POSEIDON

Plume Origin and SubsurfacE Investigator Destined for tritON

Mission Proposal

Delft University of Technology

Faculty of Aerospace Engineering

AE4876-11

Planetary Sciences II

Triton Lander Mission Proposal

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February 17, 2023

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POSEIDON Mission Summary	
Main scientific questions	- Can Triton sustain life? - What is the origin of Triton?
Key areas of analysis	-**Planetary interior**: Determining the internal structure and whether or not it contains a subsurface ocean. -**Plumes**: Taking samples of plume ejecta and analysing it in search of organic molecules. -**Surface**: Analysing Triton's surface composition and the molecules found on it for the purpose of comparative planetology. -**Atmosphere**: Analysing the characteristics and composition of Triton's atmosphere.
Spacecraft architecture	A main lander with most of the payload, suplemented by a rocket-propelled plume experiment craft (ROPE)
Payload	**Interior structure instrumentation**: Seismology instrument, composed of a 2-axis seismometer measuring frequencies up to 10 [Hz], and a 3-axis seismometer measuring frequencies from 1 to 50 [Hz], mass estimated at 1 [kg]. **Surface imaging instrumentation**: Mastcam-Z employed on the Mars Rover Perseverance, with a resolution of 1600x1200 [pixels], a bit depth of 11 [bits/pixel], a wide field of view of 25.6[°]x19.2[°] and narrow field of view of 6.2[°]x4.6[°], a wide and narrow spatial resolution of 28.4 [mm/pixel] and 6.7 [mm/pixel] at 100 [m] respectively, a focal length of 26-110 [mm]. Measuring 110x120x260 [mm], weighing 4 [kg] and consuming 23.6 [W] during operation and 15 [W] on standby. **Plume instrumentation**: 1 - A Gas Chromatograph - Mass Spectrometer (GCMS) for biogenic methane detection, with a measurement range of 50-500 [g/mol], a resolution <1 [g/mol], with a SNR = 10 [dB], weighing a total of 11.5 [kg] and consuming 82 [W]. 2 - An Imaging Cytometer for cell organisation, with a measurement range of 10,000particles/second>particles/second , a resolution of 1 [nm] and SNR = 30 [dB], weighing 3.5 [kg] and consuming 32 [W]. **Atmosphere instrumentation**: Totaling 5 [kg] and an average power of 15 [W]. 1 - A thermocouple with measurement range of 20-250 [K], with a resolution of 0.02 [K] and accuracy of 0.5 [K]. 2 - A pressure sensor with measurement range of 0-50 [mbar], and resolution of 0.001 [mbar]. 3 - A 3-axis accelerometer with measurement range of 0-10 [g], with resolution of 0.1 [mg]. 4 - A wind sensor with measurement range of 0-10 [m/s], resolution of 0.1 [m/s] and accuracy of 1 [m/s]. **Surface Composition instrumentation**: 1 - Raman Spectrometer for biomarker identification with a measurement range of 15 - 3800 $[cm^{-1}]$, a resolution quality of 6 - 10 $[cm^{-1}]$, a mass of 2.3 [kg] and an average laser power consumption of 20 [mW].
Description of lander	Stationary lander Telecommunications: Orbiter communications relay. Power: Plutonium-238 Radioisotope Thermoelectric Generator, 110 [W] Beginning Of Life power.
Description of plume experiment	Rocket-propelled platform Navigation system: LIDAR-guided navigation, antenna and transceiver pairing for return trip. Primary propellant type: Hydrazine. Primary propulsion: Two 445 [N] Thrusters. Secondary propellant type: N_2 Cold gas propellant. Secondary propulsion: Four 52 [N] Thrusters. Power: Battery-powered, 393.48 [W] power draw, 48.3 [Wh] energy requirement. Total mass: 105.6 [kg]. Dimensions: 100x60x40 [cm].
Mission profile	Launch and transfer: T2040 transfer [1], launching on 28/12/2039, arriving in the Neptune system on 20/04/2056. Launcher: Ariane 64 (preliminary). Landing site: To be determined by orbiter. Mission duration: 6 months, with extensions possible up to 1.5 year mission duration. Decommissioning: Abandoning the lander on Triton, with its power source removed from all instruments. RTG is expected to decay naturally.

Contents

1 Executive Summary

The outer planets of the Solar System represent both a mystery and an opportunity. The Voyager 2 probe visited the Neptune System for the first time in 1989; since then, no other mission has investigated the planet at the farthest reaches of the Solar System and its singular moon. As a consequence, little is known about this intriguing destination. As a moon, Triton stands out for its uniqueness in the orbit of Neptune, making up 96% of the orbiting mass around the body. It is also unique compared to other moons in the Solar System due to its curious retrograde orbit, the nature and origins of which have not yet been fully discerned. Triton also belongs to the category of icy moons, which have sparked debates about the potential presence of organic molecules within their icy shells. All of these factors make Triton one of the most attractive scientific objectives in the Solar System.

The POSEIDON mission will be the first mission to land on Triton and send back scientific data. It will characterise its surface composition, revealing details about the moon's cryovolcanic activity and geological past; it will yield additional clues on its internal structure, settling the debate on the presence of an internal ocean and the mechanisms that create it. It will also study Triton's plumes in detail, searching for potential biomarkers that could give an indication about the presence of life elsewhere in the Solar System.

The mission aims to answer two fundamental scientific questions: what the origin of Triton is, and whether or not it can support life. The former question can be explored by different means. POSEIDON aims to combine a comparative planetology approach with a deep analysis of Triton's features in an attempt to answer the questions. A close inspection of the planet's surface may yield indications of it being a Kuiper Belt Object, captured at some point in the near or distant past. A clearer understanding of Triton's interior structure — including the likely presence of a subsurface ocean — might yield insights into the nature of this potential capture event, and reveal the mechanism behind the plumes that litter the surface of the body. The latter question of whether Triton can support life is investigated through the analysis of organic molecules that may be ejected from Triton's plumes. If found, these might yield clues as to what kind of molecules and compounds can be found deep within the moon's icy shell, where minerals are thought to flow freely and abundantly within the subsurface ocean, which itself is kept liquid and warm by the heat of the moon's core — both of these being essential ingredients for life as we know it.

Triton's interior holds a number of mysteries, from the origin of the plumes found on the surface to the likely presence of a subsurface ocean. Determining the interior structure of the moon will shed light into the possibility of the moon containing substantial amounts of liquid water — a primary ingredient for any body to harbour life — and present a clearer picture of Triton's recent past, through means of measuring the thickness of its icy shell. The determination of the interior structure is done through the use of novel techniques employing seismometers.

Triton's plumes are particularly fascinating as they serve as a window into the moon's subsurface. Through in-situ measurements of the plumes' composition as well as some measurements of their seismic activity, further insight can be gained into the presence of a subsurface ocean, and the possibility of life. Gas chromatography, mass spectrometry, and flow cytometry measurements will all be performed on samples taken directly from the plumes below Triton's surface to give POSEIDON the best opportunity to detect potential biomarkers. These biomarkers include methane produced from biogenic processes, polynucleotides, and lipids. POSEIDON's rocket-operated plume experiment will navigate into the plumes and collect samples, keeping them in their ambient conditions until analysis on the lander can be performed.

Inspection of Triton's surface can give new insights into its origin, the presence of life, its current geological activity, and the driving force behind resurfacing events. Investigating geological features, such as the undulating high plains, walled and terraced plains, zoned maculae, and cantaloupe terrain by means of high resolution imaging can help to characterize the surface processes that are ongoing on the body, and what internal processes are driving these. POSEIDON will analyse the icy surface for biomarkers, hoping to find similar types as those found on other Kuiper Belt Objects, as this could provide an answer to the origin of Triton. Furthermore, finding these potential biomarkers in the surface ice could help in determining whether life on Triton is possible, as biomarkers could travel through plumes and deposit on the ice over time.

Although a secondary science objective, the atmosphere of Triton is very unique among solar system bodies due to its very low, but highly varying density and pressure, as well as its tenuous weather system. In order to gain a more thorough understanding of this atmosphere and how it might relate to similar bodies, a number of sensors will be used to measure pressure, temperature, wind, and acceleration, thereby characterising key atmospheric properties during the initial descent of the lander. This will provide crucial height-varying information not possible to be gathered from other means. Once the lander has touched down, these sensors will operate intermittently to gather data on the short term transient properties of the local atmospheric environment.

The payload used to perform the measurements mentioned above will be hosted on a single stationary lander platform — as is customary for missions to mostly unknown planetary bodies — thereby improving its reliability compared to a rover. The mission will be launched towards the end of December 2039 and will reach Neptune in April 2056, before approaching Triton through a series of manoeuvres and flybys around the different bodies in the Neptunian system. An optimal landing site will be selected following a period of global mapping of the moon's surface from orbit: this ideal position would be in the neighbourhood of an active plume, keeping an approximate distance of 1 [km] while being as close as possible to any relevant geological sites in the vicinity. This step will be followed by the Entry, Descent and Landing procedure, which will employ a powered gravity turn manoeuvre, and during which the lander will take measurements of the moon's tenuous atmosphere. The gravity turn manoeuvre will be controlled by a Guidance, Navigation and Control unit (GNC), and a hazard avoidance system, ensuring that a safe final landing site is reached based on the information gathered by the on-board Inertial Measurement Unit (IMU), radar altimeter and camera. Once the lander is resting safely on the surface of the target body the Early Operational Phase (EOP) is initiated, and all systems of the lander and its experiments are initialised and calibrated. The communication link to the orbiter — which will act as relay during the entire mission — is established, permitting to transmit health and descent data to the ground support team on Earth. At the end of the EOP, the 6 months —with a possible extension of 1.5 years — long operational phase is kicked off with the activation of the planned experiments. The Rocket-Operated Plume Experiment (ROPE) will be deployed as soon as the closest plume location relative to the lander has been established with the necessary degree of certainty. ROPE will then fly towards the plume and perform the aforementioned measurements, then return to the lander, whereafter the data gathered will be sent back to Earth. In order to sustain these operations, the POSEIDON lander will utilise an MMRTG provided by NASA as its main power source. In addition to this, a secondary Lithium-Ion rechargeable battery pack will be onboard to provide the necessary power during periods in which the MMRTG's power supply is insufficient. The ROPE craft will be powered by a system separate from the lander, and will rely entirely on Lithium-Ion batteries to meet its power needs during operation. Once the mission is deemed complete — whether this be after six months or two years — the lander will begin its own decommissioning by physically disconnecting the MMRTG from the bus, in order to prevent any possible battery explosions or interference with future missions to Neptune or Triton.

The lander bus design is shown in Figure 1.1, and was used as a reference for the overall system mass and power budgets. Along with the main scientific instruments, the lander contains a robotic manipulator arm to aid in instrument deployment and the operation of the spectrometer. The lander has overall dimensions of 2.75 x 2.75 x 1.4 [m] [LxWxH], and a mass of 466[kg]. The average power draw of the lander is under the 110[W] output of the MMRTG, except during initial descent, during which supplemental power is supplied by a secondary battery source.

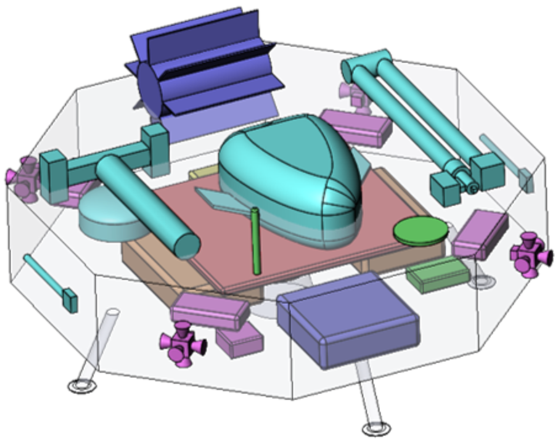


Figure 1.1: Isometric view of the POSEIDON lander bus with associated components.

Science Case 2

The main scientific objectives of the mission are outlined in this chapter. First, Section 2.1 provides a general overview of the relevance of Triton in the study of the outer solar system, why icy moons are of primary importance to study, and the related key science questions which will be addressed by the mission. Following this, Section 2.2 presents a literature review on the three main axes of research on Triton and icy moons in general. Section 2.3 formulates hypotheses and research questions on a range of selected topics which will be addressed by the mission, based on the aforementioned literature review and key science questions. The chapter is concluded with a reflection on the synergies of POSEIDON with other missions which are planned to occur in the same time frame, presented in Section 2.4.

2.1 The importance of Triton

The largest moon of Neptune, Triton, is an icy world located at 30 [AU] from the Sun. The moon has been studied since the mid-twentieth century using Earth-based telescopes. The Voyager 2 mission holds the title of being the only man-made object to observe Triton up close, having performed a flyby lasting a few hours, and yielding numerous famous images, such as the one shown in Figure 2.1. This brief encounter revealed a moon similar to Pluto in size. It follows a heavily inclined retrograde orbit around Neptune, and boasts a thin nitrogen atmosphere, cryogenic plumes, and a geologically young surface with a temperature as low as 38 [K] [2]. The relevance of this intriguing moon in the grander scheme of the exploration of the solar system is presented in two distinct ways; the first, by focusing on its nature as an icy world, as presented in Subsection 2.1.1; the second, by considering its hypothesised link to Kuiper Belt objects, as is discussed in Subsection 2.1.2. Subsection 2.1.3 outlines the key science questions that arise from these two aspects of Triton.

2.1.1 An Icy Moon

Common consensus used to hold that the solar system is devoid of life everywhere except on Earth. [3]. However, mankind's increasing understanding of other worlds and the increased knowledge of how life is able to adapt to harsh environments has given room for hope. It is generally understood that four essential items are necessary for a planetary body to potentially support life[4]:

1. Energy, which can be supplied from the sun, the planet/moon interior, tidal heating, etc.
2. Water, which can be found in (subsurface) oceans.
3. Nutrients, which are at the basis of any life form.
4. Time, as the molecules which are at the basis of life are complex and take time to form based on more simple organic ones.

Two hypotheses exist that relate to life in the solar system. One is that life may have emerged and thrived on planets like Mars, only to retreat underground or perish altogether. The other states that icy moons are the strongest candidate for alien life in the solar system due to their large liquid water content [4]. This reason has led to great interest in the exploration of icy moons within the scientific community, given the likelyhood of them containing subsurface water oceans. [2]. While the former hypothesis has received lots of attention, with several missions being launched to Mars and Venus in the past decades, the moons of gas giants have received little attention, being explored through flybys of missions primarily aimed at other bodies.

A broad understanding of the habitability of icy moons can only be obtained through a thorough survey of the main ones present in the solar system, as this would allow for comparative studies to draw meaningful conclusions on the habitability criteria to be used, if one is found to support life. Previous space missions to the outer solar system, such as Galileo, Cassini-Huygens, and Juno focused on the exploration of Jupiter, Saturn, and their moons [5, 6, 7]; the New Horizons mission studied Pluto and its moon [8] through a flyby; and the

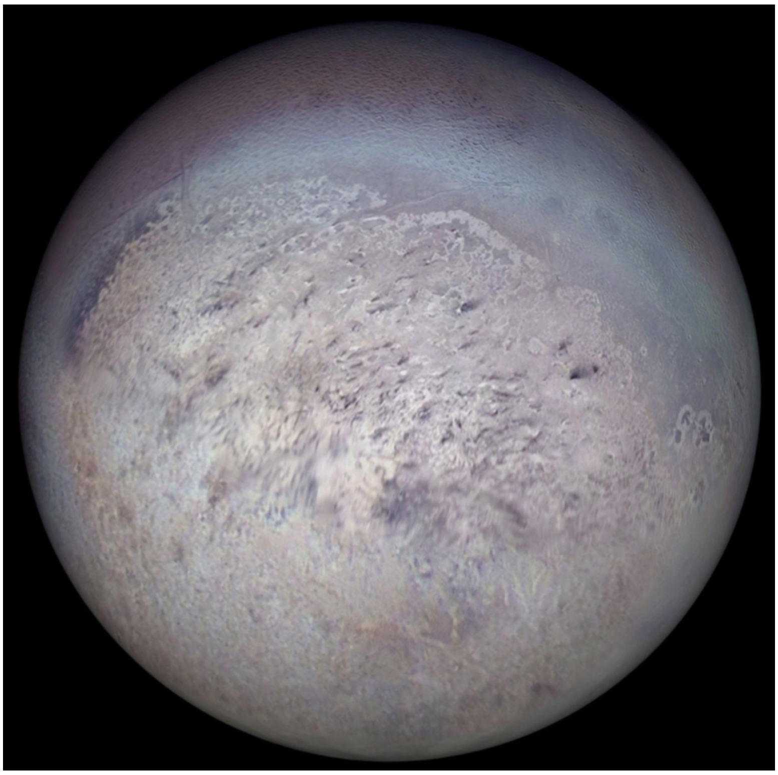


Figure 2.1: Image of the sub-Neptunian side of Triton taken by Voyager 2

Voyager mission performed a Grand Tour including a flyby of Neptune and its largest moon: Triton. Those missions allowed for preliminary studies of icy moons such as Europa and its subsurface ocean [9], Enceladus and its plumes [10], Triton and its young geologically active surface [11], and Titan and its Earth water-like methane cycle [12]. Those preliminary findings gave rise to a variety of future missions which will take place in the next decades, as will also be discussed in Section 2.4, to further study those moons in particular and their habitability. However, no mission had (or is planned to have) Neptune and Triton as prime targets until now, despite the latter's uniqueness in terms of geological activity, and relevance in the study of icy moons and habitability in general. There is a need for a complementary mission to Triton to enable further comparative studies and obtain a complete survey of the icy moons of the solar system and their characteristics. As explained by Hansen *et al.* [2], the search for life is the most advanced for Europa, Titan and Enceladus, where missions are already planned to be sent to answer questions such as "is there life anywhere else in our solar system besides Earth? What conditions are required for life to appear and evolve? Do the oceans of moons of other planets provide habitable environments?" [2, p. 9]. If life is not found through missions such as Europa Clipper or the Titan Dragonfly, the search for life will continue in other places. In case life is found, other questions will arise, such as "is there life elsewhere? Are all hospitable oceans supporting some type of life form?". For both scenarios, Triton will be the primary target to answer these questions and further define the criteria defining the conditions for life to emerge.

2.1.2 A Kuiper Belt Object

The Kuiper Belt is a region behind the orbit of Neptune which is still vastly unknown, composed of icy remnants of the formation of the solar system as we know it [13]. Those primitive remnants remain broadly unchanged since the formation of the solar system, providing an invaluable window into the study of the formation of the farthest regions of the system. Additionally, it is believed that the Belt acts as a reservoir for the short-period comets which can be observed from Earth, in the same manner as the Oort Cloud is postulated to be the source of long-period comets [14, 15]. A general study of Kuiper Belt Objects (KBO) would help to further uncover clues about the formation of planetary systems in general, resolving some existing mysteries, but also raising new ones which help mankind advance its current understanding of the solar system in general.

It has been hypothetised that Triton is a past Kuiper Belt object which was captured by the gravitational pull of Neptune in the early phases of the solar system, which could have resulted in differentiation through tidal braking, due to its highly inclined and retrograde orbit [2]. According to McKinnon and Kirk [16], this hypothesis is further supported by the twin-like nature of Triton and Pluto, due to their very similar size, density, and atmospheric and surface compositions. Additionally, other Kuiper Belt objects are themselves similar to Pluto / Triton, and the hypothesis of Pluto being an escaped moon of Neptune is disputed by the observation of the 3:2 dynamical resonance of Neptune and the dwarf-planet, which makes the latter's orbit remarkably stable [17]. Although the capture of an object is seldom as it needs to lose enough energy while in the sphere of influence of Neptune such that it does not escape, the capture is believed to have occurred at a time when the flux of material close to Neptune's orbit was much greater. This means that it is likely that such a capture event happened at least once during the formation of the Neptune system [16]. Two main theories are put forward for the capture of Triton: (1) Triton would have collided with a regular satellite in the protosatellite disk during a flyby of Neptune, resulting in a great enough energy loss to remain in the sphere of influence of the centre body; (2) Triton was part of a binary object which passed close to the gas giant, resulting in the separation of each pole of the binary, one part staying in Neptune's orbit, which became Triton and the other being slingshotted into outer space [2].

A thorough study of the characteristics of Triton in terms of its interior, surface and atmosphere, would help to assess with more certainty whether the moon is indeed a captured Kuiper Belt object. Furthermore, if the hypothesis is confirmed, Triton would become a window into the next stage of the exploration of the dwarf planets of the Kuiper Belt [2].

2.1.3 Key Science Questions

The two most important aspects of Triton in the grand scheme of solar system exploration were pointed out in the previous two subsections, by considering its nature as an icy moon and likely ocean world, and its likely Kuiper Belt origin. The POSEIDON mission proposes exploring this fascinating and compelling destination through the use of a lander to investigate the moon in greater detail than achievable by an orbiter. The key science questions which will be tackled through this mission are in close alignment with the aforementioned relevance of Triton and the interests of the scientific community. The following questions were selected:

First Science Question

Does Triton support life ?

