National Aeronautics and Space Administration
PLANETARY MISSION CONCEPT STUDY FOR THE 2023–2032 DECADAL SURVEY
7 June 2021

Triton Ocean World Surveyor

A NEPTUNE ORBITER & TRITON EXPLORER

Candice Hansen-Koharcheck
Science Lead
University of Arizona | Planetary Science Institute
cjhansen@psi.com

Karl B. Fielhauer
Study Lead
Johns Hopkins University
Applied Physics Laboratory
karl.fielhauer@jhuapl.edu

www.nasa.gov

Data Release, Distribution & Cost Interpretation Statements

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The data contained in this document may not be modified in any way.

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Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Mission Concept Studies program. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

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Study Participants

Role	Name	Organization
Leadership		
Science Champion	Dr. Candice Hansen-Koharcheck	Planetary Science Institute
APL Study Lead	Mr. Karl Fielhauer	Johns Hopkins Applied Physics Laboratory
Science Team		
	Dr. Emily Martin	Smithsonian Institution
	Dr. Carol Paty	University of Oregon
	Glen Fountain	Johns Hopkins Applied Physics Laboratory
	Dr. Lynnae C. Quick	NASA Goddard Space Flight Center
APL Technical Team		
APL Science Interface	Dr. Abigail Rymer	Johns Hopkins Applied Physics Laboratory
	Dr. James Roberts	Johns Hopkins Applied Physics Laboratory
		Johns Hopkins Applied Physics Laboratory
Instrument Performance	Mr. Hari Nari	Johns Hopkins Applied Physics Laboratory
	Ms. Lillian Nguyen	Johns Hopkins Applied Physics Laboratory
Program Manager	Mr. Dewey Adams	Johns Hopkins Applied Physics Laboratory
Systems Engineering	Mr. Karl Fielhauer	Johns Hopkins Applied Physics Laboratory
	Dr. Clintion Edwards	Johns Hopkins Applied Physics Laboratory
	Mr. Max Harrow	Johns Hopkins Applied Physics Laboratory
Mission Design	Dr. Martin Ozimek	Johns Hopkins Applied Physics Laboratory
	Dr. Juan Arrieta	Nabla Zero Labs
Cost Estimation	Mr. Lawrence Wolfarth	Johns Hopkins Applied Physics Laboratory
Operations	Mr. Mike Norkus	Johns Hopkins Applied Physics Laboratory
Propulsion	Mr. Seth Kijewski	Johns Hopkins Applied Physics Laboratory
Mechanical	Mr. Mark Bryant	Johns Hopkins Applied Physics Laboratory
Design	Mr. Kurt Gantz	Johns Hopkins Applied Physics Laboratory
Thermal	Mr. Robert Coker	Johns Hopkins Applied Physics Laboratory
Radio Frequency & Radio Science	Mr. Reza Ashtari	Johns Hopkins Applied Physics Laboratory
Power	Mr. Dan Gallagher	Johns Hopkins Applied Physics Laboratory
Guidance, Navigation & Control	Dr. Glenn Creamer	Johns Hopkins Applied Physics Laboratory
	Ms. Sarah Flanigan	Johns Hopkins Applied Physics Laboratory
Avionics	Mr. Krik Volland	Johns Hopkins Applied Physics Laboratory
	Mr. Steve Cho	Johns Hopkins Applied Physics Laboratory
	Mr. Christan Champo	Johns Hopkins Applied Physics Laboratory
	Mr. Justin Kelman	Johns Hopkins Applied Physics Laboratory
Software	Mr. Adrian Hill	Johns Hopkins Applied Physics Laboratory
Scheduler	Mr. Andrew Soukup	Johns Hopkins Applied Physics Laboratory

PLANETARY MISSION CONCEPT STUDY FOR THE 2023–2032 DECADAL SURVEY

Triton Ocean World Surveyor

A NEPTUNE ORBITER & TRITON EXPLORER

Could Neptune’s largest moon, Triton, be an ocean world?

