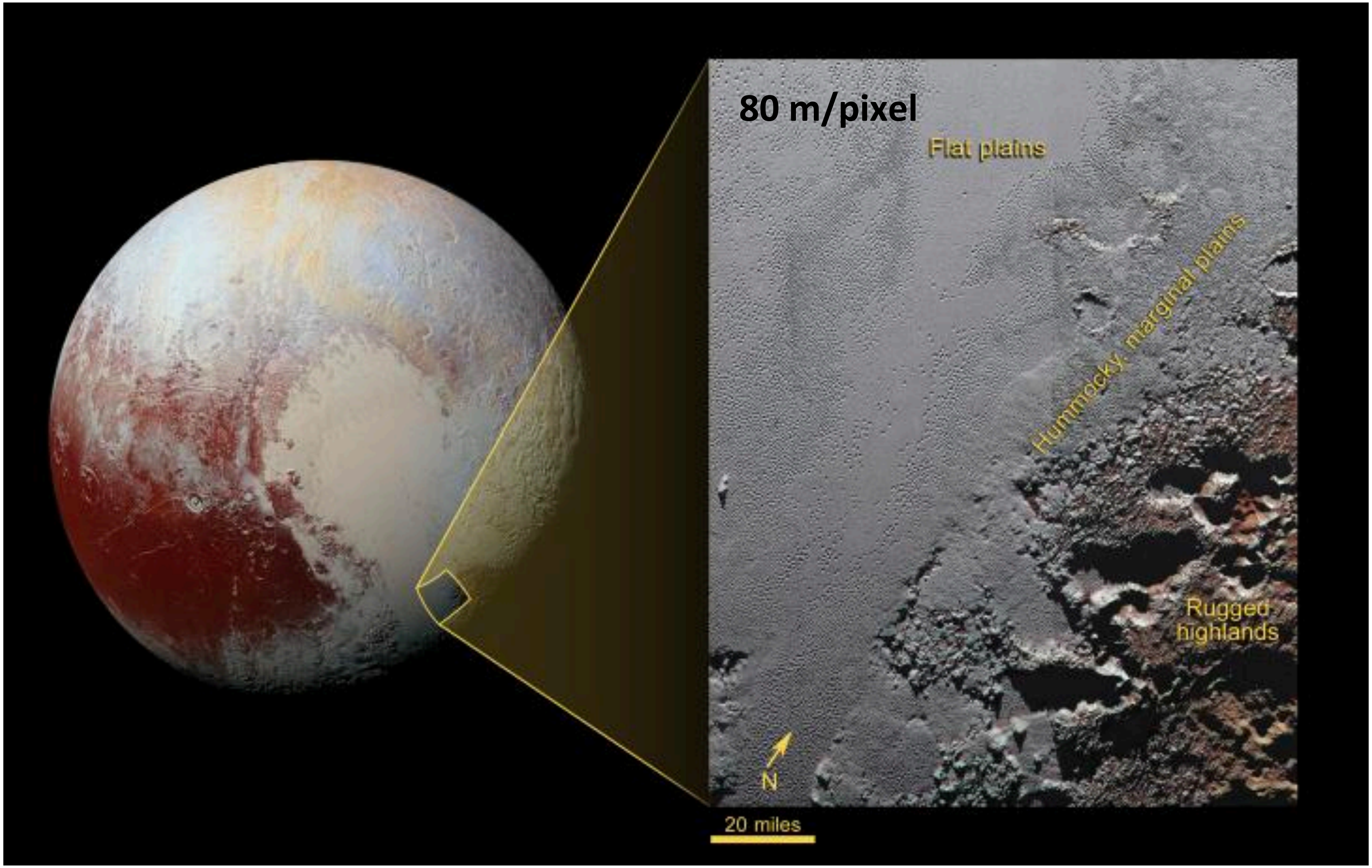
Charon



Pluto Surface Coverage: NAC (Panchromatic and Color)

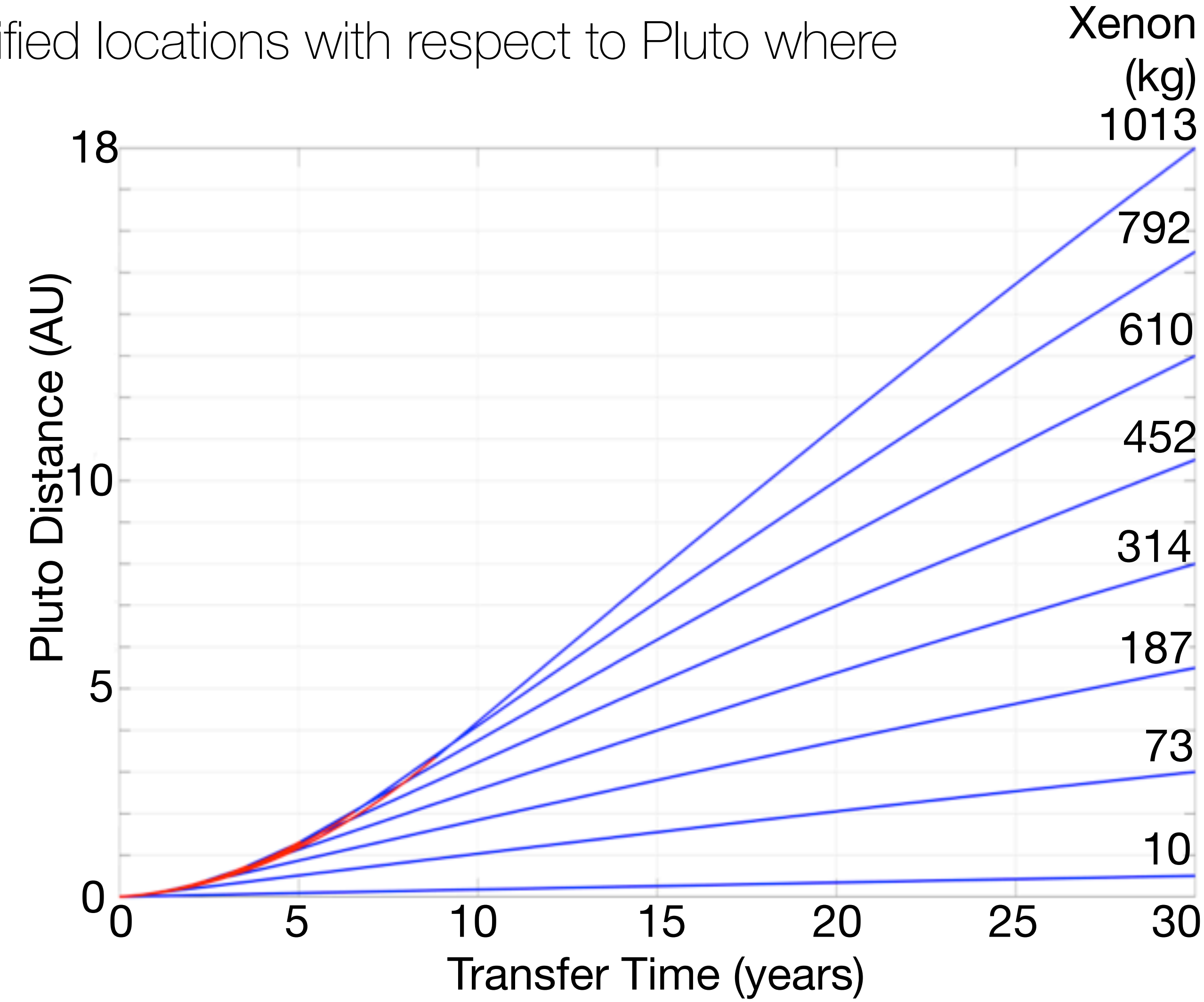


NAC imaging context:



Extended Mission: Post-Pluto KBO Tour

- Statistical modeling identified locations with respect to Pluto where KBOs could exist
- Results for late 2050s
  - Deviation:
    - 1 AU: ~40 km
    - 3 AU: ~70 km
- Xenon propellant available limits Pluto departure velocity, and thus transfer time to further KBOs
- Design has 250 kg reserved for post Pluto KBO flyby



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Post-Pluto Possible Targets

Name	H_V	Estimated diam.[1] (km)	Approx. departure	Transit duration (yr)	Min. & Max. distance (au)
(470308) 2007 JH43	4.5	600	2061-2066	20	4.39-4.46
(182294) 2001 KU76	6.6	230	2060-2066	17-20	3.02-4.37
2004 HN79	7.1	180	2060-2066	18-20	2.63-4.27
2004 HZ78	7.3	165	2060-2061	16-19	3.37-4.29
2015 KD176	7.4	160	2060-2070	20	3.93-4.05
(523704) 2014 HB200	7.5	150	2060-2061	17-20	3.61-4.27
2013 JR65	7.9	125	2060-2067	13-17	2.26-3.73
2000 FT53	8.3	100	2060-2066	17-20	2.09-4.35
2004 HY78	8.3	100	2060-2064	15-20	2.55-4.48
2015 KO173	8.8	80	2060-2070	12-19	0.41-4.26
2015 KQ175	8.9	75	2060-2070	20	3.60-3.83
2015 GH54	9.7	55	2060-2070	18-20	1.47-4.04

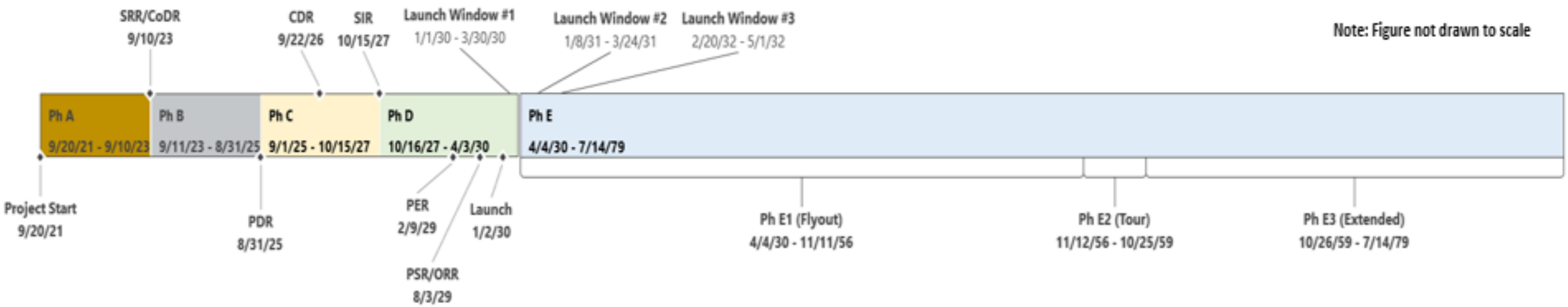
[1]Assuming a visible geometric albedo, p_V, of 0.08

- 150 km (statistical) KBO can be reached in 8 years

Trajectory Summary

- Interplanetary
  - 27.3 year time of flight
  - Direct to Pluto via Jupiter gravity assist
  - Accommodates a pre-Pluto KBO flyby
  - Requires SLS Block 2 and with kick stage
  - Jupiter phasing incompatible after 2032 launch
- Pluto Tour
  - 3.1 years for planned tour
  - Surveys Pluto and Charon via four different periodic orbits in the Pluto-Charon three body dynamics model
    - *Accommodates opportunistic flybys of the other smaller moons*
  - Efficient transfers between periodic orbits enabled by EP low thrust transfer arcs
- Post Pluto KBO
  - 250 kg propellant reserved for post-Pluto KBO flyby
    - *150 km (statistical) KBO can be reached in 8 years*
    - *125 km (known, 2013 JR65) KBO could be reached in 13-17 years*
    - *600 km (known, 2007 JH43) KBO could be reached in ~20 years*