Second Science Question

What is the origin of Triton ?

Overall, the added value of having a lander to investigate those questions relies on the ability to take direct measurements of the surface or material from the plumes, and to take close up measurements of the body in general. Additionally, the two key science questions will be split up into more direct sub-questions which are to be tackled by the lander mission as clues to answer the overarching mysteries of the moon. The two science questions will be investigated through a literature study of the three main aspects of any planetary body: its interior (existence of a subsurface ocean and plumes), surface (geological processes and surface composition), and atmosphere, in the following section.

2.2 Structure of Triton

In this section, three main aspects of the moon's composition are investigated through a review of the available literature, aiming to outline the limitations of mankind's current knowledge of Triton. Subsection 2.2.1 provides an overview of the current literature on the interior of the body by specifically considering the existence of a subsurface ocean and the moon's plumes, Subsection 2.2.2 tackles the surface through its composition and the geological processes at hand, and Subsection 2.2.3 deals with the knowledge of Triton's atmosphere.

2.2.1 Interior

Given the very limited data provided by Voyager 2, not much is known about Neptune's moon's interior. The little knowledge and understanding available is based off of models, which simulate the internal structure based on assumptions about different mechanisms which might shape it, such as radiogenic heating and tidal dissipation.

Triton has a radius of approximately 1353 [km], with an average density of approximately 2065 [kgm^{-3}]. This relatively high density suggests that the moon has a dense silicate core of approximately 950 [km] in radius [18].

McKinnon and Kirk [19] suggest that the moon's interior may be differentiated, based on different surface features displaying signs of melting and the distribution of different ices over the surface. However, the exact nature of Triton's interior is not very well known. Different models exist, for instance, Gaeman et al. [18] modelled the body's interior using three differentiated layers: a silicate core with a radius of 950 km, overlain by an $NH_3 - H_2O$ ocean and an H_2O ice shelf. In their model, spanning thousands of years, the thicknesses of these two layers change over time. Determining the moon's interior more accurately would not only be a benefit on its own, but it may help in the task of determining its origin, given what is known and theorised about similar bodies in the Kuiper Belt. For instance, a thick H_2O ice layer may suggest similarities to other Kuiper Belt objects, like Pluto and Eris [20].

2.2.1.1 Subsurface Ocean

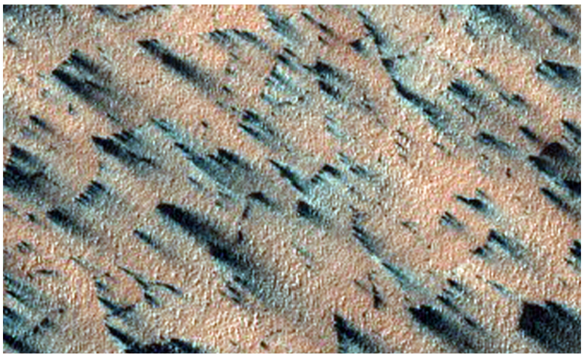
As briefly discussed in Subsection 2.2.1, there is a strong indication that there may be a subsurface ocean within Triton's icy shell. Several studies have suggested different origins for Triton's theorised subsurface ocean. Hussmann et al. [20] modelled various outer solar system bodies assuming an equilibrium between radiogenic heating in the different bodies' rocky cores and the heat loss through the ice shell. The results presented in this paper suggest that an ocean with a depth between 130 and 190 km may exist on Triton. Ross and Schubert's results [21] suggest, among other things, that the moon's semi-major axis decreases drastically for the first 50 [Ma] (megaannum) after a possible capture event. After that, the pace of evolution slows as Triton cools and an equilibrium temperature with the radiogenic heating is reached. It takes another 750 [Ma] after that in order for Triton's orbit to be fully circularised. Their results also suggest that radiogenic heating alone is enough to maintain a liquid ocean inside Triton, in line with Hussman et al. [20]. Gaeman et al. [18] model the interior structure of Triton in a similar fashion, suggesting that Triton's icy shell acts as a form of "tidally-heated blanket", which significantly slows down the rate of freezing. This effect would be driven by Neptune's orbital eccentricity. Their results suggest that eccentricities as small as $5 \cdot 10^{-7}$ would be enough to maintain temperatures above the freezing point in Triton's interior for 1.8[Ga] — with a higher eccentricity of $5 \cdot 10^{-5}$ being enough to sustain those temperatures for 4.5[Ga].

Much information about Triton's origin hinges on whether a subsurface ocean can be found. If some of the aforementioned models are accurate, then the ocean most definitely exists. The nature of the ocean — specifically, how deep it is — may give us a clearer indication of its origin by comparison with similar bodies in the Kuiper Belt. However, the potential exists for the subsurface ocean to be a direct result of a capture event. If that were the case, one would expect to find an ocean deeper than the 130-190 [km] indicated by Hussman et al. [20], as a consequence of the added heat from tidal dissipation and the "heated blanket" proposed by Gaeman et al. [18]. However, a deeper ocean may not necessarily be an indication of a capture event; it may simply be the result of some mechanism we do not yet understand, or some variables being different from those assumed. It is also possible that the capture occurred a long time in the past, too long for there to be surplus heat from tidal dissipation. This, however, is hard to determine, given Triton's nearly circular orbit. Ultimately, the mission should aim to refine our understanding of these variables in order to rule out some of these hypotheses.

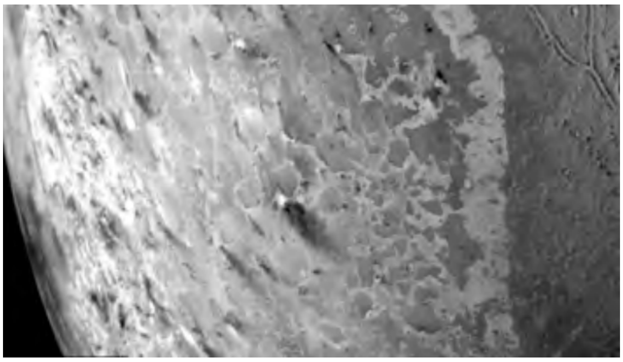
2.2.1.2 Plumes

During Voyager 2's Triton flyby, at least two active plumes were found on the surface [22, 23]. These plumes consist of long clouds of more than 8 [km] in height and 100 [km] in length, and are thought to be the source of numerous dark deposit fans on Triton's surface [2]. However, much remains unknown about their composition, structure, lifetime, and source. Observing Triton's plumes can provide information about the potential existence of a subsurface ocean, and reveal biomarkers which could define some necessary conditions for habitability.

Specifically, investigating the source of Triton's plumes allows for a better understanding of the subsurface processes on Triton, as well as the potential existence of a subsurface ocean. The source of Triton's plumes is so far unclear. When planetary scientists first studied the plume behaviour on Triton, the reigning theory was that these plumes were solar-driven, as are seen on Mars [24]. The ice is translucent, allowing visible light to pass through. However, it is opaque to thermal wavelengths, which leads to a build-up of heat and vapour



(a) Mars' surface [HiRISE ESP_011960_0925] [28]



(b) Triton's surface [25]

Figure 2.2: Comparison between the appearance of dark fans on Triton and Mars from plumes.

pressure below the surface. This pressure eventually can rupture through the ice, causing these plumes [25, 26]. The plumes were also concentrated around the subsolar latitude during Voyager 2's flyby [2], which is a location on Triton where the Sun is perceived to be directly overhead. Finally, the dark fans seen on Triton and Mars, seen in Figure 2.2, are quite similar. Since Mars' plumes are solar driven, Triton's plumes could also come from the same origin [25]. Interestingly, Pluto has a similar nitrogen-based atmosphere in vapour pressure equilibrium with surface ice, and did not have any observable plumes based on the recent flyby from New Horizons [25, 27]. Complications like this are the major reason that the solar-driven hypothesis has yet to be confirmed. Planetary scientists also currently lack information about the spatial and temporal variability of the plumes that could help confirm a solar-driven hypothesis.

Additionally, Triton's plumes bear some similarities to the behaviour of those seen on Enceladus, which are localized plumes generated by tidal friction [29]. A similar endogenically produced heat source on Triton can suggest the existence of a subsurface ocean, and was proposed as an alternate hypothesis for the power source behind Triton's plumes [30]. In this theory, heat generated inside the moon from friction would melt the base of Triton's polar ice cap, increasing the pressure below the surface and leading to similar ruptures [2]. The plumes on Triton have an ejected vapour mass flux closer to those on Enceladus than on Mars, averaging around 400 [kg/s] on Triton [25] and 200 [kg/s] on Enceladus [31]. Additionally, the altitude and distance of the ejected particles seems to suggest a stronger source than the sun could provide [25]. While modelling seems to suggest the existence of a subsurface ocean on Triton, a better understanding of Triton's interior would help determine if the endogenic theory is more accurate. There is also a possibility that the plumes are related to other causes, such as cryovolcanism [2].

While investigating the source of Triton's plumes is an important question for understanding the interior of the moon, it is the composition of these plumes that more directly relates to the overall question of potential habitability on Triton. If the existence of a subsurface ocean is confirmed, some parallels can be drawn with Enceladus. While the methods and specific biomarkers are relevant to Enceladus, and not necessarily relevant to the Triton study, they do provide some guidelines on early experiments to perform while information about the moon is being gathered.

On Enceladus, H_2 and CO_2 were found inside the plumes, which represent chemical energy that could be used by primitive microorganisms called methanogens, which exist on Earth [32]. Of course, this may not be enough of an indication of life, as the availability of resources does not necessarily mean that life exists to use them. However, other biomarkers can be found which provide a stronger argument towards a habitable environment on Enceladus. This includes examining plume samples for replicatory polynucleotides [33], some examples being DNA and RNA for living organisms [34]. Biogenic methane, if detected in the plumes, is an indicator of metabolic processes, and can be distinguished from other types of methane by differentiating the isotopes [33, 35]. Lipids have also become a universal indicator of life, if they can be found [33, 36]. While much of this section of the scientific mission is based upon the existence of a subsurface ocean and similar processes to Enceladus, the likelihood of a subsurface ocean existing on Triton makes investigating these mysteries worthwhile. As knowledge becomes more refined based on orbiter information, the experiment can be tailored for conditions that are more likely to be encountered on Triton. Thus, the specifics regarding specific compounds and processes should not be held with the same importance in this section as the overall process of answering the question of habitability on an icy moon.

2.2.2 Surface Studies

A general surface study of Triton can be characterised through a consideration of two main aspects:

- Its geological features and processes, which can provide information on the moon's origin based on comparative studies with other Kuiper Belt objects. Particularly, signs of cryovolcanic activity were found from the images taken during the Voyager 2 fly-by in 1989 [2].
- Its composition, which can provide clues for both the habitability question (from detection of biomarkers, or molecules strictly necessary for life), and the origin science question (from comparative studies with other Kuiper Belt objects which have been or will be studied thoroughly by other missions, such as the New Horizons mission).

2.2.2.1 Geological Features and Processes

The most surprising feature of Triton's surface is its very young surface, as concluded from crater counting techniques. The age of the surface was first estimated to be at most 1 [Gyr] by [22] but more recent knowledge on the Kuiper Belt Objects shone the Voyager images under a new light, as presented by Schenk and Zahnle [37]. Those authors identified that the certain regions had an age of at most 50 [Myr], but other parts of the surface would be at most 6-7 [Myr] (using ecliptic comets flux). However, they also suggested that planetocentric bodies could be the major source of craters, resulting in the age of the surface being lower than 10 [Myr] overall [37]. Although the uncertainty in these estimates is at least of a factor of 10, it is likely that Triton is among the youngest bodies in the solar system, probably even younger than Europa. Such a young age indicates that the rate of resurfacing of the moon is high, and that it might even still be active today through processes such as (cryo-)volcanism and diaparism, which both indicate a significant partial melting of the interior, strengthening the hypothesis of a sub-surface ocean [37]. Following, the most important surface processes concepts for the case of Triton are shortly discussed.

Cryovolcanism is considered as the planetary volcanism, defined as "An eruption from an opening on a planetary surface from which magma, defined for that body as a partial melt product of mantle or crustal material, is erupted" [38], form present on icy bodies of the outer solar system, such as Triton. The process is then simply defined as an icy cold volcanism, where cryolavas are molten materials that are produced when the crust or mantle of an icy body partially melts. These lavas can be made up of water-based liquids or mixtures of solid particles and gas bubbles suspended in water, or of non-polar liquids mixed with gas and solid particles [39]. Cryovolcanism is therefore believed to be associated with a subsurface layer (ocean) of liquid water in the interior of the body [40], which could also give rise to the plumes mentioned earlier [2], (however, this is not a leading theory). Furthermore, according to Cruikshank *et al.* [24], this process "encompasses processes involving the deformation, intrusion, and extrusion of liquids, slushes, and 'warm' plastically deforming solids composed of mixtures of low-melting point materials". The physics and chemistry of cryovolcanism are then essentially the same as 'hot' volcanism as known on Earth [16], only that one occurs from the melting of icy material, while the other arises from silicate material in molten state. However, the energy source necessary to drive the volcanic process might be different: Earth-like volcanism arises from endogenic activity, whereas cryovolcanism is mostly believed to be associated to dominant exogenic processes such as crack openings from tidal friction, or solar heating [40]. The cryovolcanic processes found on the surface of Triton seem to indicate that there has been (or still is) a link between the subsurface ocean (if any) and the surface observed by Voyager II. According to Hansen *et al.* [2], diaparism (either thermally or density driven) could be one of the underlying mechanisms bringing material from subsurface layers to shallow levels in the crust. Additionally, the same paper mentions that the gradual freezing of the ice shell would yield pressurisation of the subsurface ocean, which could promote eruption of cryovolcanic magma, and the formation of cracks (yielding a more explosive volcanism, which is one of the hypotheses behind the existence of the plumes) [2]. Cryovolcanism is believed to be the main source of the resurfacing of Triton (based on the morphology and distribution of the features), resulting in the surface features which will be considered below.

Internal tectonic activity is believed to be present, based on the presence of troughs, putative strike-slip faults and graben, as well as double-triple ridges [2, 24, 41]. The ridges found on the surface of Triton (their

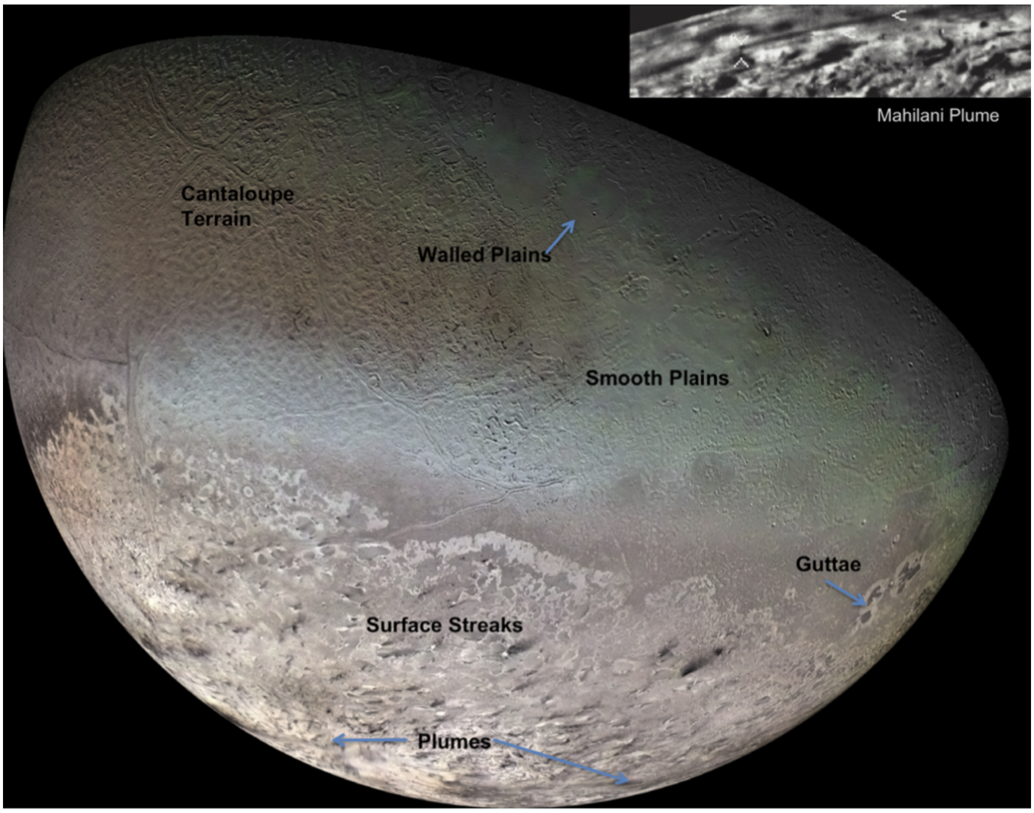


Figure 2.3: Surface features of Triton [2], modified from PIA00317. Credit: NASA/JPL/USGS.

location, size and orientation, particularly) can be used to uncover the stress mechanisms acting on its shell [2], the main candidates being global-scales mechanisms (but none was linked with a clear correlation to the mapped surface of Triton, and a global high-resolution mapping of the surface would help to resolve this mystery). Note however, that Kargel and Strom [42] described that only a few tectonic features can be seen on Triton's surface, but most cryovolcanic features are believed to be tectonically controlled.

Tidal deformation, as already mentioned earlier, is believed to have occurred on Triton from its hypothesised capture by Neptune. Numerical models have shown that such a process might have led to intense geological activity, such as the formation of the subsurface ocean from the heat dissipated in the circularisation of the moon's orbit [43]. While the circularisation of the orbit gave rise to a significant energy source, tidal heating, in the history of Triton, it can also give rise to a more direct formation of surface features through movement of land masses (tidal friction) [44].

Erosion of the surface based on interactions with its atmosphere. However, this process is believed to be negligible compared to the other aforementioned mechanisms, due to the very thin atmosphere.

Although the Voyager fly-by only imaged about 40% of the moon [2], a number of surface features were observed and analysed, as summarised by [24, p.879-949]. In the following, the most important surface features of Triton are briefly discussed, and connected to hypothesised processes mentioned above. Their location and overall shape can also be seen on Figure 2.3.

1. **Undulating, high plains**. The undulating, high plains can be found on the eastern hemisphere, and north of the polar terrain boundary. These smooth plains are centred around so-called rimless pits, that are most likely a result of icy volcanism where material emanated from the vents. The quasi-circular depressions, depicted as c in Figure 2.4a, appear to be caldera-like depressions, where the vent collapses as the icy lava leaves the vent. The composition of these icy lavas is unknown, but it is viscous enough to bury pre-existing topography of a few hundred meters. The viscosity of the icy lava is comparable to some types of basaltic magmas on Earth. This viscous behaviour can occur when ammonia-water, a favoured composition of icy lavas on other moons, is heated to 177K in Triton's mantle. The linear alignments of the volcanic pits, as shown by the arrows in Figure 2.4a, are a result of eruptions along deep-seated fissures or rifts.

2. **Walled and Terraced Plains**. Four walled plains have been identified on Triton. One of these walled plains is indicated with an R on Figure 2.4a. A walled plain consists of a flat plain that is surrounded by rougher plains. The elevation of these rougher plains is increasing in steps, the so-called scarps. The remarkably flat plains can be explained by a flow of a very liquid lava, or other liquid. The irregular pits, located in the centre of the flat plain, could be eruptive vents, or drainage pits. The outlines of the walled plains remind one of eroded shorelines, but any explanation on how this erosion occurred is missing. The terraced appearance can be explained by the disintegration of more friable or volatile materials. This mass wasting process is similar to the one that is believed to be responsible for the etched plains on the Martian South Pole region.
3. **Smooth Plains and Zoned Maculae**. A hummocky terrain can be seen at the top left in Figure 2.4b. Smoother plains can be found to the south of this maze of depressions and bulbous mounds. The origin of these smooth plains is unclear, due to lack of available resolution. It could be a result of volcanic flooding, volcanic or condensation mantling, or another form of degradation. The hummocky and smooth terrains are the most heavily created regions on Triton. The largest crater is indicated with an M on Figure 2.4b, and has a diameter of 25 [km]. The dark circular spots, surrounded by a brighter annulus, are known as maculae. These can be seen on the right side of Figure 2.4b, of which the largest is indicated with a Z. The smooth, dark patch at the centre of a macula implies the presence of carbonaceous materials, whereas the brighter annulus most likely consists of N_2 ices. The width of these annuli is relatively constant for the maculae shown on the figure. The variation in height over an entire annulus is no more than a few tens of meters.
4. **Cantaloupe Terrain, Ridges, and Fissures**. The so-called cantaloupe terrain can be found on the western half of Triton's non-polar surface. The surface is covered by large dimples and ridges. These large dimples become networks of closely spaced, interfering, elliptical and kidney-shaped depressions. These depressions are also known as cavi. The cavi are uniformly sized and do not overlap, which is a clear indication for an internal origin, when comparing it to impact craters. Cavi can be explained by a process called diapirism, where less dense material rises through denser overlying material. The buoyancy may be thermal of compositional in nature. This diapirism process has several implications for Triton's composition, namely that it has distinct crustal layering, and that the overlaying denser material is approximately 20 [km] thick. The latter can be deduced from the spacing of cavi. The ridges occur in several configurations. There are pairs of low parallel ridges that bound a central trough, and there are single broad bulbous ridges as indicated by the arrows in Figure 2.4b. There are fewer fissures than ridges present. The fissures are simple, long valleys that are only a few kilometres wide. All of these features are most likely a result of the extensions and/or strike-slip faulting of Triton's surface.

