NOSTROMO

Neptune Orbital Survey and TRitOn MissiOn

Final Presentation

esa

nostromo
Team RED
Summer School Alpbach 2024

Team RED

Alpbach Summer School 2024

Agenda

Science	Mission Design	System Design	Project Envelope
Mission Statement Science Case Mission Objectives Key Science and Mission Requirements Key Mission Drivers Measurement Principle Instrumentation Observation Strategy	Mission Overview System Drivers Launcher & Transfer Mission Tradespaces Target Orbit Final Configuration	Spacecraft Concept Subsystems Overview Mission Operations Ground Segment Critical Technology	Schedule Critical Risks Descoping Options Cost Outreach

Agenda

Science | Mission Design | System Design | Project Envelope

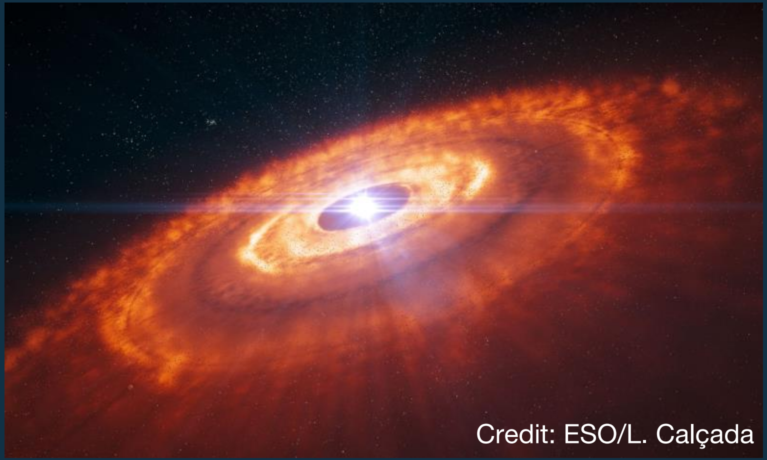
Mission Statement
Science Case
Mission Objectives
Key Science and Mission Requirements
Key Mission Drivers
Measurement Principle
Instrumentation
Observation Strategy

Mission Statement

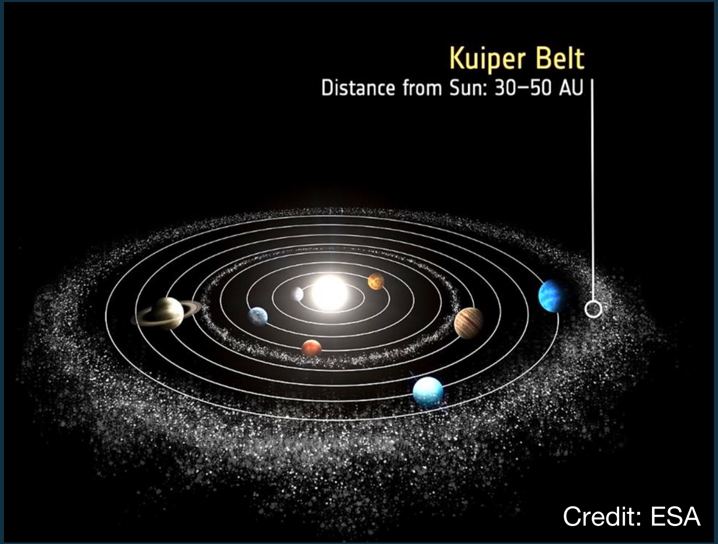
"Study Neptune and its moon Triton to better understand planetary system formation and habitability."

Credit: The Johns Hopkins University Applied Physics Laboratory

Planetary System formation



Star forms with circumstellar disk



Planets form and accrete material

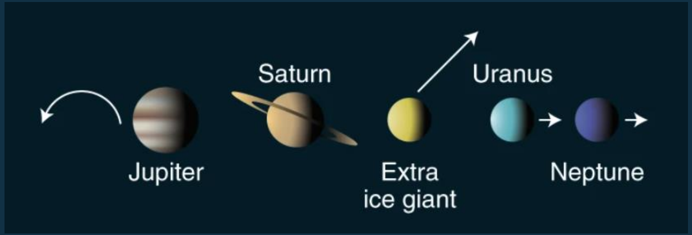
Planetary System formation

Many unknowns remain:

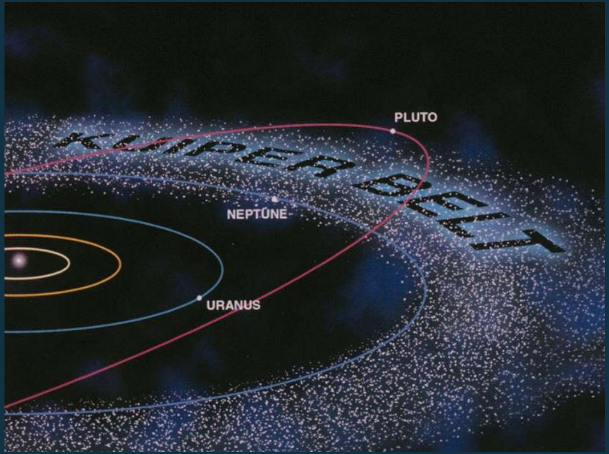
1. Role of giant planet migration
2. Formation of distant regions like the Kuiper Belt

Can be resolved by studying:

1. **Neptune**
2. **Triton**

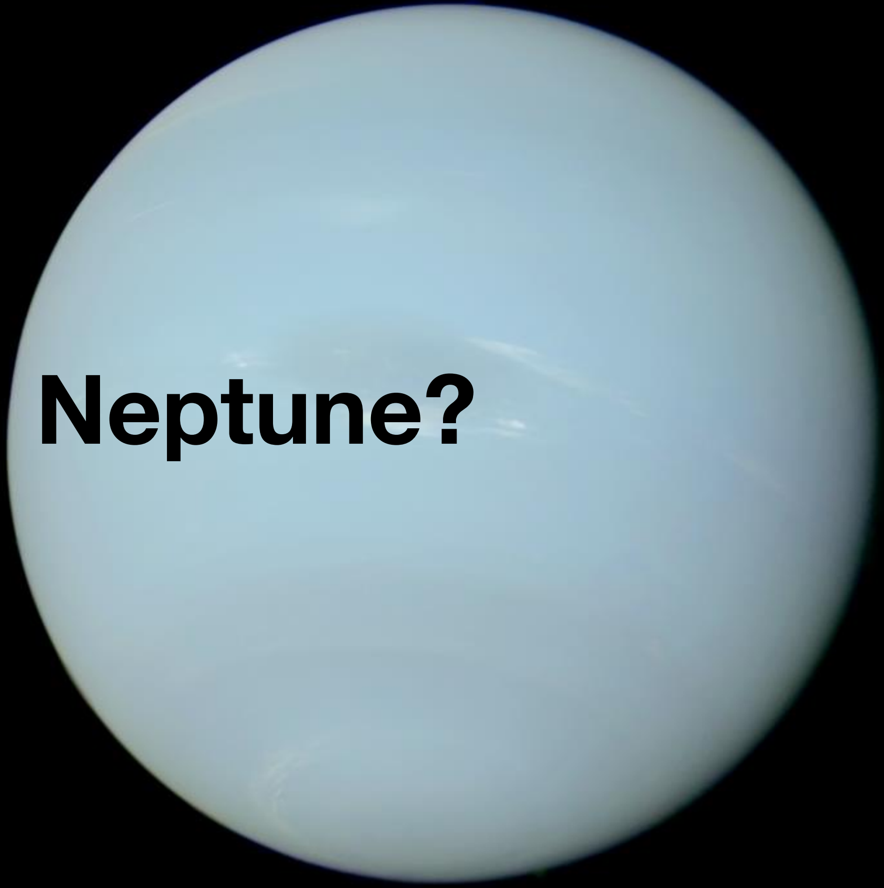


Source: Pike, R. et al. (2018)



Credit: Space Center Houston

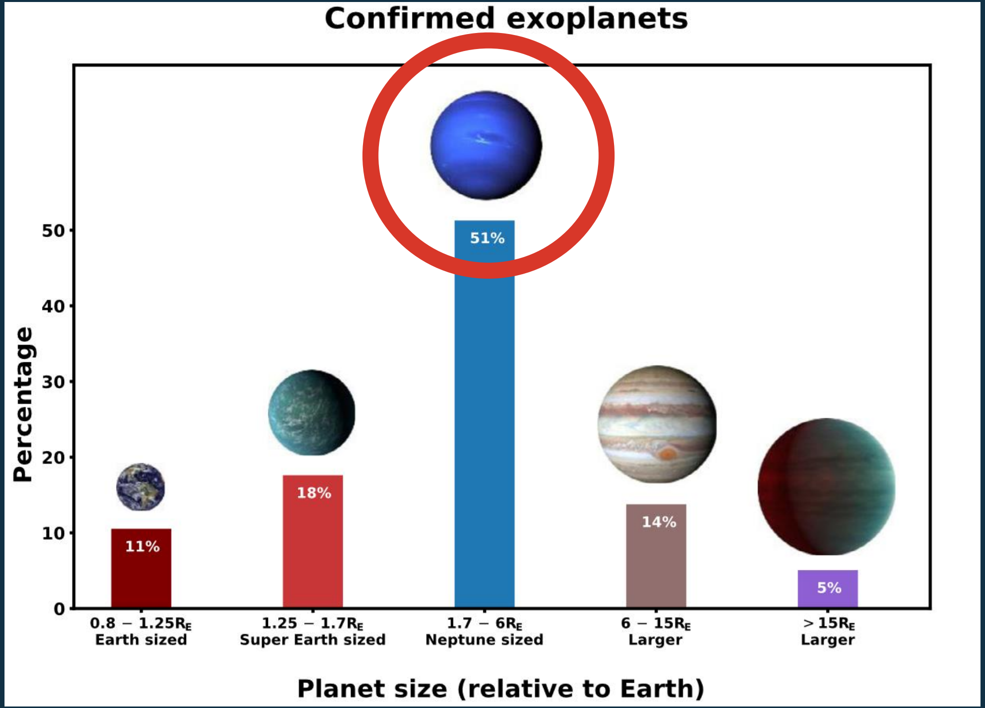
Why Neptune?



Credit: NASA / Voyager 2

Neptune as an exoplanet

- Exoplanet systems: probe planetary system evolution stages
- Benchmark for exoplanet studies
- Neptune is poorly understood



Source: Atreya et al. 2020

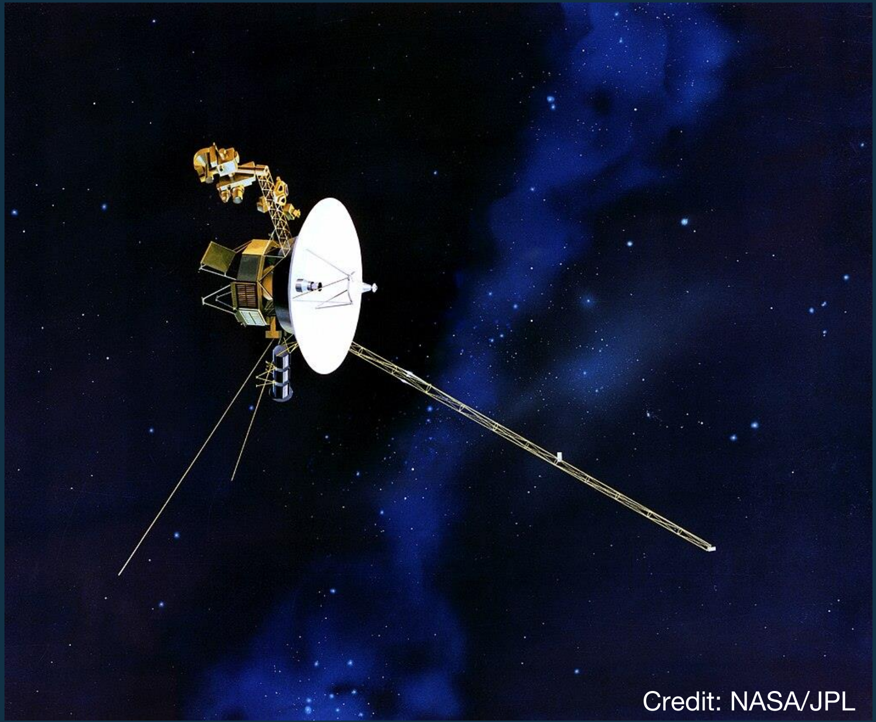
Previous research

Earth/Space-based observations

- Basic understanding of Neptune
- Discovery of Triton

Space missions

- Voyager 2 (1989 flyby)



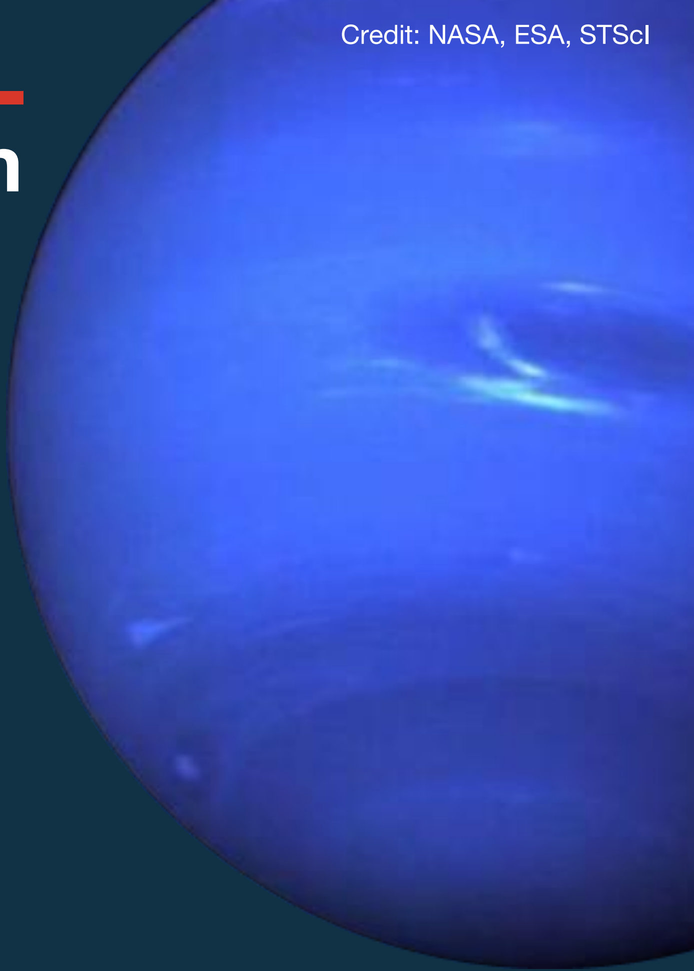
Credit: NASA/JPL

Neptune as a weather system

- Thick **hydrogen, helium, methane** & trace elements atmosphere

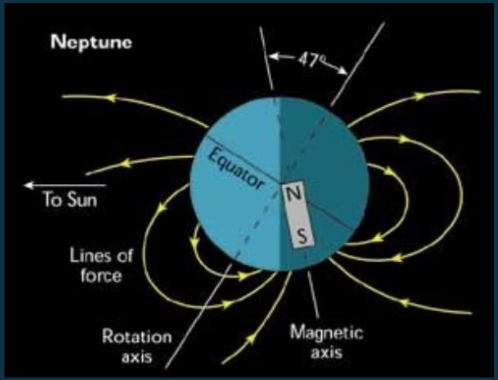
- Strong **storms and lightning** observed

- **Most meteorologically active** atmosphere in the Solar system

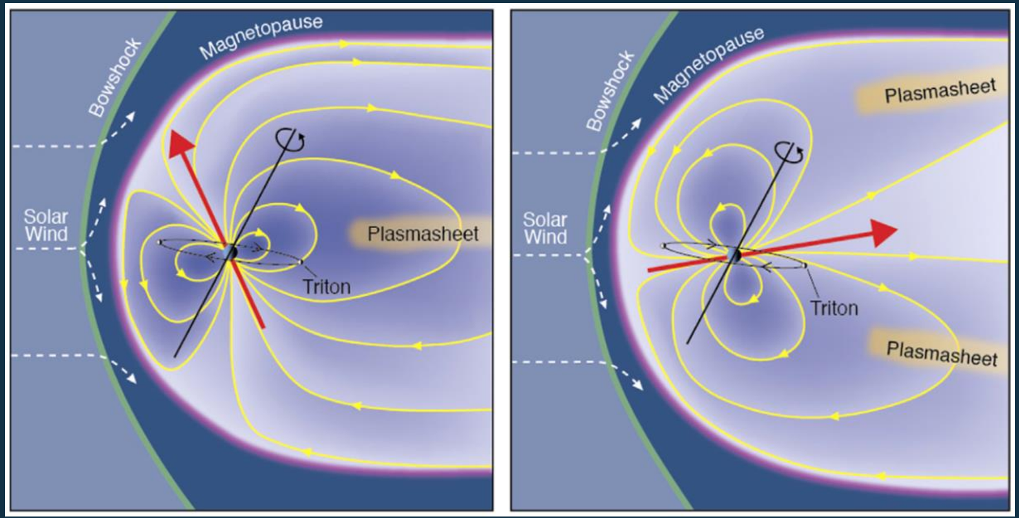

Credit: NASA, ESA, STScI

Neptune as a magnetospheric laboratory

- Unclear origin of the highly **axially-tilted**, **offset**, **multipolar** magnetic field
- **Highly dynamic** magnetosphere
- UV to IR **auroral** emissions



Credit: NASA



Credit: Fran Bagenal & Steve Bartlett

Neptune as a (common?) ice giant

- Uranus likely experienced **major collision**
- Internal structure of Neptune likely **less-altered** compared to Uranus

Best proxy for ice giants!

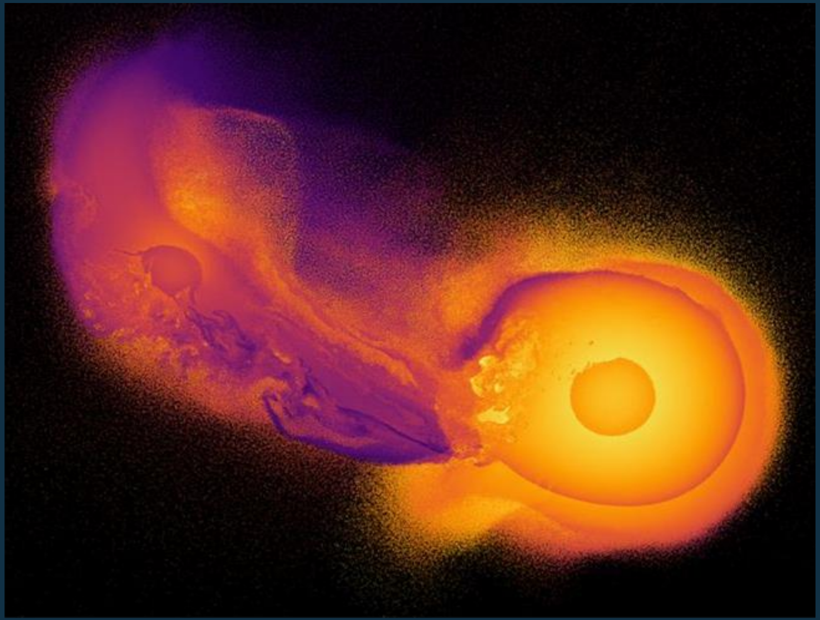


Image credit: Jacob Kegerreis, Durham University

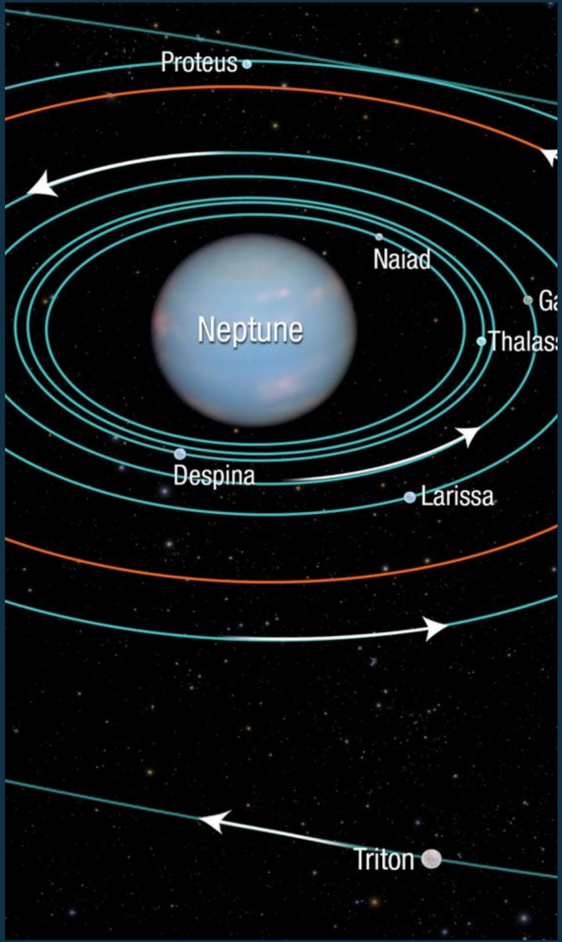
Why Triton?