Schedule



Mission Phases	Duration	Start	Finish
Phase A	24 mos.	9/20/2021	9/10/2023
Phase B	24 mos.	9/11/2023	8/31/2025
Phase C1	13 mos.	9/1/2025	9/22/2026
Phase C2	13 mos.	9/23/2026	10/15/2027
Phase D1	16 mos.	10/16/2027	2/9/2029
Phase D2	6 mos.	2/10/2029	8/3/2029
Phase D3	5 mos.	8/4/2029	1/2/2030
Phase D4 (Checkout)	3 mos.	1/3/2030	4/3/2030
Phase E1 (Flyout)	320 mos.	4/4/2030	11/11/2056
Phase E2 (Tour)	36 mos.	11/12/2056	10/25/2059
Phase E3 (Extended)	237 mos.	10/26/2059	7/14/2079

Mission Level Milestones	Start
Project Start	9/20/2021
SRR/CoDR	9/10/2023
PDR	8/31/2025
CDR	9/22/2026
SIR	10/15/2027
PER	2/9/2029
PSR/ORR	8/3/2029
Launch	1/2/2030

Launch Windows	Duration	Start	Finish
Launch Window #1	89 days	1/1/2030	3/30/2030
Launch Window #2	76 days	1/8/2031	3/24/2031
Launch Window #3	72 days	2/20/2032	5/1/2032

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Conclusion

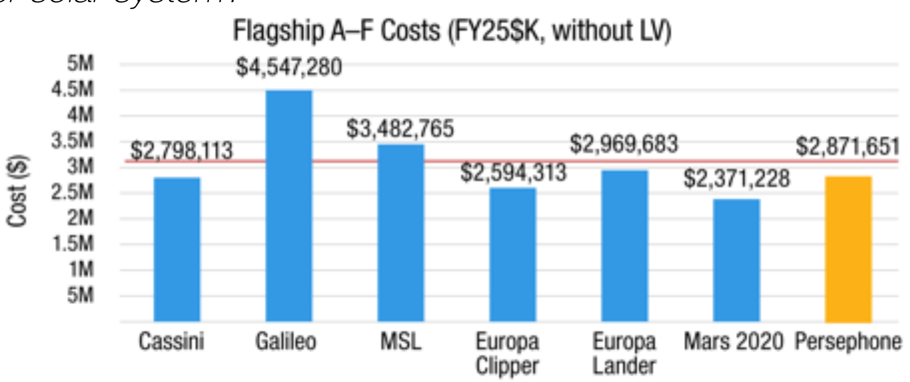
- We have closed (CML4) on a spacecraft and tour design that would provide up to 8 different KBOs:
  - A pre-Pluto KBO encounter
  - A 3.1 (Earth) year tour of the Pluto-system
  - An extended mission to another KBO

- Unprecedented KBO science
  - Three Level 1 Science Questions:
    - *What is the internal structure of Pluto and Charon?*
    - *How have the surfaces and atmospheres in the Pluto-system evolved?*
    - *How has the KBO population evolved?*

  - Two Level 2 Science Questions:
    - *What is Pluto's internal heat budget?*
    - *What is the structure of magnetic fields in the outer solar system?*

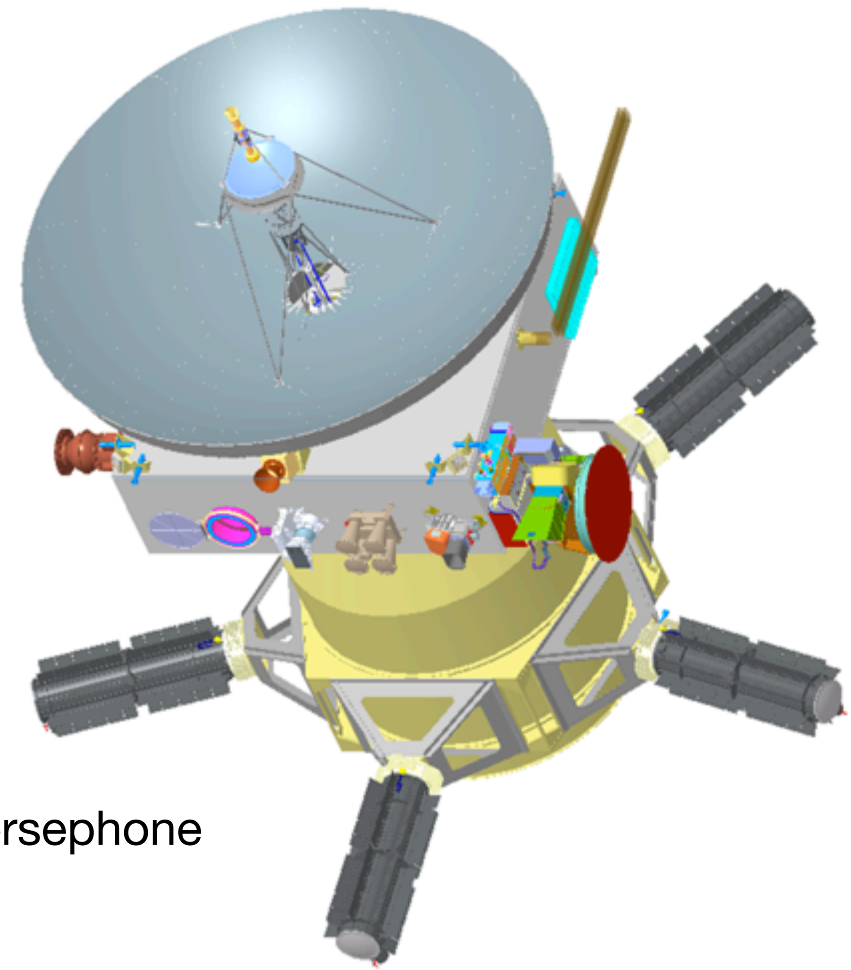
- Nominally a payload of 11 instruments

- Cost: $3.0B FY$25 (excluding all LV costs)
  - Extended mission is an additional $237M



Additional Material

Spacecraft size compared to New Horizons



Persephone

New Horizons

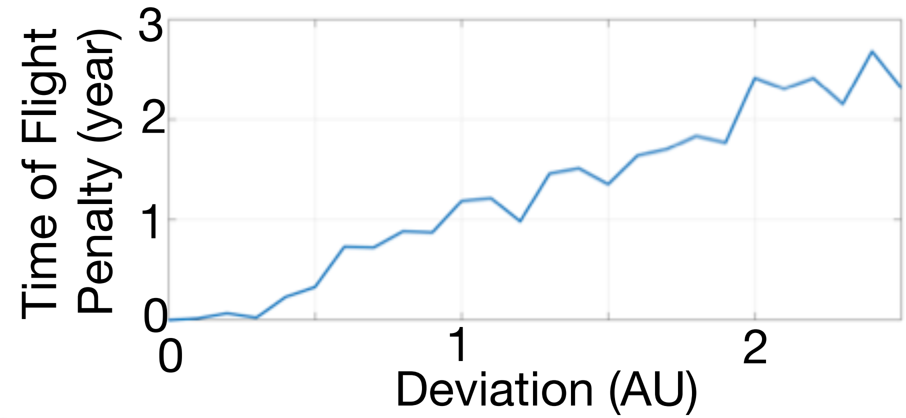
2 m

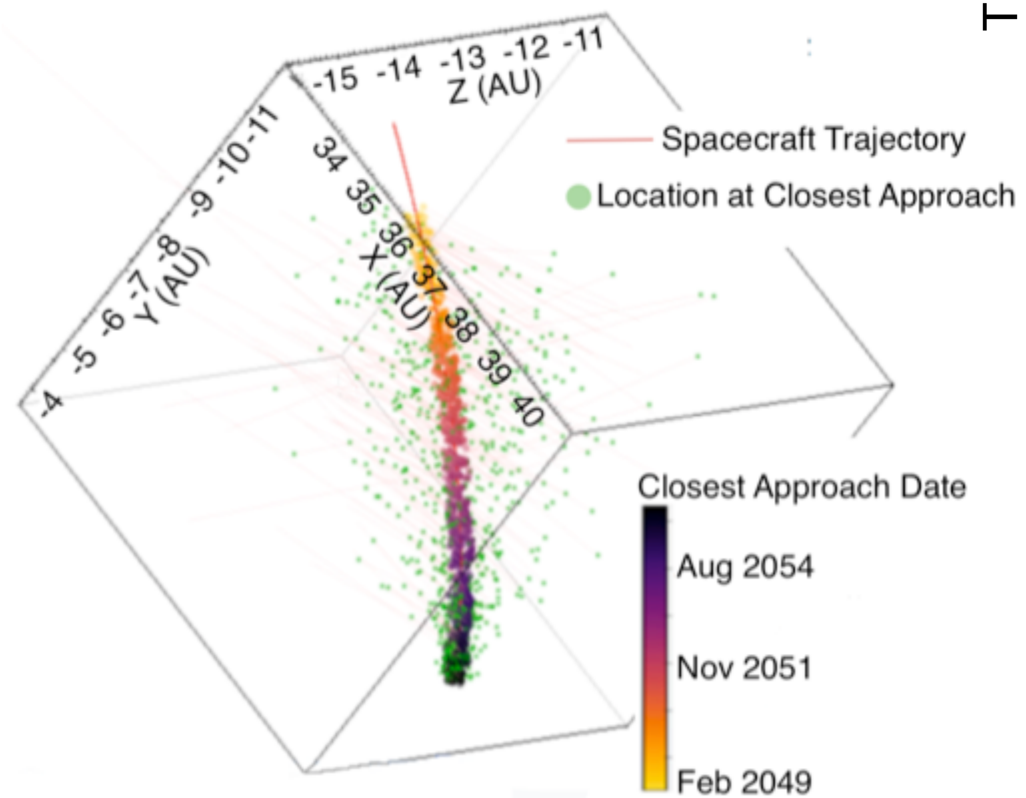
Data Volume Estimate

Observing requirement (Pluto)	Total Data Volume(Mb)		Observing assumptions
	Raw	After compression	
Global panchromatic (NAC)	141,751	70,875	Global 50 m GSD, 2k x 4k images, i e constraints
Ultra-high resolution (NAC)	86,400	43,200	5 m GSD, 10x20 km, pan plus 8 colors, 100 images
NAC Stereo (NAC)	141,751	70,875	50 m GSD, 2k x 4k images, i e constraints
8 colors (NAC)	283,502	141,751	Global, 100 m, 8 bands
Phase function: visible (NAC)	8,505	4,253	500m, global coverage, 6 phase-angle steps
Low-light level (WAC)	768	384	1 km, 50 S to 90 S, 3 images, twice
Altimetry (MLA)	36	18	30Hz, 2x12 bit, 1,500 km max range, 50 orbits
Thermal imaging (THEMIS)	74	37	10km, 4 bands, 6 global sets (vary local time)
Sounding radar (MARSIS)	15,000	15,000	30Mb/s compressed to 300 kb/s. 1,000s per periasis
Near IR spectrometer (LEISA)	263,314	131,657	0.5 km, 256 spectral bands
NIR phase function (LEISA)	11,059	5,530	5-km, 256 spectral bands, 6 phase steps
UV spectra: limb (Alice)	20,000	10,000	20 solar occultations (w/REX); 50 stellar occultations
Plasma (CODICE-Lo)	879	440	High rate: periapses + 100 hrs; low rate: 10,000 hrs
Magnetometer (MAG)	2,629	1,315	High rate: periapses + 100 hrs; low rate: 10,000 hrs
Mass spectroscopy (MASPEX)	25,000	12,500	50 periapsis passes
RF occultations of limb (REX)	2,500	1,250	50 Earth occultations.
Charon	100,000	50,000	Allocation
Small satellites	50,000	25,000	Allocation
Total		**584,084**	28 kb/s; 2 yrs; 7 passes/week; 8hrs/day= 587,000 Mb