Those geological features are the result of surface processes acting on geological time scales.

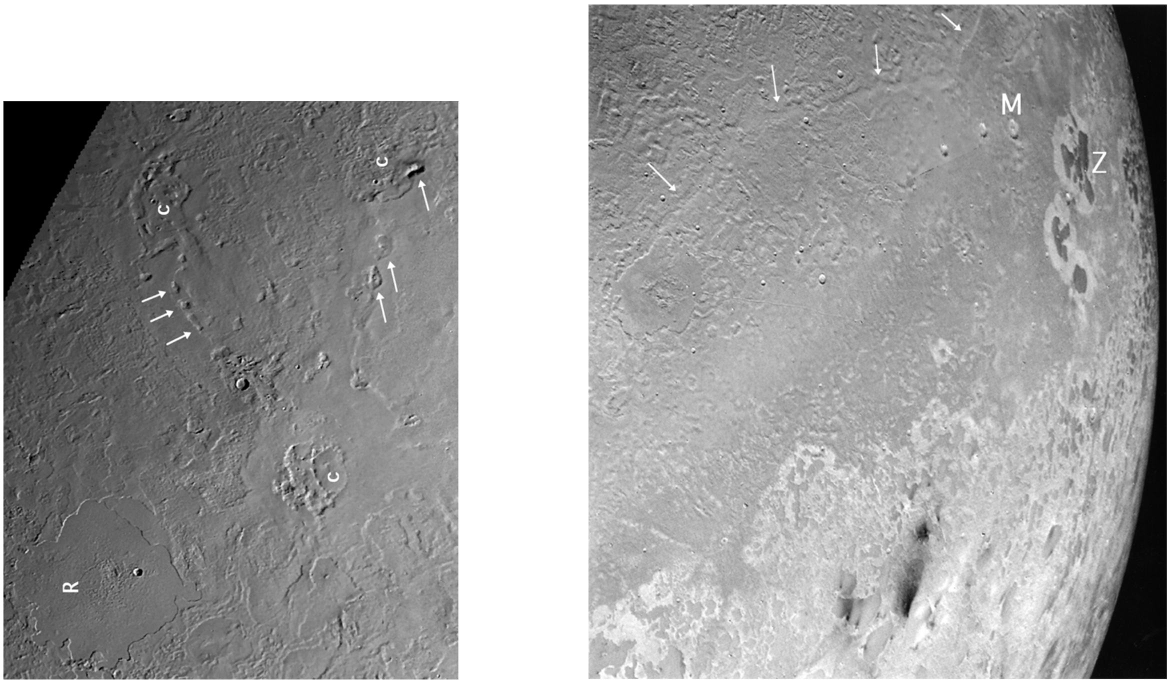
2.2.2.2 Surface Composition

From afar, Triton mostly looks like a body covered in ice. However, the ice is composed of a mixture of water ice, N_2, CH_4, CO and CO_2, which makes the moon rather diverse [45]. N_2 is the dominant molecule in the surface and makes up almost 55% of the surface ice, while water ice makes up 15-35$\%$. The other gases make up the remaining percentages [46]. The uncertainty in the percentages is believed to come from seasonal changes to the temperature of Triton, which make the N_2 melt and freeze [45].

In addition to the main molecules mentioned in the previous paragraph, there is the possibility for organic molecules, like amino acids, to be present in the ice. These could be present in the subsurface ocean and travel through the cryovolcanic plumes to the surface, where they freeze onto the ice [45]. Such molecules, also known as biomarkers, could indicate the possibility of life on Triton. However, the concentration of these biomarkers will be very low and will probably only be present close to the plumes. A surface mission is most likely required to analyse the presence of these molecules, as the low concentrations make it difficult for orbital instruments to detect.

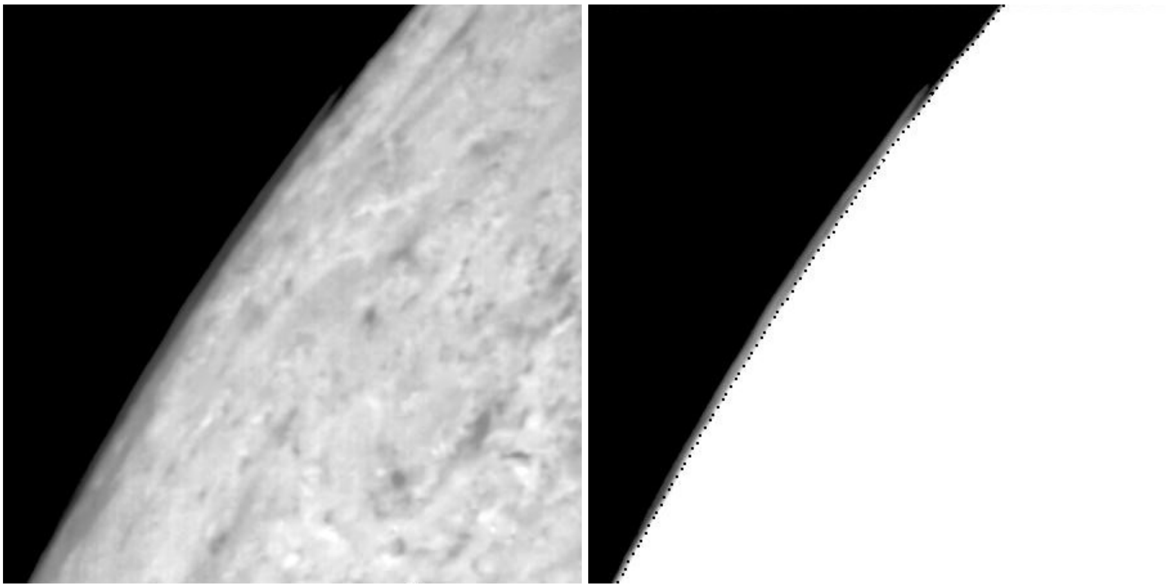
2.2.3 Atmosphere

Measurements gathered during the Voyager 2 flyby provided the first detailed look into Triton's atmosphere. Triton was observed to have a thin atmosphere extending roughly 850 [km] above the surface with an atmo-



(a) Young volcanic region on Triton. (b) Southeastern limb of Triton.

Figure 2.4: Surface features on Triton [16].



(a) Voyager 2 photo [51]. (b) Photo with Triton body removed [51].

Figure 2.5: Images of clouds in the Triton atmosphere.

spheric pressure of 1.5-1.9 [Pa] and surface temperature of 38 [K] [47]. The composition of the atmosphere was measured to be mainly Nitrogen, with small amounts of Methane and trace compounds [48].

The structure of the atmosphere is broken up into three main layers: the troposphere (0-8 [km]), the thermosphere (8-850 [km]), and exosphere (>850 [km]) [22, 49]. The troposphere, which exists through convective forces caused from solar radiation, allows a limited weather system to exist closer to the surface. The presence of winds were confirmed through observations of plumes and their deposited material, while thin clouds of Nitrogen particles were directly observed on the horizon, as seen in Figure 2.5, along with a haze believed to be made of hydrocarbons created through the degradation of Methane by UV light [50].

These winds and clouds form the basis of complex weather system which is not yet entirely understood. A limited Nitrogen cycle is theorized, with sublimation grating clouds that are later deposited as snow in other parts of the moon [50]. The transport of trace gases between the northern and southern hemispheres is also theorized, however the mechanics behind this are also not fully understood [52].

Data gathered since the Voyager flyby has both provided brand new insight into the atmosphere as well as provided evidence to support theories of its dynamic nature. Measurements taken in 1998 showed a 5% increase of temperature across the moon and were the first measurements of dynamic changes [53]. In 2010, data collected from the European Southern Observatory Very Large Telescope showed even greater variation in the atmosphere from the voyager 2 data. These new measurements, taken while the Southern Hemisphere of Triton was in summer, showed an approximate 4 times increase in concentration of Methane, an increase in atmospheric pressure to 4-6.5 [Pa], and an increase in temperature to roughly 40 [K]. Carbon Monoxide was also detected for the first time in the upper atmosphere [49]. These measurements have vital consequences for the understanding of the thermal structure, photochemistry, the ionosphere of Triton, and required modifications to existing atmospheric models [54].

2.3 POSEIDON Objectives

This section aims at defining the key scientific objectives of the POSEIDON mission to Triton, based on the literature review presented above. A lander will be used in order to tackle all or most of those objectives during the mission.

2.3.1 Interior

A detailed look into Triton's interior could provide valuable knowledge in direct connection with the two key science questions.

2.3.1.1 Interior Structure

Whether or not Triton could support life is directly linked to its internal structure. Additionally, the presence and subsequent depth of a subsurface ocean could give clues as to whether the body was originally a Kuiper Belt Object. As such, the mission objectives with regards to the interior are the following:

1. *Determining the internal structure of Triton. Is it differentiated? Is there a subsurface ocean? Could this ocean sustain life?*

As is discussed in Section 2.2.1.1, there is a high likelihood of the moon containing a subsurface ocean of some depth, with estimates ranging from 130 to 190 [km], but with the potential to be much higher figures. The presence of this ocean would suggest a source of heating, which could be the consequence of radiogenic heating, leftover heat from tidal dissipation mechanisms, or a combination of the two. A source of heat and liquid water are two of the most vital components for life; proof of a subsurface ocean would therefore present a perfect indication of the potential presence of life.

2. *Determining the causes for Triton's internal structure. Could it be a Kuiper Belt Object?*

A detailed analysis of Triton's internal structure — especially if it happens to contain a subsurface ocean — could yield an answer to the question of whether the body is a Kuiper Belt Object. The depth of the subsurface ocean, for instance, could be found to be much greater than initially anticipated. If this were the case, it could be the consequence of a relatively recent capture event. An accurate determination of Triton's interior structure could aid in modelling the radiogenic heat emitted from the moon itself. If found to be insufficient to sustain such an ocean, different factors would have to account for its existence. This would heavily suggest that the object was captured at some point in the recent past, strongly supporting the hypothesis of it being a Kuiper Belt Object.

2.3.1.2 Plumes

In studying Triton's plumes, there are two central research questions around which instrumentation should be focused, the first being:

1. *What is the source of Triton's plumes: are they solar-driven or endogenic?*

The lander will require heavy support from the orbiter in order to answer this first research question regarding the energy source for the plumes. The orbiter's ability to cover large swaths of land relatively quickly make it clearly the better candidate for gathering data about the plumes' spatial and temporal behaviour. The lander could act as a support for this research question, with a seismometer targeted at investigating the potential of endogenically generated plumes through the existence of a subsurface ocean.

2. *What is the composition of these plumes?*

The lander becomes critical for the investigation of plume composition. On Enceladus, proposed lander systems were justified as important biomarkers found in the plumes would disintegrate when exposed to the vacuum of space [33]. Such phenomena have also been experienced on Mars, with ionizing radiation from the sun degrading microbial biosignatures on the surface of Mars over a time period of 30 to 60 hours [55]. Triton is approximately 28.5 [AU] farther from the Sun than Mars is [56, 57], however its atmosphere is only 1.5-1.9 [Pa] [58], only about 0.2% of the thickness of Mars atmosphere, which itself is 1% of the thickness of Earth's [59]. Therefore, the effects of ionizing radiation should still be taken into account. The lander's relative proximity to plumes makes it a better option for examining the composition of plumes than the orbiter. However, the lander is still limited by how close it can get to the plumes, due to unknown terrain surrounding the plumes [2], and the potential for ice fracturing [33]. This will be discussed in more detail in Section 3.4 regarding landing location requirements.

2.3.2 Surface

A close-up inspection of the surface of Triton could provide information regarding the two key science questions: Does Triton support life, and what is the origin of Triton? Scientists believe that a subsurface ocean on Triton could contain forms of life, which could be proven if biomarkers are found by the lander. For this, the lander may not need to directly take a sample of the subsurface ocean, and could perhaps gain useful insights by taking a sample of the plume deposits in the ice surrounding the ice plumes. Studies on Saturn's moon Enceladus have shown that biomarkers, which are present in its ocean, evaporate and condensate on icy grains in the plumes, which were then picked up by an orbiter [60]. A similar process could be active on Triton and the biomarkers could potentially fall and freeze onto Triton's icy surface, ready to be analysed with a mass spectrometer on the lander. Therefore, the following research question can be constructed:

1. *Are biomarkers present in the surface ice of Triton?*

Regarding the science question about the origin of Triton, a similar method can be established. As mentioned before, it is believed that Triton is a Kuiper Belt Object, but that theory has not been proven yet. However, a study on KBO Arrokoth in 2020 showed the presence of certain KBO specific molecules in its surface ice [61]. In the same study, Pluto and Charon were analysed for molecules as well. With the same mass spectrometer as before, the ice on Triton could be analysed for those same molecules. The research question connected to this is:

2. *Does the surface ice on Triton contain similar molecules as those found on other Kuiper Belt Objects?*

Furthermore, as was seen in the previous section, the surface geology of Triton is truly fascinating and deserves better observations. While the orbiter mission will be able to map the surface on a global scale with high resolution, the use of the POSEIDON lander will permit to see details which would be completely missed due to the image resolution, but only for a given location (assuming no mobility of the lander). Similarly to the assessment of the volcanic nature of the Hadley Rille on the Moon based on images taken by the Apollo 15 crew [62], close up high-resolution images of the surface from the ground perspective would significantly contribute to the studies on the geological features and activity of Triton. Two main research questions then arise about geological studies of Triton's surface:

1. *Is Triton geologically active in current geological times?*
2. *How does the interplay of tidal dissipation, heat transfer, tectonics, cryovolcanism, diapirism, and surface–atmosphere interactions drive resurfacing on Triton?*

The second question was taken from Hansen *et al.* [2]. While it is obvious that the contribution of a lander mission to those two questions will be limited (compared to an orbiter capable of mapping much larger areas), a survey of the surface and particularly of its composition from a lander perspective would be an invaluable addition to the current literature and planned surveys of orbiter missions

2.3.3 Atmosphere

From the data in Section 2.2.3 it is clear that much is still unknown about Triton's atmosphere and many of the existing questions can be grouped into two overarching research questions:

1. *What is the origin of Triton's atmosphere?*
2. *How does Triton's atmosphere change over time?*

For the first research question, two main hypotheses have emerged. The first provides evidence for Triton originally having a larger atmosphere that has been lost over time, similar to that of Mars [63]. Although there is some evidence to support this, including similarities between the Martian and Tritonian atmosphere, there is much more evidence to support the second hypothesis. This hypothesis states that Triton's atmosphere is formed through a combination of surface ice sublimation and cryo-volcanism. This is backed up by the composition of the atmosphere matching closely with the composition of surface ices [52]. The recent discovery of a special form of ice that is a mix of both Nitrogen and Carbon Monoxide, providing a closer link between the atmosphere, surface composition, and plume composition, adds further data to this claim [64]. Although this origin is not completely certain, it would also help to explain some of the dynamic changes that occur in the atmosphere over time.

There have been many different hypotheses on the origin and nature of the dynamic changes in Triton's atmosphere. The most recent observations agree with the hypothesis that the atmosphere periodically grows and shrinks on a seasonal basis as ice sublimates and re-freezes [65]. One possibility that follows along this track is that the entire atmosphere of Triton freezes solid during winter seasons of low solar flux. The atmospheric thickening observed recently during the summer months would fit this trend of seasonal variation [65].

Due to the limited amount of data on the atmosphere of Triton, and the similarities between the moon and Pluto, attempts have been made at comparative planetology between these two bodies' atmospheres. While general characteristics are shared, there are still many differences between their atmospheres. Gaining further data on the atmosphere will aid in offering a better comparison to Pluto while also providing data that can aid in answering the key science question of the origin of Triton.

As the research questions related to the atmosphere only partially intersect with the overall mission science goals, they are relegated to secondary questions that should not take up much of the lander's resources. Additionally, due to the long term nature of both of the posed research questions and the short term limitations of lander missions, no direct answers can be given to either question through the data that can be gathered. Instead, a sub-question that relates to both original questions can be given:

i. *What are the mechanisms of surface-atmosphere interactions?*

In order to properly answer this question, the atmosphere needs to be accurately characterized. In order to properly characterize the atmosphere, temperature and pressure data needs to be taken, ideally throughout the entire height profile of the atmosphere. Ion concentration information is also useful, though not strictly necessary. Atmospheric composition data is also needed, and combined with the other readings will give very detailed insight into the current state of the local atmosphere. In combining these accurate local readings with more broad observations taken from an orbiting platform across the entire moon can aid in helping to characterise the entire atmosphere. This data, in addition to helping to refine Triton's atmospheric models, could also provide information on trace compounds that may be too faint to detect from orbit, yet still play a key part in the atmosphere. This will also help to validate atmospheric origin hypotheses. By comparing this data with data taken from the local surface ice, the relationship between the two can be better understood.

Taking these measurements repeatedly over time, especially in both the day and night, will give insight into the small dynamic changes in the atmosphere that may also give insight into larger dynamic processes. Using visual observations to characterise cloud formations and wind patterns will also play a role in this, allowing better understanding of Triton's weather and the material transport that may happen between the Northern and Southern hemispheres.

Taken together, these measurements will help to provide a thorough characterization of the local atmospheric environment and how it changes over a short timescale. Such information can aid in potentially validating existing hypotheses on the mechanisms of surface-atmosphere interactions.

2.4 Synergies with Other Missions

The overall goal of current deep space missions lies in the search for extra-terrestrial life, or extra-terrestrial habitats. This is clearly seen from the most recent Mars missions, but also from the space programs targeting deep space locations such as Jupiter, Saturn, (and now) Neptune, and their moons. Another class of space missions which can contribute towards this overarching objective, are space telescopes. A particular example is the James Webb Space Telescope (JWST), which can perform measurements of the moons of the gas giants from the Earth-Sun L2 point it 'orbits'. In this section, the contribution of the POSEIDON mission to current space exploration research, with respect to other missions, is briefly discussed.

First, the relevant scientific measurements performed by the POSEIDON lander mission will directly be enhanced by the accompanying orbiter (named TRITEIA) mission, which has the goal to provide a more global survey of the surface of the moon. Those measurements will provide more context to the clues gathered by POSEIDON, and the data gathered from the ground will supplement the orbiter mission measurements. This makes the POSEIDON-TRITEIA mission a single entity, with each part complementing the other.

Furthermore, the mission fits in the much greater picture of the ongoing survey of icy moons in the outer solar system. Various missions have been planned and will be launched in the coming years to investigate in great detail the characteristics of those moons and their potential habitability. Figure 2.6 from [2] gives an overview of how far the search for life is on the icy moons Europa, Enceladus, Titan, and Triton. As mentioned at the beginning of this chapter, while it is clear that the search for life is much more advanced for the three first bodies, studies of Triton are therefore most important to ensure a complete survey of icy moons and continue the search for life (in case life is not found on either Enceladus, Europa, or Triton), or to answer questions about whether life exists elsewhere and if all hospitable oceans support some type of life form (if life is found).

The global search for life in the solar system will be carried out by a few missions which all fit in this larger picture. (1) The orbiter missions Europa Clipper and JUpiter ICy moons Explorer (JUICE) will specifically target the icy moons of Jupiter, with a strong emphasis on Europa to study its surface and subsurface [66]. But JUICE will also perform fly-by's of Ganymede and Callisto. (2) The dragonfly mission will explore Titan's surface and atmosphere using a dual quadcopter [67]. (3) Several missions to Enceladus have been discussed, but none have been confirmed yet. A mission to Enceladus, however, is very likely to be planned in the near future, as it was categorised as a very attractive target and the prime candidate for a future mission focused astrobiology objectives outside Earth's biosphere, in the Voyage 2050 document from the European Space Agency (ESA) in 2021 [68]. It is clear that the POSEIDON-TRITEIA mission then fits perfectly in the big picture of deep space exploration, fulfilling the gap by exploring Triton, a promising icy moon of the Neptunian system.

