# The TUNE & PIANO Mission

*Understanding Ice Giants and their Environments*

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## Abstract

`TUNE` (Triton Unveiler & Neptune Explorer) and `PIANO` (Probe for Inner Atmospheric Neptune Observations) is a mission composed of an orbiter and an atmospheric probe, proposed to investigate Neptune, Triton, and the Neptunian magnetospheric environment. With one-hour probe measurements within Neptune's atmosphere, more than 40 Triton flybys and 600 Neptune close encounters planned, the `TUNE-PIANO` mission will provide insights into the formation, uniqueness, and habitability of Ice Giant systems both within and outside of our Solar System.

## 1 Introduction

### 1.1 Scientific Motivation

Neptune and Uranus are key to understanding the Solar System and its formation. Nevertheless, they are some of the least studied objects of the Solar System. Their compositions are not much constrained and their interesting atmospheres are not well known. Some of the Icy moons of Neptune and Uranus are thought to have in their interiors the key elements for habitability, such as liquid water, energy, and a complex chemistry. Also, as of 2024, about 40 % of the discovered exoplanets have radii and masses comparable to that of Neptune. Studying the Ice Giants in our Solar System will provide essential constraints on current atmospheric and interior models for planets of comparable size and mass and will allow us to determine how unique our Solar System actually is.

The Neptune-Triton system was chosen as the target for the `TUNE` in the first place because of Triton. Triton, the largest of Neptune's moons, is one of the most interesting bodies in our Solar System due to its retrograde orbit, the potential subsurface ocean, and as it might be a captured Trans-Neptunian Object (TNO). Other elements that made us choose the Neptunian system over Uranus are the more active atmosphere of Neptune and his lower rotation axis tilt, which leads to a magnetosphere that is thought to be more representative of a typical Ice Giant. This mission aims to answer the following scientific questions:

- How was Neptune formed and what is its internal and atmospheric structure?
- What is the magnetospheric environment within the Neptunian system?
- Do the conditions around Neptune and Triton allow for the formation of a habitable subsurface environment?

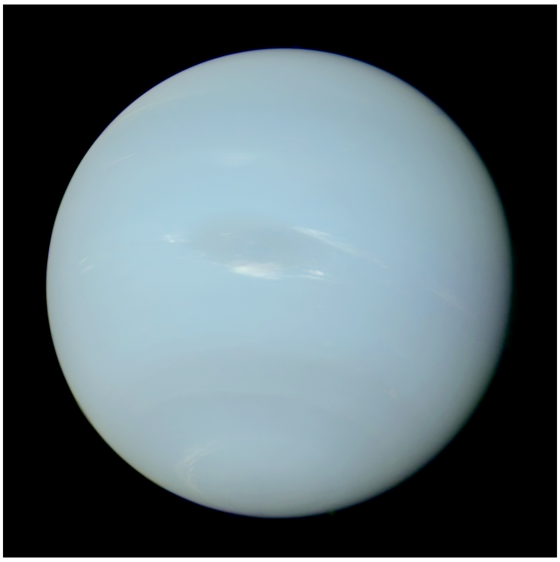

Figure 1: Color-calibrated image of Neptune taken through the green and orange filters on NASA's Voyager 2 narrow-angle camera (Credits: NASA).

### 1.2 Science Background

Voyager-2 was the first and only spacecraft to perform close flybys of the Uranian and Neptunian systems in January 1986 and August 1989 respectively. Voyager's encounter with Neptune (closest approach of 107 000 km) revealed an atmosphere particularly active, especially in comparison with Uranus. Neptune's atmosphere presents large cloud formations featuring the highest wind speeds in the Solar System with velocities up to $400\,\mathrm{km\,s^{-1}}$ [1]. One cloud is visible in Fig. 1. The internal structure and composition of Neptune are poorly constrained and both likely differ from the one of the Gas Giants. In particular, the lack of knowledge about the water and helium content and of the ice-to-rock ratio does not provide many constraints on the internal model of Neptune. The internal composition of Neptune provides valuable insights into the formation and evolution of the Solar System. Understanding the migration patterns of planets during the early stages of the Solar System remains one of the key unanswered questions in planetary science [1]. In-situ measurements of Neptune's internal composition can offer valuable data on the time and location of planetary formation.

The Voyager-2 magnetometer revealed that Neptune's magnetic field axis is tilted by 47° compared to its rotation axis, thereby creating a unique magnetospheric structure which is currently poorly constrained and understood. Neutral escape from Triton's atmosphere is thought to be the main contributor to the Neptunian particle environment, yielding ion densities (mainly $H^+$ and $N^+$) between $1\,\mathrm{cm^{-3}}$ and $8\,\mathrm{cm^{-3}}$ as well as neutral densities up to $100\,\mathrm{cm^{-3}}$ [2]. The Cosmic Ray Subsystem (CRS) of Voyager 2 detected energetic ions and electrons with energies between 20 keV and 20 MeV in the radiation belt of Neptune [3], with which Triton interacts during a fraction of its orbit due to its orbital plane inclination of $\sim$23°. Finally, Voyager-2 detected low-frequency electromagnetic and electrostatic plasma waves at Neptune [4], but many questions remain regarding their generation mechanisms and implications for particle acceleration in the Neptunian magnetosphere. Triton may be one of the most intriguing and interesting objects in the Solar System. Its retrograde orbit suggests it was likely not formed inside the Neptunian system but captured by the Ice Giant [5]. Triton could therefore have belonged to the TNO class and share similarities to Pluto, being in a 3:2 resonance with Neptune. The capture will have had dramatic effects on Triton, dissipating enough energy to melt the icy mantle of Triton multiple times over and perhaps forming a temporary thick atmosphere [6]. However, the exact formation history of Triton remains unknown. Surprisingly, given its distance to the Sun, Triton shows significant geological activity as suggested by its young surface and features which could be associated with cryogenic volcanism (Fig. 2). Several kilometre-tall dark plumes were observed about 50° south of the equator on Triton [7]. This location means that they disappear into "winter" darkness around the 2070s, making it extra important to go back sooner rather than later. While it is suggested that these plumes are composed of Nitrogen, carrying aloft carbon-rich materials and possibly ice crystals, their exact composition and origin remain unknown. This geological activity, coupled with a possible sub-surface ocean on Triton motivates the search for habitable conditions in the Neptunian system.