Pre-Pluto KBO Statistical Model

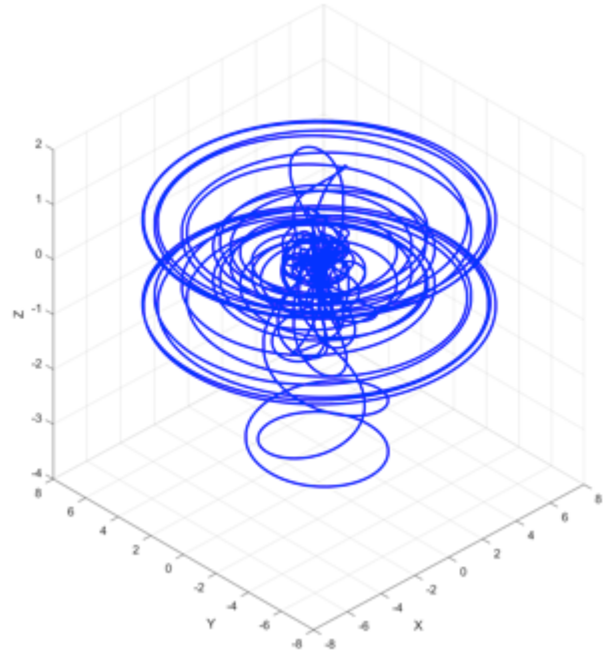
- Statistical modeling identified locations in inertial space where KBOs would exist along the nominal trajectory to Pluto





Pluto tour overview

Leg	Duration (days)	Revs	Start Time (Days)	End Time (Days)	Prop Used (kg)
Entire Tour	**1131**		**0.0**	**1130.5**	**62.3**
Orbit 1 Science	46	4	0.0	184.5	
Orbit 1 Dep Phasing	1		184.6	185.4	
Orbit 1 to 2 Xfer	28		185.4	213.7	16.1
Orbit 2 Arr Phasing	28		213.7	242.0	
Orbit 2 Science	69	3	242.0	449.8	
Orbit 2 Dep Phasing	39		449.8	488.7	
Orbit 2 to 3 Xfer	30		488.7	518.7	29.8
Orbit 3 Arr Phasing	78		518.8	596.3	
Orbit 3 Science	154	1	596.3	750.2	
Orbit 3 Dep Phasing	0		750.2	750.2	
Orbit 3 to 4 Xfer	16		750.2	766.3	16.4
Orbit 4 Arr Phasing	89		766.3	855.5	
Orbit 4 Science	91	3	855.5	1130.5	



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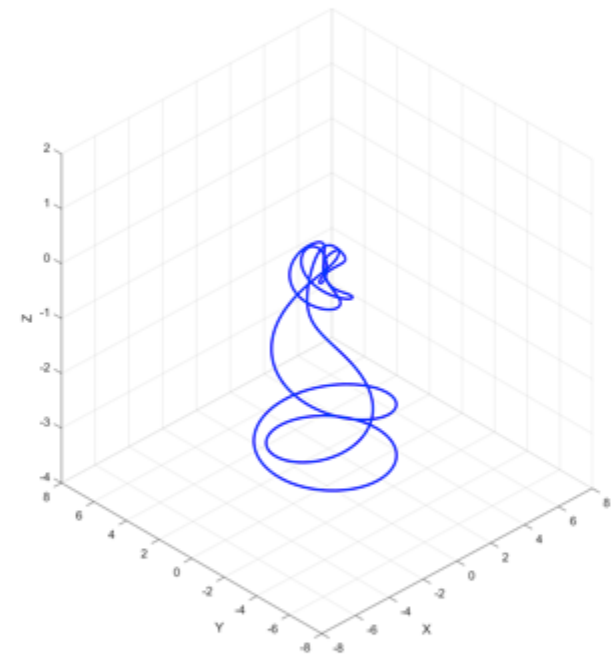

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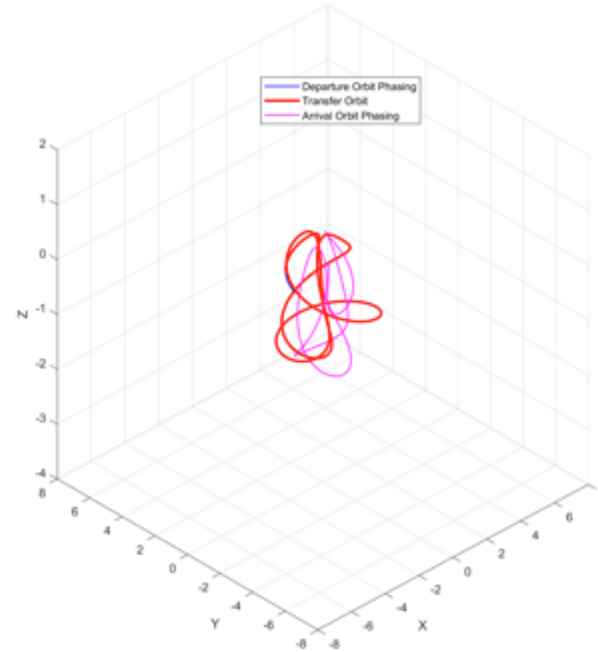

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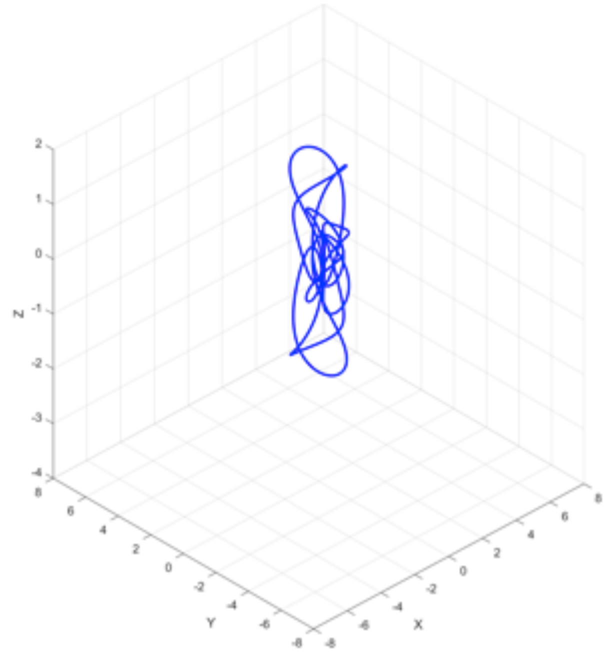

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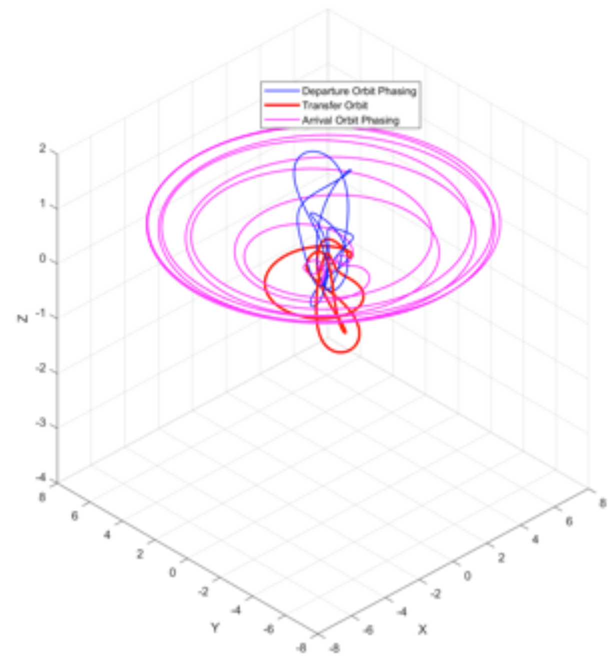

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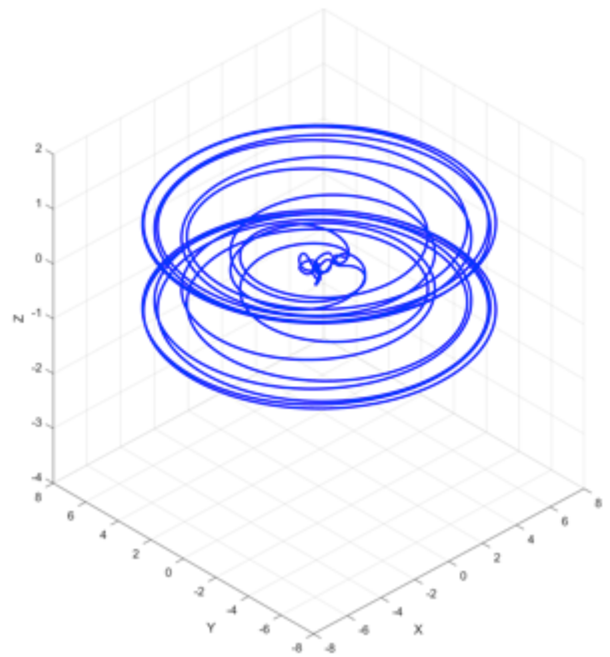

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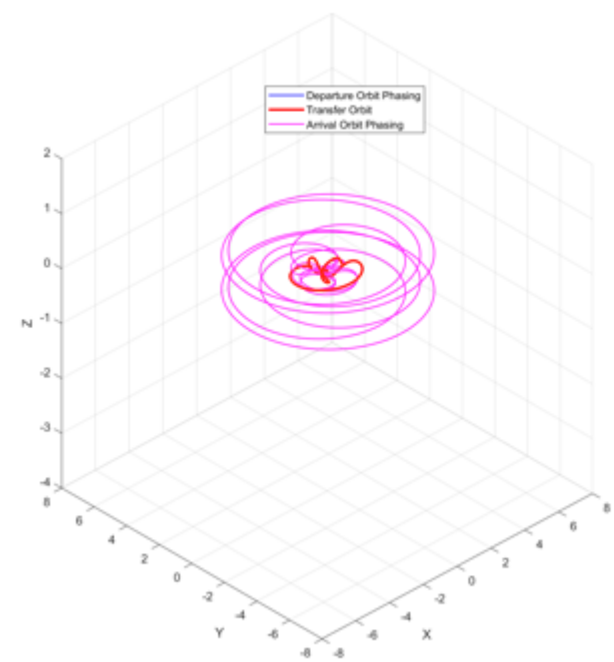