Credit: NASA / Voyager 2

Triton as a captured Kuiper Belt Object[1] (KBO)

- Triton: **Retrograde** orbit
- Kuiper Belt: region with **pristine material**

Unique opportunity to study a KBO



Credit: NASA

[1] Source: Agnor and Hamilton, 2006, 10.1038/nature04792

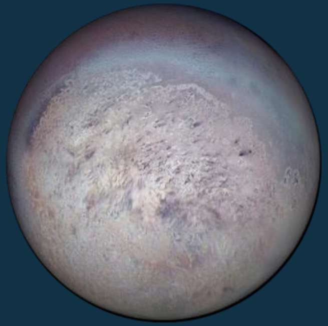
Triton as a more evolved KBO

- Likely internally **differentiated**
- **Bridge** between primitive and evolved bodies

Undifferentiated KBO

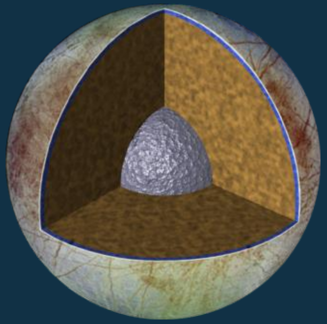
Credit: NASA

Triton



Credit: NASA/JPL

Europa

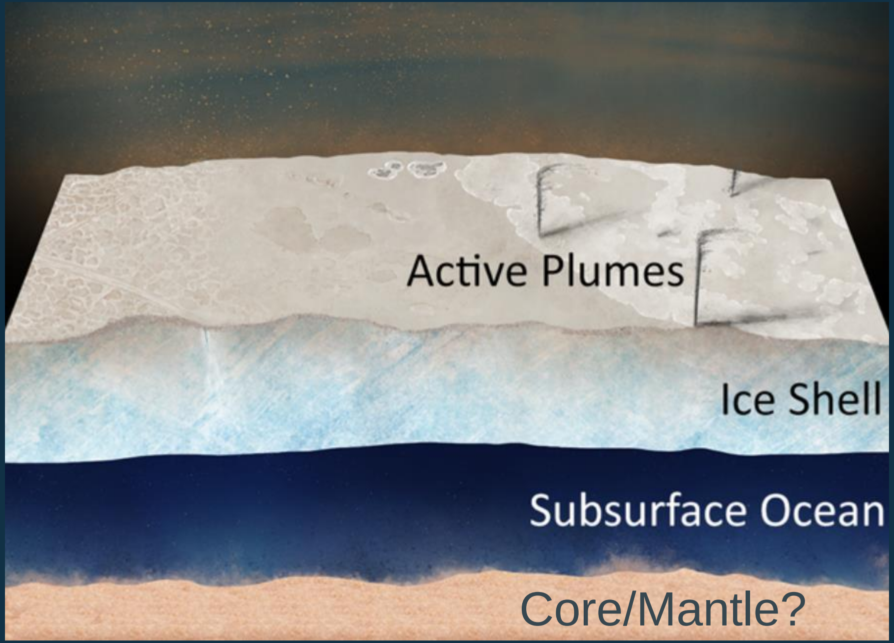


Credit: NASA/JPL

Less evolved ➡ **More evolved**

Triton as a possible habitable object

- Potential **subsurface ocean**
- **Plume** activity
  - **Dark** plume deposits
  - Possibly rich in **complex organic compounds**



Credit: NASA/JPL-Caltech

Previous proposal

Neptune Odyssey

- Orbiter & Probe
  (NASA planetary science & astrobiology Decadal Study, 2023-32)
- Not selected due to **lack of available trajectories** in that time frame

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- **Less-restricted** launch window
- **Reduced complexity**

Objective 1

Investigate the **origin** and **evolution** processes of **Neptune** as a proxy for exoplanets to advance planetary system evolution theories

Sub-objectives:

1. Study the **interior structure**.
2. Characterise the composition and dynamics of **atmosphere**.
3. Characterise the **magnetospheric** environment.

Objective 2

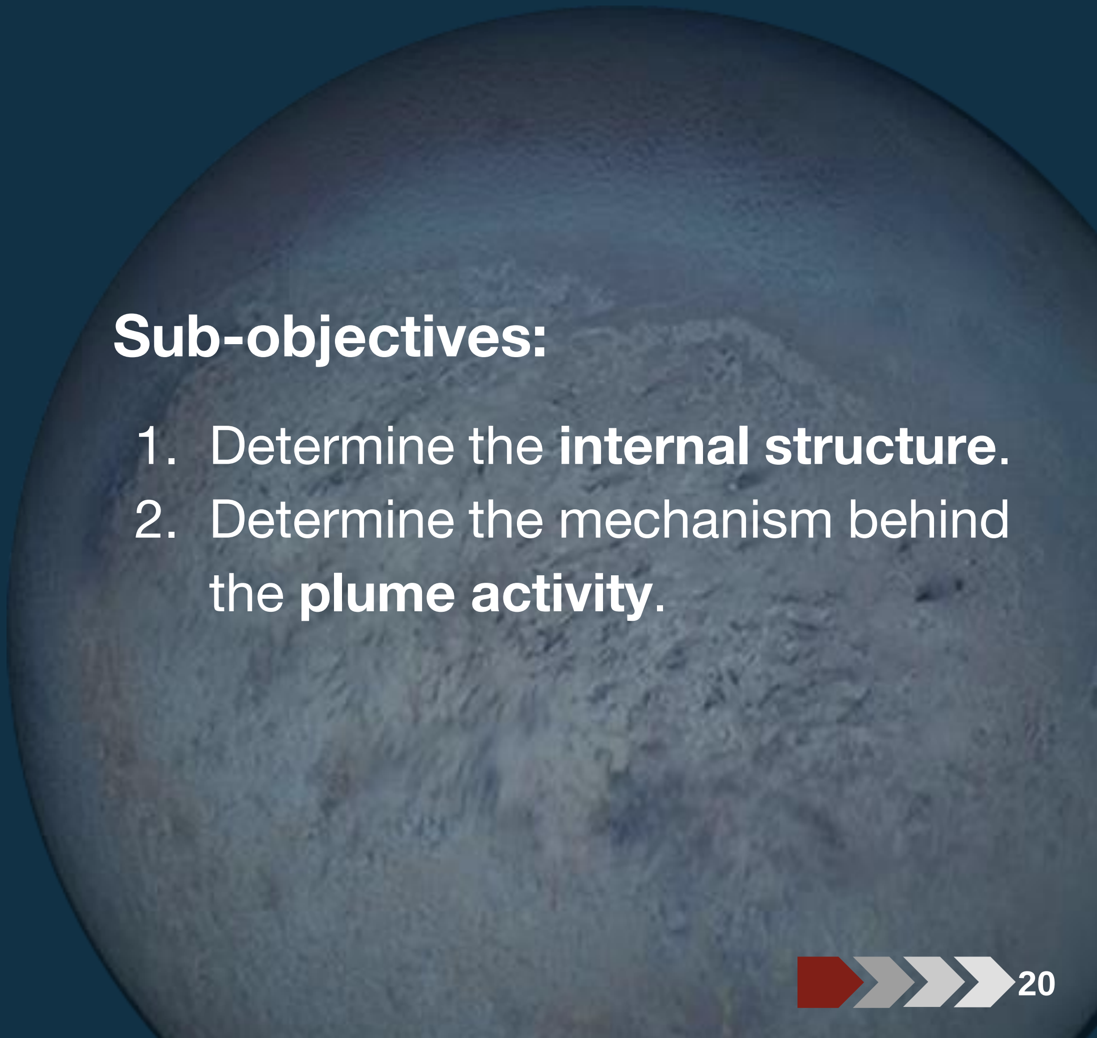
Understand the **formation** and **evolution** of **Triton** as a key to understanding the formation of our Solar system

Sub-objectives:

1. Determine the **surface properties**.
2. Characterisation of the **atmosphere**.
3. Understand the **interactions** between Triton and Neptune.

Objective 3

Investigate if **Triton** is a **habitable environment** and how it compares with other possible habitable environments



Sub-objectives:

1. Determine the **internal structure**.
2. Determine the mechanism behind the **plume activity**.

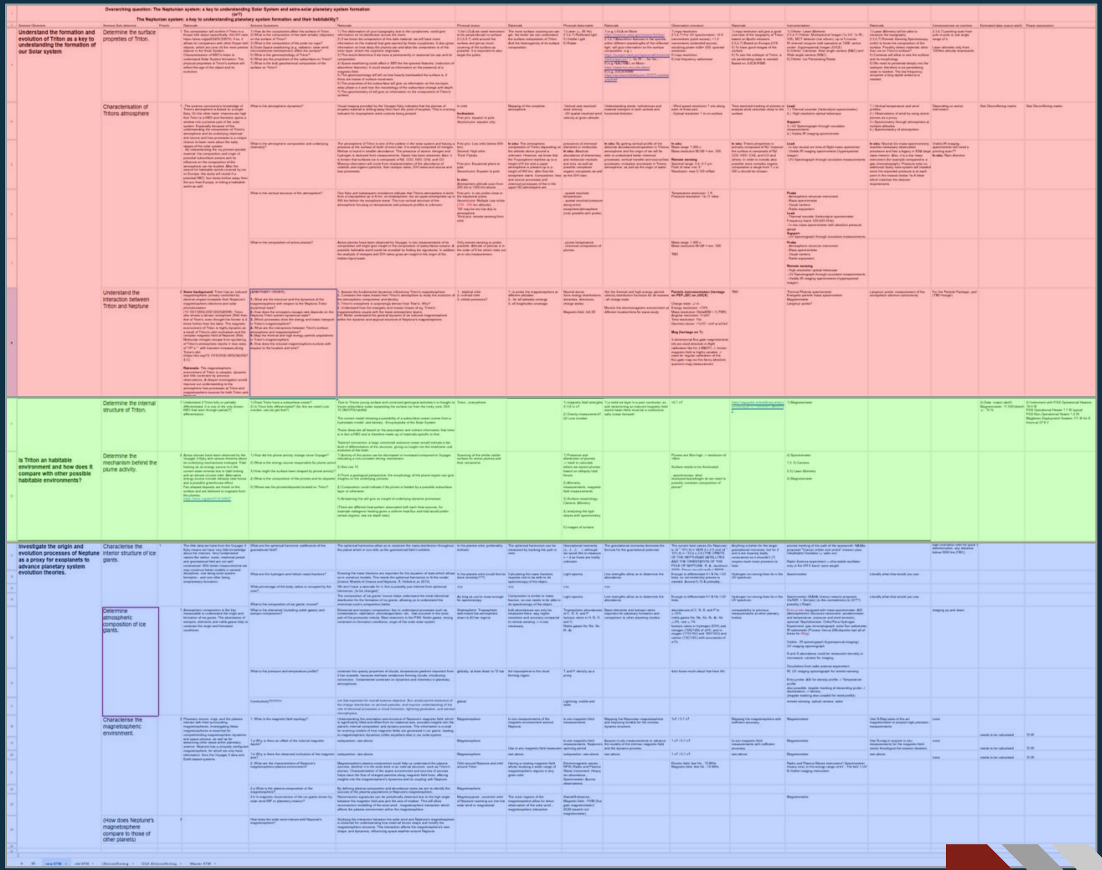
Science Traceability Matrix

- 3 main science objectives

  SO1 SO2 SO3

- More than 24 science questions

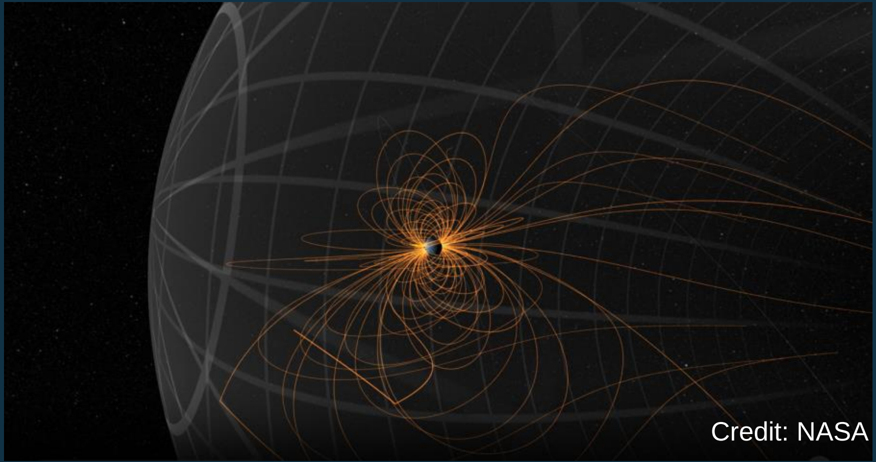
Objs	Sub-Objs	Sci. questions	Physical regions/observables	Precision & instrumentation



SO1.3: Characterise the magnetic environment of Neptune

SO1.3.1: What is the topology of the magnetic field?

- **Measurable**: time-resolved magnetic field of Neptune



- **Measurement requirements:**
  The magnetic fields of Neptune shall be measured:
  - along **3** perpendicular **axes**
  - with an accuracy of **0.1 nT**
  - with a frequency of **1 Hz**
  - during the mission lifetime

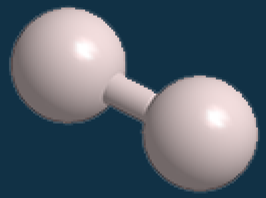
- **Instrument requirements:**
  Instrument needed: **a dual sensor fluxgate configuration combined with a scalar sensor**
  The magnetometer shall have a:
  - measurement range of **±50’000 nT**
  - measurement accuracy better than **0.1 nT**
  - minimum measurement frequency of **1 Hz**

SO2.2: Characterisation of Triton's atmosphere

SO2.2.2: What is the atmospheric composition and underlying chemistry (incl. source/loss and ionisation processes)?

- **Measurable**: Absolute abundance of elementary and molecular neutrals and ions, possible more complex organic compositions and the D/H ratio.

- **Measurement requirements:**
  In-situ measurements shall:
  - detect neutrals and ions in the mass range **1** to **300 amu**
  - have mass resolution **$M/\Delta M \geqq 500$**
  - be performed in the range from **200** to **1000 km** altitude



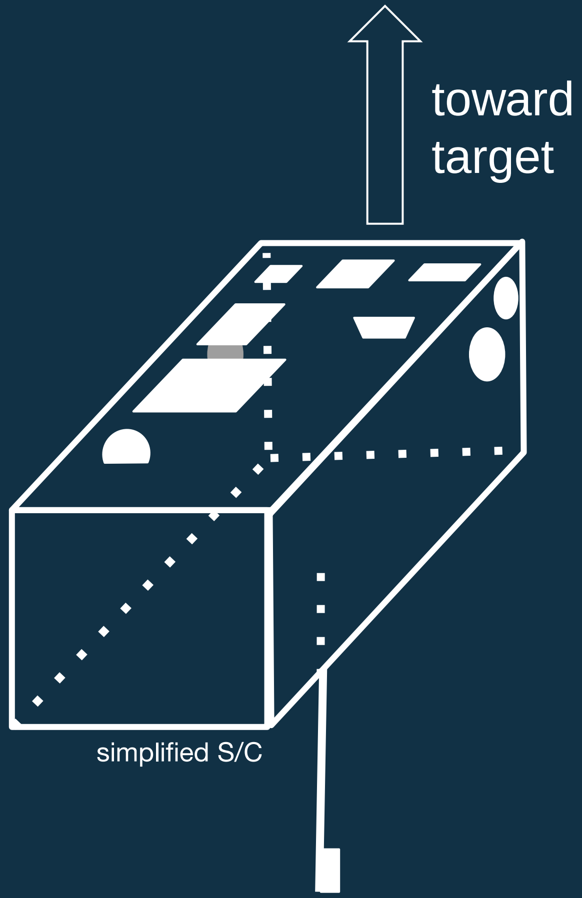
- **Instrument requirements:**
  Instrument needed: **Time-of-flight neutral and ion mass spectrometer**
  The mass spectrometer shall:
  - take a spectra at least every **25 s** in Triton’s orbit
  - have two top-level modes: ion detection, neutral particle detection
  - be able to operate at an ambient pressure of **5×10^{-5} mbar** or lower

Mission Drivers

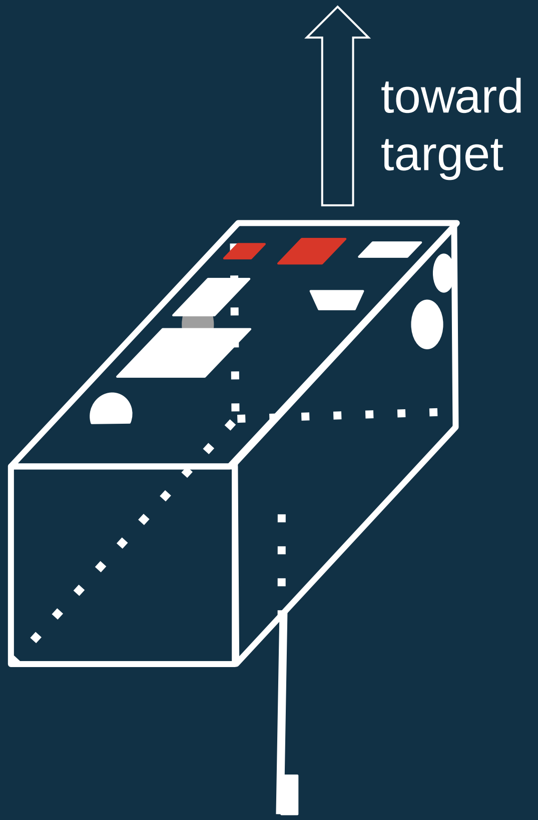
- **Mapping of Triton's surface to study the dark plume deposits**
  High inclination orbit around Triton to map the whole surface
- **Composition mapping of the atmospheres of Neptune and Triton**
  Distance smaller than 4000 km from Neptune and 900 km from Triton
- **Sample ions and electrons in different regions of Neptune's magnetosphere**
  Orbits with different apoapsis
- **Measuring the magnetic field of Neptune**
  Requires observation time of at least 180 hours

Instrument Suite

1. Optical Cameras
2. Mass Spectrometer + Pressure Gauge
3. VIS - IR Spectrometer
4. UV Spectrometer
5. Magnetometer
6. In-situ Particle Environment Package
7. Radio Science
8. Laser Altimeter



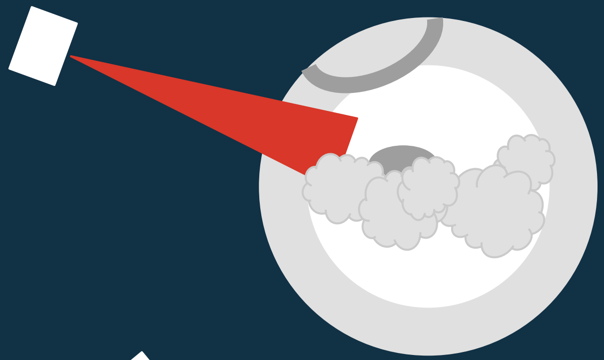
1. Optical Cameras



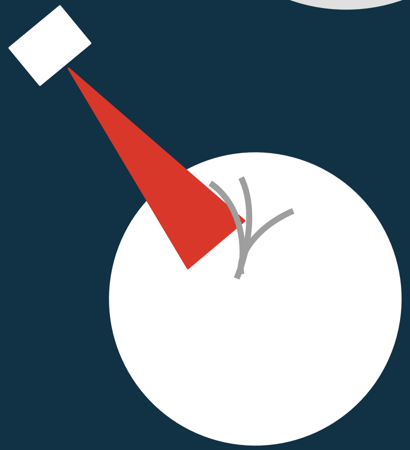
1. Optical Cameras

- Wide Angle Camera (WAC) and Narrow Angle Camera (NAC)
- Remote imaging of:
    - **cloud** structures, **dark spots and lightning**
    - **aurora** on Neptune
    - Triton’s surface: geological **structures**
    - **plume** morphology and spatial distribution

- Possible detection and imaging of other Neptunian moons



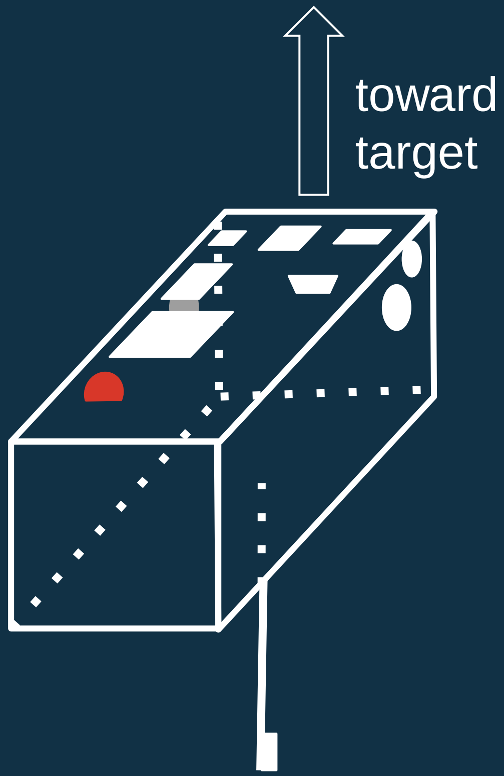
Characterise Neptune’s atmosphere and Triton’s surface [SO 1.2, 1.3, 2.1, 2.3]



Specifications

- WAC: low resolution, full coverage
- NAC: high resolution, small features obsv.