Figure 2: Global colour mosaic of Triton (Voyager 2) combining high-resolution images taken through orange, violet, and ultraviolet filters. The dark spots on the bottom of Triton are the suspected plume deposits. (Credits: NASA)

## 2 The `TUNE` mission

The `TUNE-PIANO` mission concept, which consists of an orbiter and atmospheric probe (`PIANO`), will provide high-quality data of the Triton-Neptune system to a wide range of scientific communities, including Solar System and Planetary Formation, Comparative Planetology, Exoplanet Sciences, Planetary Atmospheres, Space Plasma Physics, or Astrobiology. The orbiter will be placed in a Neptune-centric elliptical orbit. The atmospheric probe `PIANO` will perform in-situ measurements in the atmosphere of Neptune to investigate its composition and physical properties as a function of altitude down to 10 bar. For correct insertion into the Neptunian atmosphere, the `PIANO` probe will be released by the orbiter one month before the Neptune Orbit Insertion (NOI) burn. The probe will enter Neptune's atmosphere on the night side of Neptune while the orbiter flies over it and extracts the data. Entry on the night side of Neptune does not impact our results.

The initial phase of the mission will take one year, during which the eccentricity of the orbit will remain large, therefore Neptune's magnetosphere can be thoroughly measured. During this time, we will perform about 15 Triton flybys to perform in-situ measurements and slowly rotate the perigee of the orbit around Neptune (see Sec. 5). In the second part of the mission, which will last four years, the focus will be more on Triton and the orbit will be accordingly adjusted to allow for more flybys. To reach the science objectives (see Sect. 3) the orbiter will perform more than 600 orbits.

After the nominal scientific operations of `TUNE`, the mission design allows for a mission extension if the spacecraft is considered safe to operate. On mission termination, the orbiter will perform a controlled entry in Neptune's atmosphere following the COSPAR recommendations, with a possibility of performing measurements until loss of communications.

## 3 Science Objectives

The science objectives of the `TUNE` mission are summarized in the following:

SCI.1 Determine Neptune's atmospheric composition, its dynamics, key isotope ratios, and the clouds and haze compositions.

SCI.2 Measure how the pressure and temperature change with altitude in Neptune's atmosphere.

SCI.3 Determine Neptune's interior structure and composition, and study the history and formation of the rings and moons.

SCI.4 Study the energy balance and energy transport mechanisms of the Neptunian atmosphere.

SCI.5 Study the formation and current structure of Neptune's magnetic field.

SCI.6 Determine the plasma composition in the Neptunian system and study the plasma interactions between Neptune and Triton.

SCI.7 Determine Triton's interior and study its geological processes.

SCI.8 Determine Triton's surface composition and processes.

SCI.9 Determine Triton's atmospheric composition and study the composition and physical parameters of the plumes.

## 4 Instrumentation

Most scientific observations require a close orbit around Neptune at distances between $1\,R_N$ and $6\,R_N$ with a wide coverage of latitudes and longitudes both on the dayside and nightside. At least 40 Triton flybys are required at varying altitudes between 200 km and 1000 km altitude for multi-spectral imaging. Our mission also includes stellar occultation measurements at both Neptune and Triton. Magnetospheric and plasma measurements require an initial orbit with a large apogee and eccentricity to scan all domains of the magnetosphere between $1\,R_N$ and $50\,R_N$.

Due to the low solar irradiance at Neptune, all our optical instrument heritage will be based upon the New Horizons mission but will include advances made for the JUICE mission. Most other instruments can trace their heritage solely to the JUICE mission.

The orbiter scientific payload includes 9 instrument packages:

- The **High-resolution Cameras** (HRC), including a narrow and wide Field-of-View (FOV) visible camera, will image the surface of Triton with a ground resolution higher than $150\,\mathrm{m\,pix^{-1}}$. The HRC will also image the rings and the atmosphere of Neptune, and perform a survey of the moons of Neptune. The wide FOV camera will be used for navigation and public outreach.
- The **Pushbroom IR/Visible Hyper-spectral Imager** (IVHI) to investigate the composition of Triton's surface and atmosphere, as well as Neptune's atmosphere and clouds with a spectral range of 0.5-5.5 µm (5 nm resolution) and surface resolution of $150\,\mathrm{m\,pix^{-1}}$ on Triton.
- The **UV imaging Spectrometer** (UVS) will be used to investigate Neptune's atmospheric composition and auroras, the composition of Triton's plumes and perform stellar occultation. It will have a spectral range of 55-250 nm ($\Delta\lambda = 1\,\mathrm{nm}$).
- The **Sub-mm heterodyne radiometer** (SHR) will investigate Triton's and Neptune's atmosphere isotope ratios and composition in the spectral range of 200-1000 µm.
- The **Altimeter** will be used to investigate the subsurface structure of Triton by measuring radial uplift due to the tidal response, the surface small-scale roughness and the albedo of Triton's surface.
- The **Magnetometer** (MAG) will measure magnetic fields in $\pm 60\,\mu\mathrm{T}$ to investigate the origin of Neptune's magnetic field, as well as the interior structure of Triton.
- The **Ultra Stable Oscillator** (USO) will be part of the communication electronics and will be used to perform radio-science experiments to investigate the interior structure of Neptune and Triton.
- The **Plasma Environment Investigator** (PEI) will measure ions (10 eV-5 MeV), electrons (10 eV-10 MeV), and atoms and molecules (0.01 eV-4 keV) using five sensor heads to characterize the particle environment at Triton and in the Neptunian magnetosphere.
- The **Plasma Wave Investigator** (PWI) will measure electromagnetic and electrostatic plasma waves in the 10 Hz to 60 kHz 60 kHz frequency range using four Langmuir probes and one 3-axis Search-Coil Magnetometer to investigate particle acceleration processes inside Neptune's magnetosphere.

`PIANO` will include the following instruments:

- **Time of Flight mass spectrometer** (TOFMS) will perform in-situ measurements of the atmospheric composition as a function of altitude.
- The **Atmospheric Structure Instrument** (ASI) will measure the atmospheric temperature and pressure profiles.
- The **Doppler Wind Experiment** (DWE) will measure the wind speeds and directions with an accuracy of $0.1\,\mu m\,s^{-1}$. The experiment also includes a USO.
- The **Nephelometer** will measure aerosols and their scattering properties within Neptune's atmosphere with a sensitivity of $1.1 \times 10^{-8}\,m^{-1}\,sr^{-1}$.
- The **Net Flux Radiometer** (NFR) will investigate how energy is transported within Neptune's atmosphere using 7 filters in the 0.2-300 µm spectral range.
- The **He Abundance Detector** (HAD) will measure the Helium-abundance in Neptune's lower atmosphere as a function of altitude.

# 5 Mission Design

Neptune is the furthest planet in our Solar system with an average distance to the Sun of 30 AU. This distance constitutes one of the main design challenges of the `TUNE` mission. Different options to reach Neptune have been analyzed, where the easiest option would be a direct transfer from Earth to Neptune. Since this transfer requires hyperbolic excess velocities of over $9\,km\,s^{-1}$, this is not feasible, as it exceeds the performance envelope of current and planned European launchers.

Other options utilize planetary swing-bys to increase the energy of the spacecraft's orbit. Almost all such trajectories have a flyby at Jupiter, due to its gravitational potential. Due to the relative position between Jupiter and Neptune, useful swing-by opportunities occur only every 13 years for around one year. This cycle is the main driver for the trajectory design.

We decided to target the Jupiter swing-by window in 2044. To reach Jupiter, multiple swing-by trajectories have been investigated. The main trade-off parameters were travel duration, $v_{\text{inf}}$ after launch and the required $\Delta v$ for Neptune orbit insertion. The last two are directly linked to the achievable dry mass and have therefore the highest importance. `TUNE` will have an Earth-Venus-Earth-Earth-Jupiter-Neptune trajectory with a targeted launch window in October 2037 which can be seen in 1. This trajectory requires a $v_{\text{inf}}$ at departure of $3.4\,km\,s^{-1}$ and an arrival $v_{\text{inf}}$ of $9.8\,km\,s^{-1}$ and takes 19 years. Alternative launch windows are in November 2037 and in Q4 of 2038. The probe will be deployed 27 days before performing the NOI burn. The $\Delta v$ budgets

| **Location** | **Date** | $V_\infty$ (km s$^{-1}$) |
|---|---|---|
| Earth | October 2037 | 3.4 |
| Venus | March 2038 | 5.3 |
| Earth | January 2039 | 9 |
| Earth | January 2041 | 9 |
| Jupiter | September 2044 | 6.5 |
| Neptune | November 2056 | 9.8 |

Table 1: Planetary swing-bys with date and v-inf during TUNE trajectory

for this manoeuvre and the operation in the Neptunian system are shown in 2.

| **Maneuver** | $\Delta v$ (km s$^{-1}$) |
|---|---|
| Neptune Orbit Insertion | 2.7 |
| Periapsis raising maneuver | 0.22 |
| Triton swing-bys | $50 \times 0.01 = 0.5$ |
| Total delta-v including 20% margin | 3.76 |

Table 2: Delta-v Budget

The NOI manoeuvre puts `TUNE` into a highly-eccentric retrograde orbit with an apoapsis radius of $50\,R_N$, coplanar to Triton's orbit. This high eccentricity is necessary to observe the entire magnetosphere including the shock bow it forms at the interaction with the solar winds. At the apoapsis of the first orbit, the spacecraft performs a burn to raise the periapsis to two Neptune radii to fulfil the observation requirements. `TUNE` will stay for about one year in an orbit with this semi-major axis, using Triton swing-bys to rotate the argument of perigee to fully analyse the magnetosphere. This process is called orbit cranking and has been used in the tour design for Cassini-Huygens [8]. A similar technique is orbit pumping, which we will use to transition to an orbit with an apogee closer to Tritons. This orbit is used to have closer, longer and more frequent Triton flybys. A visualisation of the orbits can be seen in 3