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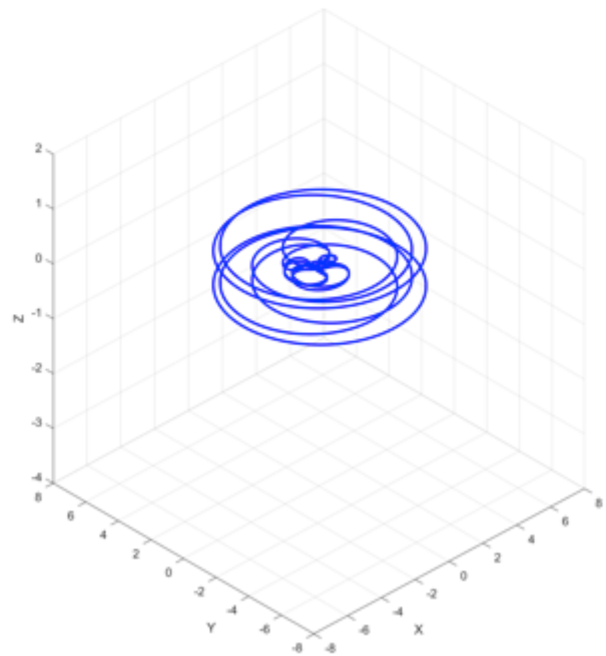
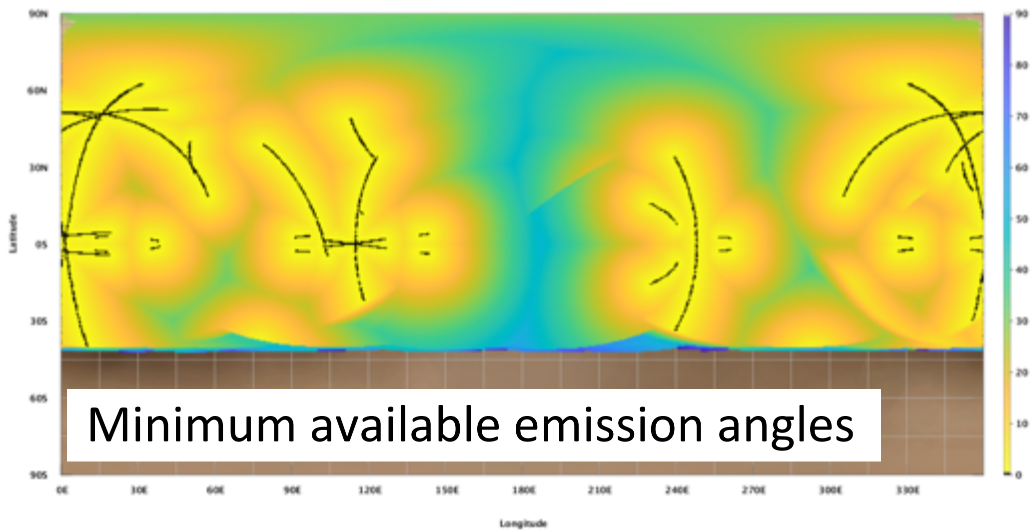
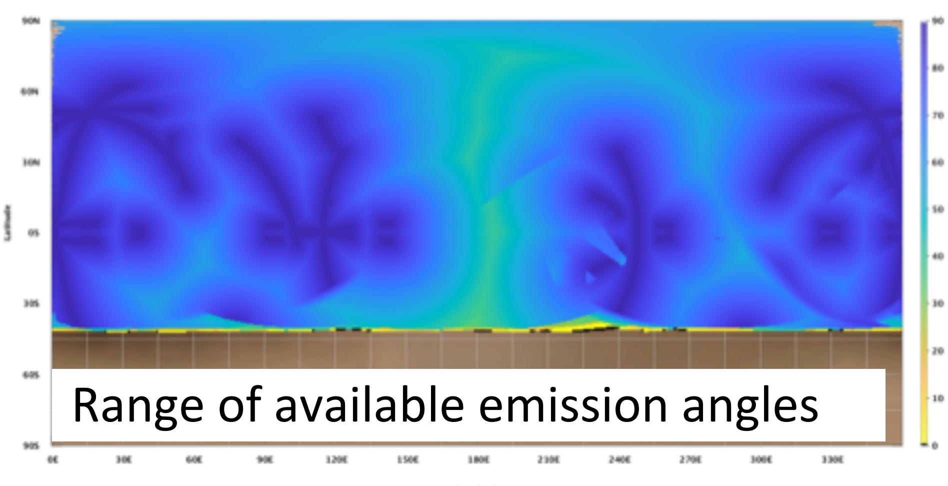
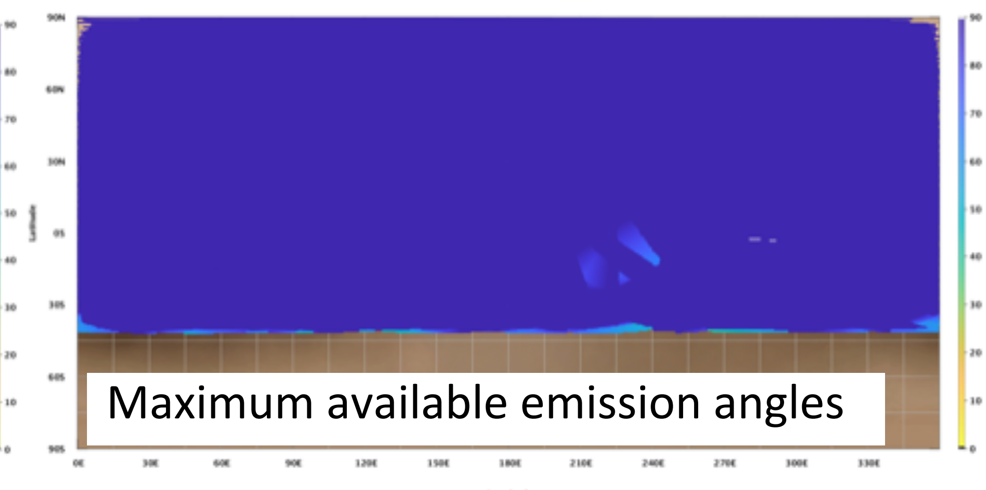


Pluto Surface Coverage: NAC (Panchromatic and Color)

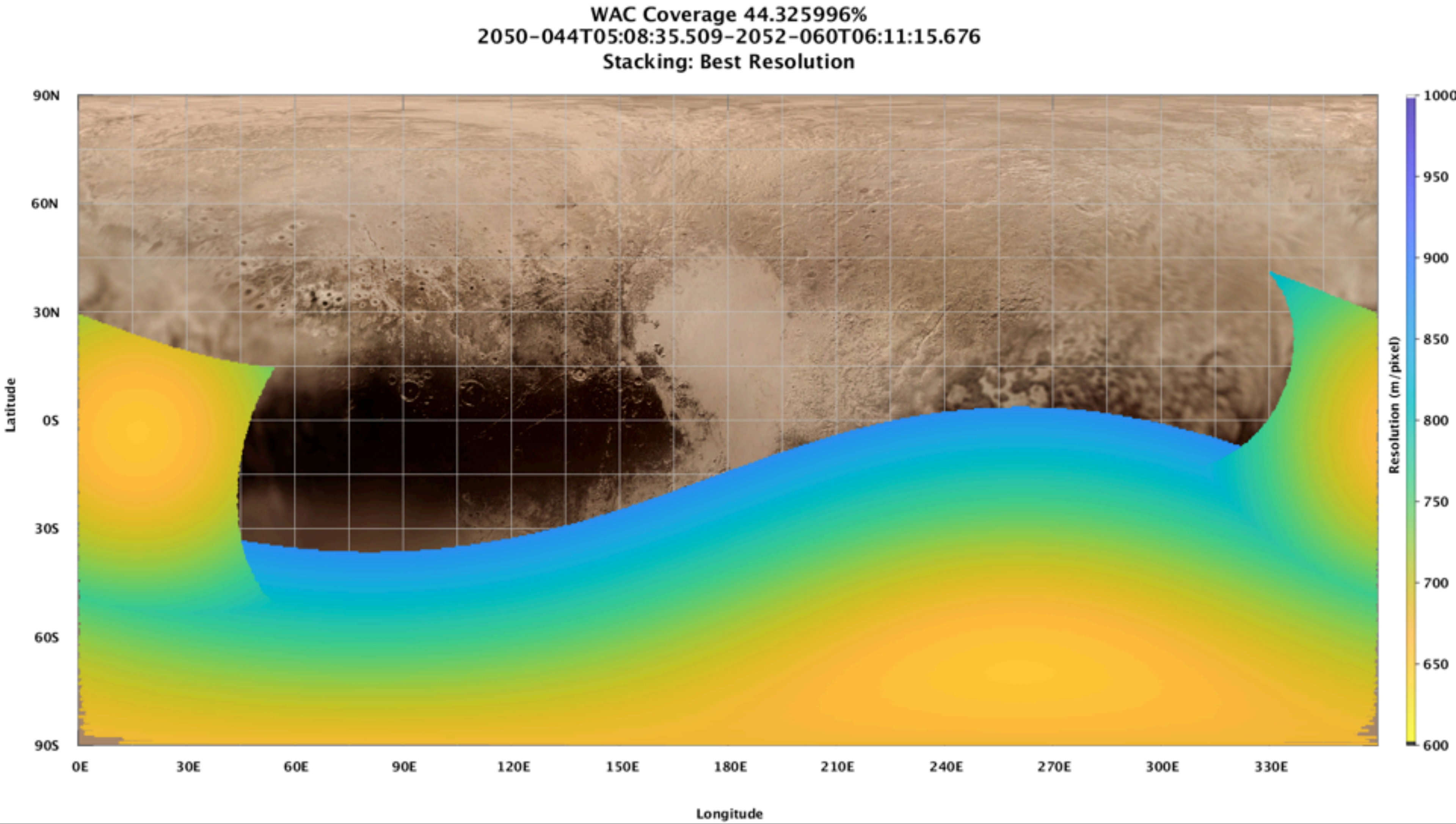
- Plot shows angles available over the entire mission: 4 tours, 11 total cycles.
- For most areas of Pluto, a wide variety of emission angles is available for stereo and phase-function measurements.