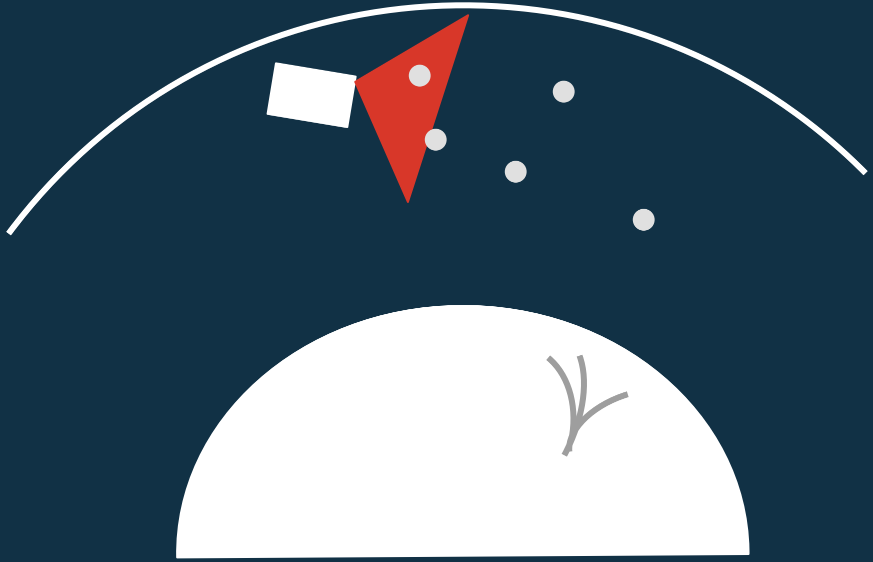
2. Mass Spectrometer & Pressure Gauge



2. Mass Spectrometer & Pressure Gauge

In-situ absolute **abundance measurements** of:

- elementary and molecular **neutrals and ions**
- possible more **complex organic** compositions
- **D/H ratio** in Neptune's & Triton's atmosphere



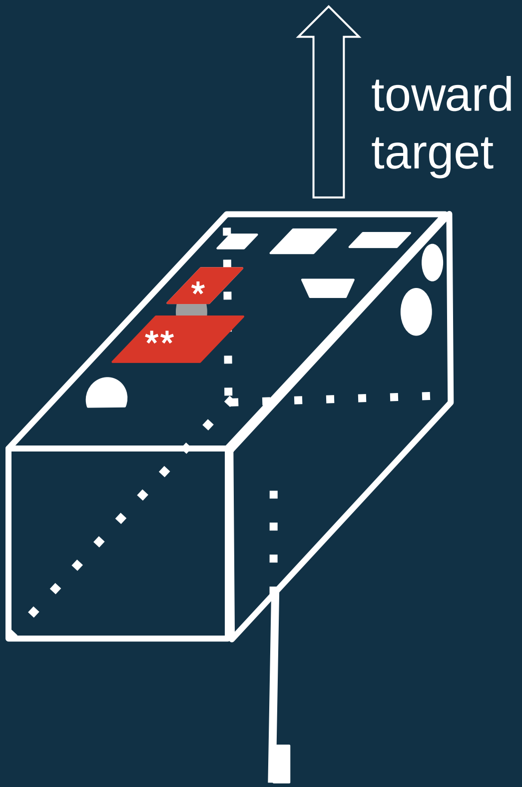
Determine the atmospheric composition of Neptune & Triton [SO 1.2, 2.2]

Specifications

- mass range: (1 - 300) amu
- mass resolution $M/\Delta M$ = min. 500 amu
- spatial resolution: 50 km or better

3. UV Spectrometer*

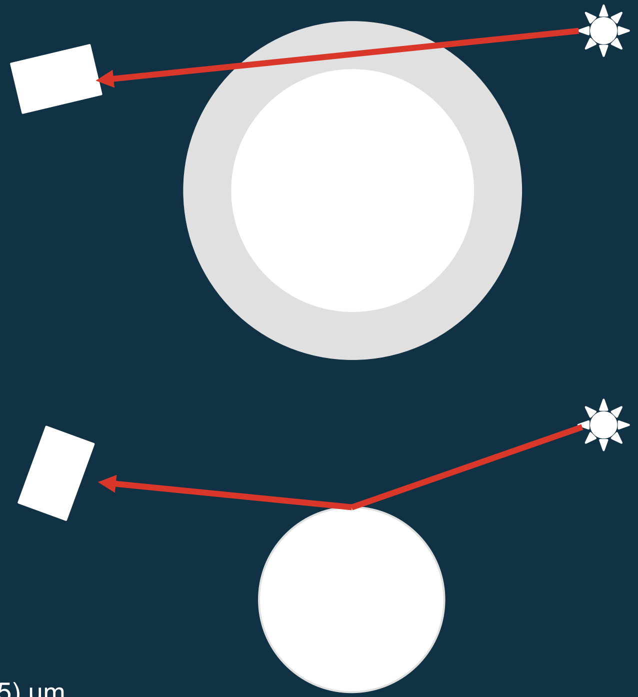
4. VIS-IR Spectrometer**



3. UV Spectrometer

4. VIS-IR Spectrometer

- Stellar **occultation**
- Scans of Triton’s **surface**
- Observations of Neptune’s **aurora, atmosphere**, **rings** and **lightning**



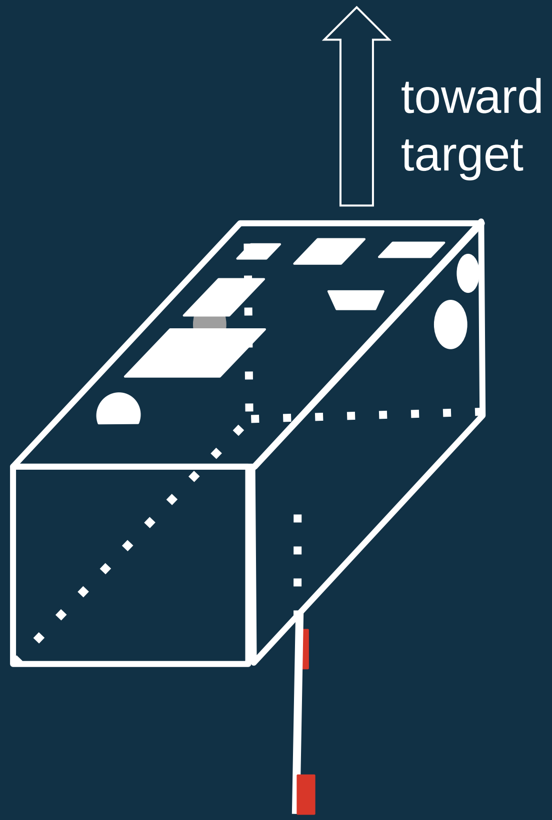
Characterise the interior structure and the atmosphere of Neptune and Triton and determine the surface properties of Triton [SO 1.2, 1.3, 2.1, 2.2, 3.2]

Specifications

- spectral range: (68 - 210) nm
- spectral resolution: 0.6 nm for point source
- spatial resolution: 350 μrad/pixel

- spectral range: (0.5 - 5.55) μm
- spectral resolution: 0.6 nm [Vis-NIR], 5 nm [IR]
- spatial resolution: 180 μrad/pixel

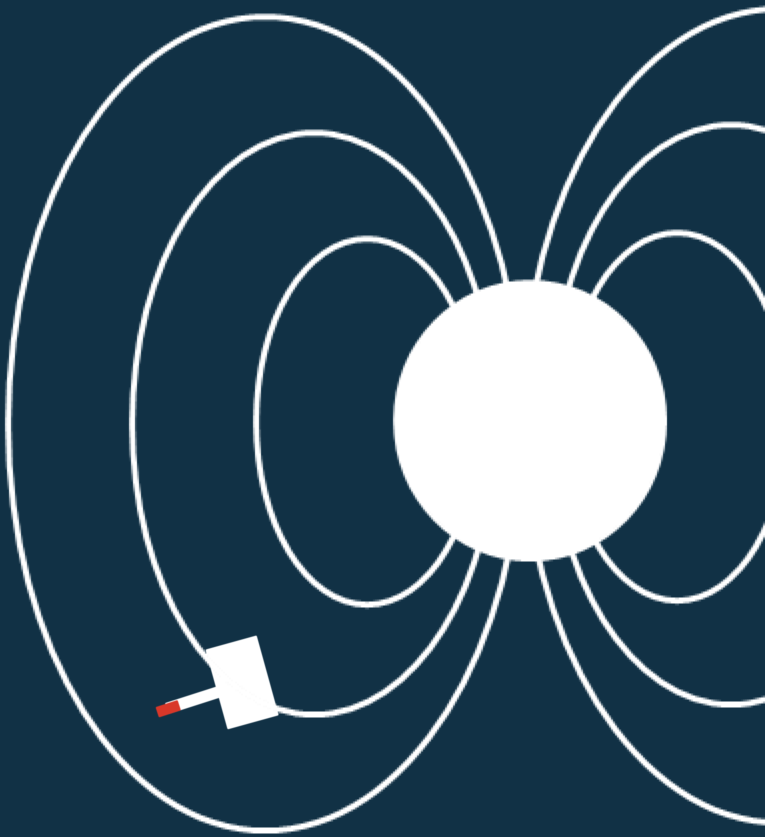
5. Magnetometer



5. Magnetometer

- **Magnetic field** measurements along 3 axes.

Determine the internal structure and the magnetospheric environment of Neptune, detect possible subsurface ocean in Triton and understand the interactions between Neptune and Triton [SO 1.1, 1.3, 2.3, 3.1, 3.2]



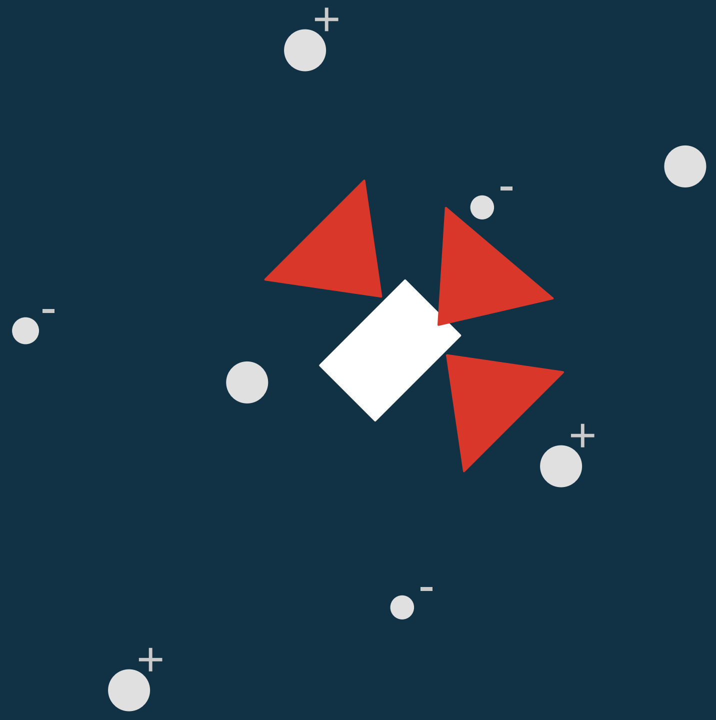
Specifications

- accuracy: 100 pT
- science mode (1 Hz) / burst mode (64 Hz)
- range: ± 50’000 nT

6. In-situ Particle Environment Package

6. In-situ Particle Environment Package

- Provides the 3D distributions of **ions and electrons**
- Global Energetic Neutral Atoms (**ENAs**) imaging of magnetosphere

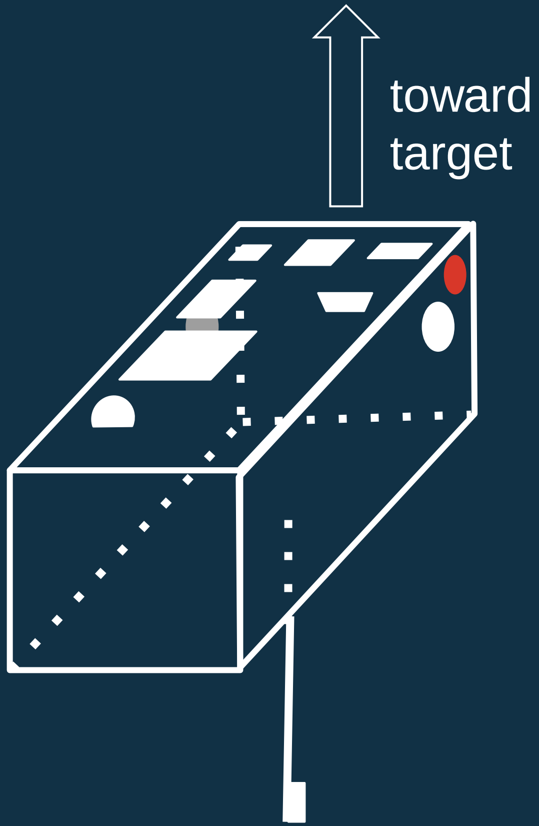


What are the characteristics of Neptune's and Triton’s magnetospheric plasma environments? [SO 1.3, 2.3]

Specifications

- Ion detector: 1 eV – 41 keV
- Electron detector: ~1 eV – 50 keV
- Neptunian ENAs ~0.5 – 300 keV, FoV: 90˚ x 120˚
- Data Processing Unit (DPU)

7. Radio Science

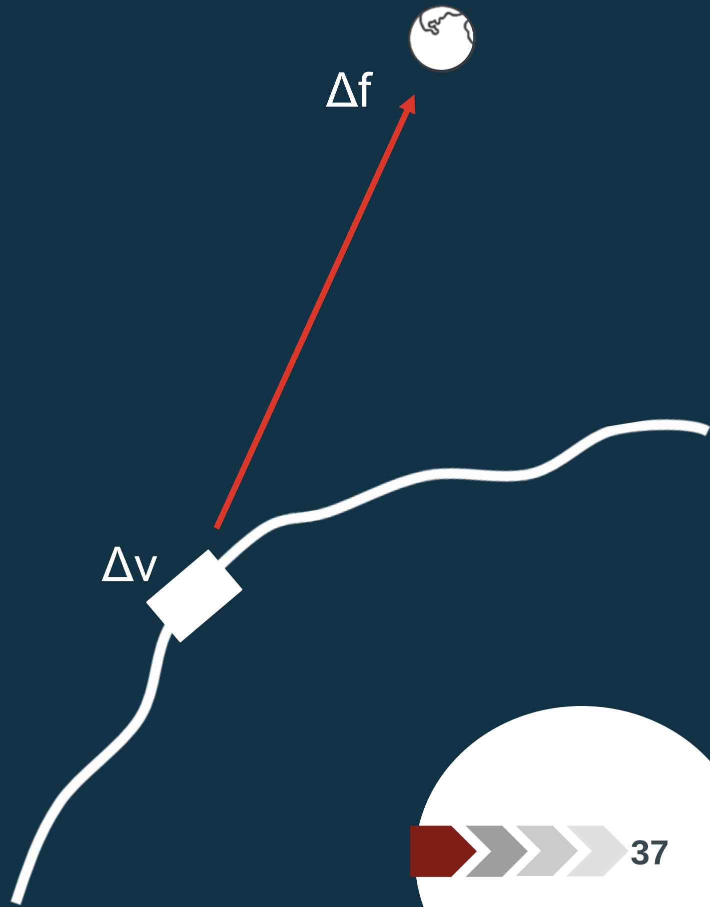


7. Radio Science

- Tracks **Doppler shift** in radio signals sent between spacecraft and Earth, radio signal occultation.

- Reveals changes in spacecraft's velocity due to **gravitational forces** from Neptune.

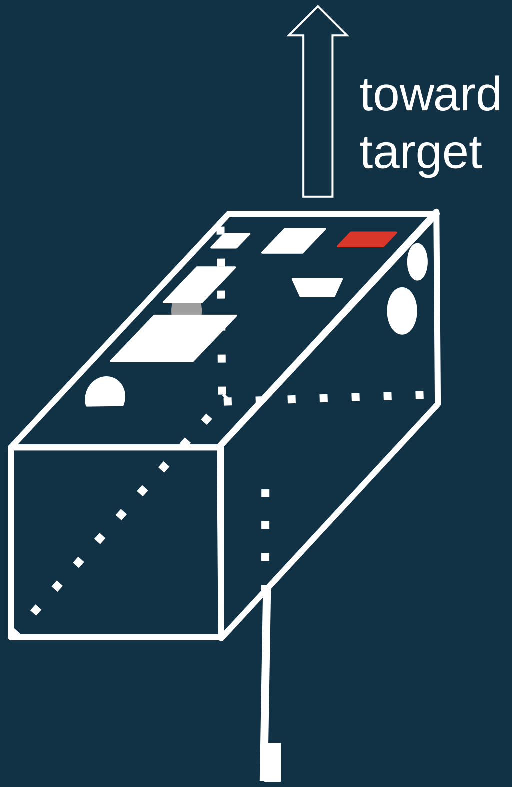
Constrain interior structure of Neptune and Triton. [SO1.1, 3.1]



Specifications

- Accuracy: $\Delta v = 10\ \mu m/s$
- Uses Ultra Stable Oscillator and 0.5 m Ka band antenna, which is already used for COM

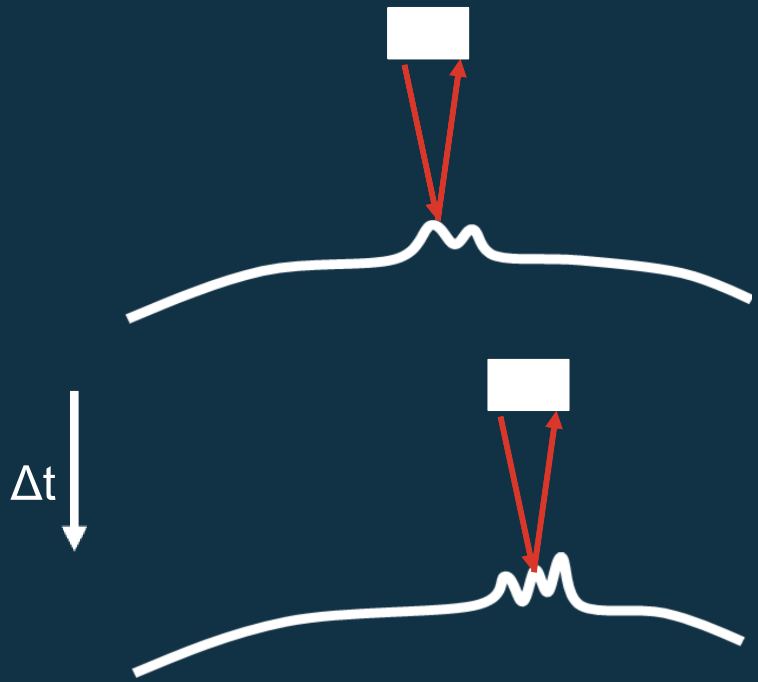
8. Laser Altimeter



8. Laser Altimeter

- **Topographical mapping** of Triton
- Measure **periodic surface elevations** to detect tidal deformation

Constraints on ice-shell thickness and presence of subsurface ocean. [SO 3.1]



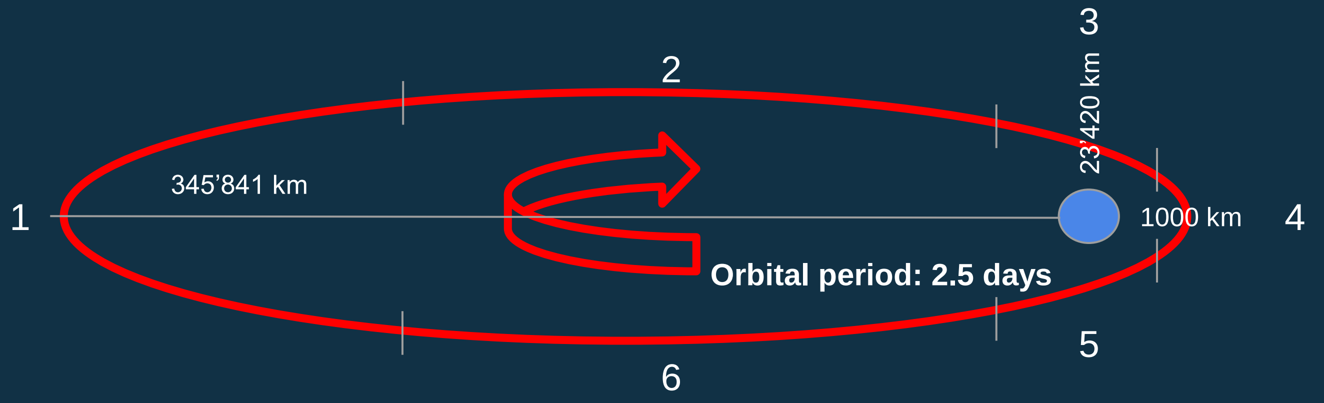
Specifications

- Repetition rate: 10 Hz
- At altitude 400/1000 km: surface spot size = 20/50 m

Instrumentation: Heritage and Development

Instrument	Identified critical sub-systems (TRL drivers)	Instr TRL	Heritage
Optical Camera	**Redesign of lens system for NAC/WAC.**	5-6	ROSETTA
Mass spectrometer + pressure gauge	**Redesign of detector. Components availability and operation modes drive TRL.**	4-6	JUICE
VIS - IR spectrometer	**Complete redesign of thermal system, apertures, optics.** Functional performance needs to be demonstrated in the laboratory.	3-4	JUICE
UV Spectrometer	**Redesign of aperture and optics drives TRL.** Critical functions of new design needs to be verified	4-6	JUNO / JUICE / Cassini
Magnetometer	**Components availability and operation modes drive TRL.**	4-6	JUICE / MESSENGER / JUNO
In-situ particle environment package	**Components availability and operation modes drive TRL.** Removal of three instruments possible wrt. pep on JUICE.	4-6	JUICE (only 3 instruments out of package)
Radio Science	**Components availability and operation modes drive TRL.**	4-6	JUICE
Laser Altimeter	**Components availability and operation modes drive TRL.**	4-6	BepiColombo

Observation Plan: Neptune

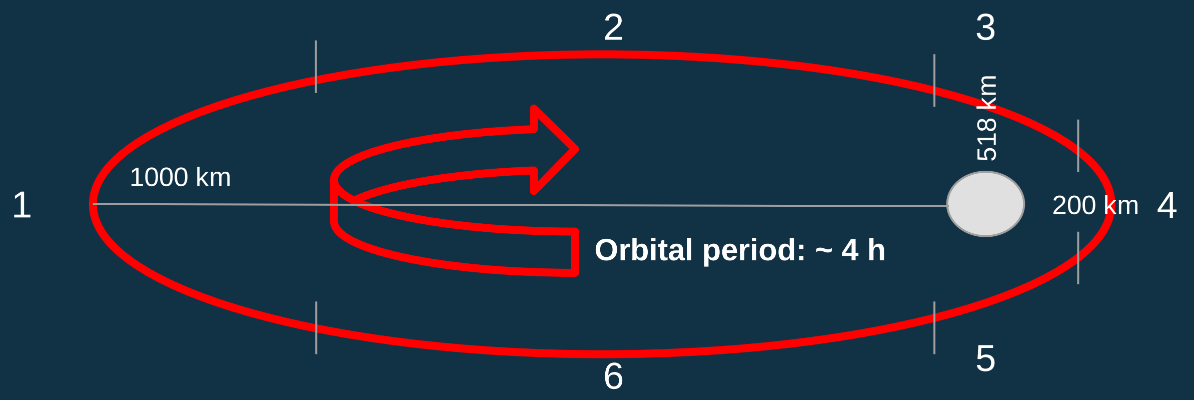


Primary
Secondary

* daylight
**nighttime

Instrument / Phase	1	2	3	4	5	6
Optical Camera		low res global*	low res global*	high res localized*	low res global*	low res global*
Mass Spectrometer				In situ		
Vis-IR Spectrometer	Occu. Nept/Trit	Ilightning/aurora low res global and high res localized**	low res global*	high res localized*	low res global*	lightning/aurora low res global and high res localized**
UV Spectrometer	Occu. Nept/Trit	lightning/aurora low res global and high res localized**	low res global*	high res localized*	low res global*	lightning/aurora low res global and high res localized**
Magnetometer						
In-situ Particle Environnement Package	Magnetosphere particle meas	Magnetosphere particle meas	aurora particle meas		aurora particle meas	Magnetosphere particle meas
Radio Science	Occu. Nept/Trit	gravity science	gravity science	gravity science	gravity science	gravity science
Laser Altimeter						

Observation Plan: Triton



Primary
Secondary

* daylight
**nighttime

Instrument / Phase	1	2	3	4	5	6
Optical Camera	low res global*	low res global*	high res localized*	high res localized*	high res localized*	low res global*
Mass Spectrometer	In situ	In situ	In situ	In situ	In situ	In situ
Vis-IR Spectrometer	low res global and Neptune obs*	low res global*	high res localized*	high res localized*	high res localized*	low res global*
UV Spectrometer	low res global and Neptune obs*	low res global*	high res features*	high res localized*	high res localized*	low res global*
Magnetometer						
In-situ Particle Environment Package	part meas of Nept magnetosphere	part meas of Nept magnetosphere	part meas of Nept magnetosphere		part meas of Nept magnetosphere	part meas of Nept magnetosphere
Radio Science	occu. Nept/ gravity science	occu. Nept/ gravity science	occu. Nept/ gravity science	occu. Nept/ gravity science	occu. Nept/ gravity science	occu. Nept/ gravity science
Laser Altimeter	topology mapping	topology mapping	topology mapping	topology mapping	topology mapping	topology mapping

Agenda

Science | Mission Design | System Design | Project Envelope

Mission Overview
System Drivers
Launcher & Transfer
Mission Tradespaces
Target Orbits

Mission Design Drivers

1. **Orbital Mechanics**
   - Launcher Performance
   - Planets' alignment
   - Neptune and Triton Insertion

2. **Instrumentation Facilitation**
   - System Mass, Data & Power
   - Instrument Operations
   - Thermal needs

3. **Communications**
   - Distance to Earth
   - Ground Segment
   - Science needs

Mission Overview

Mission Launch	Journey to Neptune	Neptune Science Orbit	Triton Science Orbit	End of Life
Mission launch window between 2048 and 2054.	Transfer to Neptune.	Injection around Neptune, beginning of science phase 1.	Injection around Triton, beginning of science phase 2.	Decommissioning of the S/C on the surface of Triton marks the end of the mission.
	14-22 years	approx. 4 years	approx. 1 year	earliest 2067, latest 2081

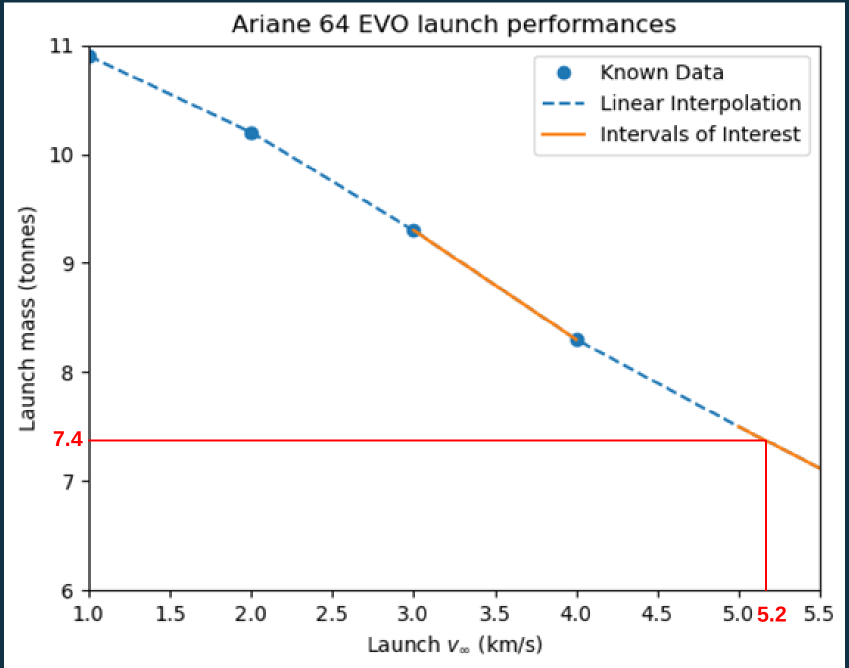
Launcher

Conflicting requirements:

- Injection velocity (5.2 km/s)
- Payload mass (7.02 t)

Ariane 64 EVO:

- Fairing diameter 5.4 m
- Fairing height (14 or 20 m)
- 7.4 to 7.6 tons to Earth escape



Mission Design Tradespaces

Jupiter Neptune Transfer

Identify the launch window.