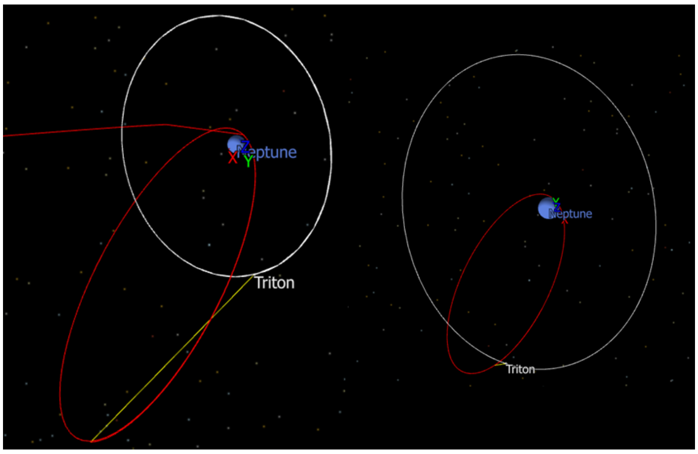


Figure 3: High-eccentricity orbit (left), Triton investigating orbit (right)

## 6 Space Segment

The design of our spacecraft is the result of trade-offs between the observation requirements (pointing accuracy, observation time, mission lifetime, instrument data rates, etc.), and the constraints related to the environment and location of Neptune (thermal, radiation, limited power and telecommunications, etc.). For a mission to Neptune especially, the long mission lifetime, the low data rate and the need for RTGs posed the biggest problems for our spacecraft design.

### 6.1 Probe Design

To have a successful probe insertion into the harsh Neptune environment, careful analysis of all the subsystems must be conducted. The analysis depends on the atmosphere's temperature, density and pressure profile, as well as the entry parameters of the probe.

After careful consideration of possible orbits, the probe was chosen to enter the atmosphere in retrograde. To have less heat flux and a trajectory suitable for data relay during the whole descent the flight path angle is $-25°$. Therefore, the relative velocity is $28\,\mathrm{kms}^{-1}$. With these considerations among others, the subsystems were designed, as seen in 4.

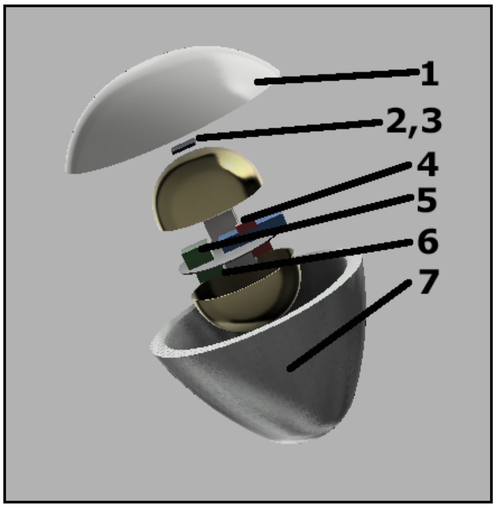


Figure 4: Probe design with the critical subsystems, where each one is described in section 6.1

1. **Back shell**: A lightweight shell, provides thermal insulation and acts as a barrier regulating the pressure throughout the different stages.
2. **Parachute**: Crucial to slow down the descent of the probe at the right velocity, it is optimized with the time window of the possible data relay and preferred depth of 10 bar for the scientific goals. Simulations revealed that a parachute size of 15 m was optimal for the descent.
3. **Data relay**: An S-band low-gain antenna is mounted at the rear of the probe to ensure omnidirectional communication with the medium-gain antenna of the orbiter. Its 2 kbps datarate allows for transmission of 0.95 MB of scientific data.
4. **Thermal control**: During the cruise phase, the probe's electronics require the temperature to remain higher than $-10°$. We use 37 Radio-isotopic Heat Unit (RHU) distributed evenly around the probe to maintain the interior of the descent module within operational temperatures and alleviate the need for battery capacity for thermal control. Multi-layer insulation will be used for all external parts.
5. **Data management**: Placed in the centre of the probe to centralise internal communications between the instruments and the data transmission system.
6. **Power supply**: The electrical power subsystem (EPS) ensures power for all subsystems and scientific instruments. Two lithium thionyl chloride batteries are used: one low-voltage (6.8 V) to power a timer circuit activated upon probe separation from the orbiter, and a high-voltage power (26 V) cell.
7. **Heat shield**: Without a heat shield, the probe would not survive the entry into Neptune. By modelling Neptune's atmosphere, including the entry parameters and the probe size, it was possible to constrain that the heat shield mass can be between 50-100 kg, taking into account the heat load, g-load and time of deceleration [9].

### 6.2 Orbiter Design

#### 6.2.1 On Board Data Handling (OBDH)

The overall system design and the preliminary electrical architecture of the system can be seen in Figure 5. The onboard computer (OBC) of `TUNE` is responsible for the control functions of the system, including communication, navigation, attitude and orbit control. The OBDH system is split into the OBC and a payload computer, responsible for data compression, analysis and storage until transmission.