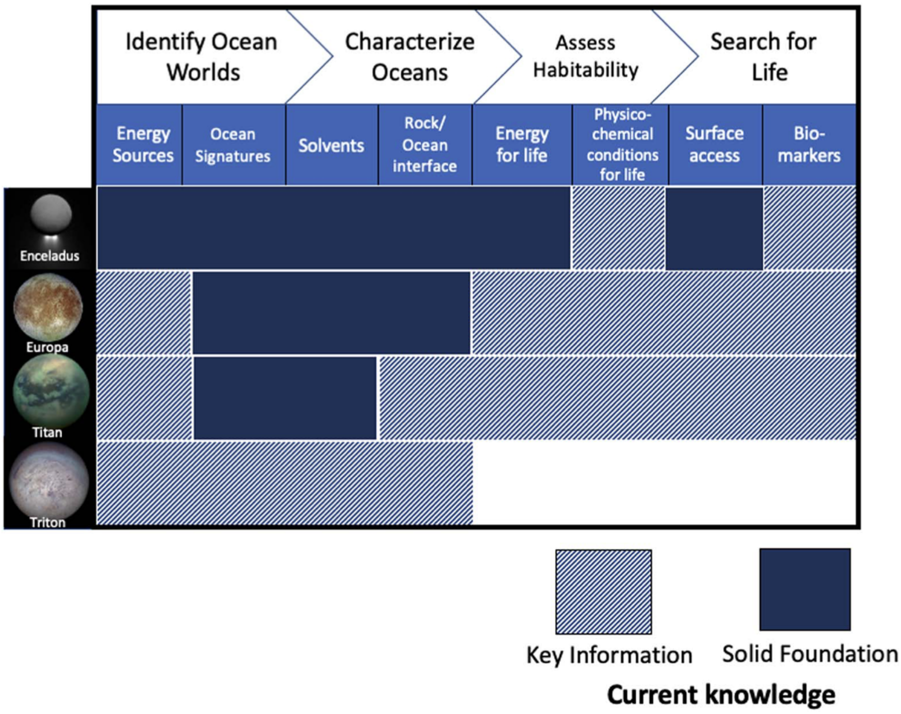


Figure 2.6: State of the search for life for Enceladus, Europa, Titan and Triton [2].

Finally, the JWST will perform some observations of the Neptunian system and Triton. An approved proposal to perform observations of Kuiper Belt objects (including Triton) has been submitted [69], and include MIRI Medium Resolution Spectroscopy; MIRI Imaging; and NIRSpec IFU Spectroscopy measurements of Triton. This data will become available 1 year after it was gathered, meaning that it will be possible to use it in combination to the POSEIDON-TRITEIA mission data. More activities related to the Neptunian system and Triton might be planned in the future.

3 Scientific Requirements

This chapter presents the science requirements of the POSEIDON mission, along with their justification. These requirements are organized into two categories: Level 1 (L1) and Level 2 (L2). L1 requirements are the top-level science requirements that are directly linked to the science objectives of the mission. L2 requirements are derived science requirements that specify the scientific capabilities of the mission's systems to enable the achievement of the L1 requirements. The flow from L1 to L2 requirements is described in each case. The L2 requirements serve as the link between the L1 requirements and the system engineering requirements.

This chapter consists first of requirements necessary for answering the main open questions of POSEIDON's mission, which is followed by additional requirements that will help POSEIDON achieve these goals, such as the landing location.

3.1 Instrument Functional Requirements

A number of requirements are required in order to fulfill the scientific objectives from Chapter 2. This section will mostly focus on the requirements that are directly linked to how measurements are taken. For each main science question the relevant requirements have been listed here, together with a brief rationale.

The two main questions for the POSEIDON mission is whether Triton supports life, and what is the origin of Triton? This led to the sub-questions that address investigating Triton's plumes and its sub-surface ocean, the search for biomarkers and the interaction between surface and atmosphere. Direct measurements from the surface of Triton could provide valuable information that could help in answering most of these questions. With this in mind, requirements were generated that the POSEIDON mission should fulfill in order to make the mission a scientific success. These requirements are listed in Table 3.3.

REQ-SCI-01 helps to gather critical information regarding the internal structure of Triton. With wave propagation the different sub-surface layers of Triton could be quantified and this could help in determining its internal structure, and potentially the power source behind the plumes. Requirement **REQ-SCI-02** and its sub-requirements mention POSEIDON's ability to measure biomarkers from plumes, which could provide answers about the composition of the plumes, and the possibility for life on Triton by extension. Sub-requirement **REQ-SCI-02-1** is aimed at ensuring the lander's measurements contain in-situ information that is not directly accessible by an orbiter platform. By taking measurements below Triton's surface, the components of the plume are not yet exposed to the radiation that can disintegrate them. Sub-requirement **REQ-SCI-02-2** is a planetary protection measure aimed at ensuring that the plume composition experiments are not impacted by the lander mission itself, and that damage to any potential ecosystems is avoided. The remaining sub-requirements for **REQ-SCI-02** are aimed specifically at the type of biomarkers that have the most potential to exist.

A high resolution imaging camera could send close-up pictures of the surface of Triton that, in conjunction with imagery from the Triton orbiter, could help in characterizing Triton's surface processes. Therefore, requirement **REQ-SCI-03** was created. Also close to the surface, POSEIDON could be able to detect biomarkers in the surface ice, as this could indicate a link to a Kuiper Belt Origin. **REQ-SCI-04** deals with this science aspect. Finally, questions arose regarding the thin atmosphere on Triton and their interactions with surface features that were identified during the Voyager mission. To answer this, POSEIDON should be able to observe the atmosphere on properties like temperature, density, composition and potential wind speeds. This is summarized in the all-encompassing requirement **REQ-SCI-05**. In order to ensure the entire atmosphere is properly measured, sub-requirement **REQ-SCI-05-1** was created.

Table 3.1: L1 and L2 scientific requirements to complete the science objectives.

Code	Level	Description
REQ-SCI-01	L1	POSEIDON shall be equipped with an instrument that can detect seismic waves on Triton.
REQ-SCI-02	L1	POSEIDON shall be capable of measuring biomarkers from plumes.
REQ-SCI-02-1	L2	POSEIDON shall be capable of taking direct measurements from areas of the plume below Triton's surface.
REQ-SCI-02-2	L2	POSEIDON shall not significantly impact the composition of the plume during its operations.
REQ-SCI-02-3	L2	POSEIDON shall be capable of distinguishing biogenic methane from other methane sources.
REQ-SCI-02-4	L2	POSEIDON shall be capable of identifying polynucleotides.
REQ-SCI-02-5	L2	POSEIDON shall be capable of identifying lipids.
REQ-SCI-03	L1	POSEIDON shall be capable of imaging the surface of Triton when landed.
REQ-SCI-04	L1	POSEIDON shall be capable of measuring biomarkers in surface ice.
REQ-SCI-05	L1	POSEIDON shall be capable of measuring properties of Triton's atmosphere.
REQ-SCI-05-1	L2	POSEIDON shall be able to take atmospheric measurements during initial descent.

3.2 Instrument Performance Requirements

A number of instrument specifications related to each of the scientific requirements from the previous section can be created, which determines what the performance of POSEIDON's instruments should be. This is for each instrument specific, therefore the specification type for each instrument is listed in the fourth column. A comprehensive list of specifications can be found in Section 4 for each instrument. To show traceability, the most important specification of each instrument has been mentioned. A reasoning or similar instrument has been given in the final column if possible.

Table 3.2: Instrument specifications for the scientific requirements of the POSEIDON mission.

Code	Level	Instrument	Specifications	Reasoning
REQ-SCI-01	L1	Seismic Detector	Frequency Range: 0.08-50 [Hz]	A study related to seismic waves on Europa found that a frequency band of 0.08-10 [Hz] was required [70]. High frequency seismic waves also need to be detected and this makes the upper limit at least 50 [Hz].
REQ-SCI-02 **REQ-SCI-04**	L1	Biomarker Detector	Resolution: <1 [ppbw]	Instruments for similar biomarker detection on Mars required detection better than 1 parts per billion weight [71]. This holds for both the plume. detector and the surface-ice detector.
REQ-SCI-03	L1	Surface Imaging Camera	Resolution: 1600x1200 [px] (pixels)	The imaging equipment of POSEIDON shall be able to image the surface of Triton with a resolution equal to the Mastcam-Z of NASA's Perseverance rover [72].
REQ-SCI-05	L1	Atmospheric Thermocouple	Accuracy: 0.5 [K] Resolution: 0.02 [K]	The temperature profile of the atmosphere shall be gathered during lander descent with a resolution comparable to the Huygens HASI instrument [73].

3.3 Lifetime

To this date, there has been only one lander mission on an icy moon of the outer solar system (somewhat similar to the case of the POSEIDON lander on Triton): the Huygens lander part of the Cassini-Huygens mission in early 2005 [6]. The Huygens probe was designed for an operational lifetime of a few hours and could therefore only survey the atmospheric and surface characteristics of the body at a certain given time. The objective of the POSEIDON lander is to provide such survey but to also be able to provide data on the evolution of the environment over time. For this reason, a relatively large nominal mission lifetime has been selected (and therefore stems for the use of a Radioisotope Thermoelectric Generator (RTG), as will be seen in Chapter 5). Particularly, the seismology measurements require quite some time to be valuable and permit to register a seismic event of the body it is on. As a comparative example, the Viking 2 Mars lander only registered a potential seismic event after 80 [sols] [74] and no other was registered until a failure in the seismology measurement system around 500 [sols], only meteorological interferences were registered.

Additionally, given the long interplanetary transfer time (from 13 to 18 years), the fact that an RTG is generally produced a few years before the launch (2-3 years), and the nominal operational time of RTGs in general (up to about 20 years); nominal mission lifetimes larger than 1 year are likely unreasonable (this also becomes clear from the work presented in Chapter 5 from the characteristics of the RTG and the interplanetary transfer) [1]. Overall, a nominal mission duration of 6 months is deemed reasonable, with a goal to extend the mission until 1.5 years on the surface of Triton.

[1]Although the mission could be extended to reach 1.5 years or more, planning for a shorter nominal mission duration is safer.

Table 3.3: Mission lifetime requirement.

Code	Level	Description
REQ-LF-01	L1	The POSEIDON mission shall have a nominal mission duration of 6 months. (goal: 1.5 years)

3.4 Landing Location Requirements

Due to the limited information that Voyager 2 was able to gather about Triton in its single flyby, selecting a landing location is difficult in advance. Only 40% of the moon has been seen during this initial flyby [75], meaning that there could be better landing location candidates that have not been discovered yet. However, some preferred landing regions would be valuable at this stage, as landers have limited range due to power constraints. Thus, it is important to land near interesting features on the moon, while also finding somewhere that is safe.

One geographically localized feature on Triton is its plumes, which were concentrated around the subsolar latitude during Voyager 2's flyby [2]. Based on the solar-driven hypothesis, this would suggest that the plumes would move with the subsolar latitude, and would be concentrated around the location of that point on Triton at the time of arrival. However, if the plumes are localized due to tidal forces as is seen on Enceladus, their location when POSEIDON arrives would be less clear. It is also possible that the plumes are not localized at all, and that there are other plumes in the unexplored part of Triton.

These unknowns suggest that the best course of action is to use an orbiter platform to map out the surface of Triton to find an area with plumes and other scientific features of interest nearby that is also safe. These features of interest are described in greater detail in Section 2.2.2. The requirements for a landing location, as well as for the orbiter platform that would be responsible for helping to find the location, are listed in Table 3.4.

Table 3.4: L1 and L2 scientific requirements for the landing location. For L2 requirements, traceability to the relevant L1 requirement is shown in brackets.

Code	Level	Description
REQ-LL-01	L1	The orbiter shall find suitable landing regions for the lander system.
REQ-LL-01-1	L2	The orbiter shall identify ice that is thick enough to support landing.
REQ-LL-01-2	L2	The orbiter shall image the surface with a spatial resolution equal to or better than 1 [km].
REQ-LL-02	L1	POSEIDON shall remain operational after landing on the surface of Triton.
REQ-LL-02-1	L2	POSEIDON shall land on terrain with slope of less than TBD [°].
REQ-LL-03	L1	POSEIDON shall be capable of reaching desired scientific destinations.
REQ-LL-03-1	L2	The elevation of the landing site shall not exceed TBD [m].
REQ-LL-03-2	L2	POSEIDON shall land at most 2 [km] away from plume openings.
REQ-LL-04	L1	POSEIDON shall be capable of communicating with the orbiter after landing.
REQ-LL-05	L1	The landing process shall not directly interfere with areas having a high potential to harbour life.
REQ-LL-05-1	L2	POSEIDON shall land at least 1 [km] away from plume openings.
REQ-LL-06	L2	POSEIDON shall land on a surface that can support the landing loads.

The resolution of the orbiter's imaging system should be high enough to distinguish plume sources, which are thought to be up to 3 [km] in exit diameter [2, 24]. A resolution that is better than the expected plume exit diameter is preferred, in order to accurately characterize the terrain around the plume. The safe landing distance requirement **REQ-LL-05** is also derived from this camera resolution requirement, as the orbiter is responsible for locating a suitable landing location. Compared to landing on Titan, Venus, or even Mars, the thin atmosphere of Triton makes uncertainties related to atmospheric descent irrelevant [76]. Thus, it should be possible to land with more precision than the wide landing ellipses seen on previous missions.

3.5 Planetary Protection

The focus on planetary protection procedures for the POSEIDON mission focus mainly around preventing contamination of the potential subsurface ocean and plumes. As such, along with ensuring a limited number of bio-contaminants exist on the lander, requirements must be put in place to ensure the lander and all its auxiliaries remain stable on the surface. To cover this first part, POSEIDON will follow the requirements and protocols laid out in NASA standard NASA-STD-8719.27 [77]. Based on the destination of Triton and the fact that no contamination probability analysis can be performed at this stage, POSEIDON will be classified as a Class IV mission in regard to this standard, and will follow all relevant requirements accordingly. In addition to this classification, the inclusion of instruments designed to specifically detect biomarkers will require additional precautions to limit the number of spores present on the instruments and lander. No external analysis on the amount of contaminants accepted for these instruments has been performed, and thus will follow the relevant requirements in the NASA standard.

The presence of radioactive material within the onboard RTG also poses a potential threat to the long-term Planetary Protection of Triton. The long half-life of Plutonium-238 means that steps must be taken to limit the possibility of potential radioactive contaminants entering Triton's subsurface ocean. To this end, the requirement is put in place that the landing location of the lander must be geologically stable for the lifetime of the radioactive material. This requirement will play a major role in the selection of a proper landing site. A brief summary of these imposed requirements can be found in Table 3.5.

Table 3.5: Mission lifetime requirement.

Code	Level	Description
REQ-PP-01	L1	The POSEIDON mission shall abide by all regulations laid out in NASA-STD-8719.27 [77]
REQ-PP-01-1	L2	The POSEIDON mission shall land on a surface that is geologically stable for the next 1000 years.

4 Science Payload

This chapter presents the different payload instrumentation which will be present on-board the POSEIDON mission to Triton. This science payload aims to satisfy the science objectives and requirements given in the previous two chapters.

4.1 Seismic Instrumentation

The main lander will be equipped with a single passive three-axis seismic sensor; this instrument will allow the craft to record different geological events, provide insights into the presence of a subsurface ocean, and possibly provide an estimate for the thickness of the ice shelf as well.

While the principal determination of the presence of a subsurface ocean will come from the orbiter's magnetic field measurements, the seismometer can assist by attempting to measure Triton's response to certain geological events. By measuring any potential P- and S-waves, one can draw conclusions with regards to the radius of Triton's core, and the thickness of a liquid layer — and as a consequence, the thickness of the ice shelf as well. This is not without its challenges, however. Studies have been conducted on the possibility of measuring internal structures on other icy moons (Kovach et al. [70]), and they conclude that while it is possible to carry out these measurements with a single seismometer, it is more challenging than using an array of them. Unfortunately, the possibility of landing other seismometers on Triton seems unlikely, and so other methods must be used in order to compensate. One example is the use of measuring strategies like seismic attenuation profiling [78]. The seismology instrument used by the lander would be composed of a 2-axis broadband seismometer — able to capture tidal and long period motions up to 10 [Hz] — and a 3-axis short period seismometer measuring high frequency movements from 1 to 50 [Hz]. This configuration would allow for the measurement of most seismic events, whilst providing a degree of redundancy due to their significant overlap in frequencies [79].

4.2 Imaging Instrumentation

Imaging the surface of Triton can help to characterize the surface processes that are ongoing on the body, as per **REQ-SCI-03**. It has been decided to only look at more recent, and future, missions when looking at suitable imaging payloads. The reason for this is that these missions use more current, and advanced, image capture techniques, and have a higher overall image quality. An obvious downside of a higher image quality is the data rate required to send these images back to the orbiter, and consequently to Earth. Advanced compression methods and a high-power communication system are required to accomplish this.

Four different imaging payloads have been considered: the Instrument Deployment Camera (IDC) from the Insight Mars Lander [80], the Mastcam-Z from the Perseverance Rover [72], the NaTeCam from the Tianwen-1 [81], and the StereoCam from the planned Phootprint mission [82]. The Mastcam-Z was chosen after careful consideration, mainly due to the high-resolution sensor and the ability to zoom. Both the IDC and StereoCam were eliminated due to their lower resolution, and the low technological readiness level (TRL) (level 4) of the StereoCam. Finally, the NaTeCam was eliminated due to it being manufactured by the Chinese National Space Administration, thus lacking documentation that the team could use to analyze its performance properly. The specifications of the Mastcam-Z can be found in Table 4.1.

Table 4.1: Mastcam-Z characteristics [83]

Characteristic	Value
Resolution (S x L)	1600 x 1200 [px] (pixel)
Bit Depth	11 [bits/px]
Field of View (FOV)	Wide: 25.6[°] x 19.2[°]
	Narrow: 6.2[°] x 4.6[°]
Spatial Resolution (Wide Zoom)	0.57 [mm/px] (at 2[m]) - 28.4 [mm/px] (at 100[m])
Spatial Resolution (Narrow Zoom)	0.14 [mm/px] (at 2[m]) - 6.7 [mm/px] (at 100[m])
Focal Length	26 - 110 [mm]
Dimensions (HxWxL)	110x120x260 [mm] (per unit)
Mass	4 [kg]
Power	23.6 [W] (operational), 15 [W] (standby)

The ability to zoom in allows for higher spatial resolutions for long distance imaging compared to regular cameras. Interesting geological features can be captured in more detail, and the zoom functionality can compensate for uncertainties in landing location. The spatial resolution can be linearly extrapolated by using the information in Table 4.1. Table 4.2 provides spatial resolution information for different target distances. It must be noted that the Mastcam-Z is currently being used on Mars which has a significantly different thermal environment compared to Triton. A thermal protection system (TPS) must be added to the camera setup to ensure temperatures that stay within the specified operating temperature range. This will add power and mass to the imaging payload.

Table 4.2: Extrapolated spatial resolutions of Mastcam-Z

	Wide FOV	**Narrow FOV**
Target Distance [m]	**Spatial Resolution [mm/px]**	**Spatial Resolution [mm/px]**
1000	284.0	76.1
2000	568.0	153.3
3000	851.9	230.4
4000	1135.9	307.6

4.3 Plume Instrumentation

POSEIDON consists of a suite of instruments to study the composition of Triton's plumes and distinguish any potential biomarkers. To do this, the payload uses a combination of instruments used on previous space missions, including a gas chromatograph - mass spectrometer, a flow cytometer, and a microscopic imager.

4.3.1 Gas Chromatograph - Mass Spectrometer

A gas chromatograph - mass spectrometer (GCMS) is an instrument that would primarily be used to differentiate between biogenic methane sources and methane produced through other environmental processes. It does this by measuring the isotopes of each methane compound [33]. More specifically, it can measure the balance between the carbon isotopes C_{12} and C_{13}. If the two are in equilibrium, there is then a reasonable chance that there is an ecosystem that favours the existence of life [84]. A GCMS can also potentially be used to identify lipids in a mixture [33].

A GCMS is a combination of two scientific instruments. A gas chromatograph is useful for determining the components of a flowing mixture, such as Triton's plumes. It consists of a tube filled with an inert carrier gas travelling through the center and a liquid coating along the wall. A liquid sample from the plume is inserted and then vapourized. Heavier gases with higher boiling points tend to interact more with the liquid and thus travel slower, while lighter ones tend to interact more with the gas. A typical gas chromatograph would measure the components that hit the detector, and typically at what time they hit the detector. However, the amount of a certain component in the mixture cannot be directly measured through the chromatograph alone [85].

Therefore, it is important to attach a mass spectrometer to the output of the gas chromatograph, which can then ionize the incoming vapourized particles and distinguish them according to their mass/charge ratio [86]. In this way, specific information about the components of a fluid mixture can be gathered.

While this is a very useful instrument for studying composition, it comes with its own set of technical challenges. GCMS technology has been employed on previously proposed planetary exploration missions, such as the ExoMars rover [84]. That GCMS implementation is searching for polynucleotides and other lipids on Mars. It contains 32 single-use ovens to vapourize samples for analysis. Thermal energy and control are major concerns for this system, because the vapourization ovens are required to reach 800 [°C] [84]. Additionally, since the speed at which some particles move through the inert carrier gas is dictated by temperature, temperature control becomes extremely important. Sometimes, temperature control up to tenths of a degree is required [85]. In the plumes, the temperature is expected to be less than 40[K] [2]. The GCMS on the ExoMars rover has an operational temperature range of -40[°C] to 20 [°C], meaning that thermal control in the plumes would require an enormous amount of energy. Thus, any payload responsible for collecting information from inside Triton's plumes should be used solely as a sample collection device.