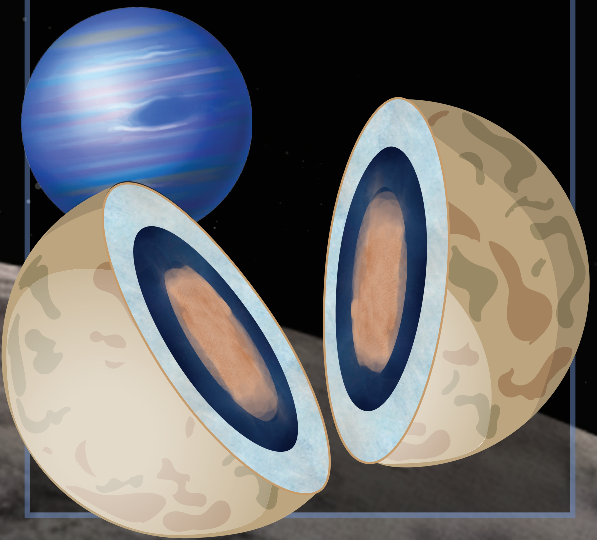
As both a captured Kuiper Belt object and likely ocean world, Triton is a scientifically rich and compelling target for a New Frontiers mission. It is volatile-rich due to its formation in the outer solar system, and its unusual surface geology may be the product of cryovolcanism. Additionally, Triton's highly inclined orbit around Neptune makes it the only ocean world thought to be primarily heated by obliquity tides … yet Triton has been explored by just one spacecraft, Voyager 2, in 1989.

A Neptune orbiter with a robust modern payload performing multiple Triton flybys offers the opportunity to perform comprehensive photogeologic and spectral mapping of Triton's surface and volatile distribution, probe the deep interior of Triton with electromagnetic sounding and geodesy, and study time domain variability of Triton's surface, atmosphere, and interaction with the Neptune's magnetosphere. Compiling observations from multiple flybys of Triton would enable characterization of ocean properties, such as salinity and thickness, necessary for ascertaining habitability.

Solving a Geologic Mystery

The Triton Ocean World Surveyor is a concept mission study that will address key questions raised by Voyager 2’s flyby of Triton nearly 32 years ago. The Triton Ocean World Surveyor mission would:

- Determine whether Triton is an ocean world, ascertain its interior structure, and decide whether Triton’s ice shell is in hydrostatic equilibrium and de-coupled from the interior.
- Characterize Triton’s surface composition and geology, and look for changes, including plumes and their composition.
- Determine the nature of the moon-magnetosphere interaction at Triton.
- Determine the composition, density, temperature, pressure, and spatial/temporal variability of Triton’s atmosphere.



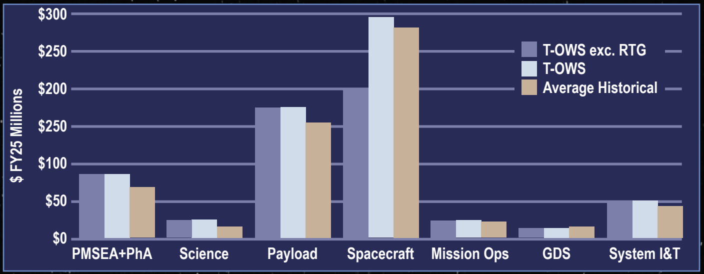
2–3 Year Triton Tour
35–45 Science Flybys

16 Years to
Neptune Orbit Insertion

Launch 2031
Falcon Heavy Expendable
+ STAR 48BV Kick Stage

Affordable Mission Designed for New Frontiers

	FY$25K w/o LV	FY$25K w/ LV
A–D Subtotal	647.0	716.8
A–D Reserves	310.8	323.9
RTG Surcharge	26.0	26.0
A–D PIMMC	983.8	1,066.7
E–F Subtotal	680.6	680.6
E–F Reserves	170.2	170.2
E–F PIMMC	850.8	850.8
Total PIMMC	1,834.5	1,917.5