#### 6.2.2 Propulsion

`TUNE` needs a propulsion subsystem to perform its Neptune Orbit Insertion burn, navigate in the Neptunian system and control its attitude. To perform high-thrust manoeuvres with high specific impulse, a bipropellant system was chosen. Due to its strong heritage and its low freezing point, we decided to use monomethylhydrazine (MMH) as fuel with dinitrogen tetroxide ($N_2O_4$) as oxidizer. Since this bipropellant can be also used for the ADCS thruster, we save tank mass and reduce complexity. To store the propellant, we decided

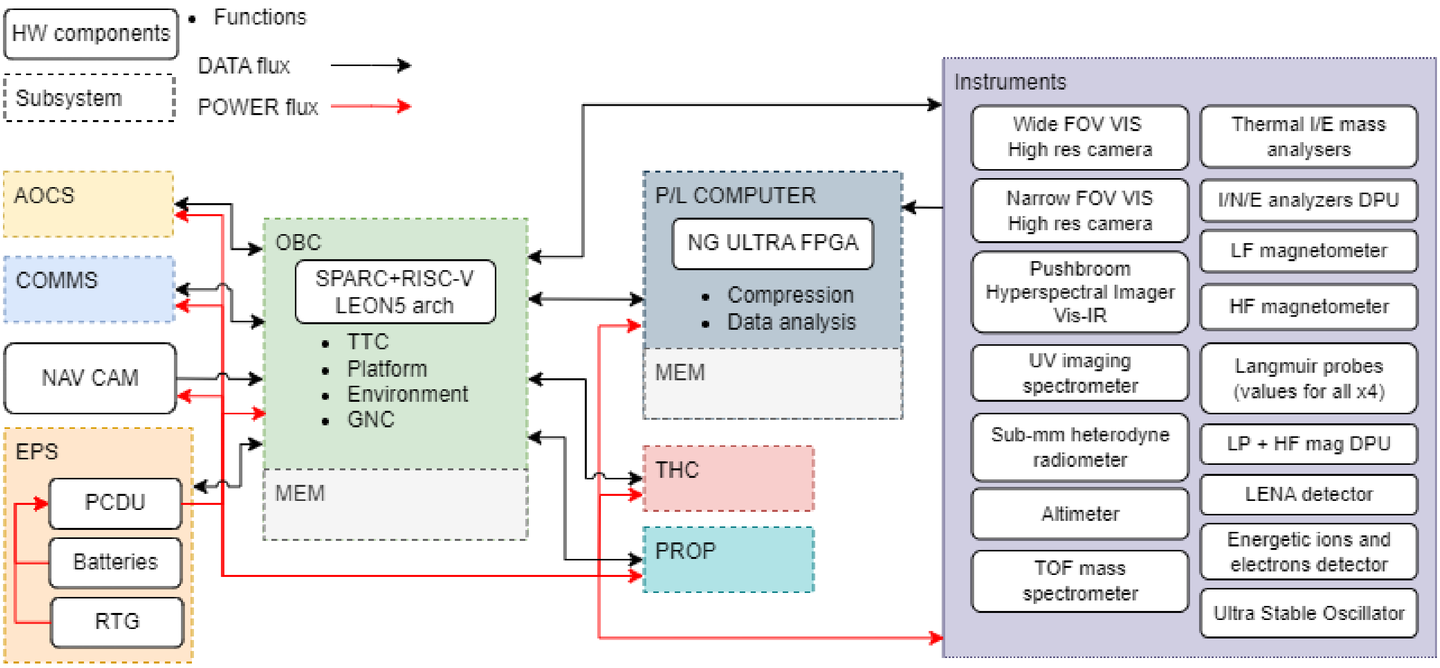


Figure 5: Data and power flow of `TUNE`.

to go for a setup of two propellant tanks, two oxidizer tanks and two pressurizer tanks. This has the advantage of keeping the COG stable and adds redundancy in case of a potential leak or blockage. Helium is chosen as a pressurant gas due to its low mass compared to nitrogen. The MMH tanks will be cylindrical with semispherical ends to fit on the spacecraft and reduce their thickness as much as possible. The smaller oxidizer and pressurizer tanks will be 0.5 m and 0.27 m spherical tanks. For the engine itself, the main design drivers were lightweight design, high thrust and reliable re-ignitability. We decided to go with two engines with gimbaled nozzles to be redundant in case of failure. We sized the engine similar to the R-42 from *L3Harris* currently under development. Such an engine is able to provide 900 N of thrust with a specific impulse of 303 s at a very low mass of 5-10 kg.

### 6.2.3 Structure

The spacecraft structure is mainly driven by the mechanical loads experienced by the space segment during launch and by the volume required to accommodate the instruments and propulsion system. To accommodate the critical components and the requirements of the scientific instruments, such as nadir pointing, the overall configuration of the orbiter was chosen as shown in Fig. 6.2.3. This includes a hexagonal shape for the outer body of the main structure, with the main support structure being a cylinder extending through the length of the main body. This cylinder is an extension of the Payload Adapter (PLA6) of the chosen launcher made of carbon-fibre reinforced polymer (CFRP). Support structures are placed internally from the walls to the cylinder for structural integrity and accommodation of the payloads as shown in 6.2.3. The outer walls of the structure were chosen to be a honeycomb aluminium structure enclosed between two 5 mm aluminium walls.