The GCMS on the ExoMars rover is one component of the Mars Organic Molecule Analyzer (MOMA) instrument [71]. It has a mass detection range of 50-500 [g/mol], with a signal-to-noise ratio of 10 and an atomic mass resolution of less than 1 [g/mol] [71]. This should be applicable to the Triton plume analyzer as well, because it is meant to distinguish between C_{12} and C_{13}. As the instrument performance requirement **REQ-SCI-02** is based on the requirements of the ExoMars mission [71], the instrument performance should be comparable as well. The entire MOMA instrument weighs 11.5kg. While this includes the GCMS and another instrument, this is a suitable estimate considering the additional thermal protection that will be required on Triton.

4.3.2 Flow Cytometry and Microscopic Imaging

A flow cytometer is able to analyze individual suspended particles in a flow very quickly by using a laser, which produces a specific spectra that can be detected and used to understand cell organization and distinguish potential mechanisms for life. This is important for the detection of larger biomarkers, such as polynucleotides [33, 87]. Microscopic imaging can serve as a useful complement to this information by providing a visible image of the suspended particles. Some flow cytometers are combined with microscopic imagers to form an imaging cytometer. While cytometers are good for their high throughput and sorting applications, imaging is invaluable for collecting structural data about the particles in the flow [88].

A major technical challenge with flow cytometry and microscopy is the miniaturization and automation of these technologies [33]. Typically, these measurement devices require a full desk setup to do useful science [89]. They also typically use some manual intervention to group cells appropriately for analysis [90]. Thus, there is no existing space-based reference designs for this instrument. However, work is progressing in the field of microflow cytometry and automated microscopy [91, 92, 93]. In particular, a microflow cytometer used on the International Space Station weighs 10[kg] and can analyze blood samples [94], while other systems for specific analysis purposes have been shrunk to 3.5[kg] [91]. Thus, it is conceivable that this technology could be repurposed and further miniaturized for plume reading.

4.3.3 Sample Collection and Protection

As justified by the power requirements of the GCMS, it was decided to use a sample collection payload inside the plumes rather than a payload that would perform experiments. This has the drawback of risking some damage to the samples before they are brought back to the lander. This damage could come in the form of physical collision, or from incoming radiation. Additionally, significant thermal changes might affect the sample, as the conditions for biomarker survival may be quite delicate. However, carrying multiple ovens onboard for experimentation is also not feasible, as the increased mass from these ovens would make it more difficult to reach the plumes. Weight and power savings for this sample collection payload are crucial, as the lander is expected to land at a safe distance away from the plume.

A few designs are put in place in order to protect the samples during transit back to the lander. The first is redundancy. Sixteen samples will be collected, which can be split between the GCMS and the flow cytometer.

Table 4.3: Plume instrument summary, including full specifications. No information was available on power specifications for an imaging cytometer of comparable size, so it was scaled down from an industrial imaging cytometer. Resolutions are provided for the mass spectrometer [g/mol], the flow cytometer [nm], and the microscopic imager [μm/pixel]. Range for the flow cytometer is defined by passband filter width and particles per second analyzed as these are important for particle sorting.

Instrument	Purpose	Mass [kg]	Average Power [W]	Measurement Range	Resolution and Quality	Reference Designs
Gas chromatograph - mass spectrometer	Biogenic methane detection	11.5	82	50-500 [g/mol]	<1 [g/mol], SNR = 10 [dB]	MOMA [84, 71]
Imaging cytometer	Cell organization	3.5	32	10000 particles/s>particles/s , 40 [nm]	1 [nm] SNR = 30 [dB] 30 [μm/pixel]	Microflow [94] EnEx [33] Opportunity [100] Nexcelom [101] Best practices [102, 103]

This provides some insurance in case some damage occurs to some samples. This insurance is also important as the payload may not be able to complete multiple trips to the plume. The second measure is radiation protection. While the sample collection process is not expected to be very long, it is known that biomarkers can disintegrate when exposed to radiation. Inspiration can be taken from radiation shielding seen on satellites in Earth orbit. The thickness and material of the radiation shielding depends on how long the samples are expected to be in transit, and on the radiation environment expected on the surface of Triton. The final measure for sample protection is thermal and pressure control. It is important that the sample is maintained in the same environment as it was found in the plume. Otherwise, the advantages of using an in-situ lander experiment are reduced. To achieve this, pressure and temperature sensors should be onboard the sample collection payload, measuring the conditions at the time of sample capture. The samples can then be controlled to match those conditions using thermal cooling devices such as cryopumps and keeping each container sealed so that pressure is maintained.

The container doors will be actuated using a sequence of small, low-temperature resistant motors from Moog [95]. The pressure sensors need to cover a wide range of pressures with sufficient accuracy to ensure there are no major leakages in the sample containers. Since it is unclear of the composition of the plumes, a standard industrial pressure sensor is used [96]. The temperature sensor requires a bit more effort to source, as typical ultra-cold temperature sensors can only measure down to -200[°C] [97]. It is therefore necessary to use specialized cryogenic temperature sensors, which can go down to -271.8[°C] [98].

4.3.4 Other Potential Instruments

The antibody array is another instrument that has been suggested for astrobiological research from the Enceladus Explorer [33] and the HADES Europa lander [99]. Similar to the flow cytometer, this is a complementary instrument to the GCMS, and studies the composition of proteins. Given the limited mass available for the plume measurement suite, it was decided to proceed with the flow cytometer and microscopic imaging combination for its slightly broader use cases. This is important as at this stage of development it is unclear what exactly will be imaged. A more versatile payload reduces the risk of gathering no useful data.

4.3.5 Plume Instrument Summary

Table 4.3 shows some key performance details and other specifications of the proposed plume experimentation suite, including reference designs that they are based on. These performance details are partially based on the requirements provided in Table 3.2, as well as industry best practices and comparable missions.

4.4 Atmosphere Instrumentation

In order to properly characterize Triton's atmosphere, the lander is equipped with an atmospheric characterization instrument. The instrumentation that follows is based off of the MEDA and HASI instruments operated on Perseverance and Huygens respectively [104, 73]. The instrument will carry four main sensors: a thermocouple, a pressure sensor, a 3-axis accelerometer, and a wind sensor. The thermocouple, pressure sensor, and accelerometer will be the only sensors operational during the initial descent phase of the mission and will be responsible for characterizing the atmosphere. In order to limit the impact of the lander systems on measurements, the temperature and pressure sensor will be located on a small deployable boom which will aid in isolating them from the lander environment.

Once on the ground, the wind sensor will deploy to gather data on the wind profile of the local environment. The temperature and pressure sensor will also continue to gather data at a consistent, but sparse rate in order to capture transient changes to the local atmospheric environment. The specifications of each sensor are given in Table 4.4. It should be noted that the average power consumption during descent will be larger then listed due to the higher data rate, however it will be the only instrument in operation and will remain under the 100[W] limit.

Table 4.4: Sensor specifications for the atmosphere characterisation instrument

Instrument	Purpose	Measurement Range	Resolution/Accuracy	Mass [kg]	Average Power [W]	Reference Designs
Thermocouple	Atmospheric temperature profile	20-250 [K]	0.02[K] / 0.5[K]	5	15	MEDA [104, 105] HASI [73, 106]
Pressure Sensor	Atmospheric pressure profile	0-50 [mbar]	0.001 [mbar]			
3-Axis Accelerometer	Atmospheric Density Profile	0-10 [g]	0.1[mg] / 1% of full scale			
Wind Sensor	Ground wind	0-10 [m/s]	0.1[m/s] / 1[m/s]			

4.5 Surface Composition Instrumentation

Section 2.3.2 mentioned that an investigation into biomarkers in the surface ice of Triton could help answering both main science questions. The existence of biomarkers could hint at the possibility of life on Triton, but it could also determine whether or not Triton shares similarities with other Kuiper Belt Objects. To extract this data from the ice an instrument is required that is able to identify biomarkers. Section 4.3 already mentioned a system this is able to perform this task, but it cannot cover every interesting area in the investigation of biomarkers. Furthermore, it was designed to work with gases and is therefore not directly applicable to the surface ice. A system that could complement the GCMS and is applicable to Triton's surface ice needs to be found.

The Complex Molecule Detector, CMOLD, is a space-proven payload that specialises in identifying life forms and biomarkers on other planetary bodies. It consists of three independent systems that analyse liquid samples fed by a microfluidic system. One of these systems is the Raman spectroscope, which can identify individual parts of organic compounds, like the molecules that are responsible for the functionality of proteins and nucleic acids. Raman consist of a laser, an optics system and a spectrometer. The laser fires a 532 [nm] monochromatic beam onto the sample, which excites its molecules, and then guides the beam through the optics system towards the spectrometer. There, a 2048 pixel detector with a range of 15 to 3800 $[cm^{-1}]$ analyses the beam and determines the composition of the biomarkers in the sample. The detector can be altered according to the specific molecules that the mission wants to identify, but to start it has been configured to detect C-H and O-H bonds [107]. This configuration of Raman was scheduled to fly on the ExoMars rover mission in 2022 [108].

However, the Raman spectroscope works with liquid samples, so a system needs to be created that heats the ice sample without damaging potential biomarkers. It also needs to transport the sample from the ice to Raman and GCMS. Such a system could be constructed in the form of a robotic arm with a heating system at the tip. This would enable POSEIDON to take measurements of the surface ice directly while utilizing the same instruments for multiple science goals. A general layout of these instruments and the robotic arm have been given in Chapter 5.

Table 4.5: Specifications of the Raman spectrometer.

Instrument	**Purpose**	**Mass [kg]**	**Average Power [W]**	**Measurement Range**	**Resolution Quality**	**Reference Design**
Raman Spectrometer	Identifying biomarker molecules	2.3	0.020	532 [nm] laser excitation 15 - 3800 [cm^{-1}]	6 - 10 [cm^{-1}]	CMOLD, ExoMars [107, 108, 109]

Mission Design 5

This chapter presents the preliminary mission design of the POSEIDON lander. Section 5.1 will present the overall mission concept selection, ranging from the lander architecture to the landing site selection and the design of the plume experiment module. Following, Section 5.2 presents the mission profile, as planned from launch to decommissioning.

5.1 Mission Concept Selection

5.1.1 Mission Architecture

5.1.1.1 Lander Architecture

The mission architecture was a critical trade for the POSEIDON mission. Triton visits are not frequent, and thus a proposed mission should aim to do as much as possible within the available launch window. However, it is also important to ensure that the mission concept is feasible, and adheres to mass and cost constraints. The architecture trade began with concept generation for the different ways that Triton could be explored. Figure 5.1 shows the various concepts that were considered in the mission architecture trade.

There are two high-level options for the lander architecture. Either a single lander could be deployed, or multiple landers could be sent to the surface in different locations. The advantage of deploying multiple landers is that a greater percentage of the surface can be covered by the lander system. Since one of a lander mission's greatest limitations is its inability to cover large distances, having multiple landing locations enables the lander to study more phenomena than would be possible with a single lander. However, increasing the number of landers increases mission complexity. One major limitation is the number of radioisotope thermoelectric generators, RTGs, that can be sent on an interplanetary mission. As each RTG costs in the range of [€]150 million [110], it is not feasible to bring more than one. Thus, having more than one main lander is not a feasible option.

Another major driver for the mission architecture is seismology. If seismometers are desired for planetary interior studies, having more seismometers in multiple places around the moon's surface is preferred for gathering more readings from different phenomena on Triton. Having only one seismometer makes its readings significantly less useful [70]. Because of the clear utility of the lander for studying plumes, and the direct impact that studies of plume composition have on the main science question of Triton's habitability, instruments that study the plume were deemed necessary for the mission. Combined with the support technology required to reach the plume with these instruments, the lander would already be quite heavy. Adding an additional lander, whether it comes in the form of a small, battery-powered impactor, or a smaller version of the main lander, would have a very high likelihood of exceeding reasonable mass constraints defined for this mission.

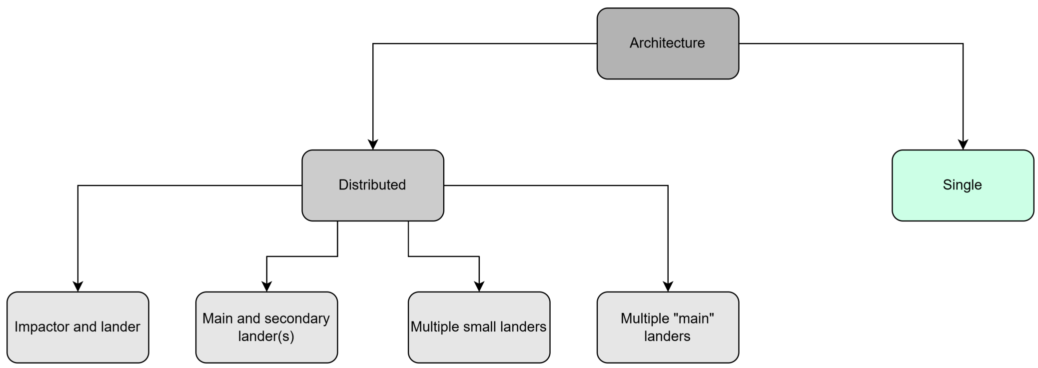


Figure 5.1: Concept generation for the mission architecture, with the selected concept in green.

Recognizing that sending multiple RTGs to Triton is not feasible, and recognizing that generating more comprehensive seismology readings is not as important as plume instrumentation for the main POSEIDON objectives, narrows the decision down to a single main lander that is capable of performing all the science necessary to provide some answers to both main science questions for this mission. Another important factor of this was general mission complexity, as a single lander is much easier to control and find a suitable landing location for than for two or more landers.

5.1.1.2 Mobility

Another important consideration for landers is their mobility. A disadvantage of landers when compared to orbiters is their limited ability to move around the surface of a planetary body. The furthest that a rover has travelled on the surface of a planet other than Earth is the Opportunity rover on Mars, which travelled 45.2 [km] in its lifetime [111]. Other landers, such as the Huygens probe [112], the Viking landers [113], and the Venera lander [114], were some of the first landers on their respective bodies, and stayed stationary.

A few potential mobility concepts are presented in Figure 5.2.

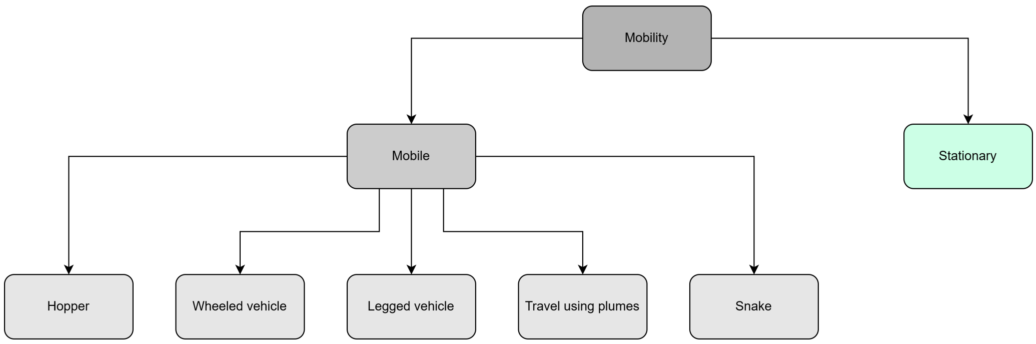


Figure 5.2: Concept generation for the mobility of the lander, with the selected concept in green.

A brief description of each design is also provided:

- **Hopper:** The hopper originates from the Triton Hopper mission concept proposal [115]. The hopper uses processed nitrogen ice from the surface of Triton to refuel itself and make rocket-propelled "hops" around the moon.
- **Wheeled vehicle:** This is a typical rover design, seen on typical Mars and lunar rover missions [116, 117].
- **Legged vehicle:** Typical lander designs [113, 118] employ some legs for support and a softer landing. The idea would be to make these legs mobile, such that the lander can move similarly to a spider or an insect.
- **Travel using plumes:** While Triton itself has a very tenuous atmosphere, a vehicle with some balloon or other flight mechanism would likely generate enough lift if carried by the plumes. Ingenuity is an example of a flight-based system in a reduced atmosphere environment [119].
- **Snake:** While there are no available reference designs for this, the basic principle is taken from the slithering of a snake, maintaining close contact with the surface of Triton and potentially using this to enter plumes.
- **Stationary:** Once a landing site is selected, the lander will be unable to move from its starting point.

Immediately, travelling using the plumes can be discarded as a viable concept, as it provides no control. The motion of the lander would be subject to the motion of the plumes, which is poorly understood. It would be very difficult to guarantee the safety of the lander, and not all of the mission objectives can even be completed with this design due to its distance from the moon's surface.

The remaining designs all have some merit as they provide various degrees of mobility. Designs like the Triton hopper can cover much more of Triton's surface [115], while the spider or snake based designs could have the traction and articulation necessary to descend into plumes and return to the surface.

However, given the overall architecture of a single main lander, a more fundamental question is whether or not the lander is able to achieve all the critical mission goals while not moving. If this is the case, it would significantly reduce the cost and complexity of the mission, allowing more research and development resources to be invested into the experimentation itself.

While the hopper, rover, legged, and snake options all provide better achievement of the science goals than the stationary lander, a stationary lander is still able to conduct surface surveys, measure the atmospheric profile, and determine plume composition by decentralizing its payloads. By finding a favourable landing location with the help of the orbiter, sites that are both interesting for study and safe for landing can be identified. With other major mission drivers including planetary protection, thermal protection, and power constraints, adding mobility to the lander when not strictly necessary may actually hinder the lander's ability to perform its main mission objectives. Thus, for the simplicity of the design, the lander was chosen to be stationary.

5.1.1.3 Telecommunication Architecture

Direct telecommunication from the surface of Triton to Earth is unfeasible as the latter would likely not be in the line of sight of the lander during its descent and once on the ground. For this reason, the accompanying orbiter mission will be used as a telecommunication relay to transmit the gathered data back to Earth. This yields a similar configuration to the Cassini-Huygens mission, where the lander also only had a few hours to transmit the entirety of the collected data to Cassini, which stored the data to later be transmitted. As this landing dates back to 2005, it is safe to assume this architecture is indeed feasible and that the telecommunication technology has developed enough to cover the even greater distance of the POSEIDON mission [120].

A difference with the Cassini-Huygens mission, however, is the available time to transmit the data to the relay satellite, as the relay will be an orbiter staying around Triton for the present mission, rather than in a fly-by. Given that the lander has enough energy to stay active for multiple orbits, more data can be gathered and sent back to Earth. Such a configuration is then closer to the one of the Mars rover missions which communicate with the Mars Relay Network [121], and an order of magnitude of the capabilities of such a telecommunication system can be obtained from a direct comparison with the Mars 2020 rover (which uses an ultra-high frequency (UHF) low gain antenna for communication with the relay satellites) telecommunication capabilities: up to 2 [Mbit/s] can be achieved, depending on the orbiter used as relay [122]. This is also with an atmosphere, which would not be present on Triton, but the distance to the orbiter might be significantly different. Nevertheless, this baseline performance is assumed to be achievable for a Triton mission, and will likely be improved over the development time.

5.1.2 Power Source

This section displays the concept generation and tradeoff for the lander's power source. Figure 5.3 shows the various concepts generated for this design. As Triton is very far away from the Sun, there is not sufficient direct or reflected solar power to support the lander's operations, without immense solar panels that would be much too large to launch [123]. Fuel cells are also not viable for such a mission. Current fuel cell designs have focused on short term manned missions near Earth, and although the development of higher power fuel cells is ongoing for longer duration missions, they are still inferior to battery storage systems when compared in performance [124]. This leaves the decision between a main battery power supply and a Radioisotope Thermoelectric Generator (RTG). The main deciding factor between these two concepts is the mission duration needed to fulfil mission requirements. As outlined in Section 3.3, a longer, multi-month mission is required, leading to a final selection of an RTG power system.