Main Drivers: Launch Vehicle, Time of Flight & Jupiter/Mars Planning

Main Drivers: Available Time, Incoming v_∞ & Science Requirements

Earth Launch	Mars Flyby (2031 only)	Jupiter Flyby	Transneptunian Cruise	NOI	Capture Orbit	Triton Tour
	L + ≈95 days	L + ≈1.9 years	L + ≈14 years	≈67 min	240 days	2–3 years

≈16 years

≈20 years

Spacecraft & Instrument Suite Draw on Substantial Heritage

LORRI Narrow Angle Camera
New Horizons

Alice Ultraviolet Imaging Spectrograph
New Horizons

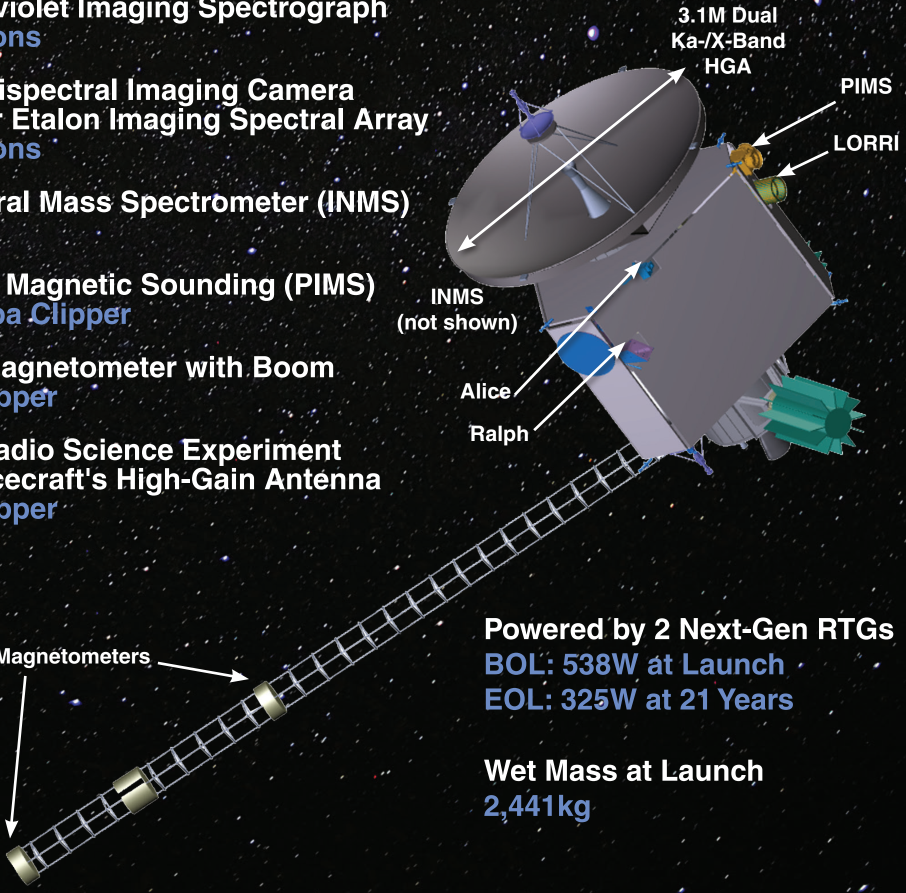
Ralph Multispectral Imaging Camera with Linear Etalon Imaging Spectral Array
New Horizons

Ion & Neutral Mass Spectrometer (INMS)
Cassini

Plasma for Magnetic Sounding (PIMS)
IVO / Europa Clipper

Fluxgate Magnetometer with Boom
Europa Clipper

Gravity / Radio Science Experiment using Spacecraft's High-Gain Antenna
Europa Clipper



Powered by 2 Next-Gen RTGs
BOL: 538W at Launch
EOL: 325W at 21 Years

Wet Mass at Launch
2,441kg

Triton Ocean World Surveyor

Planetary Science Decadal Survey

Triton Ocean Worlds Surveyor

Executive Summary

Could Neptune's largest moon, Triton, be an ocean world? As both a captured Kuiper Belt object and likely ocean world, Triton is a scientifically rich and compelling target for a New Frontiers mission. It is volatile-rich due to its formation in the outer solar system, and its unusual surface geology may be the product of cryovolcanism. Additionally, Triton's highly inclined orbit around Neptune makes it the only ocean world thought to be primarily heated by obliquity tides. *… yet Triton has been explored by just one spacecraft, Voyager 2, in 1989.*