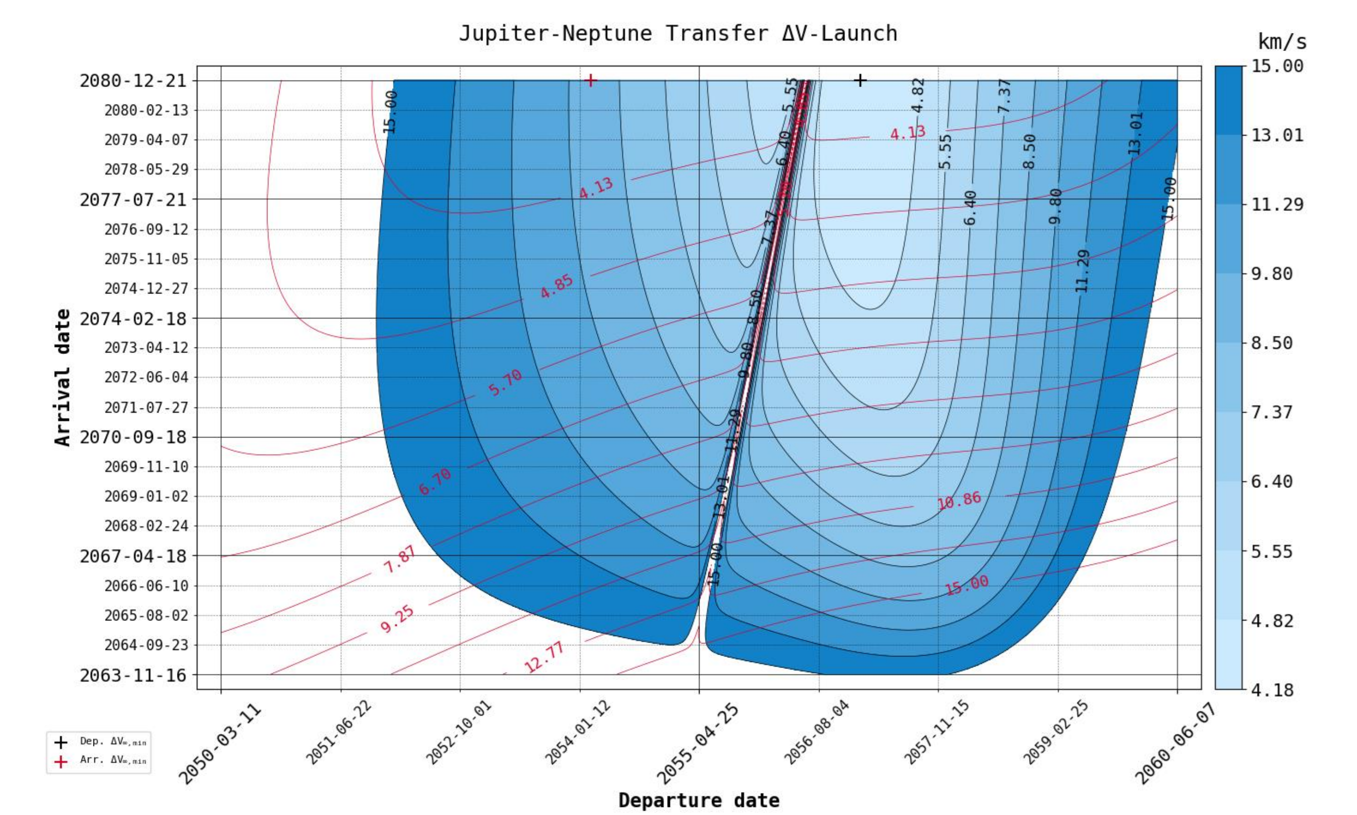
Earth Jupiter Transfer

Determine the optimal sequence of gravity assists.

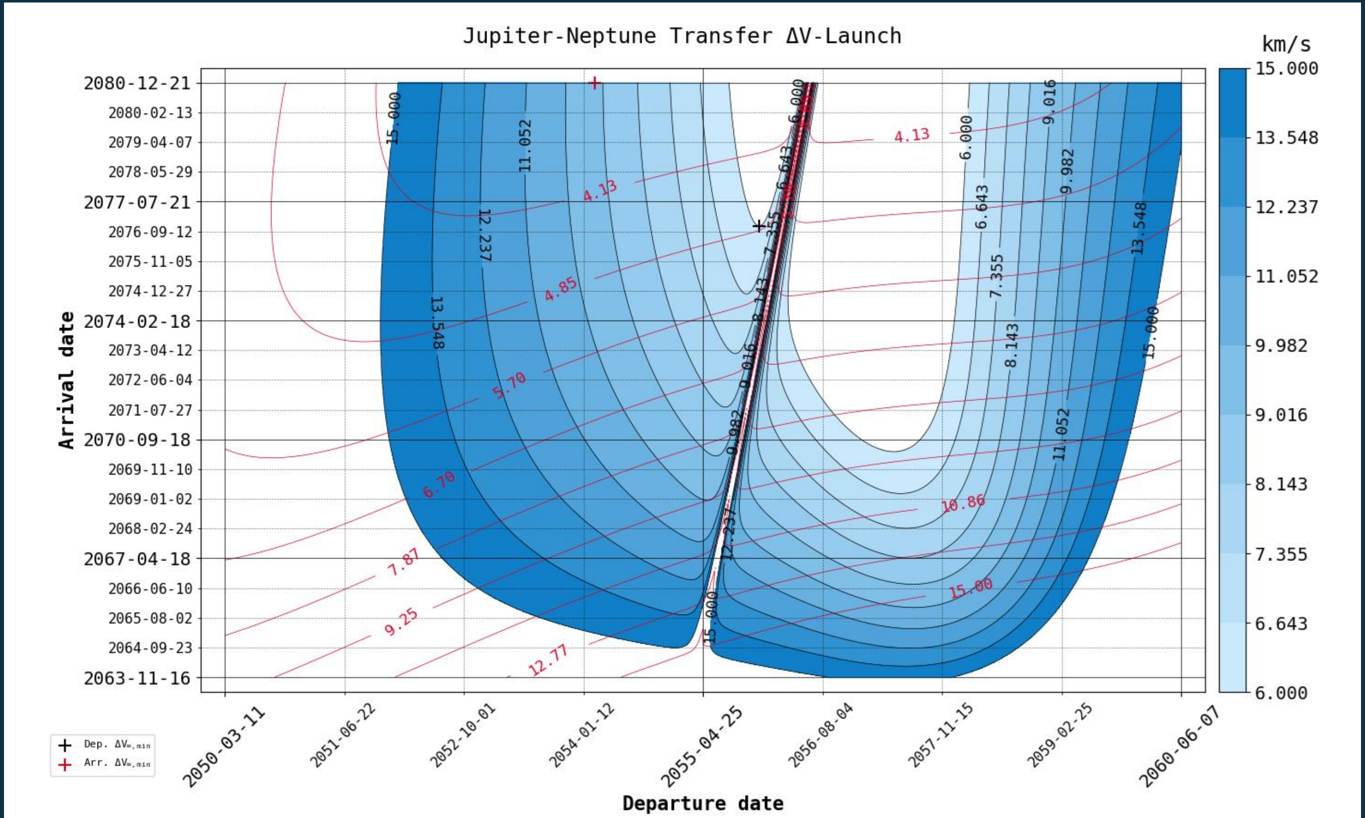
Science Orbits

Minimize injection costs while maximizing science return.

Trajectory tradespace - Jupiter to Neptune

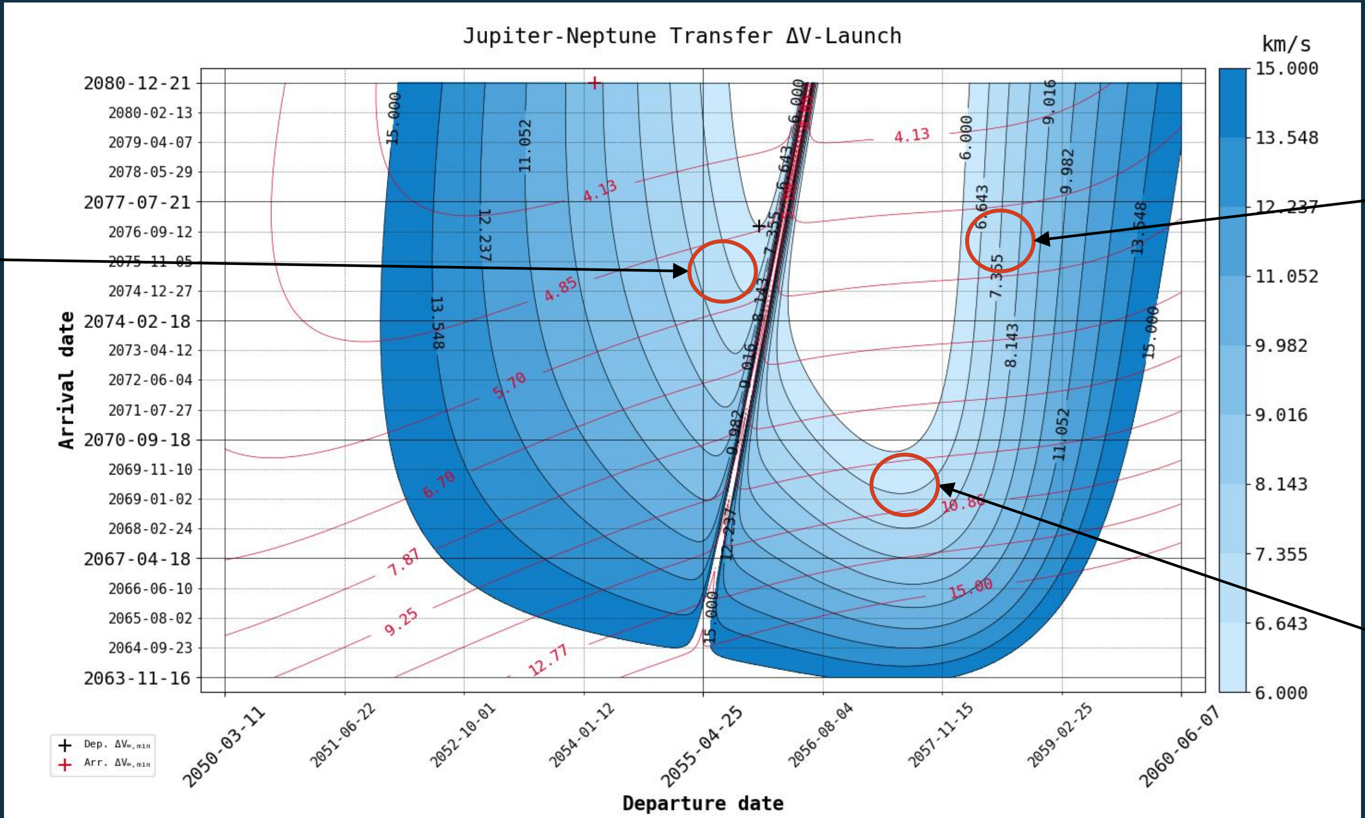


Trajectory tradespace - Jupiter to Neptune



Trajectory tradespace - Jupiter to Neptune

Higher time of flight (21 years), low injection cost (arrival hyperbolic velocity 5 km/s)



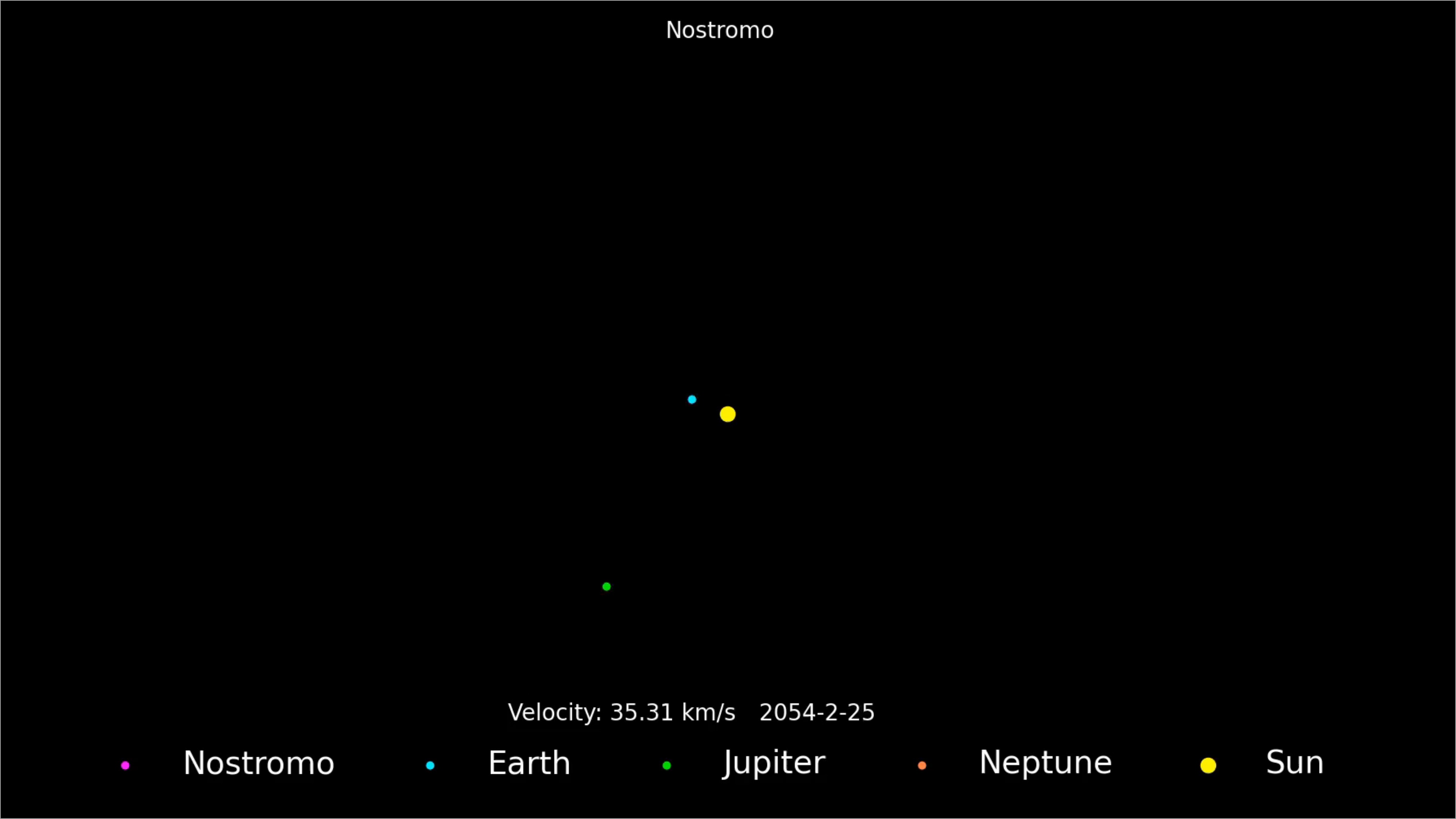
Medium time of flight (18 years), low injection cost (arrival hyperbolic velocity 5 km/s)

Low time of flight (12 years), high injection cost (arrival hyperbolic velocity 9 km/s)

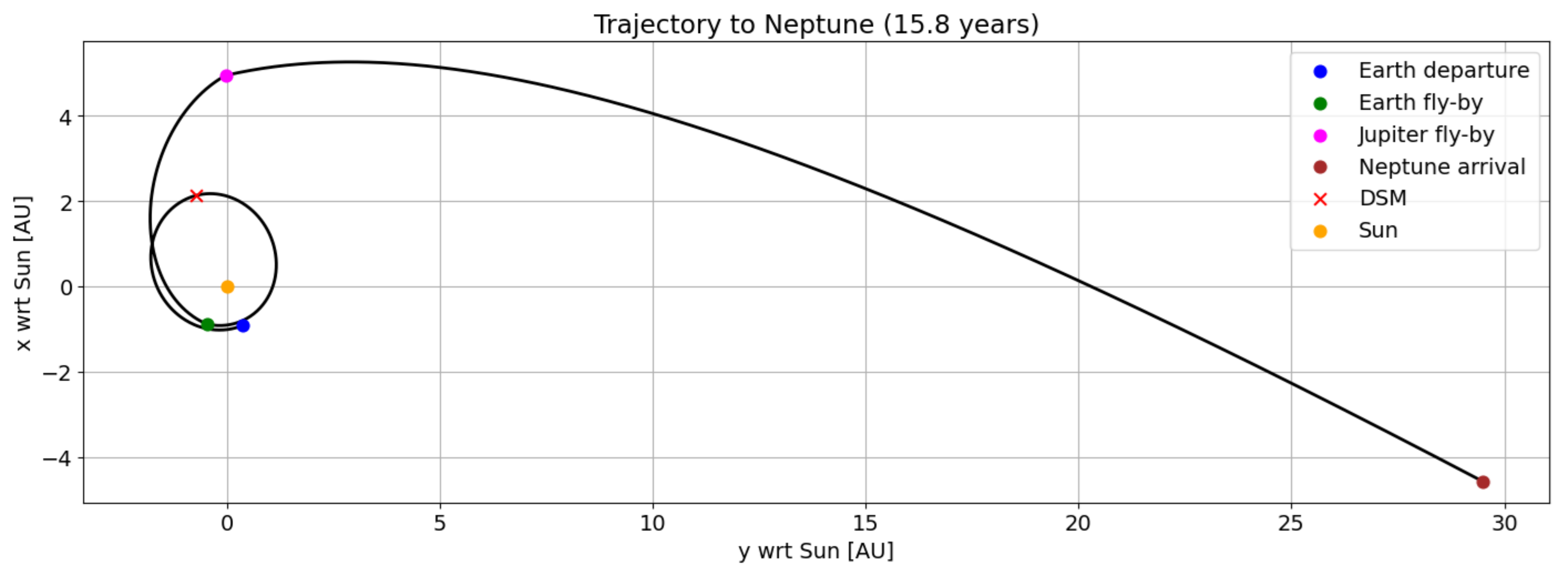
Trajectory Tradespace - Earth to Jupiter

Launch	Flyby sequence	Time of flight [years]	Launch V∞ [km/s]	C3 [km^2/s^2]	Δv [km/s]	Powered flybys	DSM maneuver
25-12-2048	EVEEJ	18.7	3.14	9.86	2.21	Yes (E,J)	No
25-12-2048	EVEEJ	20.9	3.17	10.0	1.81	Yes (E)	No
11-11-2048	EMEJ	20.7	5.19	26.9	3.28	Yes (E,J)	No
10-02-2054	E(DSM)EJ	15.8	5.23	27.3	2.32	No	590 m/s

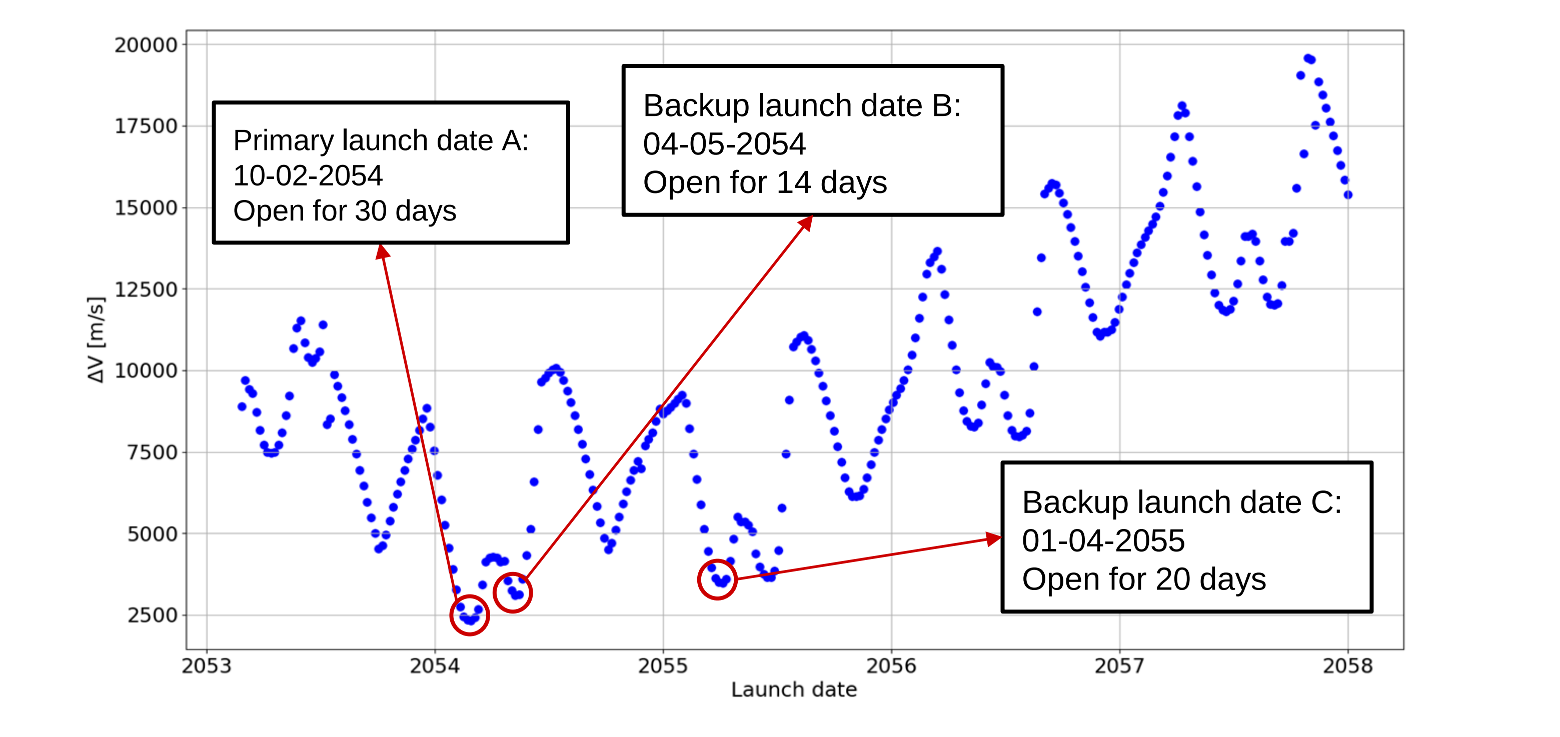
- No suitable alignments with Mars during target launch window.
- Exploiting a gravity assist at Venus constraints the minimum time of flight required to reach Jupiter to approximately 6/7 years.
- A Deep space maneuver allows to target with much more time flexibility a Jupiter GA, but it requires more Δv cost.