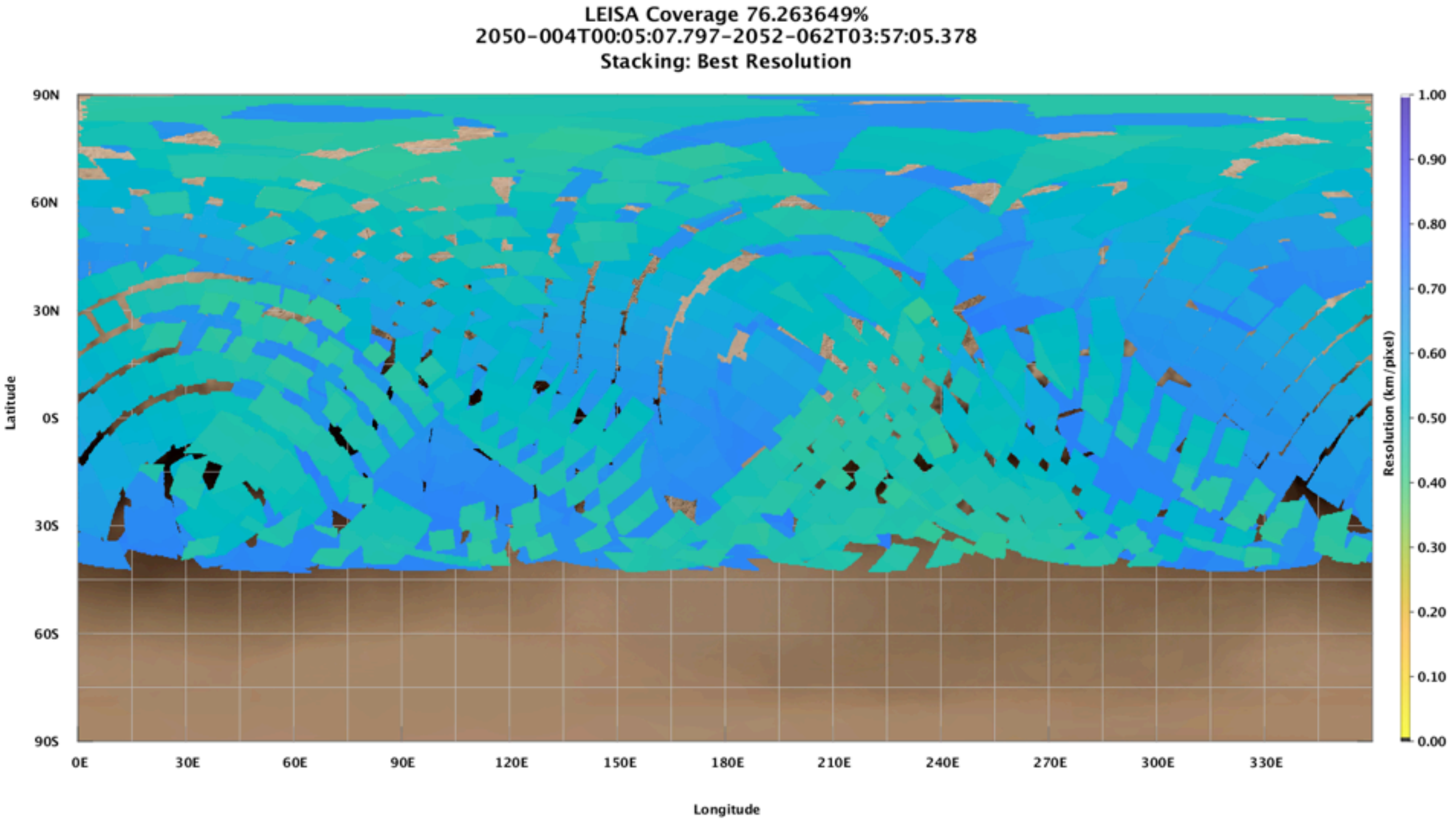




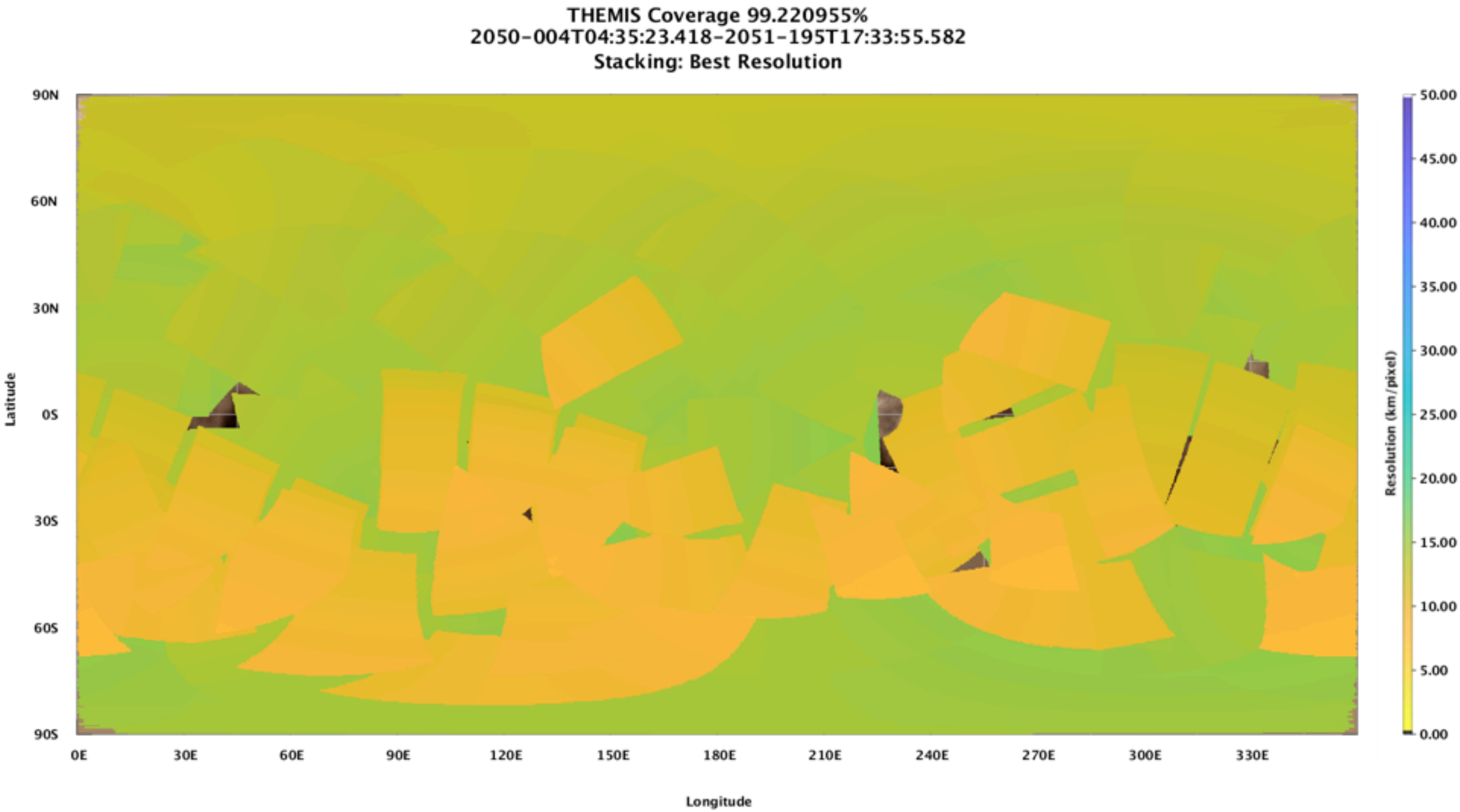
Pluto Surface Coverage: WAC



Pluto Surface Coverage: LEISA

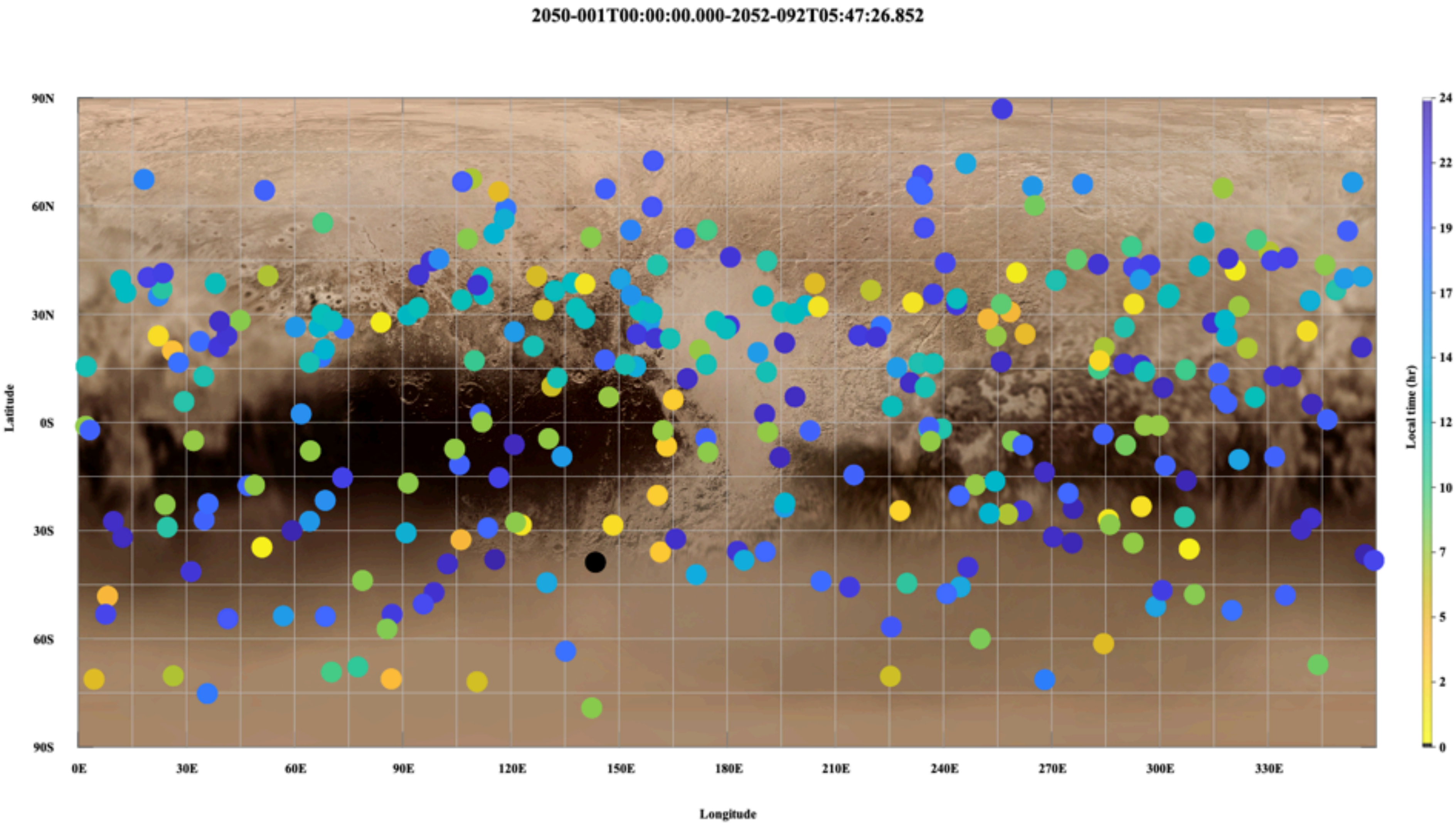


Pluto Surface Coverage: THEMIS



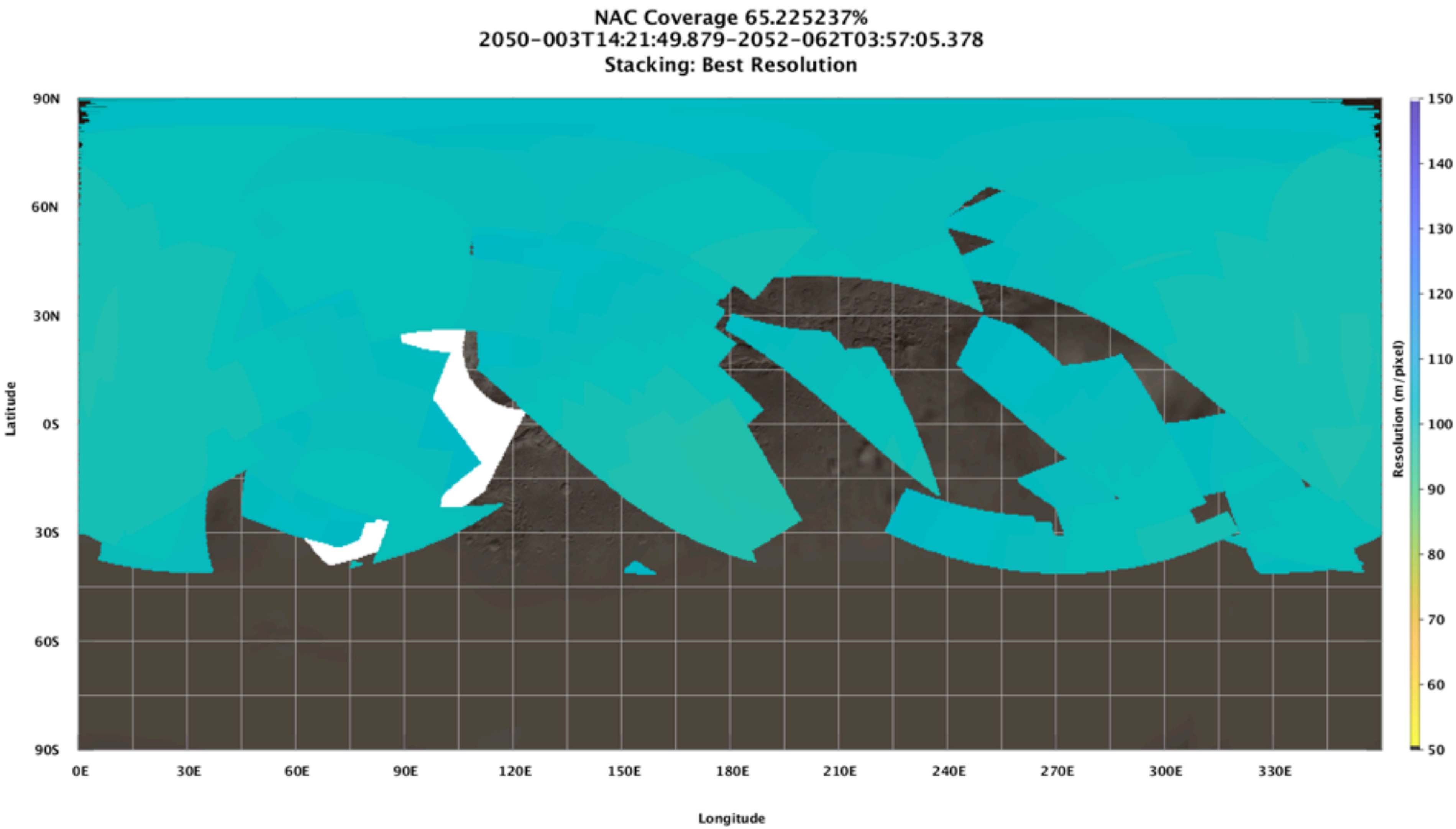
Pluto: Stellar Occultations

- These are the occultation locations for just ten of the hundreds of possible UV-bright stars.
- All locations and local times are sampled.