A Neptune orbiter with a robust modern payload performing multiple Triton flybys offers the opportunity to perform comprehensive photogeologic and spectral mapping of Triton's surface and volatile distribution, probe the deep interior of Triton with electromagnetic sounding and geodesy, and study time domain variability of Triton's surface, atmosphere, and interaction with the Neptune's magnetosphere. Compiling observations from multiple flybys of Triton would enable characterization of ocean properties, such as salinity and thickness, necessary for ascertaining habitability.

The Triton Ocean World Surveyor is a concept mission study that will address key questions raised by Voyager 2's flyby of Triton nearly 32 years ago. The Triton Ocean World Surveyor mission would:

> Determine whether Triton is an ocean world, ascertain its interior structure, and decide whether Triton's ice shell is in hydrostatic equilibrium and de-coupled from the interior.
>
> Characterize Triton's surface composition and geology, and look for changes, including plumes and their composition.
>
> Determine the nature of the moon-magnetosphere interaction at Triton.
>
> Determine the composition, density, temperature, pressure, and spatial/temporal variability of Triton's atmosphere.

To address these objectives, the Triton Ocean World Surveyor has baselined a comprehensive, high-heritage payload that requires no technology developments. The mission includes the Alice UV Imaging Spectrograph, Ralph Multispectral Vis-NIR Imaging Spectrometer, and LORRI Narrow Angle Camera from New Horizons; the Galileo Fluxgate Magnetometers; the Cassini Ion and Neutral Mass Spectrometer (INMS); and the Plasma Instrument for Magnetic Sounding that has been proposed for the IVO Discovery Mission (now in Step 2). Radio/gravity science would be accomplished via the medium/high-gain antennas.

The Trident Ocean World Surveyor launches in Jan 2030, with the backup launch period occurring 13 months later. The nominal flight mission is ≈21 years, with a Jupiter gravity assist taking place about two years into the interplanetary transfer and arrival at Neptune about 14 years later (2046). Upon arrival, the Surveyor begins a 240-day elliptical orbit at Neptune and would perform 35–45 science-oriented flybys of Triton – a tour qualitatively like the one described in the PMCS study, *Neptune Odyssey: Mission to Neptune-Triton System [Aug 2020].*

This mission study has been developed to concept maturity level 4 through a strong collaboration between the science team led by Planetary Science Institute and the technical team from the Johns Hopkins Applied Physics Laboratory (APL). The Phase A–D mission cost estimate (with 50% unencumbered reserves, excluding the launch vehicle) is $1,059M (FY$25), below the adjusted cost cap of the New Frontiers 4 AO (~$1.1B FY$25). This cost estimate demonstrates that the Triton Ocean Worlds Surveyor mission is feasible and compelling as a New Frontiers-class mission in the coming decade.

Returning to Triton is critical to answer key planetary science questions, including those about solar system formation, ocean-world habitability, atmospheres, and geophysics.

Addendum

Impact of New Frontiers Schedule Changes

This addendum to the Triton Ocean World Surveyor (T-OWS) Planetary Science Decadal Survey Concept Mission Study expands the timeline into FY2025 to demonstrate the schedule flexibility of T-OWS in response to changes to the timeline of a potential New Frontiers Announcement of Opportunity (AO). The consideration of such changes to a New Frontiers AO release date, came at the end of the study period with the final report being complete and ready for release to the National Academies of Science, Engineering and Medicine, and was prompted by the recent delay of NF5. This addendum addresses a New Frontiers AO release as late as Oct 2024, within the purview of the Planetary Science and Astrobiology Decadal Survey 2023–2032: Panel on Ocean Worlds and Dwarf Planets. The following statements can be made with regard to this study and the impact of changes in the NF AO release timeline:

1) T-OWS can launch at or under the NF cost cap.
    a. Implementation of this program will have to consider a funding profile that is commensurate with the required launch date. It may be possible to have some cost saving due to the fact that Phase B and Phase D could be shortened to be in line with a New Horizon program schedule. This savings is achievable since this program requires no new technology development.
2) The viability of the mission outlined in the final report is not impacted. Necessary are small changes to the spacecraft architecture to accommodate this change in schedule and are outlined below.
3) It does not change, in anyway, the achievable science objectives outlined in the STM.
4) It does not change the science payload.
5) It does not change the science observation plan and orbital CONOPS.
6) It does not change the required launch vehicle and upper stage.
7) It does not change the spacecraft overall design and implementation with small changes being outlined below.

Notable Changes to the Mission

Launch & Neptune Arrival

The launch window for the T-OWS New Frontiers mission would change to 18 Mar 2032 through 7 Apr 2032, it does not offer a backup until Jupiter comes back into phase in the 2040s. The required mission overall ΔV would be significant reduced while extending the C3 required to its maximum performance of the Falcon Heavy + S48BV. The cruise duration would increase from 16 to 20 years.

Opportunity	2032
Launch Period	3/18/2032-4/7/2032 (20 days)
Sequence	Earth-Jupiter-Neptune
Max C3 (km2/s2)	99.67
Mission Delta V	1159
Launch Mass Capability (Falcon Heavy + S48BV) (kg)	2096.9
Launch Mass Required (kg)	2096.9
Cruise Duration (yrs)	20.00
Arrival Date	4/7/2052

Table Addendum-1. *Updated Mission Parameters for Extended New Frontiers AO.*

Schedule

To meet the required launch date two changes to the overall schedule should be considered: (1) Reduce Phase B from 18 months to 12 months; and (2) Reduce Phase D from 24 months to 12 months. This would allow for nearly 8 months of schedule margin to the NF schedule. This should not be considered aggressive for two factors. First, there is no technology development required for this mission to launch; and this is nearly 15 months longer than the New Horizon's schedule from the end of Phase A (SRR) until launch.

Power

The longer cruise will require a small change in the power profile for the mission. The original design is operating the spacecraft as efficiently in electrical power as possible for the given technology chosen, no savings in power would be practical to pursue. Therefore, additional power to the spacecraft design is required. The T-OWS spacecraft RTG configuration would change from Mod 0 RTG (BoL=293 Watts) and Mod 1 RTG (BoL=245 Watts) to two equivalent Mod 0 RTG's with a total of 586 Watts BoL power; an increase in 48 Watts from the original design. The increase in initial power accommodates the increase in flyout time up to 26.2 years of total available RTG power. This has no additional cost impact.

The RPS office will be required to produce 144 clads of Pu238, up from 136 clads in the original design. This would fit within the constant rate of production model agreed to by DoE and NASA, and maintains the risk identified (Risk Statement #1) in this report. The change in NF schedule does not offer schedule relief to DoE that must maintain the maximum constant rate (15 clads/year) of production through 2031, with the only non T-OWS delivery to the Dragonfly mission.

Mass

The spacecraft will be required to be reduced in mass by 700kg. That offset is directly achieved by lower propellant mass required for the NOI burn. Additional mass saving is possible, but not required, by allowing for smaller propellant and oxidizer tanks due to the smaller propellant load required. This will allow for additional power savings since lower heater power will be required to keep a smaller volume warm.

Conclusion

The NF AO schedule does not change the viability or overall mission objectives as outlined in this final report. Small adjustments in the design are possible to offset the change in NF schedule with no cost impact. The schedule is achievable since it is modeled after New Horizon’s with more than a year of additional schedule and eight months reserves.