Nostromo
Velocity: 35.31 km/s 2054-2-25
Nostromo
Earth
Jupiter
Neptune
Sun

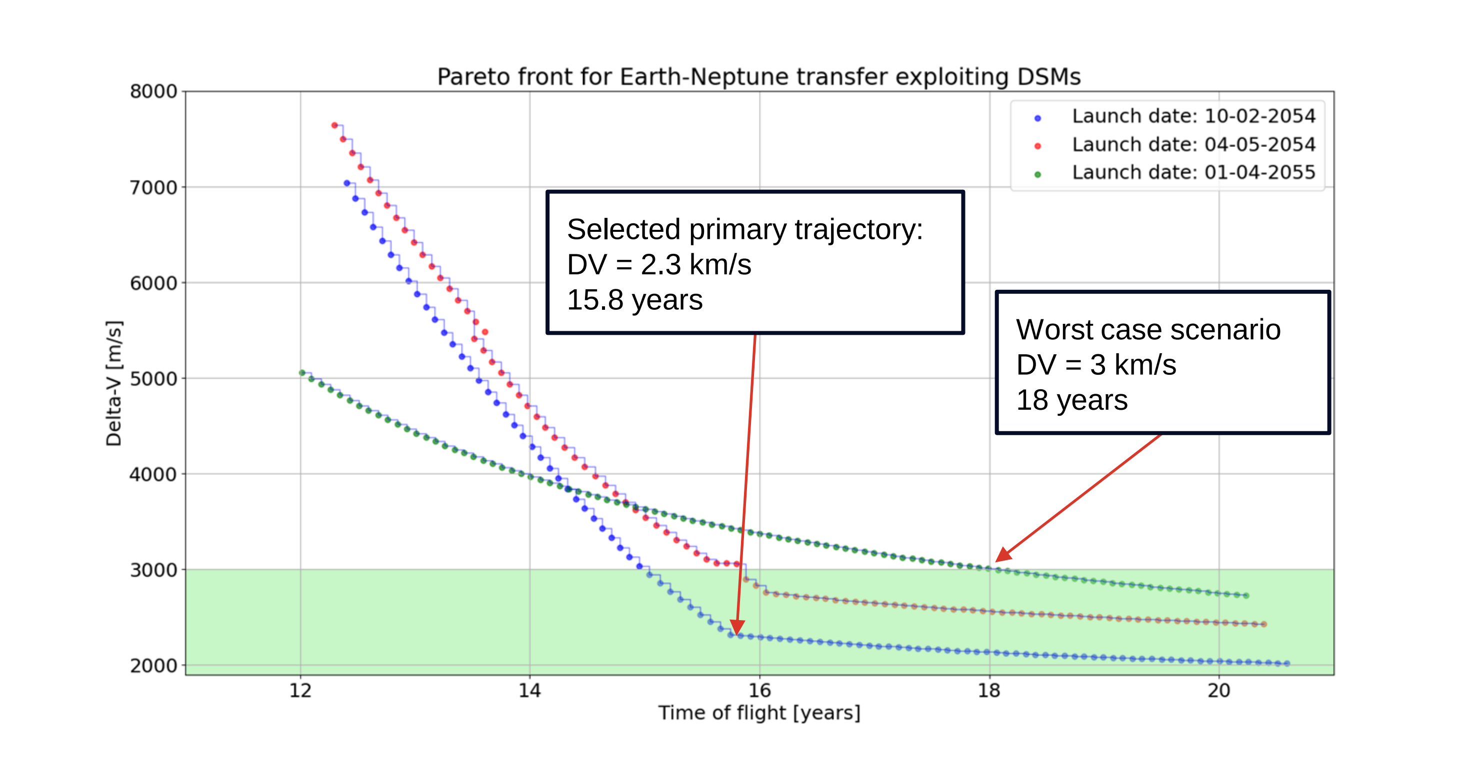
Selected trajectory



Launch window sensitivity analysis



Launch window sensitivity analysis



Orbiting Neptune

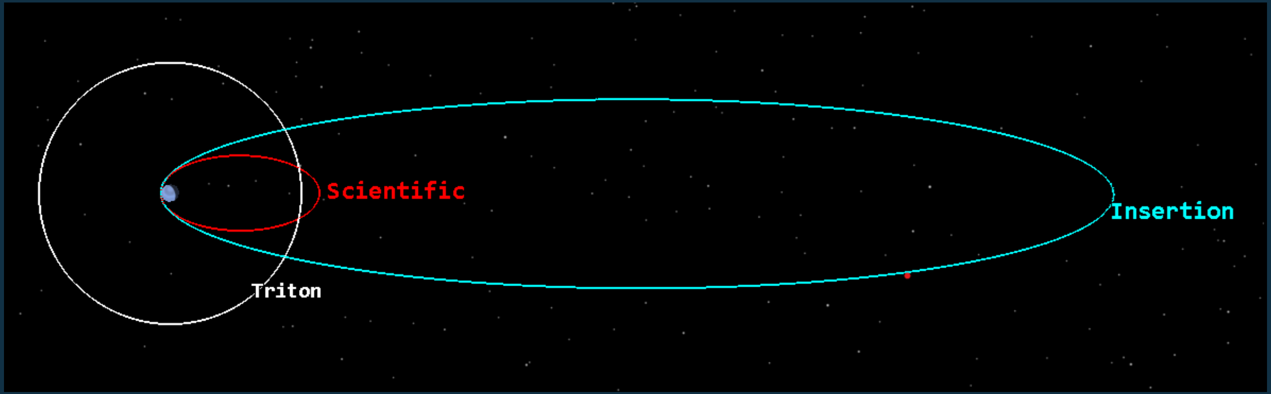
Injection orbit around Neptune:

- Eccentricity: 0.98
- Periapsis altitude: 1000 km
- Apoapsis altitude: 2'525'872 km ($103\ R_N$)
- Period: 41 days
- Retrograde in the plane of Triton

Flybys around Triton to reduce the apoapsis

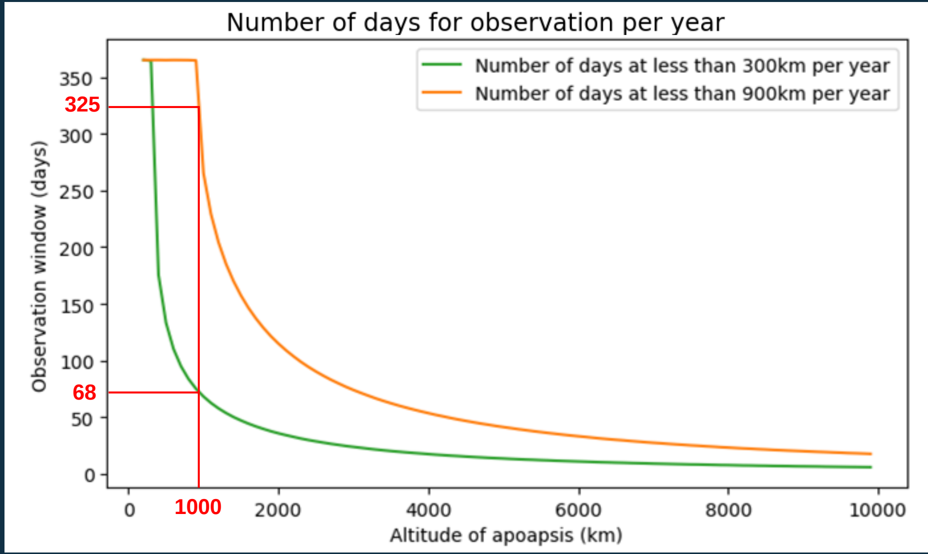
Scientific orbit around Neptune:

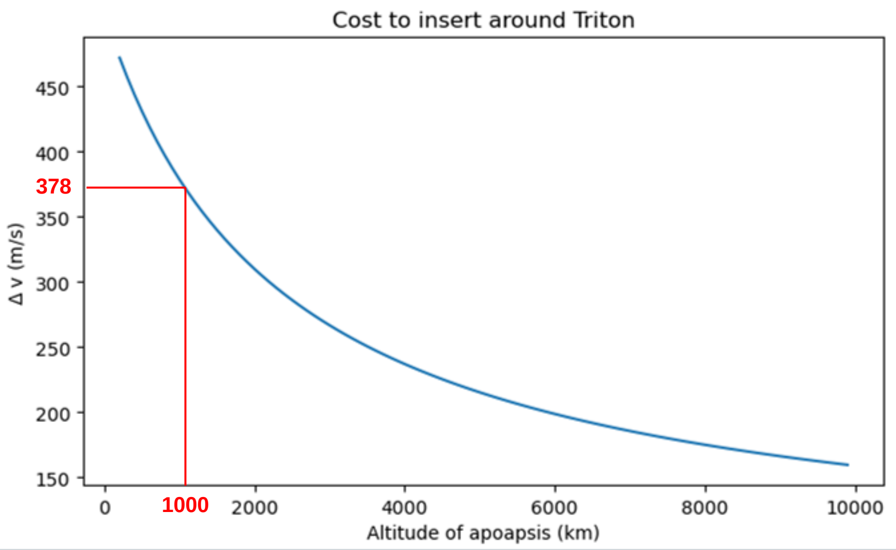
- Eccentricity: 0.88
- Periapsis altitude: 1000 km
- Apoapsis altitude: 345'841 km ($14\ R_N$)
- Period: 2.5 days
- Retrograde in the plane of Triton



Trajectory Tradespace - Triton Science Orbit

Selection of apoapsis: observation time vs injection cost





Orbiting Triton

→ **Endgame to transfer from Neptune to Triton science orbit**

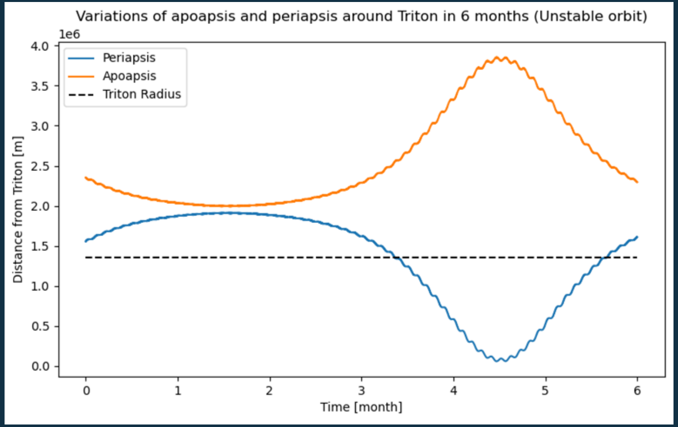
Highly inclined orbit (6 months, unstable):

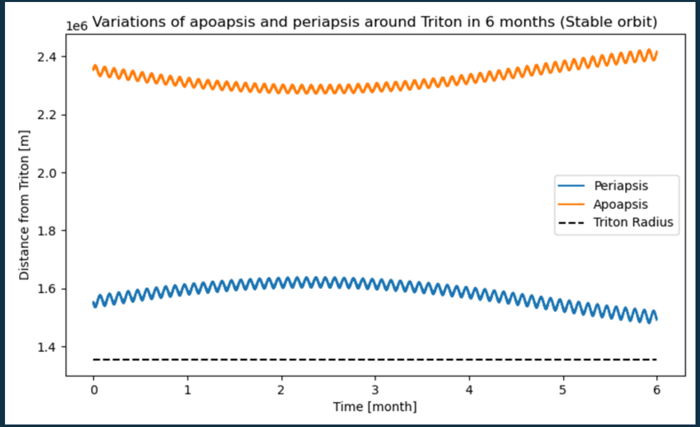
- Eccentricity: 0.20
- Periapsis altitude: 200 km
- Apoapsis altitude: 1000 km
- Period: 4 hours
- Inclination: 87° (nearly polar orbit)

Stop to compensate the change in inclination

Stabilized inclined orbit (6 months, stable):

- Eccentricity: 0.20
- Periapsis altitude: 200 km
- Apoapsis altitude: 1000 km
- Period: 4 hours
- Inclination: 35°





Orbiting Triton: station-keeping

- **Unstable Orbit:**
  - 4.5°/month inclination drift
  - 0.08 change/month in eccentricity

➔ One maneuver per month of 10 m/s for 6 months to stay on the polar orbit

- **Stable Orbit:**

➔ No cost to stay in the stabilized inclined orbit (35°) for 6 months (possible mission extension to one more year with no station keeping needed)

End of life and Decommissioning

Options:

1. Crash into Neptune using 4.3 km/s Δv maneuver where 305 m/s are used to leave Triton
   - ➔ Not feasible

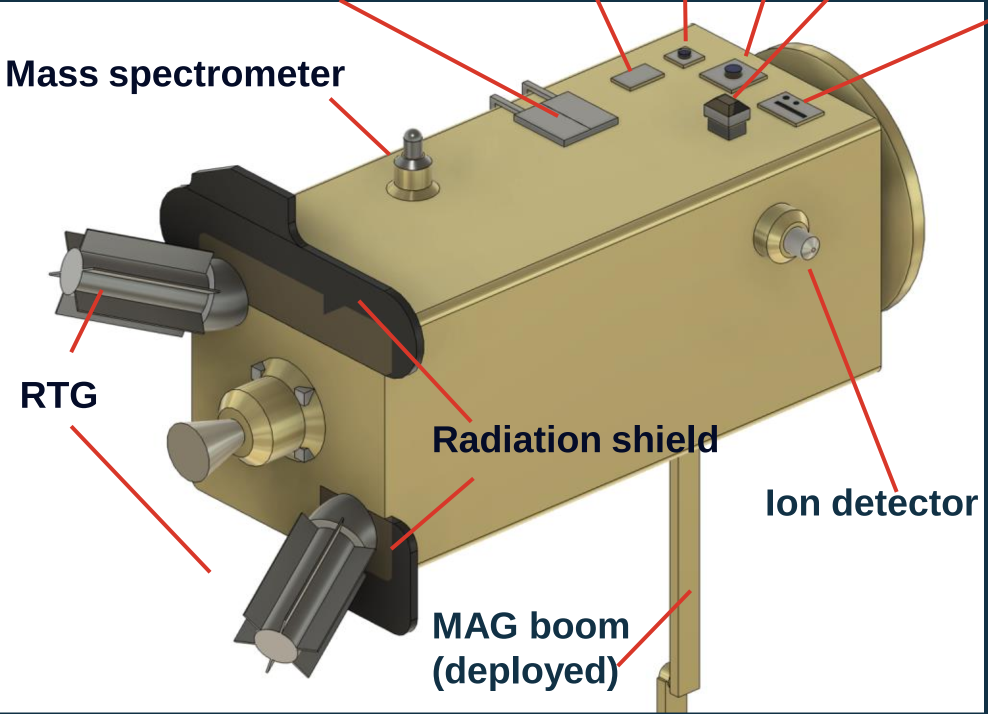
1. Crash into Triton in 6 months with a small maneuver (5 m/s)
   - ➔ Controlled reentry for 30-60 min with mass spectrometer and magnetometer turned on with communication to Earth

Agenda

Science → Mission Design → System Design → Project Envelope

- Spacecraft Concept
- Subsystems Overview
- Mission Operations
- Ground Segment
- Critical Technology

System Overview



Preliminary model SC parameters

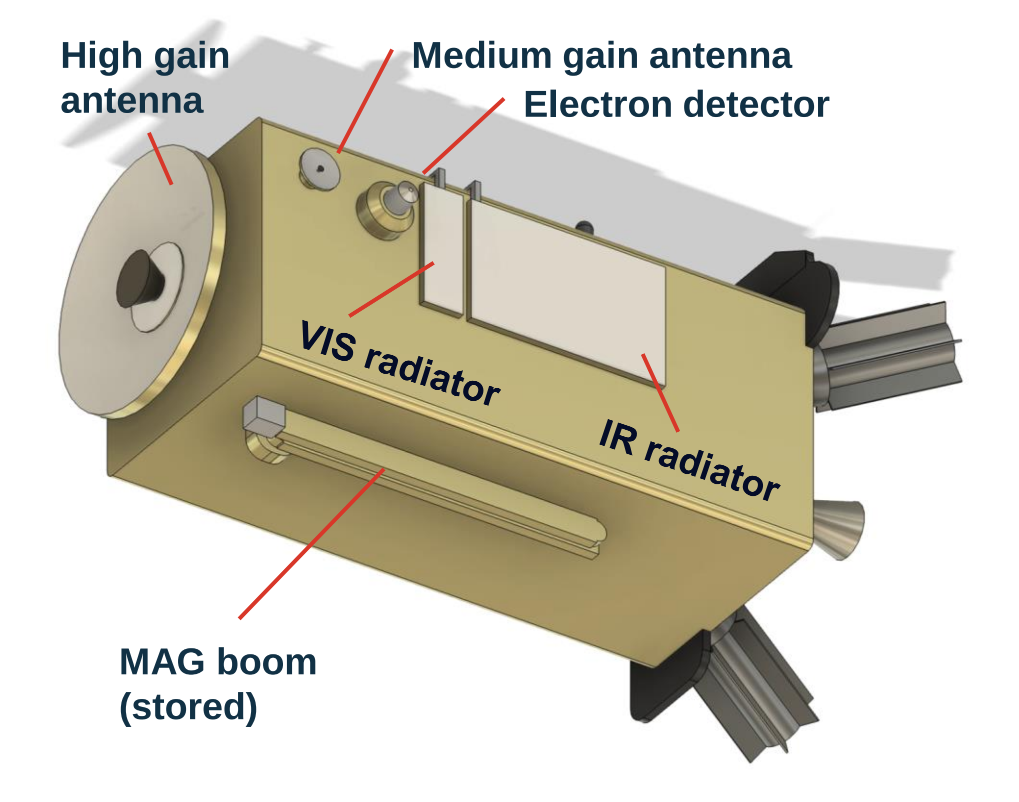
Surface Area: **159.6 m^2**

Volume: **67.4m^3**

S/C body: **3x3x7m^3 + payload**

Planet facing direction

System Overview



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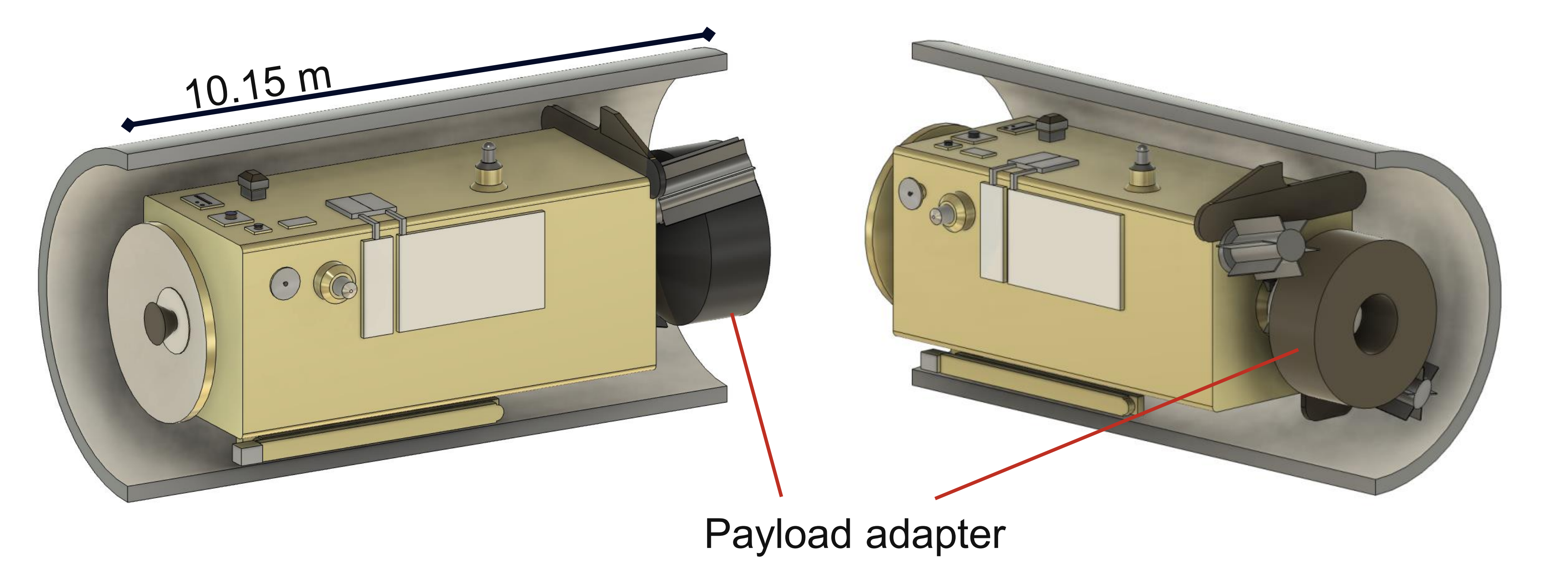