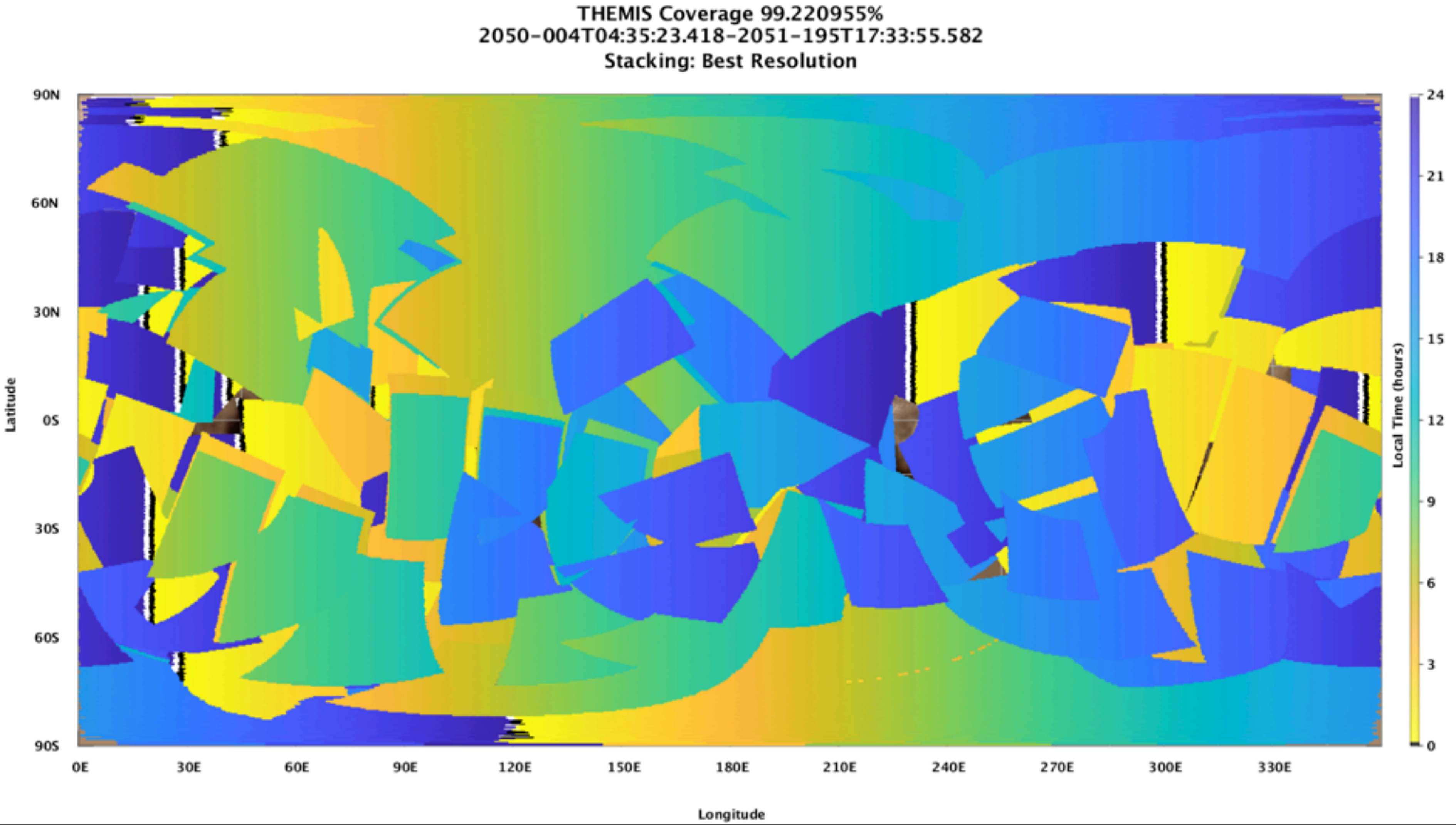


PERSEPHONE

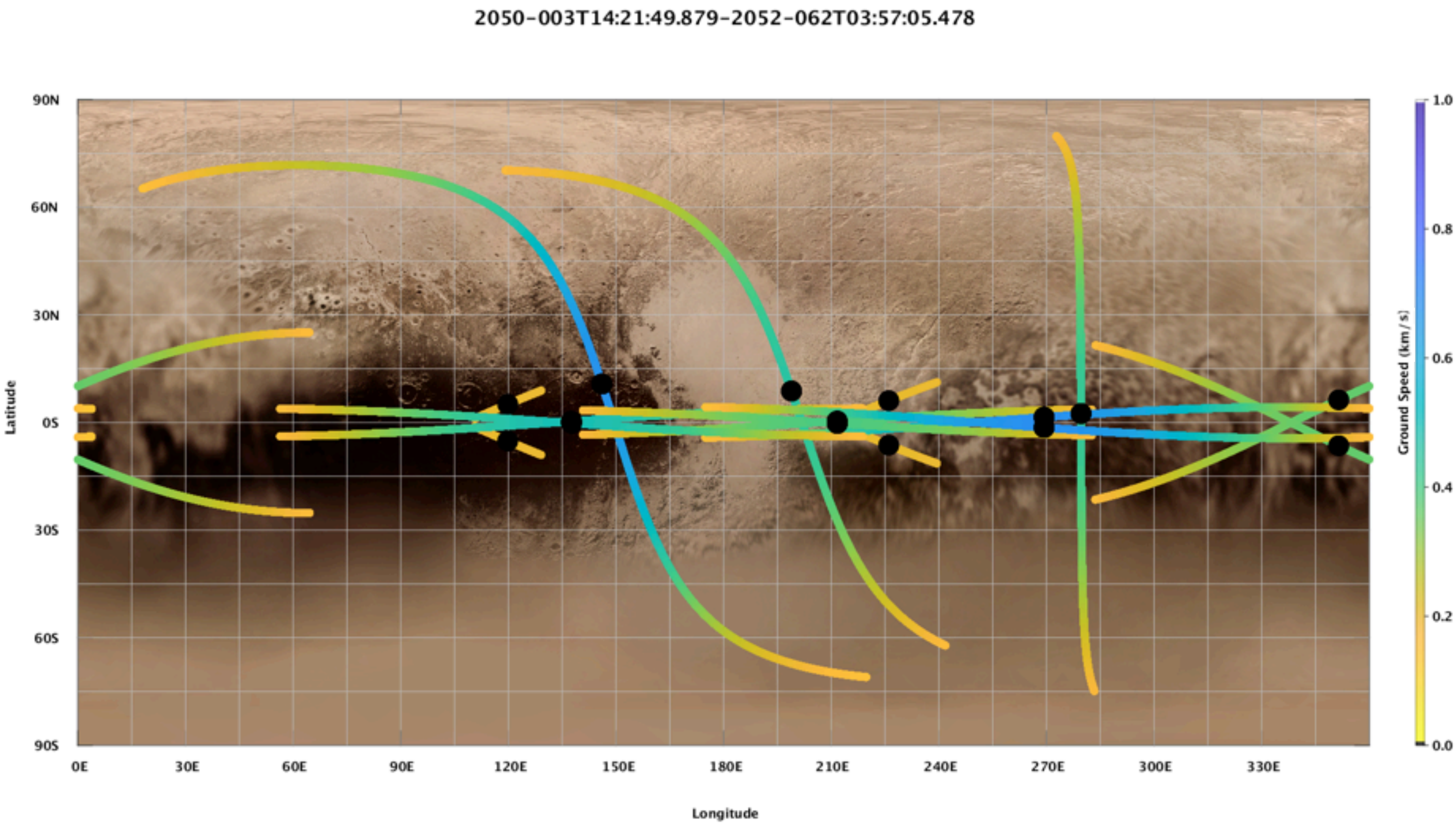
Charon Coverage: NAC (Panchromatic and Color)



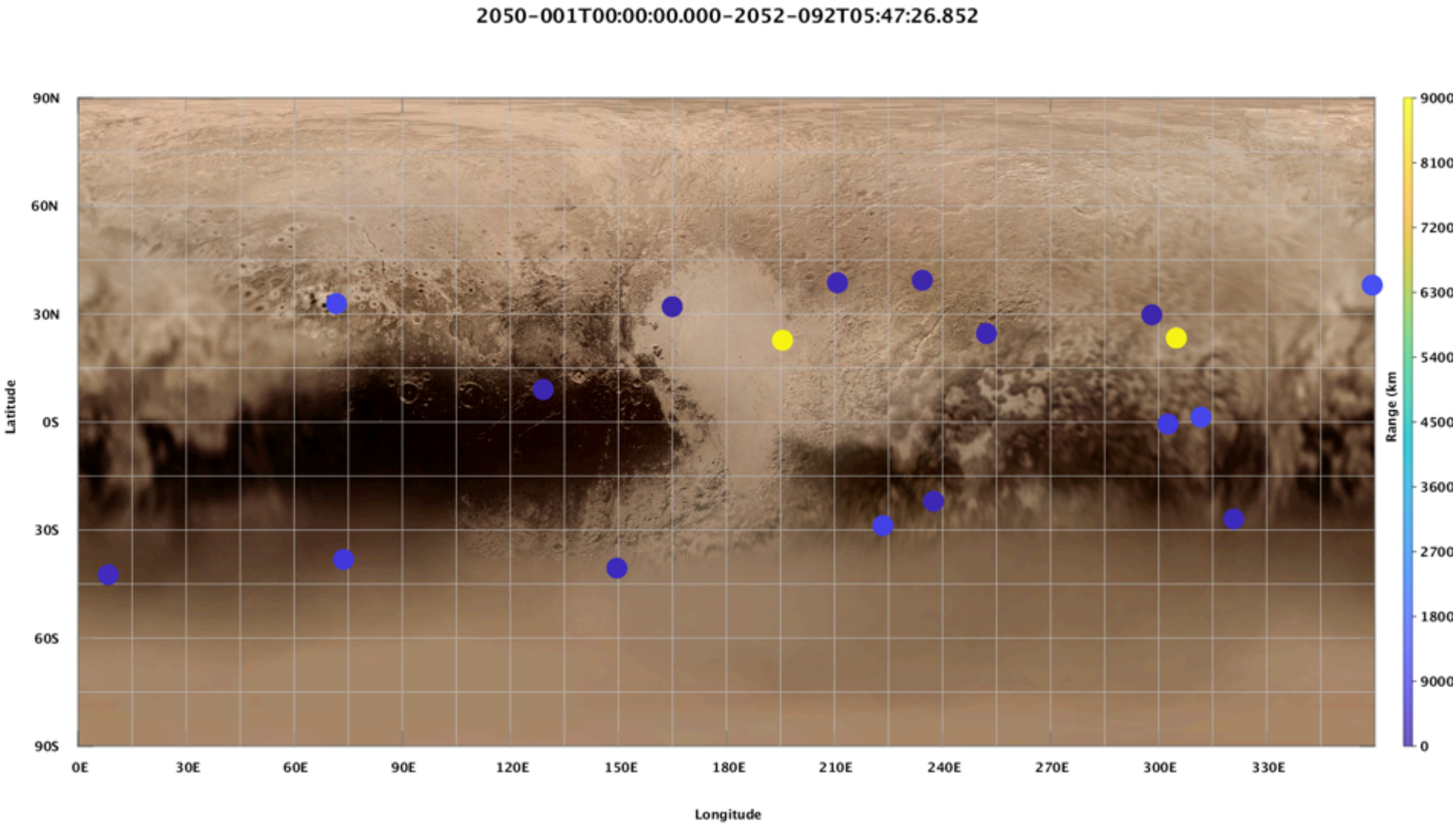
Pluto Surface Coverage: THEMIS (Local Time)