There exist two possible choices for an RTG: the American made Plutonium-238 RTG, and the European made Americium-241 RTG, the latter of which is still in development. Both RTG systems can provide a similar level or power output, however there remain significant differences between them. Due to the decay properties of Americium-241, the European RTG would have a longer half-life than the American RTG. While this would result in a more consistent power supply throughout the duration of the mission, it also leads to a lower specific energy at 1.5 [W/kg] compared to the 2.8 [W/kg] of the Plutonium RTG [125, 126]. Although the long duration of the mission would benefit from a longer-life RTG, the high power requirements of the science instruments, as well as the tight volume and mass constraints lead to the selection of the Plutonium-238 Multi-Mission

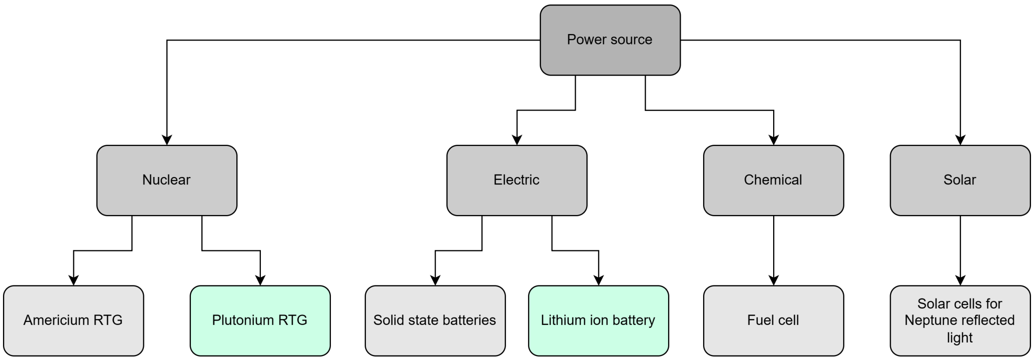


Figure 5.3: Concept generation for the power source, with the selected concepts in green.

Table 5.1: RTG Specifications provided by NASA [126].

MMRTG Technical Specifications	
Number of GPHS modules	8
Thermoelectric Materials	Lead telluride (PbTe)//Germanium telluride/Silver Antimony telluride (TAGS)
Number of Thermocouples	768
Beginning of Life Power (Watts)	110
Est. End-of-Design-Life power (Watts) at 17 years*	72
Beginning-of-Life (BOL) System Efficiency	6%
Beginning-of-Life Specific Power (Watts/kilogram)	2.8
Load Voltage (Volts)	30
Fin-root temperature (degrees C/F)	157/315
Mission Usage	Multi-mission: space vacuum and planetary atmospheres

* Design life includes three years of fueled storage before launch

Radioisotope Thermoelectric Generator. The specification of this RTG can be found in Table 5.1 In addition to this, a secondary battery system will be included to cover intermediate power requirements that might surpass the power output of the RTG that would occur during initial descent and while operating instruments, with lithium-ion chosen for its high TRL.

5.1.3 Landing Site Determination

The selection of a landing site for POSEIDON must satisfy multiple requirements in order for the mission to achieve its main science goals. A comprehensive list of these requirements are laid out in Sections 3.4 and 3.5, however the main three that are most important to a landing location are that the lander must be near an active plume, it must be near a site of geological interest, and it must land on stable ground.

Taken together these three requirements drastically limit the potential landing sites of POSEIDON. Based on the current knowledge of Triton's surface, all landing sites will be located near the edge of the southern icecap, where there exist old ices near to potential plume activity. Three potential landing sites have been circled in red in Figure 5.4, based on their proximity to potential plumes as well as geologically interesting features.

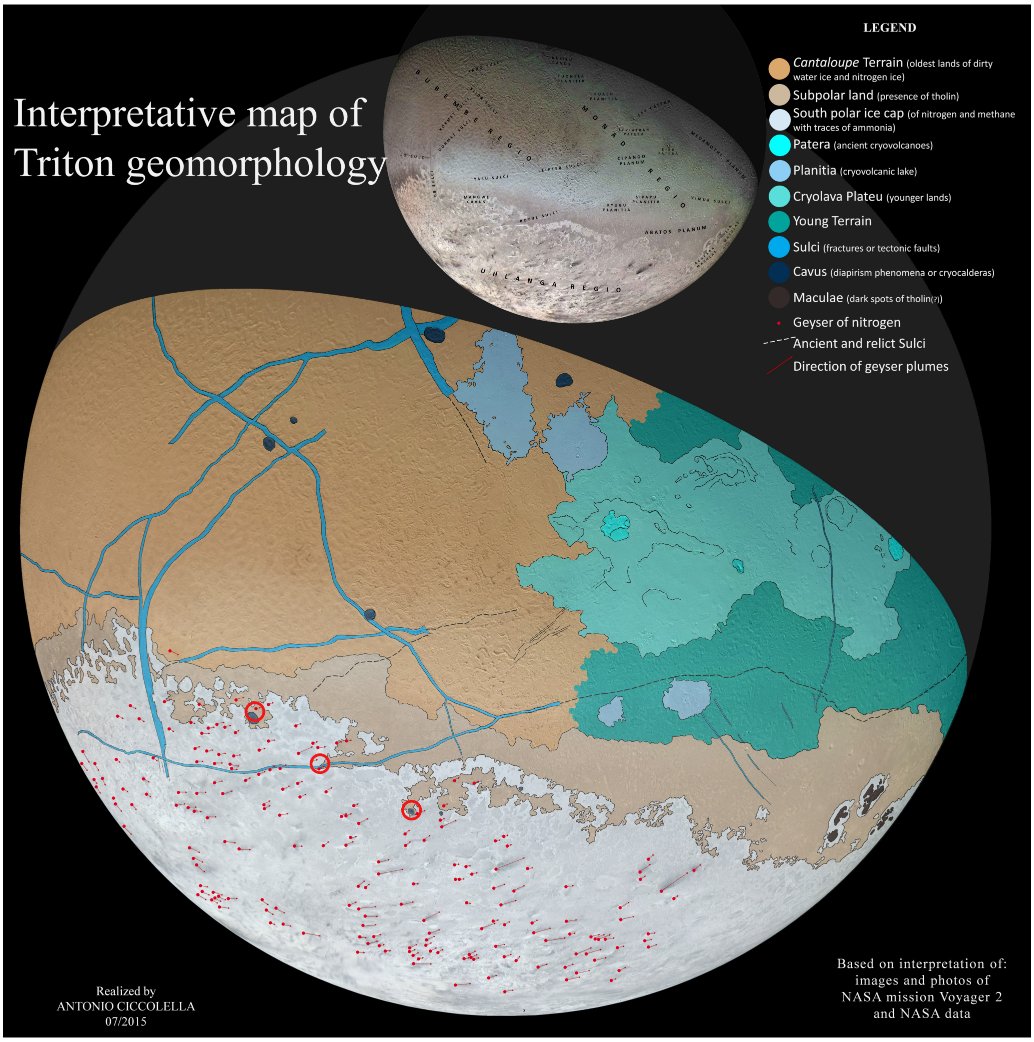


Figure 5.4: Potential landing site location for POSEIDON.

The exact landing site will be determined in-situ through live measurements and photos taken by the orbiter prior to landing. Cassini-Huygens, the joint mission from ESA, NASA, and the Italian Space Agency to the Saturnian system, found a landing location using a similar method. When planning the mission, the landing location was unclear, and information from Cassini's flybys were used to validate the descent models from planetary scientists [127]. In addition to providing more accurate and updated information on the conditions of the known Triton landscape, the remainder of Triton will also be imaged, potentially revealing other locations of interest which are deemed superior landing locations. High resolution imaging from an orbiting platform can also be used in tandem with ice penetrating radar to ensure the ice is thick enough to support a safe landing. As such the exact landing site will most likely differ from the ones proposed here, however will still contain similar characteristics. In the case that no landing site can be found that satisfies all requirements, preference will be given to a landing site situated near a plume, at the sacrifice of geological features. This will still enable POSEIDON to fulfill the majority of its scientific objectives with minimal impact to the overall mission.

5.1.4 Main System Architecture

A conceptual layout of POSEIDON can be seen in Figure 5.5, which includes all scientific instruments as well as other major subsystems. Based on this concept, the overall dimensions of the lander are: 2.75[m] x 2.75[m] x 1.4[m] [LxWxH]. This layout includes a few key support equipment that are vital to overall mission success. The first is the addition of a robotic arm. This arm will allow both for the redeployment of the seismometer away from the lander, as well as provide a larger area of operation for the spectrometer that is attached to its end. The second main addition is that of a mast, which will support the two Mastcam Zs. This mast will allow both greater elevation and field of view for the cameras, as well as grant them the ability to view the complete

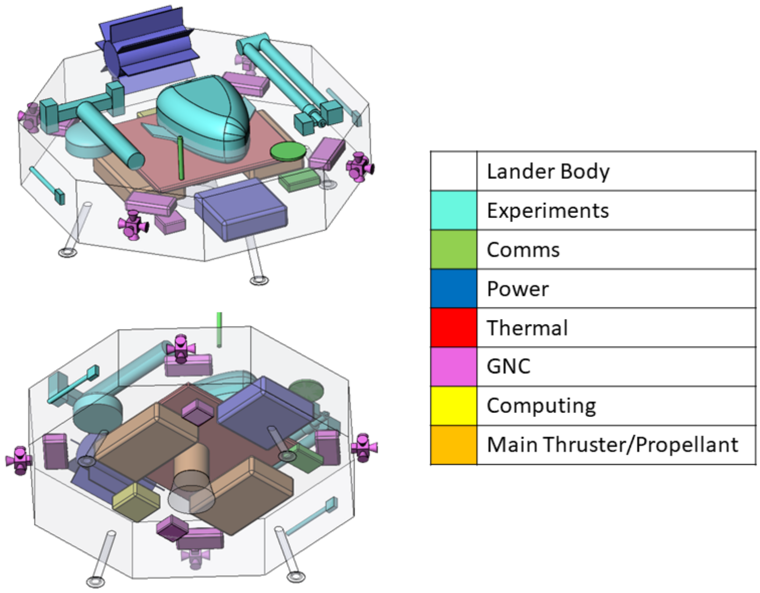


Figure 5.5: Conceptual placement of main lander components.

360 degrees around the lander.

With this specific layout, the order in which experiments are activated is critical, with the ROPE system only being able to be safely launched with all other arms and masts stowed away. Similarly, the seismometer should only be deployed once the ROPE system has launched and departed from the rest of the lander. A more detailed drawing with all components labeled can be found in Appendix A.

From this layout, mass and power budgets can be created. The mass budget, seen in Table 5.2, lays out the major subsystems that contribute to the mass of the lander. The growth margin for each component is added on top of the base mass to account for uncertainties in the initial calculations. The growth margin for the ROPE system is already included in the base mass, and can be seen further broken down in Table 5.4. The overall mass of the lander, at 466 [kg], is reasonable for a mission of this size. Compared to the Huygens probe, which had a mass of 318 [kg], the mass of POSEIDON is nearly directly comparable, with the extra mass coming from the added complexity needed to support the ROPE system [128].

The power budget can be seen in Table 5.3. This table contains multiple different power modes, and the relevant electronics that operate during each phase. All electronic subsystems with a zero value do not operate during the specified phase. In addition, a margin of 33% is added to account for losses due to cabling and other inefficiencies [134]. While during the coast and communication modes the power consumption is under the specified 110[W] power output of the MMRTG, the descent and science modes consume more power than is output by the MMRTG. This is to be expected, and is why there is a secondary power supply to cover these scenarios. During descent, this supplemental power supply will mostly be used up, and is the limiting design factor for the batteries. The power consumption listed for the science mode is an absolute worst case where every instrument operates simultaneously. The power draw can be decreased to under the MMRTG output by simply alternating which instruments operate at a single time. This same approach can be used to maximize lander life as the power output of the MMRTG falls due to its neurally decreasing radioactivity. The ROPE system is not included in this budget as its power supply is completely separate from the rest of the lander. More information on the ROPE power breakdown can be found in Section 5.1.5.4. Additionally, while the required voltage will vary between the components, most are designed to operate off a common 28[V] bus for simplicity [135].

[1] See also subsubsection 5.2.2.2, note that the EDL stage was not included in this mass budget.

Table 5.2: POSEIDON Conceptual Mass Budget

Component	Reference/Maturity	Base Mass [kg]	Growth Margin	Mass [kg]
Main propellant	Scaling Calculation [115][1]	50	30%	65
Propulsion support	Scaling Calculation [115]	40	50%	60
Main thruster	Reference Design [129]	3.5	20%	4.2
Robotic arm	Reference Design [130]	30	5%	31.5
Battery	Calculation [131]	3	20%	3.6
Comms	Reference Design [115]	4.5	30%	5.85
Heater	Reference Design [115]	5	100%	10
Main computer	Reference Design [115]	14.7	30%	19.11
Main structure	Scaling Calculation [115]	30	25%	37.5
GNC system	Scaling Calculation [115]	7,3	100%	14.6
RTG	Reference Design [132]	43.6	0%	43.6
ROPE system	Section 5.1.5.4	105,6	0%	105.6
Mastcam Z	Table 4.1	8	5%	8.4
Seismometer	Reference Design [133]	30	10%	33
Spectrometer	Table 4.5	2.3	5%	2.415
Atmospheric instruments	Table 4.4	5	20%	6
GCMS	Section 4.3.3	11.5	5%	12.075
Imaging cytometer	Section 4.3.3	3.5	5%	3.675
TOTAL MASS				**466.125**

5.1.5 Rocket-Operated Plume Experiment

This section will detail the design of the rocket-operated plume experiment (ROPE). Concept generation and selection is first discussed, before addressing details related to propulsion, navigation, as well as mass and power constraints. Finally, a high-level architecture of the payload is presented.

5.1.5.1 Plume Experiment Selection

The rocket-operated plume experiment (ROPE) is a major payload element of POSEIDON aiming to study the composition of the plumes. The payload was selected according to the requirements outlined in Section 3.1, with the payload concepts shown in Figure 5.6.

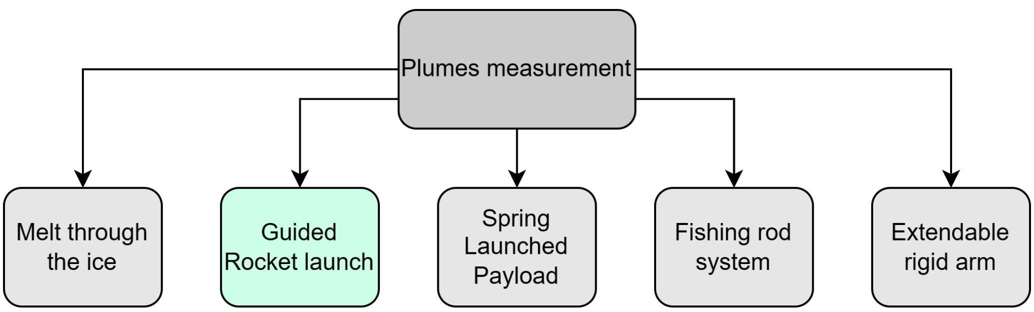


Figure 5.6: Concept generation for the plumes instrumentation, with the selected concept in green.

Based on the selected mission architecture and mobility, the plume measurement payload is restricted to a separate system that enters the plumes for measurements. Thus, measurements that require the entire lander to

Table 5.3: POSEIDON conceptual power budget

Component	Power Draw Coast [W]	Power Draw Descent [W]	Power Draw Science [W]	Power Draw Comms [W]
Robotic Arm [Estimate]	0	0	20	0
Comms [115]	0	24	0	5
Heater [Estimate]	2	2	2	2
Main computer [115]	18	18	18	18
GNC system [115]	0	40	0	0
Main thruster [129]	0	58	0	0
GCMS [Section 4.3.3]	0	0	82	30
Imaging cytometer [Section 4.3.3]	0	0	32	30
Mastcam Z [Table 4.1]	0	0	45.2	30
Seismometer [133]	0	0	8.5	8.5
Spectrometer [Table 4.5]	0	0	0.02	0.02
Atmospheric instruments [Table 4.4]	0	15	5	5
Margin for losses	**33%**	**33%**	**33%**	**33%**
TOTAL	**26.60**	**208.81**	**282.92**	**91.13**

enter the plume were not considered. Additionally, due to the power requirements of the instruments used to measure biomarkers, the payload will be used solely as a sample collection and return system. The remaining options are briefly described below:

- **Melt through the ice:** A heated drill to melt through the ice, either vertically downwards through to the hypothesized subsurface ocean, or at an angle such that the payload sticks out of the wall of the plume.
- **Guided rocket launch:** Rocket-powered payload that guides itself towards the plumes to collect samples, and returns to the lander.
- **Spring launched payload:** Payload that is launched into the plume using a high-powered spring, potentially returning with a rocket or sending the samples back separately.
- **Fishing rod system:** Similar to ice-fishing, the payload is attached to a flexible rope that is cast into the plume, then subsequently reeled back in when complete.
- **Extendable rigid arm:** The payload is attached to a long, rigid arm that reaches into the plume to collect samples.

For planetary protection and safety reasons, it was deemed necessary to land no closer than 1 km from a plume opening. An arm or a flexible piece of rope that is that long is simply infeasible for the form factor of the lander. It cannot be packaged, deployed, or stabilized effectively at that distance. For a similar reason, the heated drill is not a possibility. Due to the thickness of Triton's ice sheets (more than 100 [km] [20]), drilling vertically downward through the ice is not feasible. Such a system would require immense energy to burn through the ice, which would require some physical connection to the main lander as a battery would not be sufficient.

Due to the physical constraints of the mission and the outlined requirements, the best option for plume experiments is a ballistic launch, which can be either spring launched or through a rocket system. The advantage of the spring-launched system is reduced complexity, mass, and less risk of damage to the lander. However, it provides less control and stability inside the plume. Based on the required distance between the lander and the plume, the terrain around and inside the plume will be very unclear. A spring-launched system would need to be extremely accurate, likely with some help from the orbiter platform. Even if this spring-launched payload has rocket power for the return trip, there is no guarantee that it will be able to return or communicate with the lander due to the inaccuracy of the launch.

The rocket-powered payload design provides greater control over the plume entry and exit, at the cost of increased complexity and propellant mass. This rocket-powered payload could have its own navigation system to be able to enter the plume and navigate back to the main lander. Overall, since plume experiments are such a central focus of the POSEIDON mission, a more complex, higher reward design is warranted.

5.1.5.2 Propulsion

A drawback of the rocket-powered payload design is that the expelled rocket propellants could affect the composition of the plume, which could influence the results of the experiment and impact the equilibrium on Triton as well. The straightforward solution to combat this is using a cold gas thruster that expels an inert gas for stabilization once the ROPE has entered the plume. The cold gas thruster could also be used in the vicinity of the lander as well to protect it against the heat and volatiles expelled from a heated thruster. An example of an inert gas that can be used as cold gas thruster propellant is nitrogen gas N_2, which is already seen abundantly on Triton [48], and which is very unlikely to interact with other compounds in the plume [136]. In this context, a "cold gas" thruster would still require some heating, as Nitrogen at the temperatures on the surface of Triton (38[K]) [47] would be in liquid form [137].

The mass of the payload as well as its starting distance from the plume also determine whether or not the ROPE can use only cold gas thrusters to propel itself to and from the plume, or if it would require additional propellant with higher thrust capability. As discussed in Section 3.4, due to the size of the plume opening itself (1-3[km] [2, 24]), the lander should land at least 1km away from a plume opening to preserve planetary protection and ensure that the ice that the lander lands on is not too fragile. This sets the minimum range requirement for the ROPE at 2[km]. Due to the uncertainty of landing location, the propulsion system will be designed with 100% margin for 4[km] of range, plus 25% margin to ensure that **REQ-LL-03-2** can also be accommodated given potential obstacles and the time spent stationary inside the plume. Thus, the propellant mass should be sufficient for a straight line range of 4.5[km].

It would be ideal to use Nitrogen gas for the entire operation, as this would avoid the need for two separate propellant systems. However, propellants such as hydrazine or even hydrogen gas have higher specific impulse, enabling a higher range for a given propellant mass. These would allow the ROPE to be lighter, at the cost of increased mission complexity and danger to the Triton environment. Preliminary mass calculations show a minimum total mass of 237.8[kg] for the ROPE system using solely Nitrogen gas as propellant.

Since 237.8[kg] is a significant violation of the mass budget, it was worth considering an alternative that uses both hydrazine and nitrogen. While the Nitrogen cold gas thruster is still necessary when the rocket is in the plumes or near the lander, during the main portion of its transit it can take advantage of the better specific impulse of other propellants. A monopropellant was chosen as it would be a simpler design than bipropellants (that use separate fuel and oxidizer tanks). The calculations assume the monopropellant is used for 90% of transit, while the cold gas thruster is used for 10% of transit. Since the specific impulse of nitrogen is 70[s] [115], and hydrazine is 190[s] [138], the thrust to weight ratio of the ROPE can be taken as a weighted average of the two, based on the percentage of the time each propellant system is used. This results in a thrust to weight ratio of 0.692, compared to 0.272 for the system that only uses Nitrogen (based on comparisons with the Triton Lander [115]). While the tank and plumbing mass may somewhat increase, the overall system mass decreases to 105.6 [kg], for a straight line range of 4.5 [km].

The ROPE system will use two main 445 [N] thrusters and four cold gas 52 [N] thrusters, using components selected from Moog [139, 129]. These specific thruster ratings are selected to ensure that the thrust-to-weight ratio assumptions used in range calculations can be met.