Instrumentation Budget

Instrument	Mass [kg] with Margin	Power (standby/average) [W]	Data rate (min/max) [kbit/s]
Optical Camera: NAC & WAC	20	3.5/8	40’000
Mass Spectrometer	6	8/12	31/384
UV Spectrograph	15	12/12	32/
Laser Altimeter	20	14/43	3/10
Vis-IR Spectrometer	30	20/25	182/
Magnetometer	5	5/10	0.45 (science mode), 12.07 (burst mode)
In-situ Particle Package	8	40/50	4/7
Radio Science Experiment	Included in COM		
Total instrumentation	104	109/170	40’253/40’627

Mass Budget

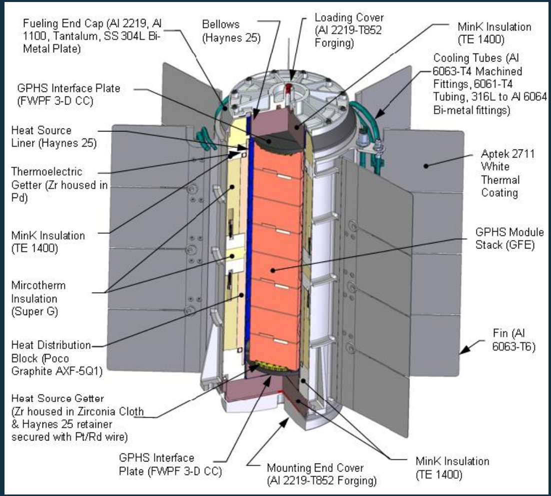
- Top-down: First estimates of subsystem masses adapted from similar concepts

- Bottom-up: Selection of specific existing components
    - onboard computer
    - ADCS sensors & actuators
    - RTGs & batteries
    - propulsion system

Subsystem	best estimate	contigency	maximum expected value	bus dry mass contributio
command and data handling	46	10%	51	3.7%
guidance, navigation & control	64	10%	70	5.2%
power	261	10%	287	21.0%
harness	77	20%	92	6.8%
thermal	75	20%	90	6.6%
communications	120	20%	144	10.5%
propulsion	197	10%	217	15.9%
structures and mechanical	305	20%	365	26.7%
payload adapter			50	3.7%
total bus	1144		1367	100.0%
payload	104	20%	150	
total dry	1248		1516	
total dry with system margin		20%	1820	
propellant			5205	
total wet			7024	
maximum possible mass Ariane64			7400	
margin kg			376	
margin %			5%	

Radioisotope Thermoelectric Generator

- 4 MMRTGs units: 238Pu 440 W (beginning of mission)
- 8000 W of thermal dissipation
- degradation after ~25 years (worst case mission scenario), 360 W power provided



Credit: NASA

Power Budget

Main drivers:
Science mode with payload suite

Science mode with radio science experiment

Power required from battery

Subsystems \ Modes	Science	Science 2	Manoeuvre	Data-Link	Safe	Cruise	Battery
Payload	170	0	0	0	0	0	0
Command & Data	38	38	35	35	36	27	2
GNC	81	81	49	66	46	46	33
Power	45	45	45	45	45	45	45
Thermal	20	20	80	20	0	0	0
COMs	0	120	0	300	120	120	15
Propulsion	21	21	130	21	26	26	26
Total	375	325	338	486	273	264	121
Margin	30%	30%	30%	30%	30%	30%	30%
Total incl. Margin	487	422	439	632	355	343	157
RTG output (WC)	361	361	361	361	361	361	361
Excess	-126	-61	-78	-270	6	18	205
Power draw on battery	126	61	78	270	0	0	0

System Propulsion

- Aerojet Rocketdyne HiPAT Dual-Mode 445-N engine
- 326 s specific impulse
- Utilizing bipropellant
- Flight-qualified, same as Neptune Odyssey concept

Credit: satcatalog.com

System - ADCS

Component selection as per Neptune Odyssey concept:

- Actuators:
  - 4 reaction wheels
  - 16 4.4 N-thrusters
- Sensors:
  - Star trackers
  - Sun sensors
  - Inertial measurement unit

Driver: slew rates in science mode, worst-case at periapsis

- Neptune: 0.02 deg/s
- Triton: 0.006 deg/s

ADCS Mode	Modes	Sensor and Actuator
Fine acquisition mode	Science 1, Science 2, Data link	Sensors : Star Trackers, Sun sensors, IMU Actuator: Reaction wheels
Rough acquisition mode	Cruise, Battery charge	Sensors : Sun sensors, IMU Actuator: Reaction wheels
Slew mode	Manoeuvre	Sensors : Star Trackers/Sun sensors, IMU Actuator: Reaction wheels/Thrusters
Safe mode	Platform/Safe mode	Sensors : Sun sensors, IMU Actuator: Thrusters

Delta V Budget

Derived from trajectory calculation:

- 30% margin on transfer (launch delay & correction)
- 5% & 100% margins as per ESA margin philosophy
- 25% margin for new development safety factor

Phase	Delta V		Margin	Delta V	
Transfer Earth-Neptune	3000	m/s	5%	3150	m/s
Insertion into Triton orbit	472	m/s	5%	496	m/s
Stationkeeping	80	m/s	100%	160	m/s
Sum				**3806**	**m/s**

Inputs	Values	
Isp	326	sec
Delta V without margin	3806	m/s
Propellant margin	25.00%	
Dry mass	1820	kg
Propellant	5205	kg
Total	7024	kg

Thermal Analysis

Main thermal drivers:

- RTG thermal interface
- Space environment
- IR Spectrometer operating conditions
  - requiring stable 90K
- Vis-NIR Spectrometer operating conditions
  - requiring stable 130K

Thermal Analysis - Spacecraft bus interior

Main contributing factors:

- SC/RTG thermal interface (main driver)
- SC absorption/emission

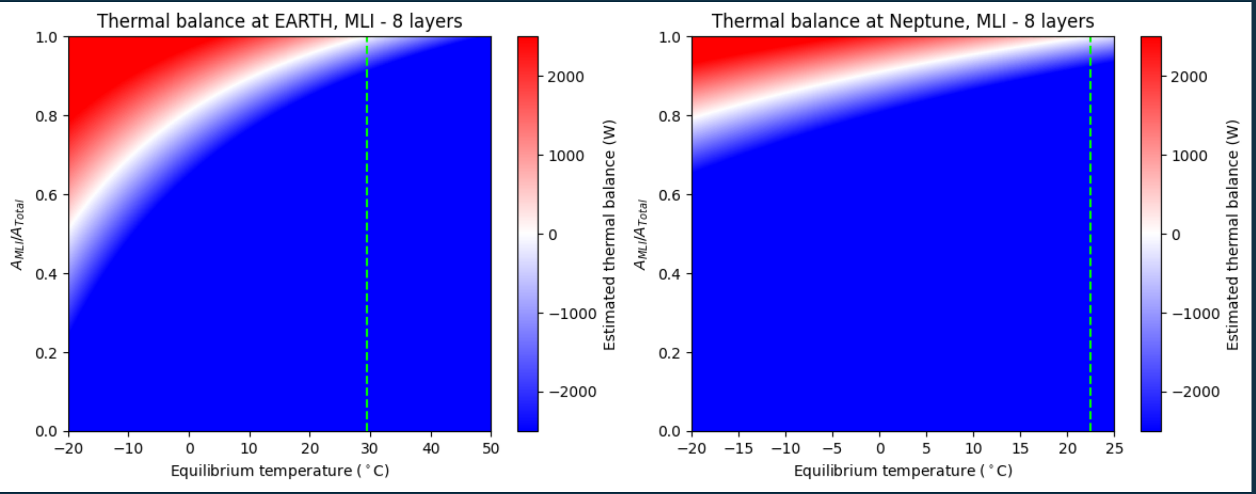


Figure: Spacecraft internal thermal balance around Earth and Neptune

Thermal Analysis - Vis-IR Operation Spec.

IR sensor requires stable 90K thermal environment (Rq-I13.1).

- System designed for Neptune environment
- Passively cooled only
  - Heatpipe & Radiator design
- Radiator sized to 3.7m²
  - sun facing at 90K
  - not sun facing 86K
- Stabilized via heating element

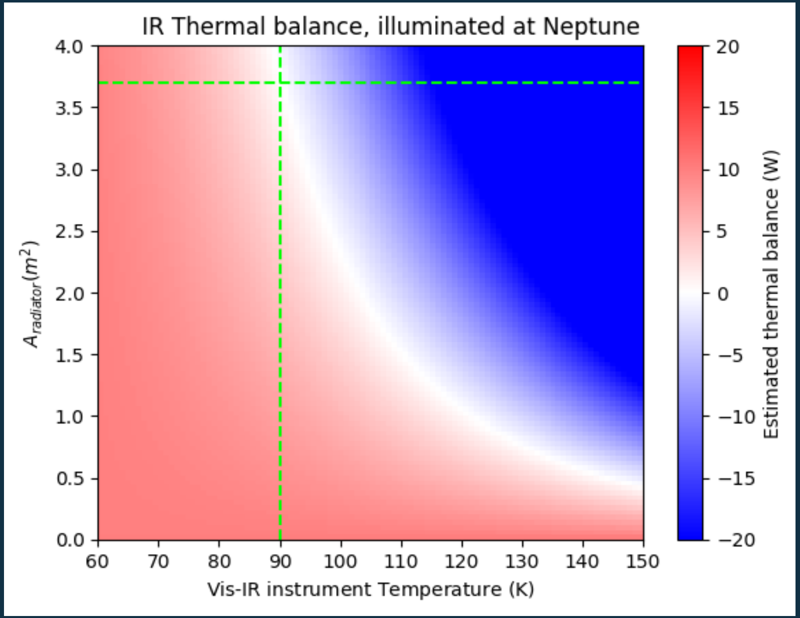


Figure: Instrumentation thermal balance, example of Vis-IR

Thermal Analysis - Vis-IR Operation Spec.

VIS-NIR sensor requires stable 130K thermal environment (Rq-I13.2).

- System designed for Neptune environment
- Passively cooled only
  - Heatpipe & Radiator design
- Radiator sized to 0.75m²
  - sun facing at 130K
  - not sun facing 128K
- Stabilized via heating element

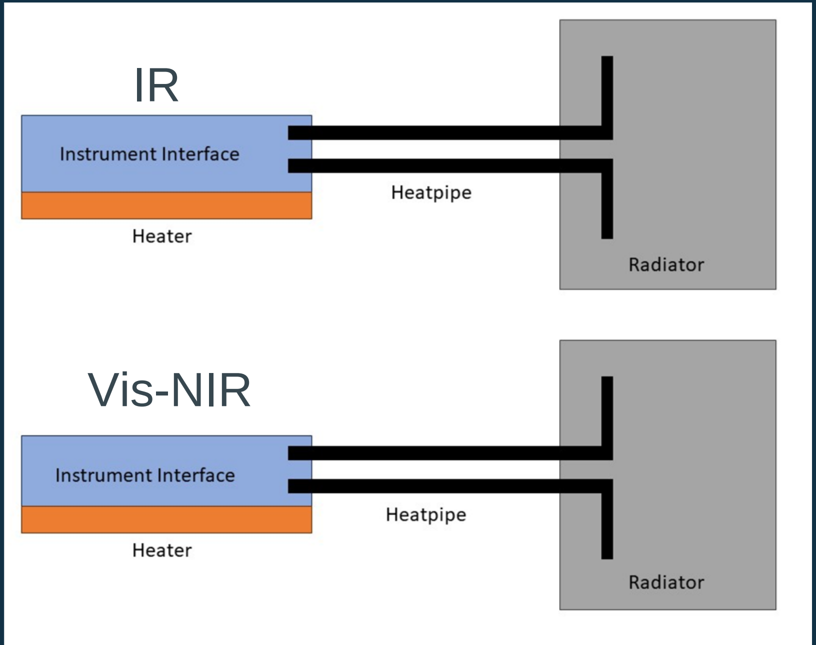


Figure: Instrumentation thermal regulation system

Ground Segment

- Ka Band (32.0 GHz)
- ESA 35m Deep Space Terminals
- CEB1 and MLG1
  - NNO1 to be upgraded
- NASA 70m terminal for critical maneuvers

Credit: ESA

Communications

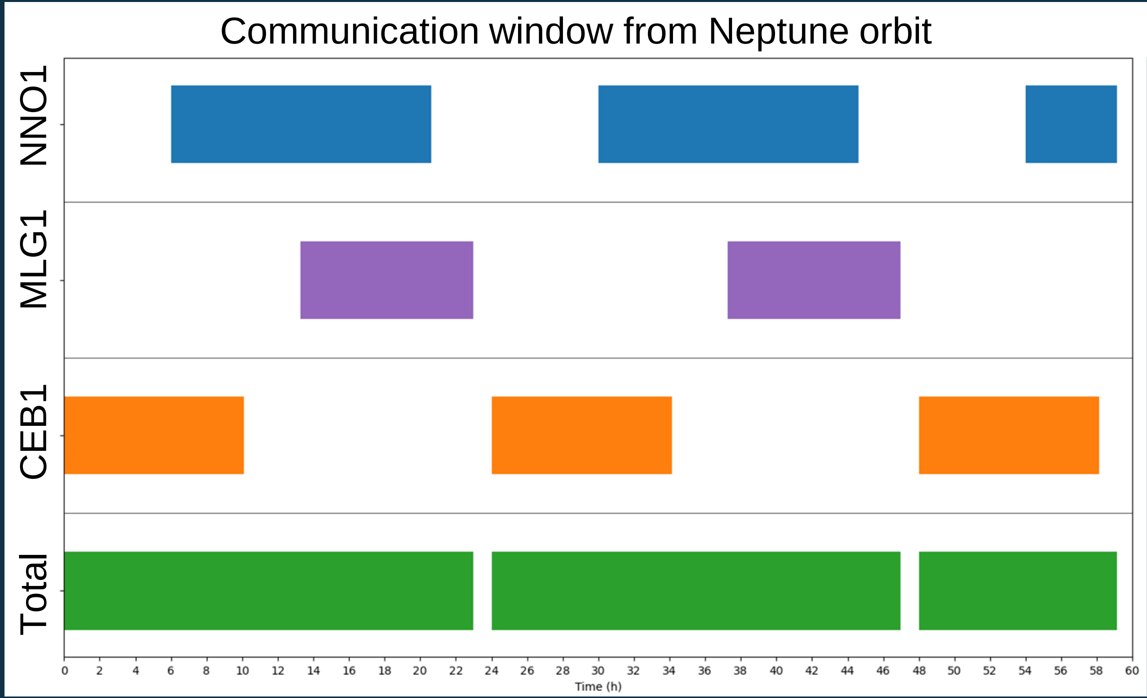
- 3m diameter High Gain Antenna
  - Science data link
  - Antenna gain of **57.4 dB**
  - Maximum downlink of **8.05 Gbit/day**
  - Maximum uplink of **1.9 Mbit/s**

- 0.5m diameter Medium Gain Antenna
  - Telemetry & Housekeeping
  - Antenna gain of **41.9 dB**
  - Maximum downlink of **104 Mbit/day**
  - Maximum uplink of **52.9 kbit/s**

	Science Data	**Telemetry**
Eb/En	-0.4 dB	-10.2 dB
Downlink	**11.4 kbit/s**	**1.2 kbit/s**
	985 Mbit/d	104 Mbit/d
Uplink	1.9 Mbit/s	52.9 kbit/s
	164 Gbit/d	5.1 Gbit/d

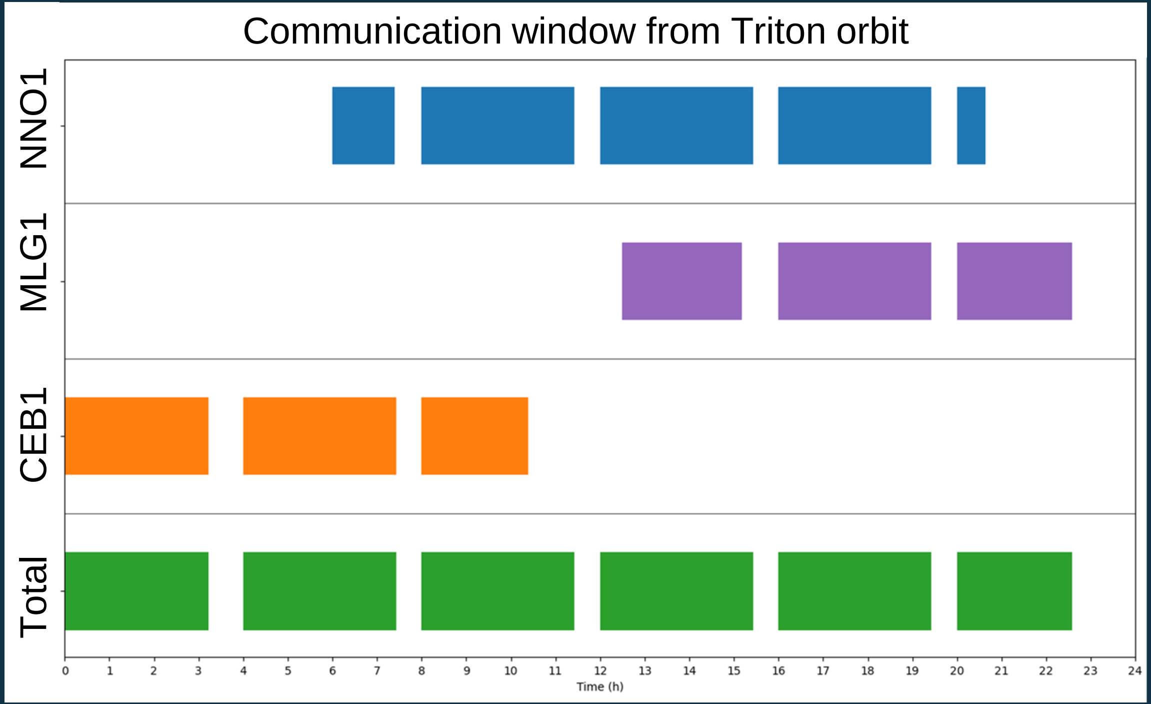
Communications Windows Neptune Orbit

COMs would allow for **23h/day available** contact time while in SCI orbit around Neptune.



Communications Windows Triton Orbit

COMs would allow for **21h/day available** contact time while in SCI orbit around Triton.

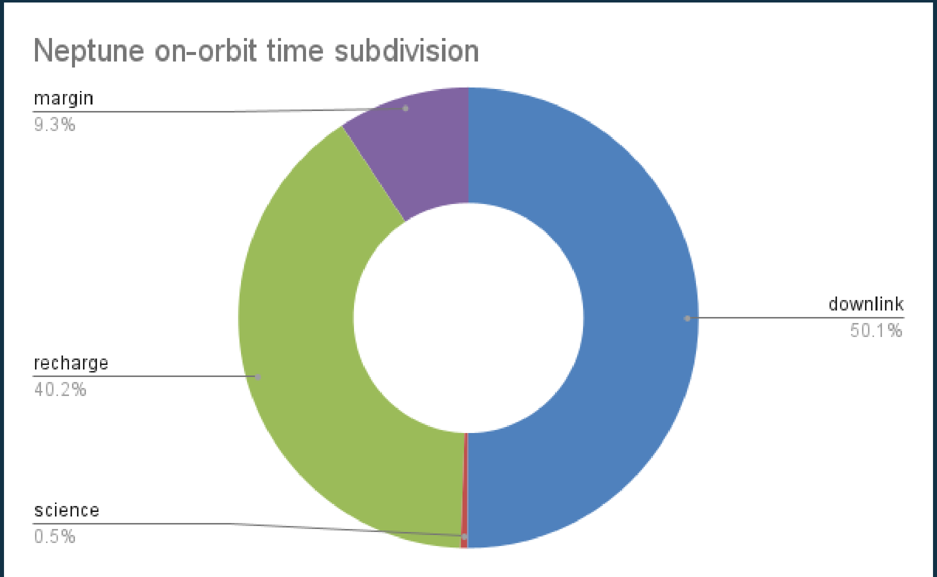


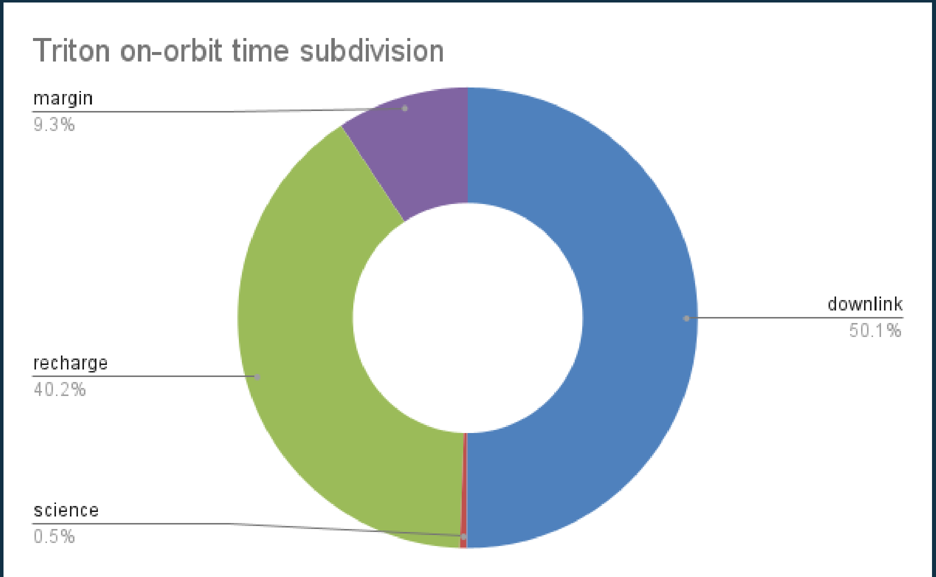
Data Budget & Onboard Computing

- Camera is dominant data budget driver (40 Mbit/s data rate)
- Consideration of
  - maximum science data rates
  - science time during orbit around Neptune and Triton
- OBC derived from reference missions:
  - Uranus Orbiter & Probe concept
  - Parker Solar Probe (flight heritage)
  - Van Allen Probe (flight heritage)

➔ 1024 GB memory

On-orbit scheduling





Driver for:
4 year science phase(1) for Neptune

1 year science phase(2) for Triton

Agenda

Science → Mission Design → System Design → Project Envelope

- Schedule
- Critical Risks
- Descoping Options
- Cost
- Outreach

Mission phases and timeline (1/2)

Phase 0	Phase A	Phase B	Phase C	Phase D
Approx. 5 years of development of technologies **Mission Objectives and Requirements Review** (MCR)	Approx. 2037 conducting **Feasibility Study** of our concept Approx. 2041 **Preliminary Requirement Review** (PRR)	**B1** 2 years selecting industrial partners **B2** 1.5 years Approx. 2045 **Preliminary Design Review** (PDR)	Approx. 4 years of designing phase ending with the **Critical Design Review** (CDR) Ready for production	Start of testing in approx. 2049 **Flight Model** (FM) testing incl. ground segment Ending with the **Flight Acceptance Review** (FAR)