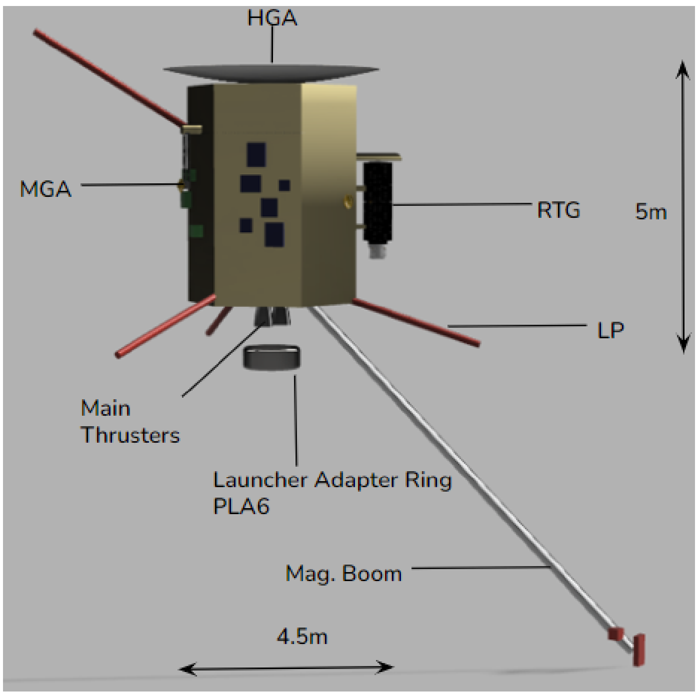


Figure 6: 3D representation of `TUNE` mission.

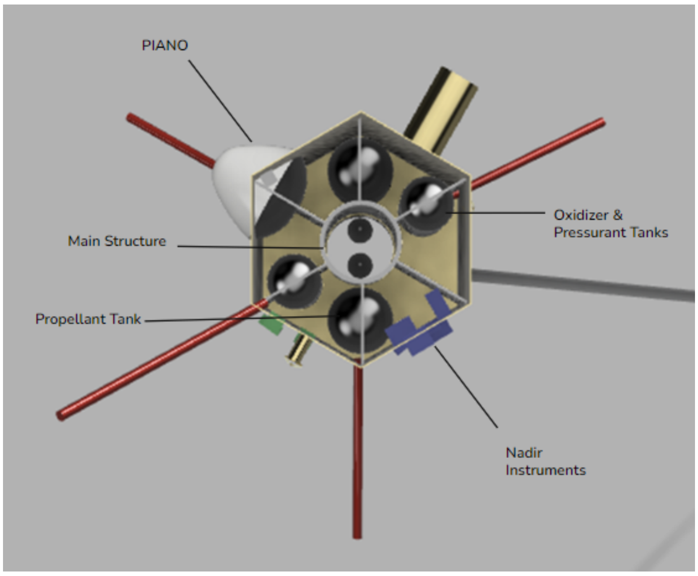

Figure 7: Internal structure of the orbiter with allocated space for the instruments and PIANO.

#### 6.2.4 Attitude & Orbit Control System (AOCS)

The AOCS system was sized based on slew rate requirements for the beginning of the orbit (full rotation in less than 100 s for a 8 ton S/C) and operations around Neptune (180° rotation in less than 20 min for a 3 ton S/C). To comply with the navigation requirements at the beginning of the orbit, the S/C is equipped with 12 thrusters with an individual thrust of 10 N positioned at its corners to maximize the lever arm with respect to its centre of gravity. Due to the high pointing accuracy required during communication and observation phases ( <0.01°), we use four reaction wheels to point the spacecraft. Based on the operational requirements, these reaction wheels must provide a minimal torque of 0.2 nm, which is compatible with the typical performance of AOCS reaction wheels. The acceleration and angular rate of the spacecraft is determined using three high-precision IMUs (2/3 redundancy). Critical absolute attitude determination systems, i.e. the Sun sensor (for early flight phase) and Star tracker, are redundant. Together, the AOCS components (Table 3) weigh a total of 137 kg (20 % margin) and consume a peak power of 112 W during science data transmission.

#### 6.2.5 Communication system

The orbiter communication system includes three antennas: (1) a high-gain antenna for transmitting science data to Earth and for the radio-science experiment, (2) a movable medium-gain antenna for telecommands and telemetry, and (3) two low-gain antennas for safe operation modes and de-tumbling.

The link budget for the high-gain antenna was estimated for the two typical orbits (small/large eccentricity) from the preliminary data rates of the scientific

| **Component** | **Num.** | **Mass** [kg] | **Power** [W] |
|---|---|---|---|
| Gyroscopes | 3 | 15 | 205 |
| Sun sensors | 2 | 0.6 | 0.5 |
| Star sensor | 2 | 3 | 5 |
| NavCam | 1 | 8 | 2 |
| React. wheels | 1 | 30 | 50 |
| Thrusters | 12 | 2 | 4 |

Table 3: AOCS component selection. The provided specifications are conservative estimates based on similar components for previous satellites and interplanetary missions.

payload. The data budget (Table 4) was derived for each of the three typical science observation schemes: (1) close Triton encounter, (2) close Neptune encounter, and (3) Magnetosphere (MS).

| | **Large orbit [GB/orb.]** | **Small orbit [GB/orb.]** |
|---|---|---|
| **Neptune** | 0.54 | 0.08 |
| **Triton** | 0.70 | 0.14 |
| **MS** | 0.08 | 0.02 |
| **Total w/ margin** | 1.80 | 0.33 |

Table 4: Data budget for the large eccentricity (15 days) and small (2.5 days) orbits. Margins include 10% link margin and 30% additional bits for error correction.

We selected a 4.5 m diameter high gain antenna (HGA) with a transmission power of 39 W in the Ka band (32 GHz). Using the ESTRACK antenna network, we can transmit up to 0.14 GB/day (8 hour intervals), allowing us to transmit the totality of the science data during each orbit. The 0.6 m diameter medium gain antenna (MGA) is based on JUICE's medium gain antenna. Its pointing system features two degrees of freedom, allowing it to point the antenna in a direction independent of the S/C pointing direction. The articulation is stowed during launch to protect the system. With this design, we can transmit up to 0.12 MB (8 hour intervals) of telemetry/telecommands in the X band. Finally, the 0.05 m low gain antennas (LGA) are used to communicate with the spacecraft in the S-band (2 GHz) in safe modes. As explained in the probe design data relay, the LGA on the probe will communicate to the MGA on the orbiter and transmit the science data.