I. Scientific Objectives

1.1 Science Questions & Objectives

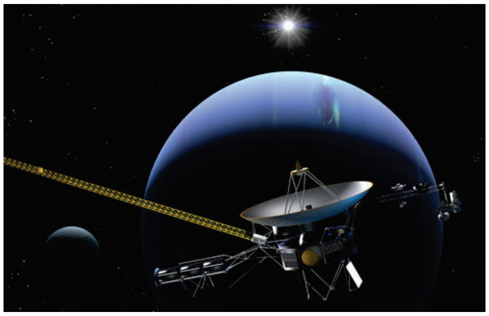


Figure 1-1. Triton has been explored by just one spacecraft – Voyager 2 in 1989. A Neptune orbiter with a robust modern payload performing multiple Triton flybys offers the opportunity to do comprehensive photogeologic and spectral mapping of Triton's surface and volatile distribution, probe the deep interior of Triton with electromagnetic sounding and geodesy, and to study time domain variability of Triton's surface, atmosphere, and interaction with the Neptune's magnetosphere.

As both a captured Kuiper Belt Object (KBO) and likely ocean world, Neptune's moon Triton is a scientifically rich and compelling target. It is volatile-rich due to its formation in the outer solar system, and its unusual surface geology may be the product of cryovolcanism. Triton's highly inclined orbit around Neptune makes it the only ocean world thought to be primarily heated by obliquity tides. Triton has been explored by just one spacecraft, Voyager 2, in 1989.

Is Triton an ocean world? Triton's surface age is <100 Ma, possibly <10 Ma, and its surface geology is unique in our solar system, with relief <1 km. As a captured KBO, the initial heating likely would have differentiated Triton. Radiogenic heating and obliquity tides can maintain an ocean today, and supply the necessary energy for surface yielding that would erase craters. Answering this question is a top priority because Triton's ocean world status is key to understanding the limits of habitability.

Has cryovolcanism sculpted Triton's surface? Triton's young surface has been heavily modified by endogenic processes, producing features unique in the solar system, including its characteristic cantaloupe terrain (Fig. 1-2), guttae, walled plans, and ring patera. Composition of these features is an important test of the formation process, but Voyager 2 did not carry a near-IR spectrometer. Our knowledge of Triton's surface composition is limited to Earth-based, disk-integrated telescopic observations. The presence of putative cryovolcanic constructs on the surface suggests that there have been times in Triton's history when communication between surface and subsurface liquid reservoirs, possibly an ocean, occurred, plausibly persisting into current geological times.

What is the distribution of volatiles on Triton's surface? We know that Triton's complement of volatiles includes N_2, CH_4, and CO, with H_2O and CO_2 forming the "bedrock". By mapping the distribution of these ices on the surface, we can study the interplay of tidal dissipation, heat transfer, tectonics, cryovolcanism, diapirism, and surface-atmosphere interactions. We can also determine if the bright southern hemisphere is a seasonal polar cap composed of N_2 or a lag of the less volatile ices.

Are Triton's plumes endogenic or exogenic? Voyager imaged at least two active plumes. Determining whether Triton's plumes are eruptions from the subsurface or a solar-driven surface phenomena is important because that will give us insights into the volatile reservoir being accessed.

What is the structure and chemistry of Triton's atmosphere and hazes? Like Pluto, Triton's nitrogen atmosphere is in vapor pressure equilibrium with N_2 surface ice, with CO and CH_4 as trace constituents. The thermal structure of Triton's upper atmosphere is quite different from Pluto however, and its haze layer is at a much lower altitude. Understanding the photochemistry of Triton's atmosphere is important to characterize the eventual precipitates finding their way to the surface.

What is the source of Triton's unique ionosphere? Studying the plasma interaction between Triton and Neptune will give us new insights into the structure and chemistry of Triton's upper atmosphere and ionosphere, and reveal how Triton loses material from its atmosphere and how this material interacts with Neptune's magnetosphere.

Where does Triton fit in the search for life? We have three confirmed ocean worlds in our solar system where the ocean itself can plausibly be accessed and studied: Enceladus, Europa, and Titan.