Mission phases and timeline (2/2)

Phase E | Possible extended science time | Phase F

10 February 2054
Launch of NOSTROMO

Back up launch date: 4 May 2054

Nominal **science phase**: 5 yrs

Mission Overview as prev. discussed

Possible extended science time

Approx. 2075
Decommissioning through controlled descent into Triton's atmosphere for safe disposal

Allowed* to crash on Triton following ESA's Planetary Protection Article IX:

Category II* : landing on Triton is allowed, but must be supported by an analysis of "remote" potential for contamination. (probability of introducing a single viable terrestrial organism of < 1 x 10-4)

Risk Assessment

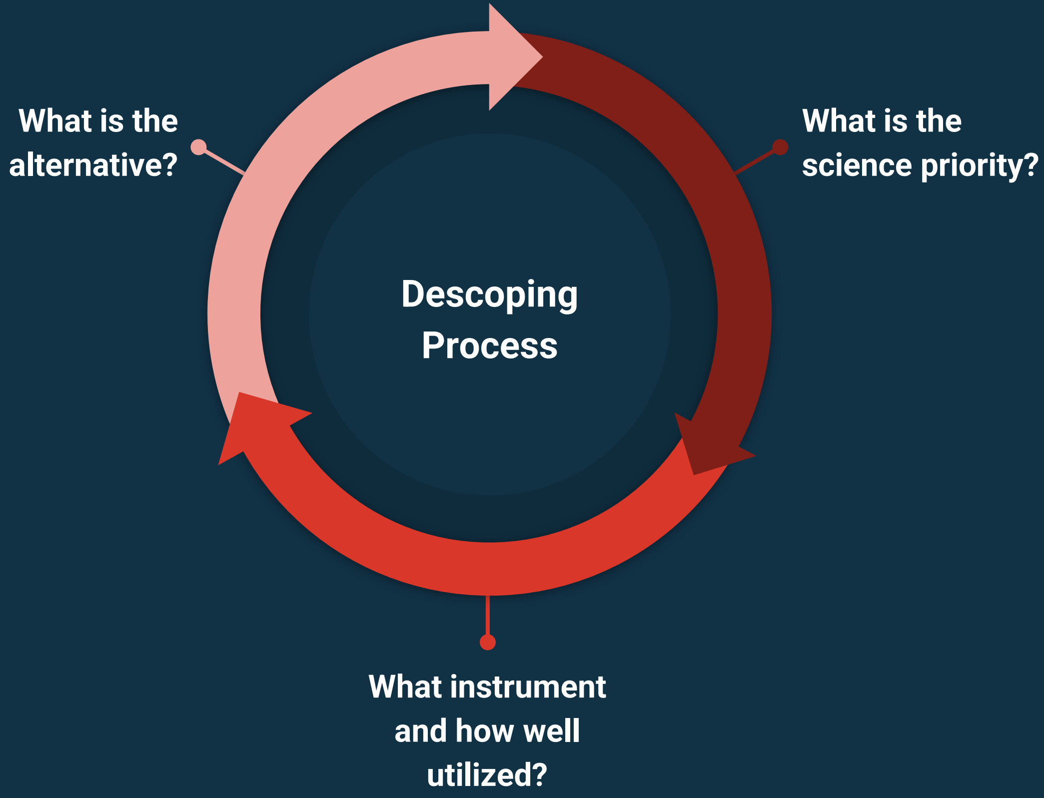
5		**R5: Planetary Protection Category change of Triton**			
4		**R4: Launch window**	**R1: personnel training** **R2: long mission lifetime: (S/C mech. parts e.g. reaction wheels)**		
3	**R8: Non-availability of instruments**		**R3: long mission lifetime: (Instr. mech. parts e.g. camera mirrors)**		
2			**R6: Failing mag boom deployment**		
1					**R7: Update of atmospheric model of Neptune**
	remote	unlikely	likely	highly likely	near certain

R#	Mitigation
1	Know-how transfer planning.
2	Redundancy and extensive testing.
3	Extensive testing.
4	Room to maneuver in planning.
5	S/C decontamination from organics needed.
6	None: Partial loss of science objective.
7	Adaption of Neptune orbit.

Preliminary Cost breakdown

Item	Estimation in Mio. €	Note
Industrial cost	650.00	Spacecraft including RTGs
Project team	162.50	
Mission and science operation cost	130.00	Due to long mission duration
Contingency & margin	141.38	
Launcher cost	150.00	Including nuclear restrictions
Total mission cost	1233.88	
Adjusted for 10% inflation	**1357.26**	**Mio. €**

Descoping



- Science Priority
- Instrument Utilization
- Alternative approaches

First to be descoped:

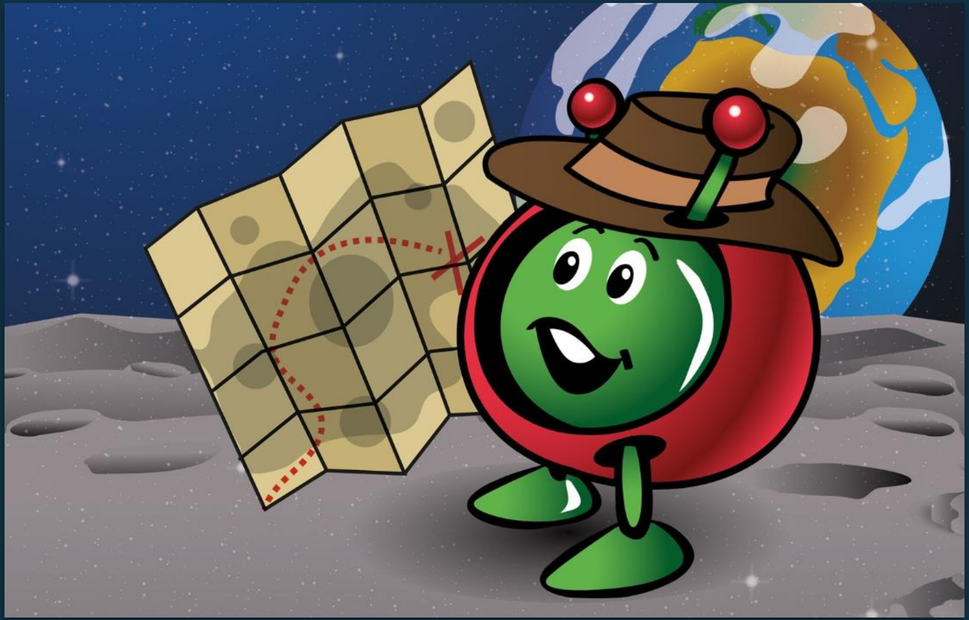
Laser Altimeter

- Only around Triton (lower prio.)
- Science partially recoverable

Outreach

In order to increase public support the following channels shall be considered:

- Education
- Traditional Media
- Social Media



Credit: ESA

Science Communities

Team Red

Tomas Formanek, Laura-Maximilia Pirker, Jiro Tanabe, Quentin Rommel, Lars Klingenstein, Ilse de Langen, Georgia Moutsiana, Julian Pflüger, Alexander Buehler, Luigi Serra, Delfine Vagenes, Gabriel Isaac Badia Estany, Romain Canu-Blot, Samuel Wyler, Aurélie Van den Neucker

Engineering tutor:
Günter Kargl
Science tutor:
Elise Wright Knutsen

Trust the process!

Thank you!

esa

nostromo

Team RED

Summer School Alpbach 2024

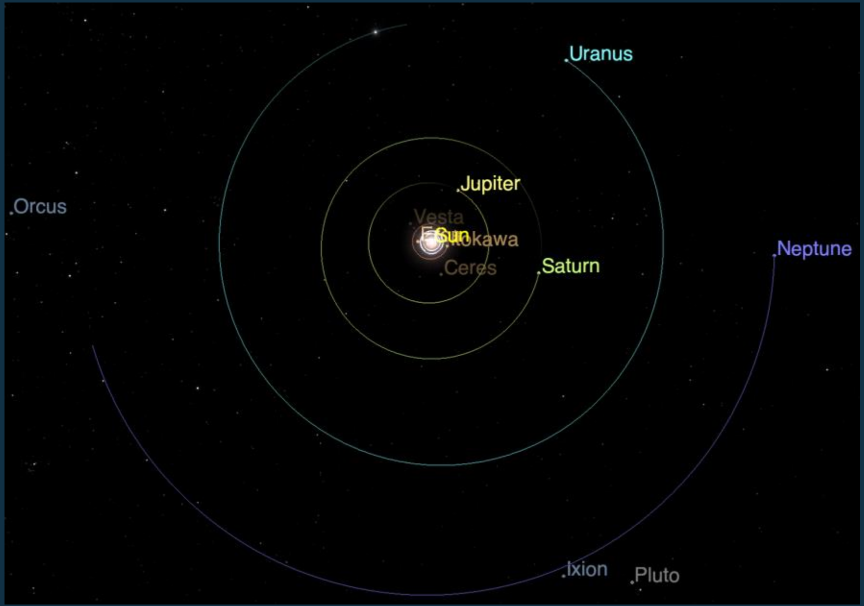
Backup Slides

•••

but wait, there is more…

Why did we not bring more instruments?

- Core science objectives can be addressed with chosen instruments
- Very specific, almost single use instruments
- Neptune is 4x further away from the sun than Jupiter
    - lots of constraints as
    - mass
    - power
    - COM



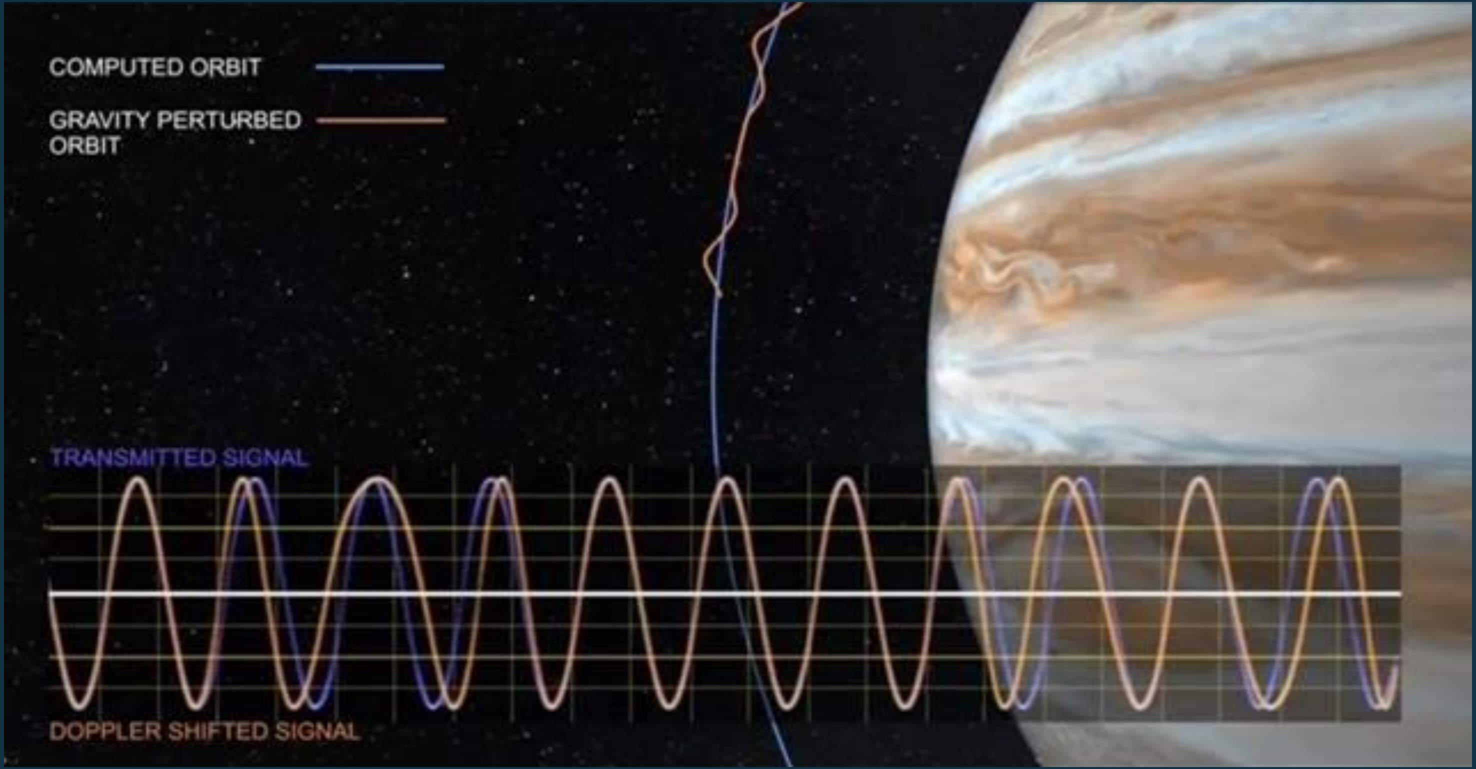
What instruments did we decide against?

Science objective	Science sub-objective	Optical Camera (NAC-WAC)	UV spectrometer	Vis-IR spectrometer	Laser Altimeter	Magnetometer	In situ particle enviornment package (high energies)	Mass Spectrometer with pressure gauge	Radio science experiment	Thermal sounder (sub-milimeter wave)	Ice penetrating radar	Radio and plasma wave instrument
Origin&evolution of Neptune	1.1 (interior structure)											
	1.2 (atmosphere)											
	1.3 (magnetic environement)											
Origin&evolution of Triton	2.1 (surface properties)											
	2.2 (atmosphere)											
	2.3 (interaction Neptune-Triton)											
Habitability of Triton	3.1 (internal structure)											
	3.2 (mechanisme of plumes)											

Why don’t we have a probe?

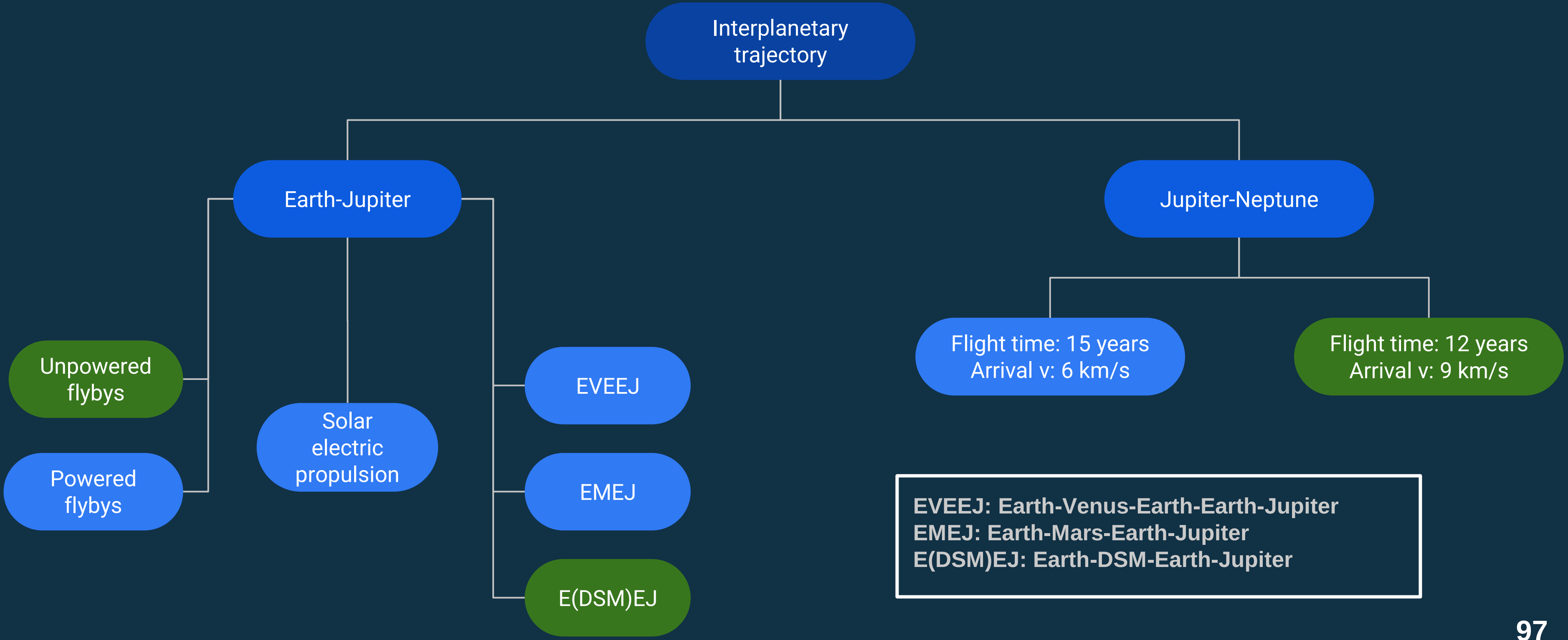
- Trade-off between science at Triton or deeper focus on Neptune
  - Triton orbit or Neptune probe

- Focus on different/more diverse science objective
  - more fundamental, long term, not specifically focused on Neptune’s atmosphere



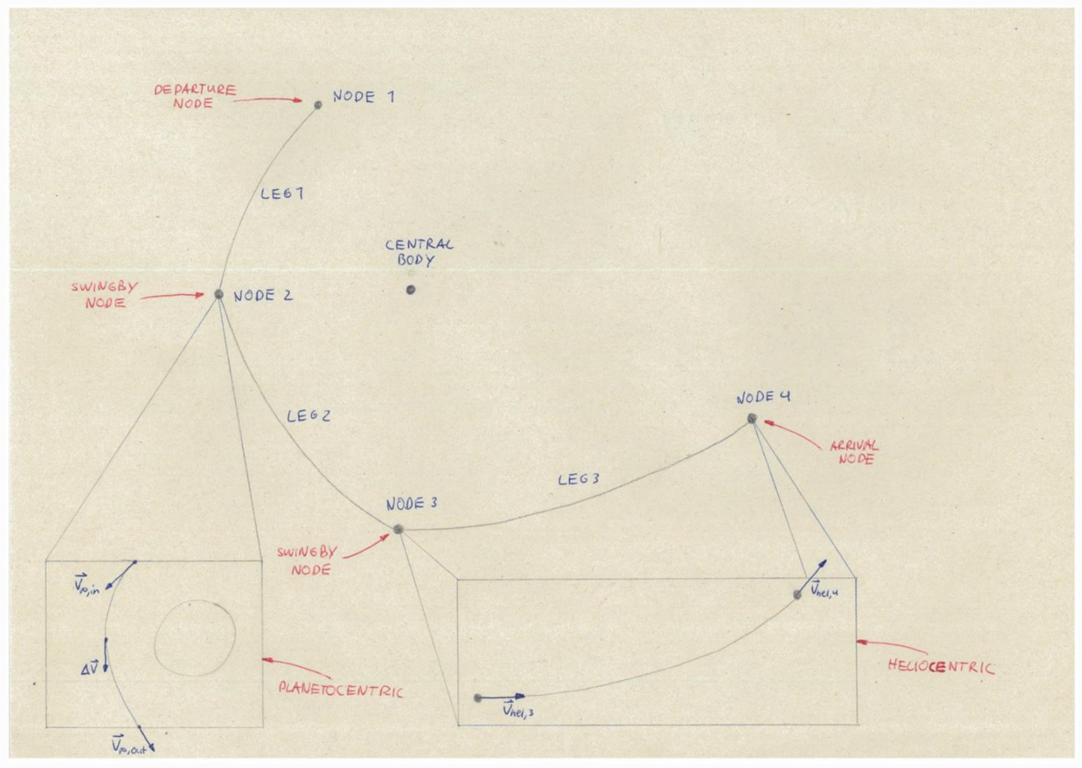
NASA Juno electronics study at Jupiter

Trajectory Tradespace Overview



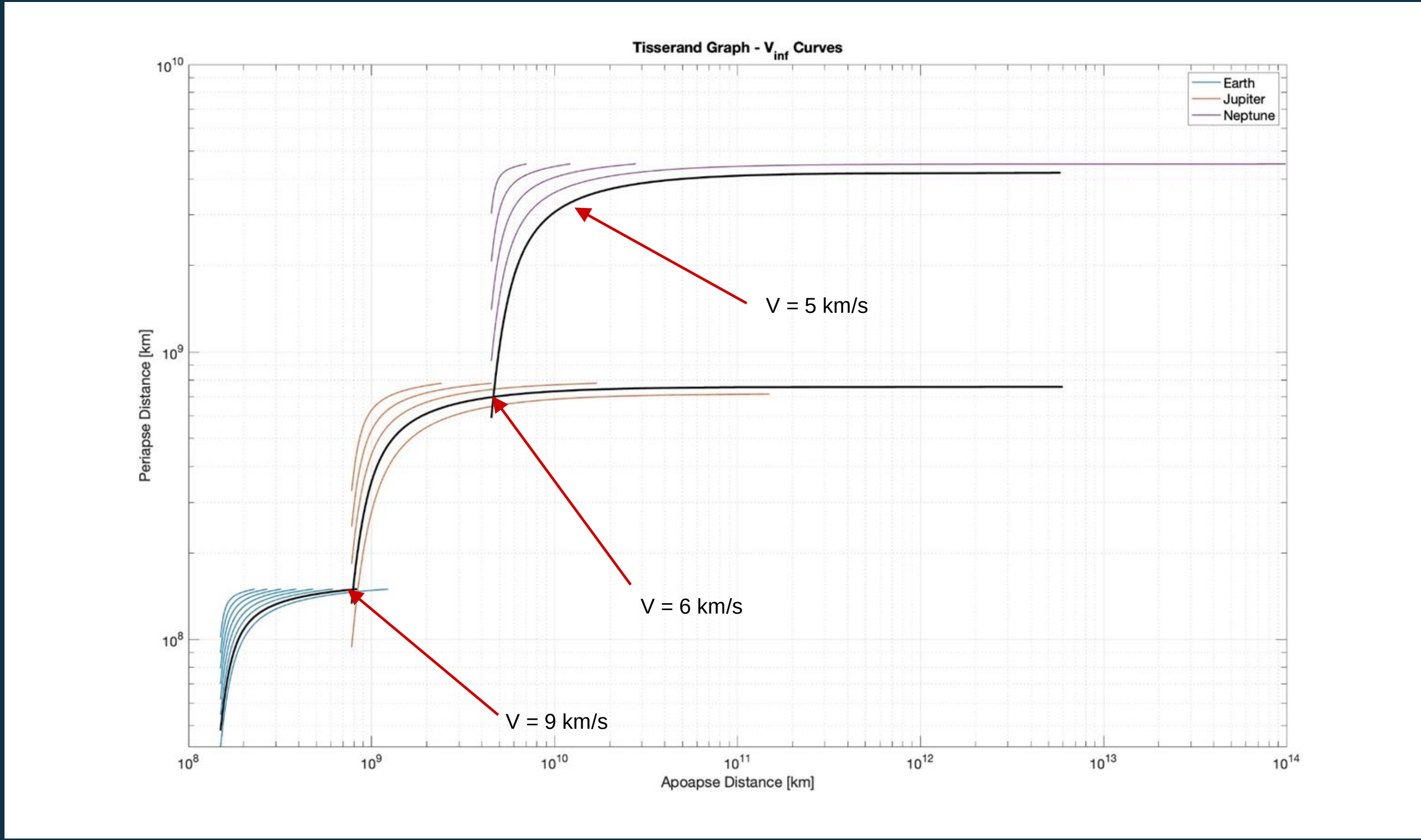
Methodology

- Interplanetary transfer modeled as multi-lambert arc trajectory.
- Science orbits:
    - Two-body-problem (2bp) for Neptune
    - Perturbed 2bp for Triton
- Design space:
    - departure time
    - hyperbolic injection velocity
    - time for each swingby nodes
    - Deep space maneuver (DSM) location (if considered)
- Constraints
    - maximum initial C3
    - minimum periapsis for gravity assist (GA)
    - Arrival declination angle at Neptune
- Global heuristic search