Another important detail is that the main propellant nozzles will have thrust vectoring capabilities, meaning that the nozzle is capable of moving in order to direct engine thrust in the desired direction. This is a preferred option to, for example, control surfaces. The tenuous atmosphere on Triton makes control that requires air flow unreliable. When inside the plume, the main thrusters will be disabled, and the cold gas thrusters will be responsible for manoeuvring and stabilization. Pulse-modulated thrusting can be used as thrust vectoring control during this period of operations.

5.1.5.3 Navigation

The ROPE will use visual cameras and light detection and ranging (LIDAR) to navigate towards the plume. The ROPE will be equipped with a colour camera, because while navigation would only require a low resolution black and white camera [119], the opportunity to collect colour images of the surface of Triton and near plumes is excellent for public relations. LIDAR is an important redundancy feature because light from Neptune and the Sun may not be potent enough to provide visual images with a high enough signal-to-noise ratio, while LIDAR technologies will still work effectively in darkness [140]. Additionally, the ROPE requires sensors when inside the plume, which is a low visibility zone. Aside from those sensors, it will also have an antenna and transceiver pairing for communication with the lander. This is important for navigating during the return trip.

The initial launch towards the plume will be calculated with some help from the images taken by the orbiter platform. After the initial launch, the ROPE will be expected to use its surroundings to autonomously adjust its course towards the plume, avoiding obstacles on Triton.

The selected transceiver is 900 [MHz] ultra-high frequency, which is the same frequency band used for communications between Ingenuity and Perseverance [119]. A 13 [MP] (megapixel) colour camera is also used for the ROPE system based on a similar camera employed on Ingenuity [119].

5.1.5.4 Design Budgets

Table 5.4 shows a total mass budget for the ROPE system. The growth margin refers to how much additional mass is added to the initial calculated mass to account for inaccuracies in initial calculations. This is separate from the margins allocated for obstacles and travel inefficiencies when calculating the range requirement.

Table 5.4: Mass budget for ROPE system

Component	Reference/Maturity	Base Mass [kg]	Growth Margin	Mass [kg]
Main propellant	Scaling Calculation [115]	19.0	100%	38.0
Cold gas propellant	Scaling Calculation [115]	2.0	100%	4.0
Main structure	Best Practice [141]	15	20%	18.0
Propellant tanks	Calculation [142]	18	5%	18.9
Navigation system	Estimate	2.5	100%	5.0
Cryocooler	Reference Design [115]	2.4	5%	2.5
Plumbing and Wiring	Reference [139], [95], [129]	10	20%	12.0
Heater	Reference Design [115]	1	5%	1.1
Battery	Calculation [131]	5	20%	6
TOTAL MASS				**105.6**

Table 5.5 shows a total power and energy budget for the ROPE system. The critical condition in this case is defined as the condition when the most power is being drawn. Since the main rocket engine will require more power than the cold gas thrusters, this condition is expected to be met when the ROPE is travelling back to the lander from the plumes. This is because the cryocooler will be engaged in order to keep the samples at ambient conditions.

The time required for travel between the lander's location and the plume was also needed for this power budget. The Triton Hopper takes nearly two and a half minutes to hop a distance of 5.13 [km] using its thrusters [115]. As the ROPE is not expected to travel in a direct path to the plume location, significant margin is added to ensure enough power will be allocated. The ROPE will therefore have 150 seconds (2 and a half minutes) to travel from the lander's location to the plume (between 1 and 2 [km]). This means that the entire period of time in which the main rocket is engaged should last approximately 5 minutes. The ROPE will spend a comparable amount of time in the plume gathering samples, to ensure stability and navigate to a suitable region of the plume using the cold gas thrusters. Thus, for components that are always on during the mission (heating, computing, navigation), the total operation time is 10 minutes.

The ROPE system is designed to run on a common 28[V] bus for most components for simplicity and due to its flight heritage [135]. Additionally, some of the thruster components only operate between 24 and 34 [V]

Table 5.5: Power and energy budget for ROPE system. Some entries are labelled as OFF in the most critical case, and thus have no power draw. However, the energy requirement is recorded over the entire time of the ROPE mission, and thus may be non-zero even if the power draw at the critical condition is zero.

Component	Status in Critical Condition	Voltage Draw [V]	Power Draw [W]	Energy Requirement [Wh]
Main rocket engine [129]	ON	28	116	9.67
Cold gas thrusters [139]	OFF	28	0	4.8
LIDAR [143]	ON	28	15	2.5
Visual camera [144]	ON	3.3	0.5	0.08
Pressure sensor [96]	ON	28	0.1	0.013
Temperature sensor [98]	ON	3.3	10×10^{-6}	1.67×10^{-6}
Cryocooler [115]	ON	28	54	8.1
Central heating unit [115]	ON	28	50	8.33
Central computing unit [2]	ON	28	10	1.67
Sample actuators [95]	OFF	28	0	1.13
Transceiver [145]	ON	3.3	0.25	0.042
Margin for losses			33%	33%
TOTALS			**393.48**	**48.33**

[139]. Some smaller components such as the camera and the pressure/temperature sensors cannot handle 28 [V], and thus some voltage regulation circuits will be necessary to ensure 3.3 [V] inputs for those components.

A margin of 33% is used to account for cabling losses and the efficiency of DC power converters. This comes from a lower bound efficiency of 75% for converters [134].

Therefore, a peak power draw of 393.5 [W], and a total energy requirement of 48.3 [Wh] (174 [kJ]) is required to support the ROPE mission. This can be covered by lithium-ion batteries with energy-to-weight ratios around 80-100 [Wh/kg] [131, 146], and average power draw around 300 [Wh]. Therefore, the battery mass itself does not need to be very high, approximately 1 kg at maximum. The critical case exceeds the ideal power draw from the batteries, however since this peak power draw is for a limited amount of time (2.5 minutes), it should be capable of handling the 14 [A] strain. This further justifies the use of a 1 [kg] battery, which provides double the required energy, enough to cover the slightly faster discharge time caused by high current draw. Distribution hardware and structural support will increase the weight of the power subsystem beyond the 1 [kg] battery weight.

5.1.5.5 Architecture Summary

Figures 5.7, 5.8, and 5.9 give three views of the ROPE system, as well as the preliminary layout of the internal components. The ROPE's approximate dimensions are 1 [m] in length, 60 [cm] in width, and 40 [cm] in height.

Another design feature that is visible from this layout is the sample container placement. The ROPE is designed wider than its height such that the sample containers have some separation from the propellant expelled by the cold gas thrusters. The cold gas thrusters are both placed on a 45° offset angle such that they do not point directly down towards the part of the plume that is being measured. Although the cold gas is inert, it is not ideal to affect the incoming samples in any capacity if it can be helped. Additionally, the sample containers are placed below the propellant tanks because the thickness of the walls of the propellant tanks can also provide radiation shielding when the ROPE is in the upright travel configuration.

Another feature is the stability wings. Considering the spacecraft is in a very tenuous atmosphere, wings may be considered unnecessary, however they are meant to keep the ROPE system in the upright configuration as often as possible, or at least to have it return to an upright condition if a control manoeuvre is performed. The wings influence the moment of inertia of the ROPE system, making it less likely to roll when in the upright position. Typical rocket systems are prone to rotate in the roll condition, which is not ideal for keeping the samples protected. The propellant tanks would not be able to shield the samples from radiation if the ROPE system is upside-down.

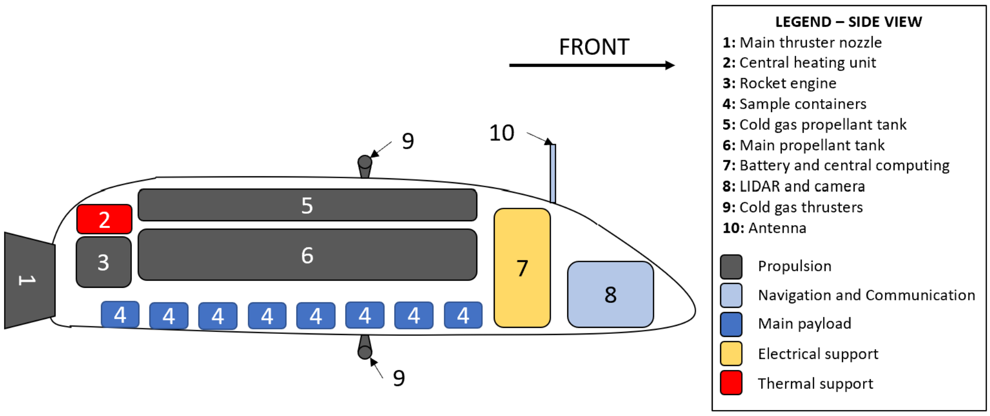


Figure 5.7: Side view of the ROPE system.

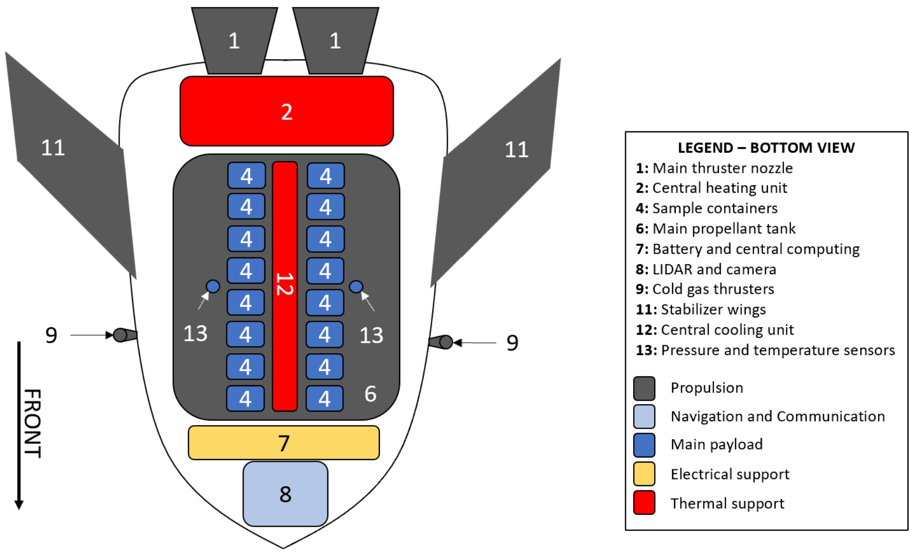


Figure 5.8: Bottom view of the ROPE system.

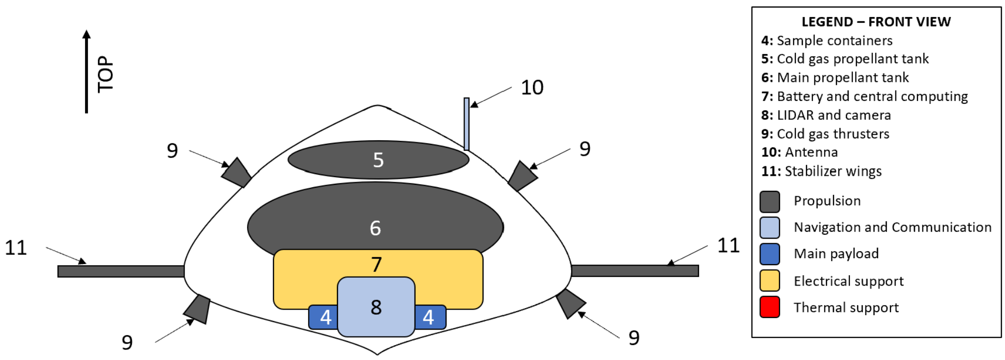


Figure 5.9: Front view of the ROPE system.

5.2 Mission Profile

In this section, the mission profile of the POSEIDON mission will be outlined. The main mission phases are discussed:

1. Launch and interplanetary transfer;

2. Triton approach and Entry, Descent and Landing (EDL);
3. Early Operational Phase;
4. Operational Phase;
5. Decommissioning.

5.2.1 Launch and Interplanetary Transfer

The first mission phases consider the travel towards the Neptunian system. First, available launch windows for the mission and their associated interplanetary transfer are presented in subsubsection 5.2.1.1. Following, an overview of the launch vehicle selection approach is given in subsubsection 5.2.1.2. Additionally, it is assumed that the complementary orbiter mission (which was submitted as a separate mission proposal) and this lander mission would be launched in the same launcher, reaching Triton as a single system.

5.2.1.1 Launch Windows and Interplanetary Transfer

Taking into account the typical development of large scale missions to the outer space system being on the order of 8 to 10 years after the mission proposal was accepted, a launch window in the horizon of the mid to 2030s would be desired. Especially since the complete mission includes the design of an orbiter, and a lander; the complete mission is quite complex and more than 10 years might be required. Another constraint arises from the lifetime of RTGs which are generally limited to about 20 years (including pre-launch and ground activities) [147], which shows the need for a shorter interplanetary transfer. Furthermore, the Ariane 64 launch vehicle (which will be the standard for European deep space missions in the 2030s) is expected to be able to reach Earth escape velocities up to 5000 [m/s] with a payload mass of up to 3500 [kg] [148]. This falls short from the approximate 12300 [m/s] required for a direct, purely chemical, transfer (neglecting inclination changes, which could be tackled by the transfer stage). A direct transfer could be achieved using the Space Launch System (SLS) [149], but the estimated cost of [$]2 billion US renders this choice unfeasible. This shows the need for an interdisciplinary transfer to be selected.

The best option would then be to use Jupiter as a main Gravity Assist (GA), to slingshot the system to the Neptunian system. Unfortunately, the phasing of the Earth and Jupiter in the 2033-2036 window does not allow for a GA using Jupiter [149]; a less-optimal Saturn GA is also unfeasible due to the Saturn-Neptune phasing in the 2025-2040s [1]. Therefore, the mission would need to occur either in the 2031-2032 or the 2036-2037 using Jupiter. Three options are then investigated at a preliminary feasibility level:

- The M2037 trajectory presented by Campagnola *et al.* [1], departing from Earth on the 26/10/2036 and arriving in the Neptunian system on the 20/04/2056. The proposed trajectory uses one Earth GA, followed by two Venus GA and two Earth GA, and one Jupiter GA (in 2045), requiring a departing escape velocity of 3.07 [km/s], one correction manoeuvre of 50 m/s after the third Earth GA, and reaches Neptune with an excess velocity of 10.8 [km/s]. This would result in a total flight time of 20.5 years, which clearly is on the high side with respect to the lifetime of RTGs.
- The T2040 trajectory presented by Campagnola *et al.* [1], departing from Earth on the 28/12/2039 and arriving in the Neptunian system on the 20/04/2056. The proposed trajectory uses one Earth GA, one Venus GA, two Earth GA, and one Jupiter GA (in 2045), requiring a departing escape velocity of 3.1 [km/s], one correction manoeuvre of 330 m/s after the second Earth GA, a 10 [m/s] deep space manoeuvre after the Jupiter fly-by, and reaches Neptune with an excess velocity of 10.8 [km/s]. This would result in a total flight time of 16.3 years.
- A trajectory departing on 28/04/2030 (which will be called M2030 in the following) and arriving to Neptune on 28/04/2043 was proposed by Hofstdater *et al.* [150], using an Earth GA and Jupiter GA (in 2033). The trajectory would require an escape velocity of 4320 m/s at departure, which is within the capabilities of the Ariane 64, but the authors proposed to use the Delta-IV Heavy. In either case, a Solar Electric Propulsion (SEP) stage would be necessary. The spacecraft would have an excess velocity of 11.42 [km/s] at arrival at Neptune

Note that no feasible trajectory was found in the years 2031-2032. The most optimal launch window before the end of the 2030s is in 2028-2029, however, it is clear that the mission would not be ready by then [150, 1].

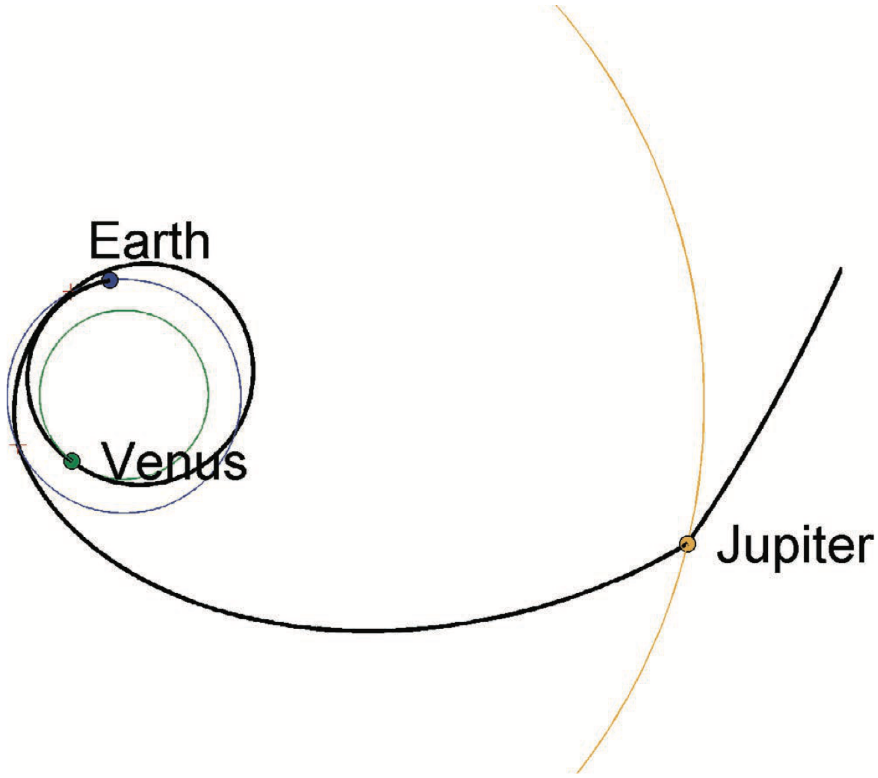


Figure 5.10: Ecliptic projection of the T2040 interplanetary transfer, based on a Venus-Earth-Earth-Jupiter sequence [1]

All trajectories are achievable by the Ariane 64, based on a preliminary analysis (by looking at the achievable excess velocity). Furthermore, they all require the most ΔV at arrival at Neptune, which is the most critical phase of the flight; but no manoeuvre putting the orbiter in a stable orbit around Triton is included. To account for the entry into a stable orbit, Campagnola and Boutonnet [147] suggest that a ΔV of about 300 [m/s] with a transfer similar to the one of JUICE would be feasible [151]. While those trajectories were designed for other missions with different payload masses, they show the feasibility of reaching Triton in the 2040s or 2050s (all trajectories would result in a payload mass reaching an orbit in the Neptune system of about 1800 [kg], which is deemed achievable for the mission).

Comparing the three trajectories, the following can be noted. The T2040 trajectory arrives at the same time as the M2037 one, but has a shorter time of flight, which is desirable for the use of a RTG. However, it requires a reasonable increase in propellant due to the larger total ΔV required. Furthermore, the M2030 orbit would result in the shortest flight time, however, the launch date would only allow for a bit less than 7 years for the complete development of the system (include manufacturing of parts, development of low Technological Readiness Level (TRL) components of the mission, integration, and testing). Overall, the only proposed launch date which allows for sufficient development time and has a short enough time of flight to accommodate for the RTG lifetime, and is overall feasible with future launcher capabilities, is the T2040, shown in Figure 5.10 [1]. In case a heavy launcher with capabilities close to the SLS, with a launch cost reduced by a factor of 10, becomes available on the market before the 2030s (such as the Starship of SpaceX), a more preferable launch date could be selected (2033-2034) using essentially only chemical propulsion; but this is unlikely.

Nevertheless, this trajectory is a proof of concept and needs to be further defined in design phase A and following.

5.2.1.2 Launch Vehicle Selection Approach

The Ariane 64 was used above for a preliminary analysis of the feasibility of the presented trajectories, however, a more thorough launch vehicle selection should be performed. While the latter will certainly become the preferred vehicle for European deep space missions, other alternatives exist or might become available by the time a final decision needs to be taken. Among the other capable launch vehicles which could be considered are the upcoming Starship, the Delta-IV Heavy rocket, Atlas V (in case the system has a mass around 800 kg maximum), or the SLS (in case a collaboration with NASA results in a lower launch cost, and for heavier systems) [150]. Note that only US-based alternatives are to be considered, given the current geopolitical context. A final launch vehicle is to be selected towards the end of design phase A based on the requirements of the interplanetary transfer, and the volume and mass of the complete mission.

5.2.2 Triton Approach

Having entered the Neptunian system, a series of manoeuvres will bring the transfer stage of the spacecraft in orbit around Triton. The details of such manoeuvres will be further investigated in design phase A, but legacy knowledge from missions such as the Cassini-Huygens or the JUICE mission indicate that it is feasible to perform a few fly-by's of other bodies in the system (namely Neptune) before reaching Triton [152, 153]. Furthermore, this is also an invaluable opportunity to gather additional data on the Neptunian system in general, before the transfer stage enters orbit around Triton. Once the system is in a stable orbit around the moon, the preparations for the lander's Entry Descent and Landing activities will be initiated.