#### 6.2.6 Power

As the use of solar power around Neptune requires impractically large solar arrays, we use a radioisotope thermoelectric generator (RTG) to deliver power to the spacecraft subsystems. This technology converts the heat generated by the decay of radioactive isotopes (most commonly plutonium-238) into electrical power. Despite this advantage, RTGs come with several constraints and risks. In particular, the heat and radiations generated can potentially damage instruments and processing units. We therefore kept the S/C consumption to a minimum to limit the number of required RTG's.

The RTG used on previous outer solar system missions was the General Purpose Heat Source RPG (GPHS-RTG), which generates a total of 300 W of electrical power at the beginning of life (BOL) [10]. As shown by Table 5, at least 2 generators of this kind (3 if we take into consideration the RTG's degradation as the plutonium decays) are required to cover the subsystem requirements. While a new type of RTG is currently being developed in the United Kingdom to replace plutonium by americium-241 [11], the latter generates even less power possesses a worse specific power than plutonium.

Taking this into consideration, the mission will use a novel Advanced Stirling Radioisotope Generator with an electrical output of 500 W (ASRG-500) [12]. This RTG uses the same fuel as the GPHS-RTG, but incorporates a Stirling engine for converting the thermal power into electrical power. This RTG is still in development (TRL 3), however a smaller version has already been tested in a laboratory [13]. In the context of this work, the ASRG-500 was assumed to have an efficiency of 20 %, which is a conservative estimate, and a degradation rate of 1 % per year. It is also important to note that, due to ARSG-500's low development status, it is still possible to adapt the mission to carry RTG's with a higher TRL (such as GPHS-RTG).

To accommodate for possible peaks and buffer some power, a Li-Ion battery with a capacity of 415 W h is used as a secondary source. The power system will furthermore include a power control and distribution unit (PCDU) capable of handling the mission requirements. Both are based on commercial-off-the-shelf (COTS) components (EXA Titan2 and EXA Colossus, respectively).

The power budget that allowed dimensioning of the power subsystem can be seen in table 5. It should be noted that it represents a worst-case scenario where, for example, a large amount of instruments are turned on at the same time, even if this would not happen in the actual mission.

| **Subsystem** | **Power SCI** [W] | **Power COM** [W] |
|---|---|---|
| Payload | 107.50 | 6.50 |
| Comms | 0.00 | 78.00 |
| Propulsion | 18.00 | 18.00 |
| AOCS | 112.20 | 112.20 |
| OBDH | 40.00 | 40.00 |
| Thermal | 20.00 | 20.00 |
| Power | 55.00 | 55.00 |
| Structure | 0.00 | 0.00 |
| **Total** | **387.97** | **362.67** |

Table 5: Power consumption by subsystem on two different power modes (science and communications). A margin of 10% was used for the grand total.

#### 6.2.7 Thermal Control System

The thermal control system is separated into two sections: the *front* and *rear* sections. The front section, containing the scientific payload, the OBC, transceivers, and the AOCS subsystems, is mostly covered with an MLI of emissivity $\epsilon_{MLI} = 0.01$. Instruments, like the IVHI, which needs to be maintained at 100 K, are thermally isolated from the other subsystems and equipped with instrument-level active thermal control based on radiators and Peltier elements. Due to the large distance from the Sun, the solar flux as well as the Neptunian albedo and thermal infrared flux can be neglected compared to the power dissipation inside the orbiter [14]. Based on 300 W of electrical power dissipated in the front section during nominal operation, 25 m$^2$ covered by MLI, as well as a total of 1 m$^2$ of exposed openings and instrument radiators, the cold case equilibrium temperature of 0 °C was estimated. The rear section includes the propellant tanks, which require a minimal temperature of 230 K, and the 2500 W (thermal power) RTG mounted on the exterior of the spacecraft, as well as protruding thruster nozzles, which cannot be covered by MLI. The side walls are covered with MLI, while the backplate is exposed with $\epsilon_{Backplate} = 0.7$. The excess heat generated by the RTG is transferred into and distributed in the rear structure by an actively pumped coolant loop. This allows active control of the thruster and fuel temperature. The equilibrium temperature of the rear section, based on the RTG thermal power, surface area and emissivity would be 21 °C at Neptune.

During Venus flyby, the spacecraft operates in low-power mode (160 W) and is shielded from the sun using the high-gain antenna. The latter is coated with a highly reflective and IR emitting paint (e.g. AZ-93), maintaining its temperature below 45 °C. The backplate is exposed to 222 W m$^{-2}$ Venus albedo flux, but will remain below 35 °C.

#### 6.2.8 Radiation Mitigation

During the Jupiter flyby, the spacecraft will pass Jupiter at a distance of at least 30 Jupiter radii, which means the spacecraft will pass outside the Jovian radiation belts.

According to the JPL Neptune Radiation Model (NMOD) [15] the dose rates in the Neptunian radiation belts are expected to be below $2 \times 10^{-4}\,\mathrm{rad\,s^{-1}}$ behind 2.54 mm of spherical aluminium shielding [16]. Assuming 2.54 mm aluminium equivalent shielding, the long-term average dose rate due to trapped particles in orbit around Neptune can therefore be expected to be significantly below $500\,\mathrm{krad\,month^{-1}}$ or 30 krad for a 5-year mission at Neptune.