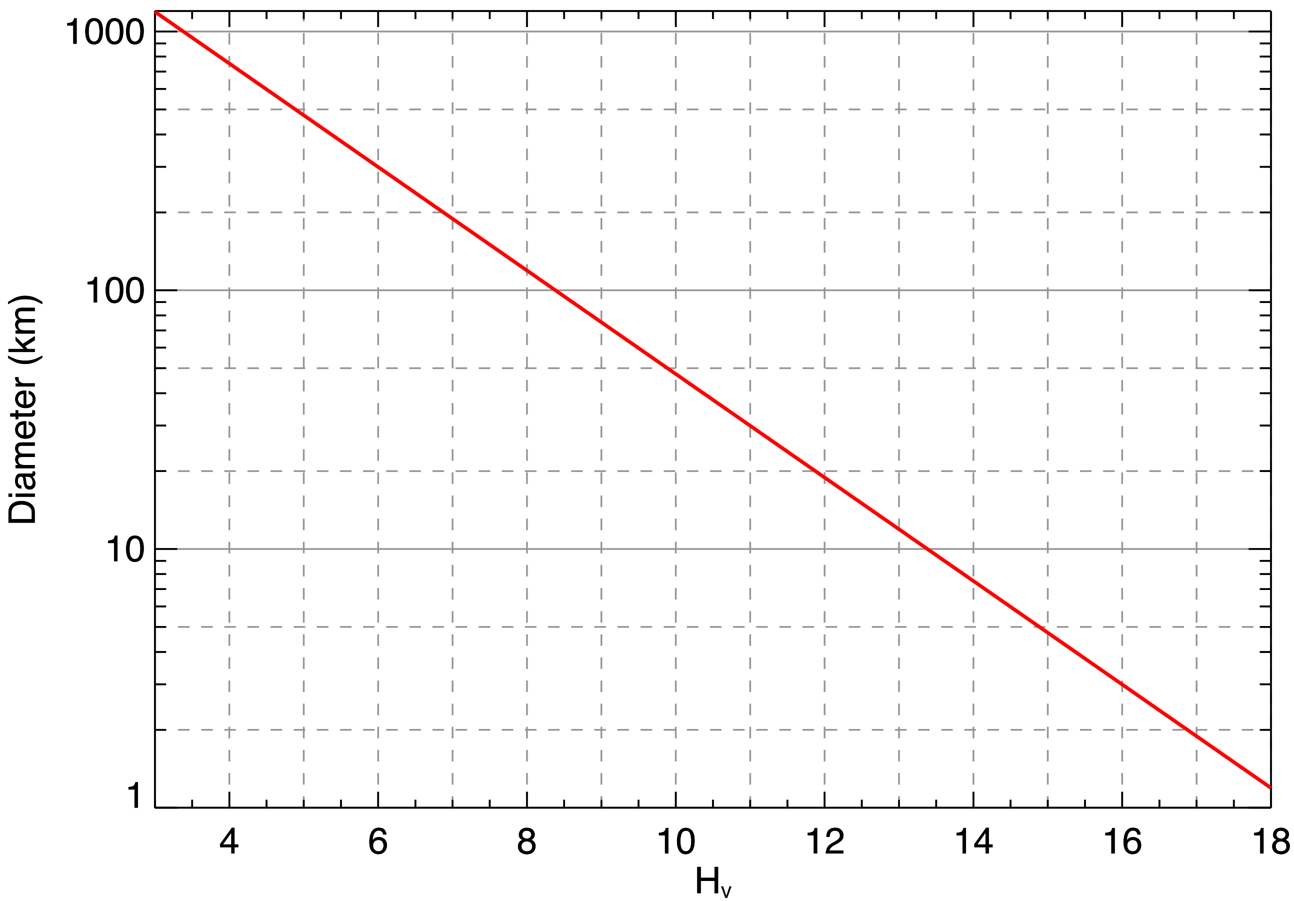
Pluto Ground Speed for Low-Altitude Encounters



Pluto: Earth & Solar Occulation Opportunities



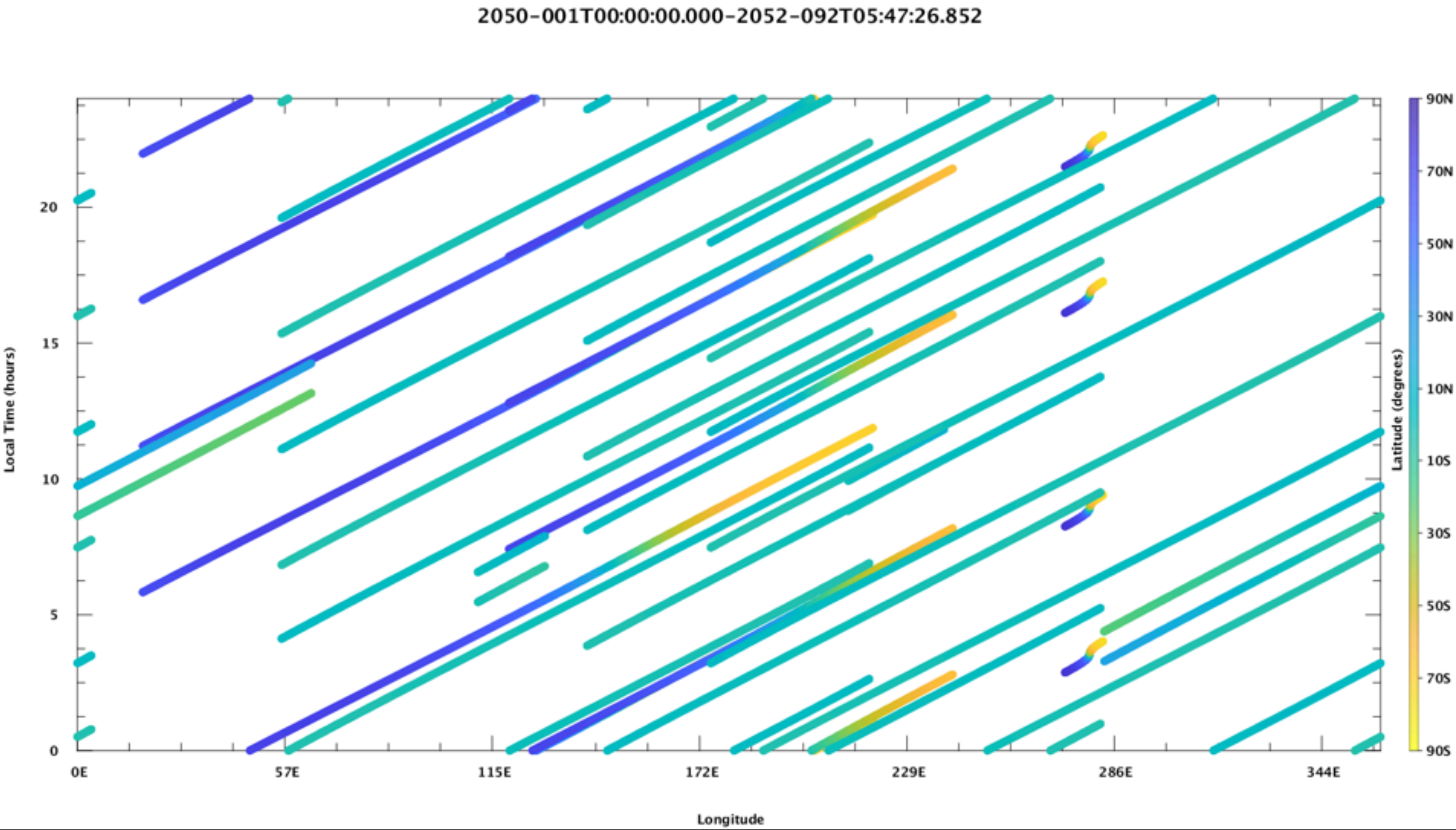
Diameter vs. H



Data Volume

Downlink Information	Pre-Pluto		Pluto/ Charon Operations	Extended Mission	
	Cruise	Cruise Hibernation		Post Pluto/ Charon Cruise	KBO Objects Operations
Number of Contacts per Week	3	1	7	1	7
Number of Weeks for Mission Phase, weeks	312	1144	104	416	52
Downlink Frequency Band, GHz	Ka-Band, 31.8-32.3				
Telemetry Data Rate(s), kbps	>28	>14	28*	12	12
Transmitting Antenna Type(s) and Gain(s), dBi	3 m, X/Ka-band Parabolic HGA X-band = 45.5; Ka-band = 57.0				
Transmitter peak power, Watts	Dual Band, 300				
Downlink Receiving Antenna Gain, dBi	34m Beam Waveguide (BWG), 78.7				
Transmitting Power Amplifier Output, Watts (RF)	150 Watts for Ka-Band, 12.5 Watts for X-Band				
Total Daily Data Volume, (MB/day)	806	403.2	806	345	345
Uplink Information					
Number of Uplinks per Day	3	0.25	7	0.1	7
Uplink Frequency Band, GHz	X-Band, 7.145-7.190				
Telecommand Data Rate, kbps	0.5	.25	.25	.25	.25
Receiving Antenna Type(s) and Gain(s), dBi	3 m, X-Band Parabolic HGA=44.7; 0.4m, X-band Parabolic MGA =27.2				

THEMIS – Local Time Coverage (Plot 2)



Key Trades

- Solar Electric Propulsion Stage: 25kW SEP Stage, dropped of at 6AU or Jupiter distance. SEP stage did not result in a decrease in Earth Jupiter Pluto transit time, due to added mass of the stage. Harder to slow down.
- DVEGA: Expands the launch vehicles options to available to mission. Increases the Earth-Jupiter-Pluto transit time by three years. Launch must occur by 2028 to arrive at Jupiter by 2031 for proper flyby phasing. No RTG's will be available at that time per Decadal Guidelines
- Launch Vehicles: Falcon Heavy, Falcon Heavy Expendable, SLS-Block 1, SLS-Block II. SLS-Block II has the shortest Earth Jupiter Transit Time and highest delivered mass.
- Upper Stages: Centaur, Castor30B. Centaur significantly increase delivered mass to Pluto/Charon system. Science goals could not be achieved without added mass.
- EP Systems: NEXT-C, Qinetiq T5, Busek BHT-600, XR-5, Apollo ACE Max—XR-5 is chosen because it has maximum thrust at minimum power
- Direct Earth Jupiter Pluto Transfer: has significantly shorter transit time and higher delivered mass when coupled with an upper stage
- Attitude Control During Cruise Phase (Three axis stabilized vs. spin stabilized): selected 3-axis stabilized to be compatible with engine gimbal system.

Key Trades - continued

- Periodic Orbit Pluto/Charon Tour: Considered several types periodic orbit designs. Periodic orbital design based on using Lagrange points transfers, provided the best ground track options to achieve science goals.
- Power Density: Both fission power system and RTG power systems were considered. RTG power was chosen to allow the Decadal report to be completed to CML-4. The cost size, weight, form factor, thermal requirements of fission sources is currently unknown, however would be a significant mission enabler. Could reduce Earth Pluto transit time by decade or more.
- RTG TID Radiation: Optical lens and instrument detector material types compatible with operational RTG environment. Separation of the RTG from the instruments payloads provides partial mitigation with further detailed analysis needed.
- Number of RTG's: Mass of Xenon continued to increase during the design phase due to the inefficiency of EP engines at lower power settings. Increasing the number of RTG's to five allowed more efficient operations of the EP engine and decreasing Earth Jupiter Pluto Transit time.
- Number of Reaction Wheels: Reliability analysis concluded that a 5-for-3 redundant design would increase mission reliability. Further analysis will be required to support the extended mission.