5.2.2.1 Exact Landing Site Determination Procedure

While a potential landing site for the lander was described above based on the data and images gathered during the Voyager 2 fly-by, Triton is still vastly unknown. Additionally, Triton is believed to still be geologically active, and new plumes might have emerged on its surface (or might have disappeared), as was detailed in Chapter 2. The resolution of current ground- and space-based telescopes do not allow for those aspects to be assessed ahead of the mission reaching the Neptunian system. Due to this uncertainty, the lander will stay in orbit while the orbiter starts a preliminary mapping of the moon's surface, to allow for the determination of the exact landing site.

This determination will be done partly automatically, with an algorithm determining the best potential areas to land the lander system. Images and rough Digital Elevation Maps (DEMs) of the shortlist of landing sites along their location on the moon will be sent to ground control such that human confirmation of the relevance of the sites can be obtained, and a final decision can be made for both elements of the mission.

To ensure that an educated choice can be made, a global mapping of Triton performed by the orbiter mission is necessary. Assuming that only the shortlist of landing site locations are transmitted back to Earth during the time of search, the full procedure is estimated to take from 15 to 30 days (about 6 days for the mapping due to Triton's self-rotation period of about 5.7 days and the orbiter orbital period of 4.61 [h] (assuming 800 [km] altitude[3]), and the rest to transmit the strictly relevant data to Earth to be assessed by the ground team). Once an exact landing site has been chosen by the landing site determination system and the ground team, a detailed digital elevation model of the region is generated, and an algorithm identifies craters close to the landing site to ensure the use of Terrain Absolute Navigation (TAN) during EDL.

5.2.2.2 Entry, Descent, and Landing

When the exact landing site is determined, and a Digital Elevation Model (DEM) of the surroundings is available, the Entry, Descent, and Landing procedure will be initiated. The first step being a transfer of the orbiter to a lower orbit, to reduce the needs for large amounts of propellants for the EDL. The details of this manoeuvre will be further developed in the following design phase, for now, it is assumed that the lander detaches from the orbiter while in a parking orbit at 200 km altitude. Right after detachment, it fires its thruster to enter an orbit set to collide with the surface of Triton. Preliminary analysis of the trajectory indicate that the velocity increment at ejection from the orbiter can be between 33.6 [m/s] and 1 [km/s] (through a simple Hohmann transfer, or by cancelling the orbital velocity completely). In the following, the first option is assumed to obtain preliminary estimates. It can be assumed that the effects of the atmosphere are negligible, no use of atmospheric decelerators will be made, and the complete deceleration will be performed by the propulsion system on-board the lander. As the atmosphere effects are largely negligible (in comparison to Earth or Mars for instance), the size of the landing ellipse of the vehicle is reduced significantly and the landing site which was selected can

[3]From personal communication with the TRITEIA design team

be attained with great precision. Therefore, after the initial ΔV, a coast towards the surface of Triton takes place until an altitude of about 10 [km]. At this altitude, an impulsive manoeuvre performed by a dedicated EDL stage takes place to reduce the largest portion of the lander velocity. At 10 [km] altitude, with a transfer orbit insertion of 33.6 [m/s], the stage velocity is 1.054 [km/s], and needs to be reduced by at least 1 [km/s]. Assuming a I_{sp} of about 320 [m/s] [115], the necessary propellant mass for a 1 [km/s] deceleration is estimated to be about 152 [kg] (the insertion takes about 6 [kg]), using the rocket equation. After this burn, the EDL stage is ejected from the lander, and the latter will perform the final stage of the descent.

As Triton is still vastly unknown, precision landing technology will be used to steer the lander to the desired landing site through Terrain Relative Navigation (TRN) and Terrain Absolute Navigation (TAN). Those permit to vary the thrust levels autonomously and to detect any hazard to avoid during the final phase of EDL. In order to do that, the following sensors and actuators are necessary:

- An Inertial Measurement Unit (IMU) to determine the state of the lander during entry, based on the initial conditions. No GPS system is available on Triton, meaning that the velocity and attitude of the vehicle can only be determined from such measurement unit.
- A camera which can be used to generate a DEM during the descent, to be used by the hazard detection and avoidance system.
- A radar altimeter with a range of about 1 km to be used for the final parts of the descent.
- Small thrusters on the sides of the lander will be used to control its attitude.

Both the camera and radar altimeter will be placed on the lower part of the lander to ensure that it has Triton's surface in view. Finally, a gravity turn manoeuvre will be used to safely reach the surface. The principle of the gravity turn then allows choosing a landing site along the incoming trajectory, based on the data gathered during the flight itself, such that the risk associated with the landing is minimised. Furthermore, this manoeuvre allows a full control on the loads experienced by the lander at touch down. A first estimate of the final manoeuvre requirements can be obtained by assuming a constant thrust acceleration and assuming that the lander (after detachment of the EDL stage) starts its thruster 10 [km] above the ground, with a velocity of 54 [m/s]. The closed-form is given by (assuming a soft landing with zero velocity at touch down),

$$\left(\frac{a_T}{g}\right)^2 - \frac{V^2}{2gh}\frac{a_T}{g} - \left(1 + \frac{V^2}{2gh}\right) = 0 \tag{5.1}$$

Resulting in a constant thrust deceleration of 1.187 [m/s/s] (which is quite high, but could be reduced by starting the deceleration earlier in the descent). The associated propellant mass for this final manoeuvre is scaled from Oleson and Landis [115], as the approach cannot be assumed to be an impulsive manoeuvre and a similar ΔV is attained, giving a propellant mass of about 50 [kg]. Additionally, note that during the entire descent the lander will be taking atmospheric measurements to characterise Triton's atmosphere structure.

5.2.3 Early Operational Phase

During the Early Operational Phase (EOP), the lander goes through procedures which have a critical impact on the rest of the mission if they are not carried out correctly. EOP arises at the end of the long travel from Earth to Triton, including EDL, which is the most critical part of the delivery of the vehicle to the moon's surface. This phase essentially consists of the initialisation and calibration of the lander bus and payload instruments to start the nominal operations (including instruments calibration). Also, a first contact is made with the orbiter to ensure that the communication architecture functions properly. Additionally, system health checks and eventual repairs are performed to ensure a safe start of the operations. Given the relatively long planned mission lifetime, EOP could take longer (take more precautions) and ground control could intervene in case of a large failure which would put the lander into a safe mode. The 8h communication time could be acceptable in case mission-critical decisions need to be taken following a failure which does not put the lander at imminent risk of mission failure (that is if the lander can survive the wait; if not, autonomous attempts of repair need to take place). The extended ESTRACK network would be used for such operations, through communication with the relay orbiter to provide commands to the lander. The secondary element of the system would have a much shorter mission lifetime due to the use of batteries, and would need to be completely autonomous (no interaction with ground control is considered at any point during the mission).

For close to nominal operations (no major faulty systems are found), EOP is expected to take around 3 weeks, depending on the exact procedures which will be followed (to be determined at a later design phase).

5.2.4 Operational Phase Activities

Once the lander has safely reached the ground and preliminary system health checks have been performed (and are positive), nominal mission operations can start. All operations need to be carried out mostly autonomously, as the two-way communication with Earth, from Neptune, take about 8h at best (which does not allow for ground control to intervene quickly during the mission).

General activities relating to the survival of the system on a daily basis are common to most spacecrafts/rovers/landers, are given below. Those operations are the most important to ensure that at least some science can be performed during the mission operations, as a significant failure in subsystems directly related to those items would likely result in a mission failure.

1. Generating, processing and distributing power to the spacecraft bus. As detailed earlier, an RTG will be used to generate the main power supply, with secondary power provided by a battery;
2. Managing the thermal balance of the system;
3. Storing selected data points until the next relay communication window, based on requirements expressed by planetary scientists on the data, and on whether it is redundant with measurements which have been stored sent to the relay previously;
4. Transmit scientific and telemetry data to the relay satellite to be transmitted to back to Earth;
5. Performing system health checks and tackling any faulty system (fault isolation and repairs).

Furthermore, note that in case the system discovers a major fault, it is common practice to shift the spacecraft to a safe mode in which special operations are conducted. Those special operations will not be detailed in this mission proposal, and will be further detailed in the Phase A of the mission design. Aside from those general operations, more specific operations exist for the ROPE payload, and the lander as separate entities, as discussed below:

5.2.4.1 Lander

The operations of the lander will be determined by which instruments are to be used at a given time. Each instrument might require some specific activities, but those are mostly unknown at this stage, and will be further detailed in the next design phase. Note that all instrumentation will not be used simultaneously, in order to lower the power requirements of the lander operations. Furthermore, The first series of experiments to be carried will be known ahead of arrival to Triton, meaning that no wait to get the experiment planning from the ground is required. Among the first most important activities to perform at the start of the mission are:

- Transmit the data gathered during the descent, which was not transmitted during EOP as it was not relevant to assess the system's health and position. This contains atmospheric data to be used for studies of the atmospheric structure of Triton.
- A 360° picture of the surroundings of the lander. This permits the ground support team to assess how successful the landing was and how close to the target the lander is (in combination with the observations of the accompanying orbiter). Additionally, this is very useful for Communication and Outreach purposes.
- The plume experiment (also discussed below) will be one of the first ones carried out, as soon as the required information about the position of the plume is known. Therefore, among the first activities performed by the lander, is the recognition of the direction to the closest plume (supposedly, the one selected in the landing site determination procedure). This information is transmitted to the ROPE system which can then begin its experiment.
- Another particular activity to be carried by the lander is the deployment of the seismic measurement unit, which needs to directly lay on the surface of the body to minimise the noise generated by the lander itself.

5.2.4.2 Plume Experiment

More specific activities arise from the use of the rocket-operated plume experiment (ROPE), which is also referred to as the payload in this section:

1. The ROPE is given the general direction of the plume from the lander.
2. The ROPE then detaches from the top of the lander.
3. Inert cold gas thrusters will propel the payload to a safe distance (>100[m]).
4. Higher power rocket will engage, beginning navigation towards the plume in the process.
5. Visual and LIDAR-based sensors will update the trajectory of the rocket.
6. When the payload approaches the plume, the rocket will be disengaged.
7. Cold gas attitude control thrusters will be engaged for the final 50[m] of flight before the plume.
8. When entering the plume, the ROPE will use cold gas thrusters for stability.
9. The payload will only travel about 10m down and into the plume. This is to ensure that the samples are present in the flow, and to make it easier for the ROPE to exit the plume.
10. The ROPE will collect 16 samples in its sample containers (8 for flow cytometry, 8 for gas chromatography-mass spectrometry).
11. The ROPE will use its cold gas thrusters to propel itself out of the plume until it has reached a safe distance.
12. The ROPE will engage the main rocket powered thruster until it reaches the lander.
13. The ROPE will disengage the main thruster for fine tuned maneuvers to dock again with the lander.
14. The ROPE mechanically docks with the lander.
15. The samples are passed from the ROPE to the single use ovens and the flow cytometry chambers for testing.
16. The main lander performs the GCMS and imaging cytometry experiments.
17. The main lander communicates the experiment results to the orbiter.

5.2.5 Decommissioning

At the end of the nominal mission duration, possibilities to extend the operations will be discussed with the European Space Agency with regard to the technical feasibility and the scientific value of extending the mission. The nominal mission duration being 6 months, with a goal to extend the mission up to 1.5 years, the design of the rover will ensure that the latter duration can be reached. However, whether an extension is given will also depend on the available budget to sustain daily operations. If it is decided to end the mission operations, the following procedure will be followed:

1. The last planned measurement sequence will be performed, and data is stored until the next pass of the orbiter above the lander.
2. The last active instruments will then be turned off for the last time, and the lander enters an idle mode until the orbiter passes over the landing site location to perform the last data dump.
3. Verify that the entire dataset has been transmitted, otherwise the lander will stay in idle mode until the next pass to ensure that all relevant data is sent.
4. Once the last data transmission has occurred, all movable parts of the lander (such as antennas or cameras) will be retracted to their initial position, if possible (such as retracting the camera close to the bus if it is on a telescopic arm). Then, those movable parts will be locked mechanically in position.
5. Following, the power generation unit (RTG) will be cut from the lander bus to ensure that no more power goes through the lander systems. This ensures that the batteries will not explode, and that no more communication occurs (to ensure no interference with future missions to Triton, if any).

As the landing site has been selected by taking into account planetary protection guidelines, no special handling of the RTG is necessary. The lander will be sufficiently far from the plumes and the RTG will degrade over the years, shortly becoming unharmful.

Obviously, the next step in the mission operations will lie in the documentation of the lessons learned and possible improvements which could be made on such a mission.

6 Communication and Outreach

In this chapter, a short description of the communication and outreach plan associated with the POSEIDON mission will be described. Those activities aim to raise the public interest in the challenge of developing and operating the flagship mission, while educating and inspiring the public on science topics related to deep space exploration. One of the most exciting remaining questions in science is the fundamental wonder of whether we are alone in the Universe. The idea that life could exist as close to mankind as on the moons of the giant planets of the system, is both terrifying and wonderful. The former exemplifies the need to inform the public on the possible extraterrestrial life that could be found, and the latter gives an opportunity to inspire future generations about fields of Science, Technology, Engineering, and Mathematics (STEM), and stimulate the next innovators and pioneers of mankind. Additionally, the mission is poised to become a symbol of Europe's investment in space exploration and the space industry. The different aspects of the program are distinguished based on the time at which they occur with respect to the mission timeline: before the launch, during the mission, or after the mission end of life.

During the development and prior to the launch, the social media platforms of the mission will be set up and will start posting regular content on the search for life and the wonders of our solar system. Informing the interested audience about the solar system structure, and its science on a weekly basis; as well as following the key milestones of the mission development. When those key milestones are reached, interviews of engineers and managers of the team will be shared on the platforms to share insights and directly show the cool engineering behind the scenes. In the same timeframe, two large documentaries on the mission will be produced (as it is a flagship mission): one on the science that will be conducted and the dangers of the mission in general which will be released a week before the launch, and another on the mission development and key milestones which will be released a week before the arrival of POSEIDON on Triton (although the latter could be produced much later as the transfer is about 16.3 years long). Finally, the public will be given the opportunity to write their name on unused disk storage to be taken on-board the mission, such that they can relate more to the mission, and recall 16.3 years later (when the mission attains its target) that they were a part of the marvellous journey through their support.

After the launch, during the interplanetary transfer of the POSEIDON mission, a lot of activities will be planned in collaboration with museums, schools, and universities to organise live events, guest lectures, and information sessions. The overall goal being that the large hype surrounding the launch of the mission does not fade away too heavily until the arrival of the lander to Triton (this is, however, quite limited due to the long interplanetary transfer). Specifically, the following activities will be organised in greater details in the following steps of the communication and outreach program development:

1. **Public lectures**: Partner with universities, science centres, and museums to host public lectures on the mission to Triton. These lectures will be given by scientists and engineers who have been related to the mission, and would inform students about the goals of the mission, related science (at a university lecture level of detail), and the expected outcomes. Furthermore, the case study of the design of the POSEIDON mission will be used to teach university students across many fields of engineering.
2. **School visits**: Partner with schools to organize visits by mission scientists or educators to classrooms. These visits will include high-school level presentations, and Q&A sessions. Similar to what was explained for the public lectures, data on the design of the POSEIDON mission will be made available to educators to provide the opportunity to shape assignments around the mission.
3. **Public events**: Host public events, such as open houses (of the European Space Agency) or festivals, at science centres, museums, or other public venues. Those events would focus on popularising the science behind the mission rather than being very detailed (in contrast with the public lectures), and could include hands-on experience. Both the possibilities of exhibits (no direct human interaction) and stands (with human interaction) will be considered.

Some of these events could be organised in partnership with the teams from other icy moons missions, to build a community around this type of mission and their goals, as missions such as JUICE, DragonFly, and Europa Clipper would be well into their operational lifetime. This allows POSEIDON representatives to be present at the events organised around missions producing science in the present, while showing the public the upcoming science which will come from Triton. In all of those events, products such as posters will be distributed to the audience. When the landing of the rover is only a few weeks away, the social media pages will start posting a lot more, and the documentary about the development of the mission mentioned above will be released, with the goal being to build up hype around the arrival of the mission.

Finally, during its operations, updates of the condition of the lander will be communicated to the public along with the scientific discoveries it has made. Most importantly, any major scientific finding arising from the mission will be clearly linked to the name POSEIDON to remind the public of the impact of the mission on the scientific world. After the lander has achieved its most important experiments (such as the plume experiment), the public lecture, school visits and public events will again be organised to speak about the scientific outcome of the mission. This will likely happen for the duration of the operational time (which is relatively short), and continue beyond the end-of-life. Some instruments such as the ROPE's navigation camera and the lander's visual camera system can also be used as promotional and educational material.

After decommissioning of the mission, the communication and outreach will happen more passively, as the data gathered by the mission will be analysed for the years (or decades) following the mission.

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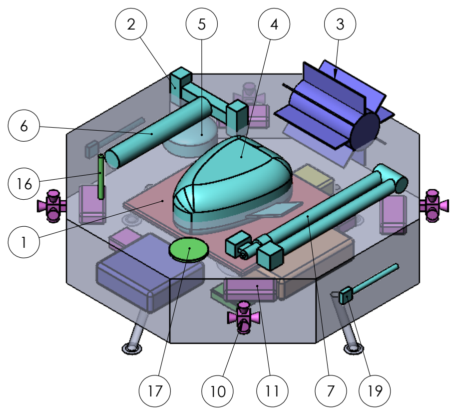
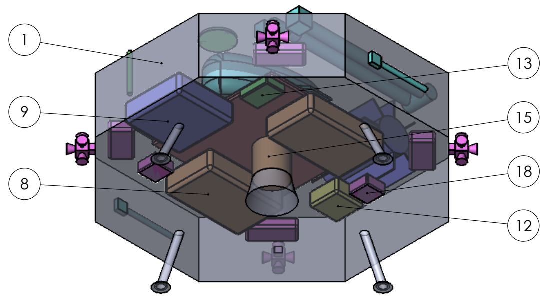
A

POSEIDON Concept Drawing





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Lander shell		1
2	Mastcam	High Res Cameras	2
3	MMRTG	RTG Power Source	1
4	ROPE	Plume Payload	1
5	Seismometer	Deployed Via Robotic Arm	1
6	Mast	Holds 2 Mastcams	1
7	Arm_Spectrometer	Robotic Manupulator and Spectrometer	1
8	Fuel	Main Engine Propellant	2
9	Secondary Batteries	Supplimental Power Supply	1
10	resistojets		4
11	resistojet fuel		4
12	OBC	Main Lander Computer	1
13	radio		1
14	thermal system		1
15	main engine		1
16	low gain antenna		1
17	high gain antenna		1
18	Landing camera		2
19	atmos sensors	Atmospheric Sensor Package	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY | USED ON
APPLICATION | DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Adam	
CHECKED	Adam	
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

11.02.2023

TITLE: POSEIDON

SIZE B | DWG. NO. ASEM - 01 | REV 1

SCALE: 1:25 | WEIGHT: | SHEET 1 OF 1

List of Acronyms B

CMOLD Complex Molecules Detector
DNA Deoxyribonucleic Acid
DEM Digital Elevation Map
EDL Entry, Descent, and Landing
EOP Early Operational Phase
ESA European Space Agency
GA Gravity Assist
GCMS Gas Chromatograph - Mass Spectrometer
GNC Guidance, Navigation and Control
IMU Inertial Measurement Unit
JUICE Jupiter Icy Moons Explorer
JWST James Webb Space Telescope
KBO Kuiper Belt Object
LIDAR Light Detection and Ranging
MMRTG Multi-Mission Radioisotope Thermoelectric Generator
MOMA Mars Organic Molecule Analyzer
NASA National Aeronautics and Space Administration
POSEIDON Plume, Origin, and SubsurfacE Investigator Destined for tritON
RNA Ribonucleic acid
ROPE Rocket-Operated Plume Experiment Growth Allowance
RTG Radioisotope Thermoelectric Generator
SEP Solar Electric Propulsion
SLS Space Launch System
TAN Terrain Absolute Navigation
TPS Thermal Protection System
TRITEIA Accompanying orbiter mission to Triton
TRL Technology Readiness Level
TRN Terrain Relative Navigation
UHF Ultra-High Frequency

C Task Distribution

Table C.1: Distribution of the workload

Student Name	Tasks
Adam Sundberg	Atmospheric science case and instrumentation; Lander system architecture and overall mass and power budgets; Landing location determination; Power source selection.
Adyn Miles	Plumes science case; relevant requirements; instrumentation; ROPE system architecture; budgets; and mission operation; Overall mission architecture conceptual trades; editing.
Lorenz Veithen	Importance of Triton; surface literature study (geological features and processes); synergies with other missions; lifetime requirement; communication architecture; mission profile (section 5.2); communication and outreach.
Stijn Handgraaf	Surface composition science case; instrument functional and performance requirements; surface composition instrumentation; communication and outreach.
Nick Frances Hoeben	Interior and subsurface ocean literature study; relevant seismology requirements and instrumentation; mission summary; editing; executive summary.
Niek Zandvliet	Surface literature study (geological features and processes); relevant imaging requirements and instrumentation; editing.