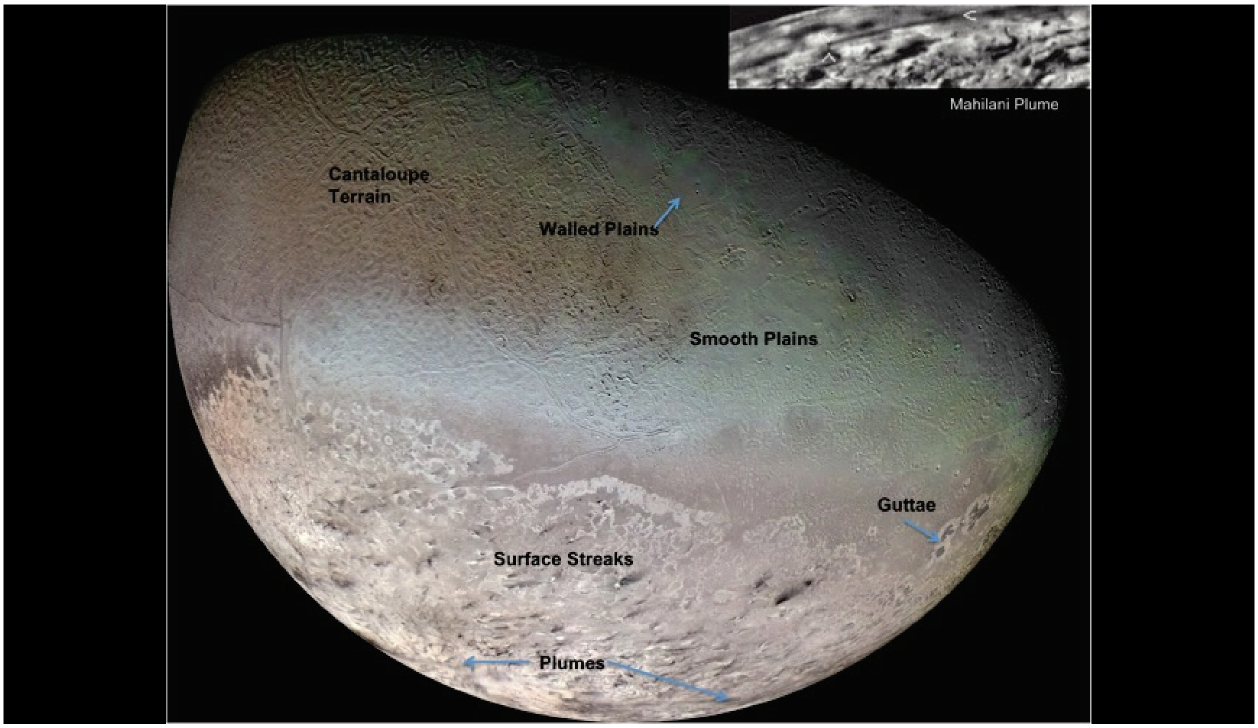


Figure 1-2. *Many of Triton's unique landforms suggest the possibility of cryovolcanism. The young low-relief surface has enigmatic geology unique in the solar system. The inset shows Mahilani plume erupting. Based on PIA00317. Credit: NASA/JPL/USGS.*

Confirmation of Triton as an ocean world, going beyond current circumstantial evidence, gives us one more place to eventually look for life, pushing the habitable zone to the outer reaches of our solar system. For this reason the Roadmap to Ocean Worlds gave a mission to Triton top priority in the coming decade.

A Neptune orbiter with a robust modern payload performing multiple Triton flybys offers the opportunity to do comprehensive photogeologic and spectral mapping of Triton's surface and volatile distribution, probe the deep interior of Triton with electromagnetic sounding and geodesy, and to study time domain variability of Triton's surface, atmosphere, and interaction with the Neptune's magnetosphere. Compiling observations from multiple flybys of Triton enables characterization of ocean properties, such as salinity and thickness, necessary for ascertaining habitability.