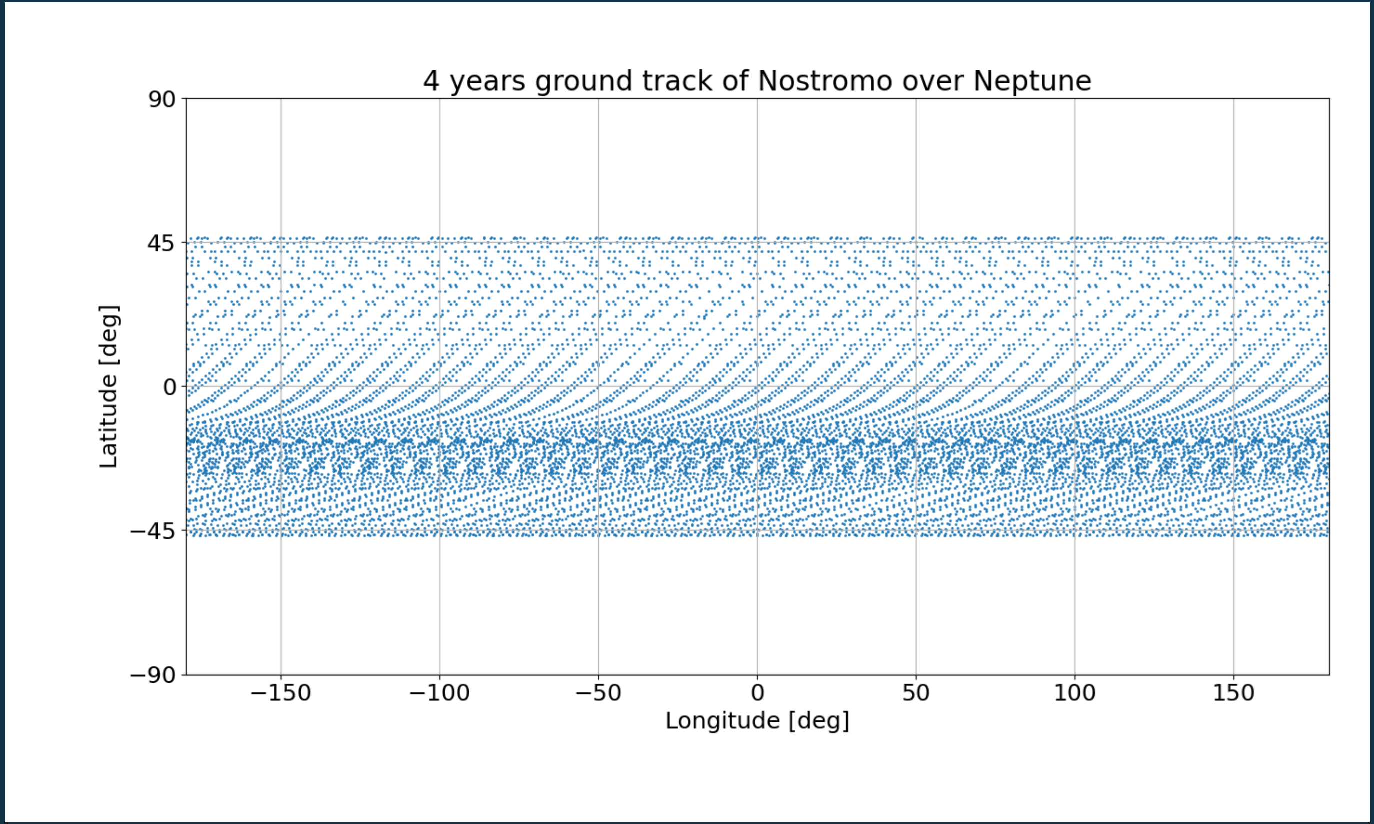


Credit: Musegaas (2012)

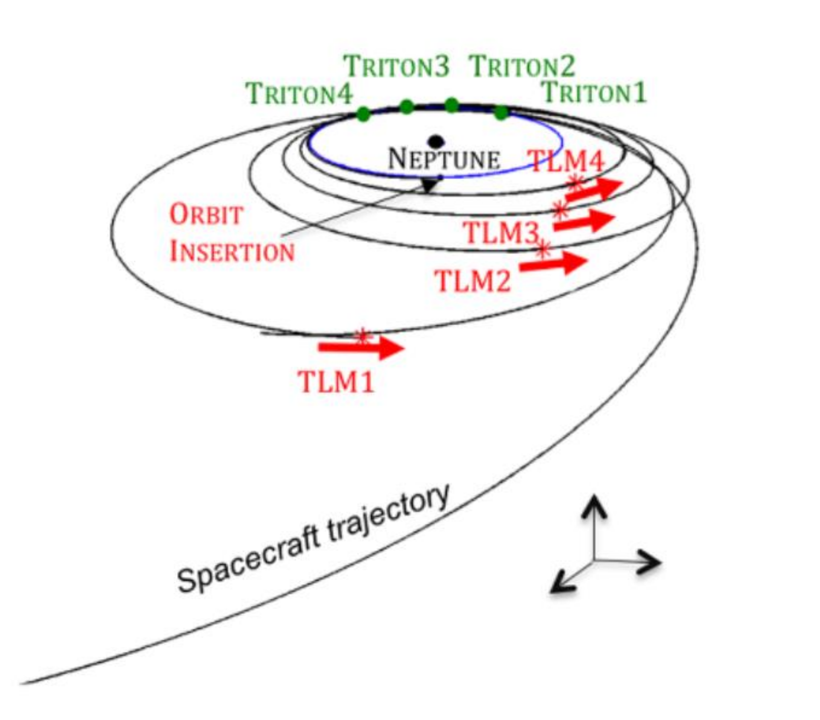
Launch window preliminary analysis



Ground track on Neptune



Neptune to Triton transfer



Credit: Campagnola, Stefano & Boutonnet, Arnaud & Schoenmaekers, Johannes & Grebow, Daniel & Petropoulos, Anastassios & Russell, Ryan. (2012). Tisserand-Leveraging Transfers.

Insertion Trajectory Design - Neptune Insertion

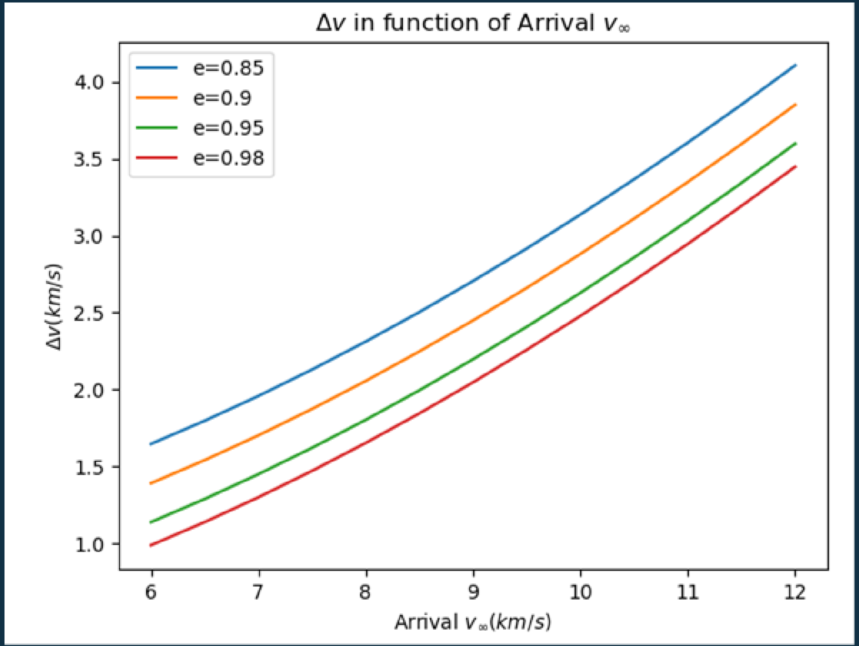
Insertion Orbit:

=> Objective: Minimize insertion cost

- High eccentricity
- Low periapsis altitude

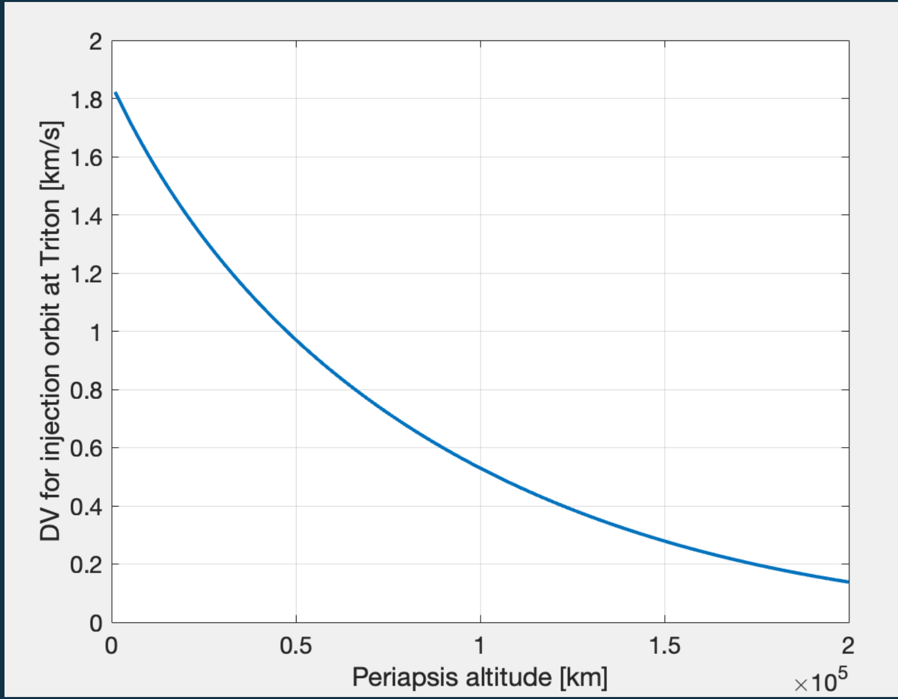
Final selection:

- Eccentricity = 0.98
- Periapsis altitude = 1000 km



Insertion Trajectory Design - Triton Insertion

- Cost from science orbit would be very high.
- It can be reduced by increasing the periapsis altitude of the science orbit.



On-orbit scheduling

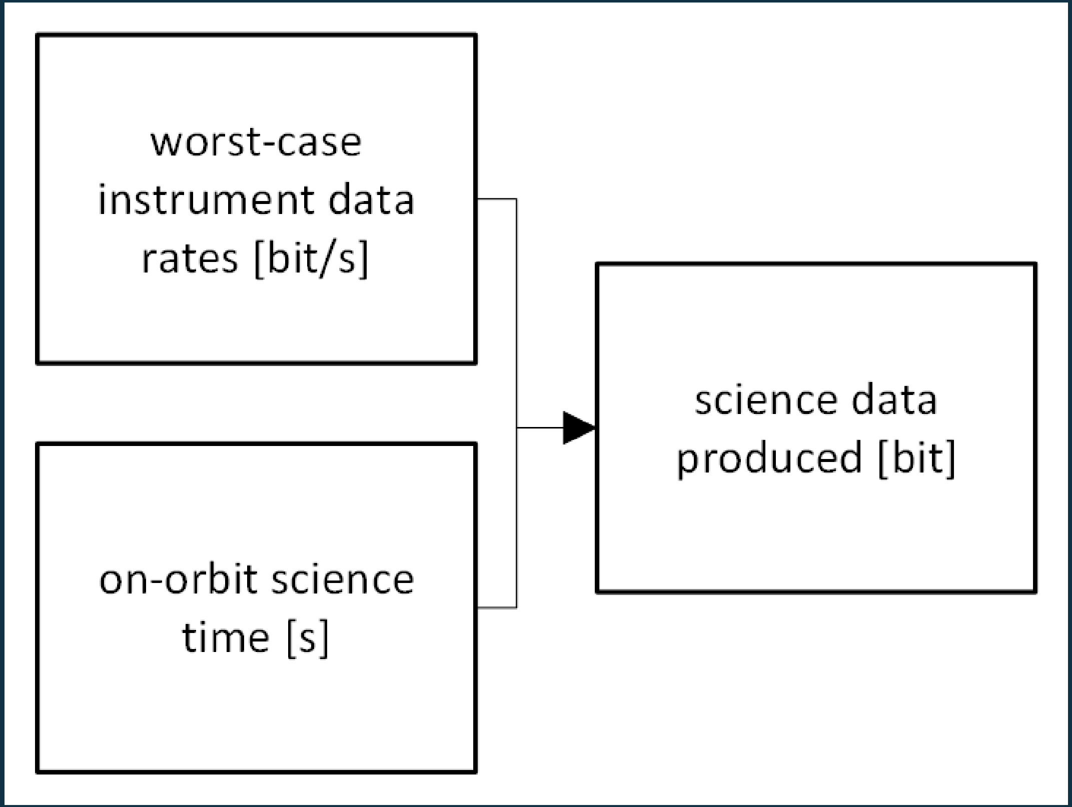
- Driving factors:
    - Science data production
    - Limited power source (rechargeable batteries in addition to RTGs)
    - Limited communication windows
- Sizing for the worst case

Power source selection: battery sizing

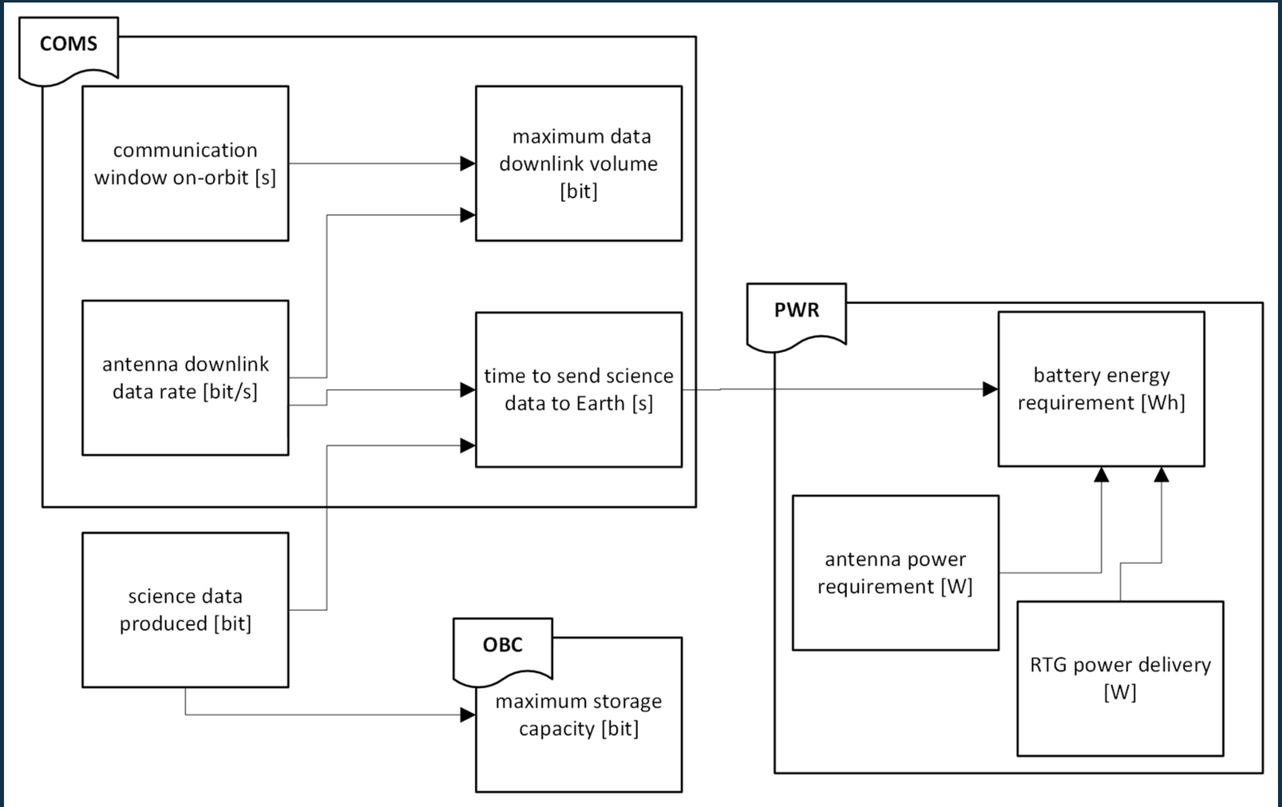
- RTGs not sufficient to cover power-intensive science & downlink power demand
- Selection of COTS SAFT VL51 ES Li-Ion battery with
  - 9300 Wh nameplate energy (~8700 Wh after ~25 years)
  - 75-cell stack (~81 kg mass) sufficient to cover ~270 W power draw in downlink mode
  - Worst-case depth-of-discharge: 61% on Neptune orbit
  - Determines ~24 h recharge time of battery

Credit: SAFT

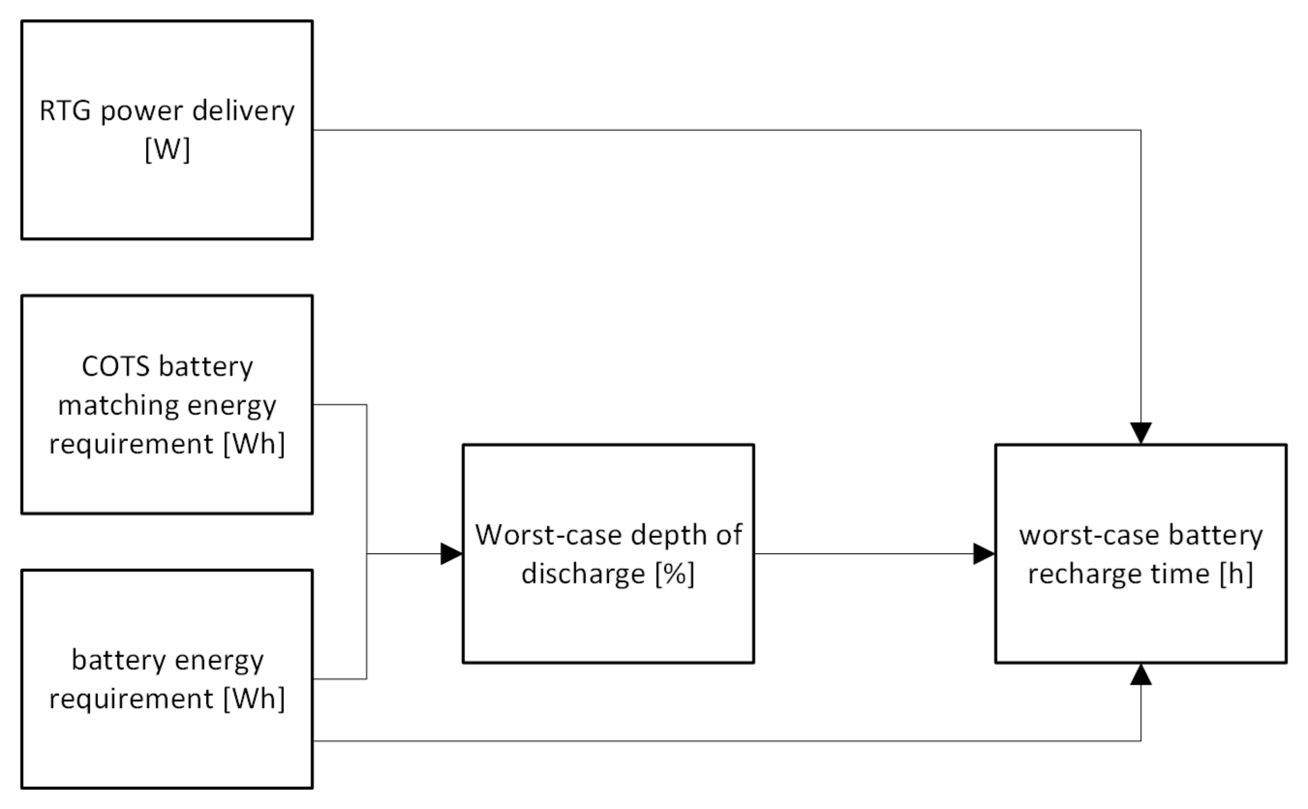
Science data production



Memory & power sizing



Battery sizing



On-orbit scheduling

- Driving factors:
  - Science data production
  - Limited power source (rechargeable batteries in addition to RTGs)
  - Limited communication windows
- Sizing for the worst case

Risk Assessment Instruments

- Due to an extended duration of the space mission, instruments may be at an increased risk of failure.
  e.g. Radiation damage, Mechanical damage, MMOD damage, Power degradation.
- The extended delay before the launch may result in the technology used to design the spacecraft to be dated.
- The risk of failure of the mirror pointing mechanism of the spectrometer need to be taken into account.

Instrumentation

Instrument	Spec #1	Spec #2
Optical Camera	WAC spatial resolution of Neptune: (0.473 - 163.698) km NAC spatial resolution of Triton: (0.9 - 4.7) m	WAC/NAC focal length: 15 / 1500 mm pixel size: 7.1 μm
Laser Altimeter	Measurement frequency: 10 Hz	
UV Spectrometer	spectral range: (68 - 210) nm spectral resolution: 0.6 nm	spatial resolution: 350 μrad/pixel
VIS - IR spectrometer	spectral range: (0.5 - 5.55) μm spectral resolution: 0.6 nm [Vis-NIR], 5 nm [IR]	spatial resolution: 180 μrad/pixel
Mass Spectrometer + Pressure Gauge	mass range of detected neutrals and ions: (1 - 300) amu	mass resolution $M/\Delta M$ = min. 500 amu
Magnetometer	time resolution: 1 s	accuracy: 100 pT
Radio Science instrument	accuracy: Δv=10μm/s	uses ultrastable oscillator
In-situ particle environment package	Measured particles: electron, ions Energetic Neutral Atoms (ENAs)	Electron energy range: 1 eV - 50 keV Ion energy range: 1 eV - 41 keV