According to the SAPPHIRE model, the dose rate due to solar energetic particles (SEP) behind 2.54 mm of aluminium shielding is expected to be below $1\,\mathrm{krad\,year^{-1}}$ [17–19]. For a total mission duration of 25 years of which 5-years are spent at Neptune, the total ionising dose (TID) is expected to be below 55 krad behind 2.54 mm of aluminium equivalent shielding.

The Neptunian radiation environment is dominated by electrons [15]. Optimised multilayer radiation shielding with low-Z materials (PE) on top of high-Z materials (Pb), can reduce TID from energetic electrons by up to 50 % compared to aluminium shielding of the same mass [20]. This could enable the use of COTS electronic components for non-mission-critical systems, reducing costs and allowing higher performance.

#### 6.2.9 Mass budget

A bottom-up mass budget was made for the spacecraft and is shown in Table 6 one the left side. Each component has a margin added based on its maturity level (5, 10 or 20 %). To the right, the mass budget for the probe is displayed. The mass budget of the probe was based on previous missions [21], as well as analysis made of the scientific instruments and subsystems.

| Component | Mass (kg) | Component | Mass (kg) |
|---|---|---|---|
| Payload | 163.44 | Payload | 31.64 |
| Propulsion | 300 | Front Shield | 91.26 |
| CDH | 21 | Back Cover | 18.59 |
| Comms | 171.6 | Separations | 13.00 |
| Antenna | 108 | Descent Control | 13.84 |
| TxRx | 48 | Inner Structure | 47.24 |
| Cabling | 15.6 | Thermal Control | 23.50 |
| Thermal | 120 | Power Supply | 5.00 |
| Power | 144 | Probe Harness | 14.38 |
| AOCS | 137 | Data Management | 5.70 |
| Structure | 430 | Data Relay | 6.89 |
| System margin | 297 | System margin | 60.00 |
| Probe | 364 | | |
| **Total dry mass** | **2256** | **Total dry mass** | **364** |

Table 6: Mass budget for the spacecraft and probe

## 7 Cost estimation

The preliminary cost estimate was performed based on the payload and presented in Table 7.

| Cost Breakdown | |
|---|---|
| **Item** | **M €** |
| RTG | 150 |
| Probe | 350 |
| Orbiter | 500 |
| **Sub Total** | 1,000 |
| MOC (+ 20% of Industry) | 180 |
| SOC (+ 20% of Industry) | 180 |
| ESA Project Team (+ 25% of Industry) | 312.5 |
| Launchcost | 150 |
| **Sub Total** | 1,818 |
| +10% Inflation | 2,000 |
| **Total + Payload** | 2,500 |

Table 7: Cost Breakdown of the Mission

## 8 Risks and Mitigation Techniques

The mission is subject to several potential risks, including issues with probe deployment, instrument malfunctions, radiation-induced damage, failure of deployable instruments, an untested OBC, and overheating of the RTG. The following mitigation strategies have been identified to address these risks:

- **Probe Deployment:** Ensure probe deployment reliability by retaining the probe onboard and maintaining adequate propellant reserves to allow for Neptune probe insertion.
- **Instrument Malfunction:** Mitigate the risk of instrument failure through comprehensive ground testing and the incorporation of redundant deployment systems to provide backup functionality.
- **Radiation Damage:** Address the risk of radiation-induced failures by implementing latch-up protection, redundant software systems, and bit error correction techniques to maintain the integrity and reliability of electronic components.
- **Failure of Deployable Instruments:** Conduct thorough pre-launch testing and validation of deployment mechanisms, and design redundancy into the system to ensure the successful deployment of instruments such as the Langmuir probe and booms.
- **OBC Lacking Heritage:** Perform extended-duration testing under space-like conditions to validate the performance of the OBC and ensure its reliability in the mission environment.
- **Overheating of RTG:** Implement robust thermal management systems and conduct regular monitoring of RTG temperatures to prevent thermal damage to spacecraft components and instruments.

# 9 Descoping options

If the mass or cost of our mission needs to be lowered we could remove the altimeter from the orbiter. This removal is justified since the instrument has one of the largest power and mass footprints yet it is only used on two science objectives. In both objectives, it is also not the only instrument used to answer the scientific question. In case the mass and cost need to be lowered even more substantially we suggest removing the probe since most of the scientific questions can also be answered by remote observations although we can not resolve the measured components with altitude and we would miss observations into deeper atmospheric layers (>1 bar).

# 10 Planetary protection

Neptune and Triton both fall into category II of the Planetary Protection scheme of COSPAR. Therefore we have to make sure to not contaminate both celestial bodies with terrestrial organisms. To mitigate the risk we will have a Planetary Protection Plan and file a Prelaunch report. Furthermore there will be monitoring by essays taken at regular intervals which will be recorded in a database of biological presence.

# 11 Outreach

The `TUNE` mission will accompanied by a large outreach campaign, similar to other large ESA missions. We want to address not just the science community but people throughout Europe and the World and they should be able to identify themselves with `TUNE`. Because of the long mission time, it will really be a space mission "to-grow-up-with" and therefore we suggest with the support of the ESERO scheme targeted projects at schools, universities etc. for children of different ages, students and the general public. Furthermore we will have a mission website and regular updates in Social Media and we propose a music composition ("`TUNE`'s Odyssey: Create the Soundtrack to Space") to send a song together with the mission to Neptune.

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