Key Trades for Further Consider and Analysis

- The thermal output from the RTG could impact instruments, but these effects could be mitigated.
- Certain sensitive instruments (e.g. IR spectrometers, thermal spectrometer, and other instruments requiring cooling) would need to be pointed away from the RTG end of the spacecraft and shaded.
- Instrument radiators would need to be shielded from view of the power system radiators.
- Optics might require blanketing or shielding to avoid distortion arising from differential heating.
- The radiated power and number of RTG's would also add to complexity of the launch configuration.
- Integrating a larger number of RTG units at the launch site is somewhat limited by several factors; a reasonable number of launch vehicle fairing access doors, workable flooring access is not readily available around the entire vehicle at the integration facility.

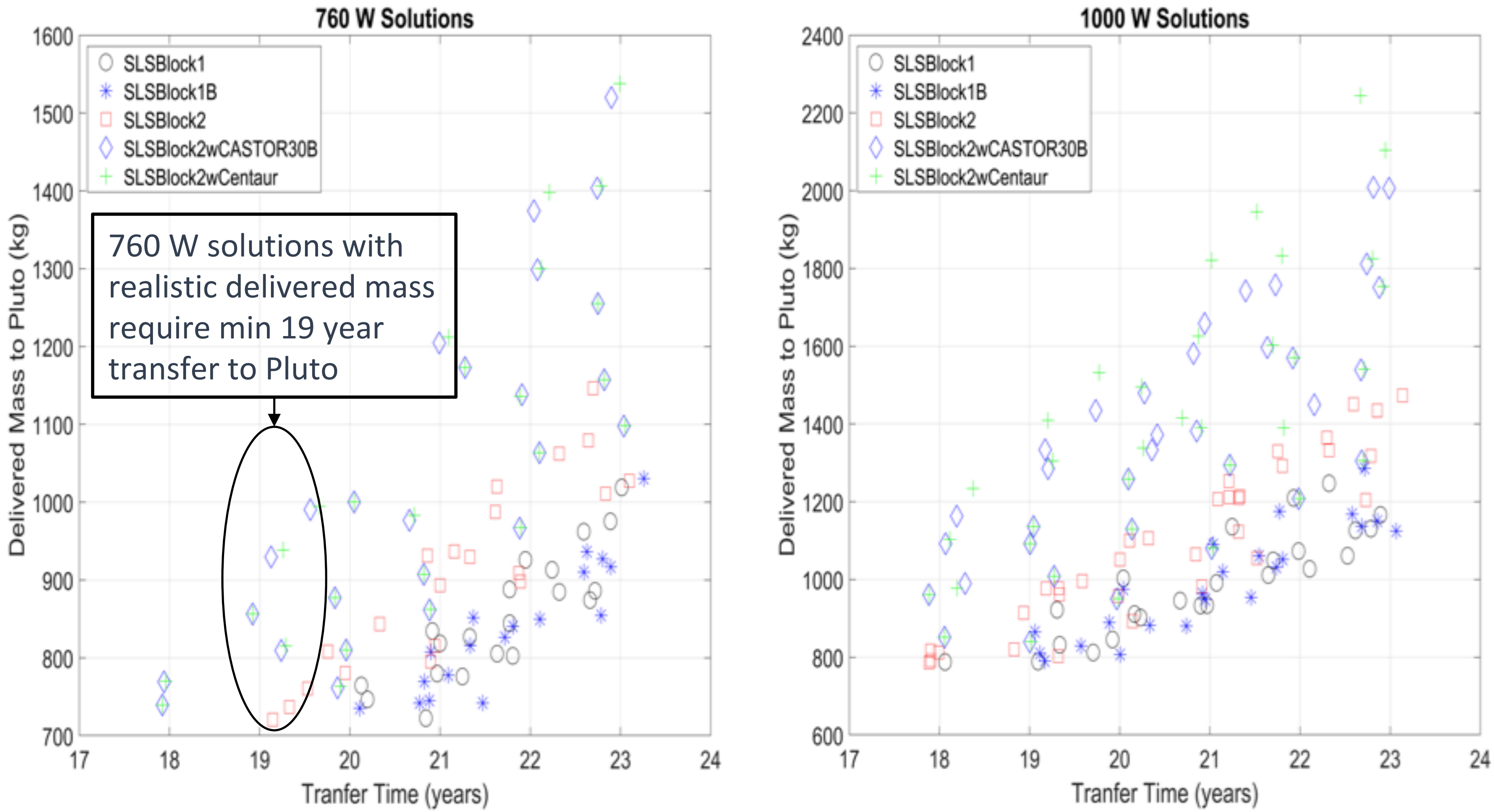
Concept Maturity Level

Upon completion of the Pluto Orbiter and KBO Tour Decadal Survey, with point designs in place, the concept is at CML 4. The architectures studied were defined at the subsystem level with estimates developed for mass, power, data volume, link rate, and cost using APL's institutionally endorsed design and cost tools. Risks were also identified and assessed as to their likelihood and mission impact, as discussed.

Concept Maturity Level Definitions

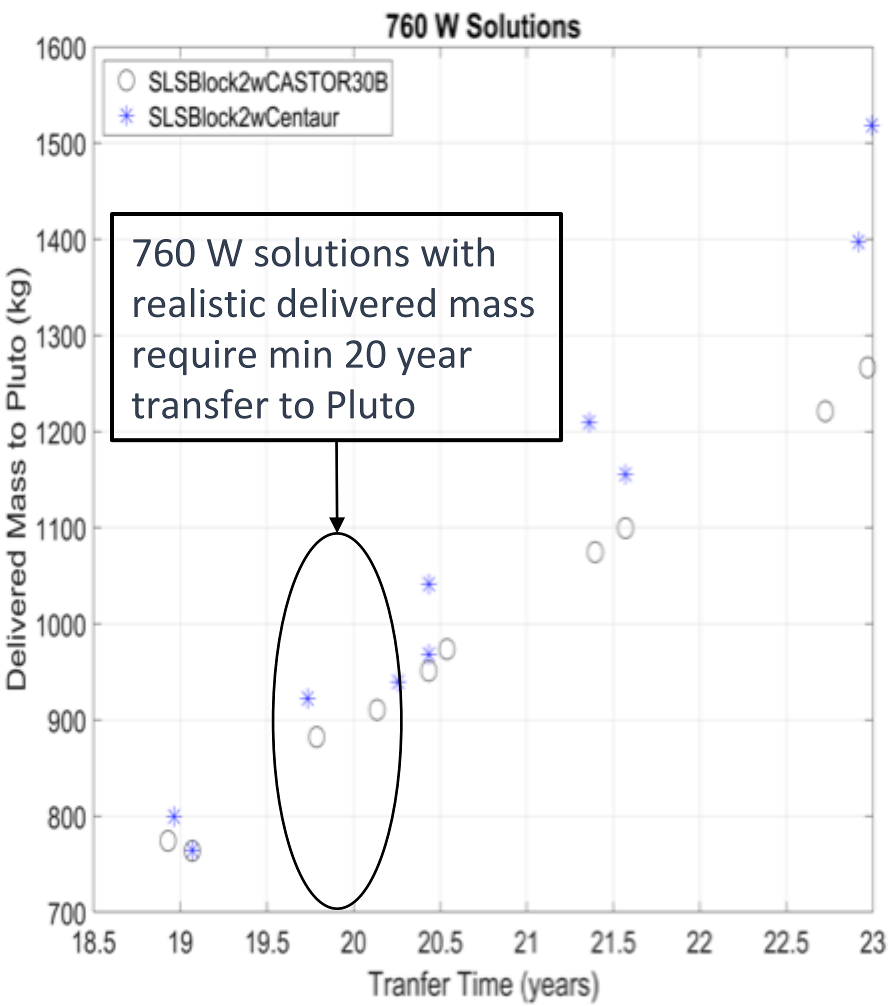
Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, 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

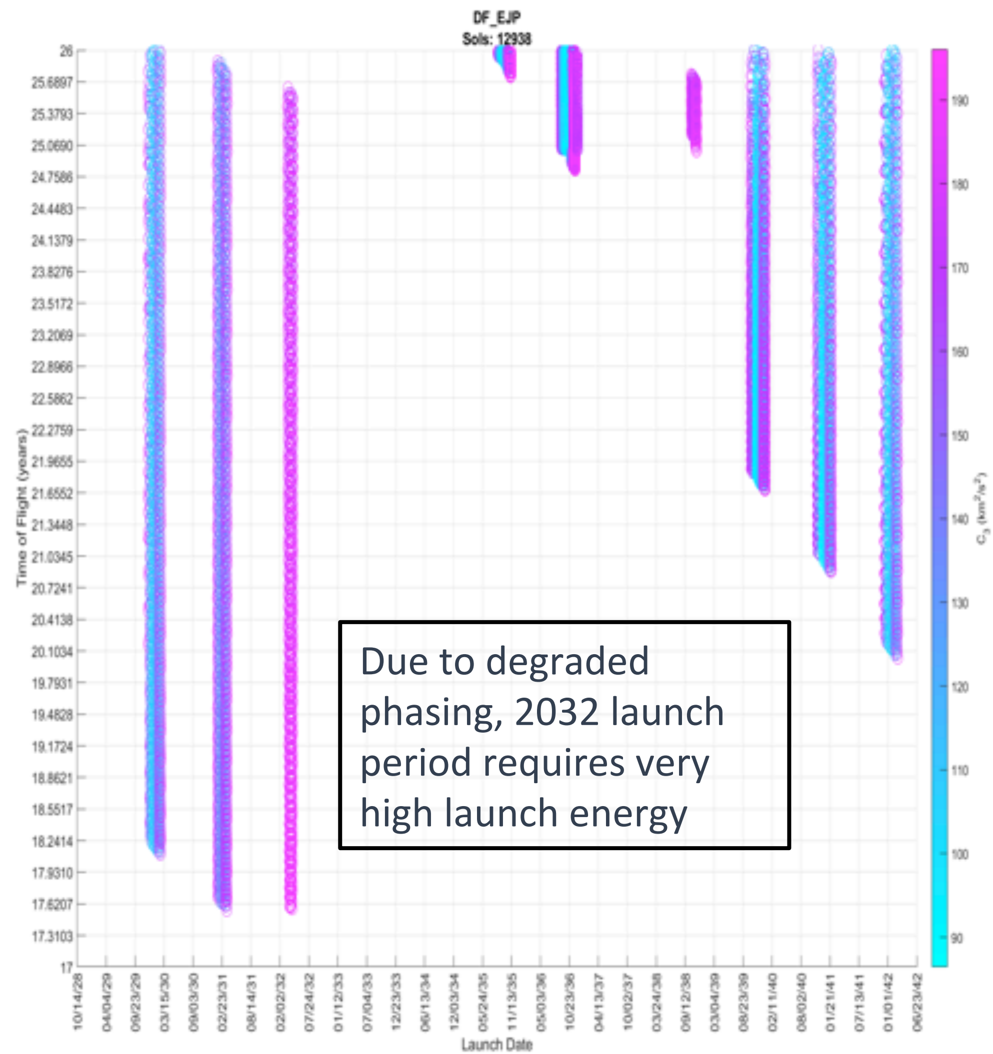
2031 Launch-Jupiter-Pluto Transfer



Strong correlation between delivered mass and transfer time to Pluto
Delivered mass = Launch mass minus Xe propellant used through Pluto rendezvous

2032 Launch-Jupiter-Pluto Transfer





Launch-Earth-Jupiter-Pluto Transfer

- DVEGA (DV + Earth gravity assist) options will prepend 3 years to direct to Jupiter transfers
  - Launch energy caps out at ~60 km^2/s^2
    - *Enables launching on Falcon Heavy Expendable (current NASA rocket offering using real performance data)*
  - Optimal phasing ends is early 2028
    - *2029 launch period linking to 2032 direct transfer has too demanding launch energy*
  - DVEGA transfers offer launch periods separated by ~3 months. For a prime and backup pair:
    - *Prime launch period can occur in early 2028 with 3 month gap*

- 760 W solutions with realistic delivered mass require min 22 year transfer to Pluto