The prioritized science objectives and corresponding instruments are as follows:

> **T1:** Determine whether Triton is an ocean world, ascertain its interior structure, and decide whether Triton's ice shell is in hydrostatic equilibrium and de-coupled from the interior. *Magnetometer, radio/gravity science using spacecraft telecom subsystem.*
>
> **T2:** Characterize the surface composition and geology, and look for changes, including plumes and their composition. *High resolution visible imager, multi-spectral Vis-NIR imaging spectrometer.*
>
> **T3:** Determine the nature of the moon-magnetosphere interaction at Triton. *Plasma/electron energy instrument (similar to PIMS on Europa Clipper).*
>
> **T4:** Determine the composition, density, temperature, pressure, and spatial/temporal variability of Triton's atmosphere. *Ion-neutral mass spectrometer, ultraviolet imaging spectrograph*

The detailed science traceability matrix including instrument performance requirements is shown in Table 1-1. This mission is in a sense still at the level of basic reconnaissance, considering that it will be only the second mission to the Neptune system, so none of the requirements are particularly demanding. No new technology development is required. The mission concept described in this study report was able to accommodate all requested instruments within a New Frontiers budget. The trajectory evaluated meets all observational requirements. If further analysis were to show that descopes had to be made T4 is the lowest priority and those two corresponding instruments could be jettisoned. Even in this case, the science return of the mission is compelling.

Table 1-1 *Science Traceability Matrix.*

Primary Scientific Objectives	Measurement	Instrument	Functional Requirement
T1. TRITON SHAPE, STRUCTURE & OCEAN Determine whether Triton's is an ocean world, ascertain its interior structure, and decide whether Triton's ice shell is in hydrostatic equilibrium and decoupled.	Determine Triton's 3D shape to 1 km accuracy per axis. Measure Neptune's magnetic field upstream/local to Triton, and fully characterize the time dependent variability (14 & 141 hr periodicity signals). At the closest approach to Triton measure the amplitude ratio of the secondary (induced field) to the primary field. Measure the upstream plasma density and energy to quantify the plasma interaction, and where possible Triton's ionospheric density profile. Need to resolve on the order of 0.05-0.1 nT to determine total ice shell thickness to ± 20% [2]. Measure Triton's low degree static gravity coefficients to determine the ice shell thickness to ±20% and to determine whether the ice shell is in hydrostatic equilibrium. TRITON STRUCTURE: Measure Triton's internal Love number k2<0.06. Both X- and Ka-Band to help cancel terrestrial ionospheric fluctuation noise.	Narrow Angle Camera (LORRI), Fluxgate Magnetometer, Radio/Gravity Science Subsystem	Image Triton's Sun-illuminated disc at <90˚ phase angle in visible or NIR wavelengths (~0.4-1 µm) from >3 evenly spaced sub-spacecraft lon/lat on Triton at 1-10 km/pixel, SNR and Dynamic Range >100. At least 16 encounters (one for DC field plus three per induced frequency) with a closest approach below 380 km (2^0.333 from body center). These encounters should be distributed over the phase of the driving frequencies, with no gaps greater than 45 deg. in phase for each frequency. The phase of each frequency is defined as (t/P MOD 1)*360, where P = {141.0, 16.1, 14.5, 13.1, 7.2} hours. High-gain antenna to Earth; lidar to nadir (preferable). High resolution (10s m/pixel), close flyby imaging. Need ranges at ~50 ground-track intersections. Two-way coherent Doppler tracking (< 0.1 mm/s for 60-s count time) when Sun-Earth-Probe angle (SEP) > 10°. Repeated images of the same point at multiple True Anomalies.
T2. TRITON SURFACE AND PLUMES Characterize the surface geology and composition and look for changes, including plumes and their composition	Measure surface geological and composition properties; spatial-temporal changes. Visible image resolution better than 3 km/pixel. NearIR resolution 5-10 km. Composition and images of plumes and deposits. Image southern hemisphere at resolutions equivalent to Voyager (1 - 5 km) in order to look for changes in plume existence, size and/or location.	Multispectral Vis-NIR Imaging Spectrometer (Ralph), Narrow Angle Camera (LORRI)	Map all available illuminated terrain (i.e. not in polar night) with 12 flybys to better than 3 km/pixel. Passes should be spaced ~30 deg in longitude, with phase angle <45 deg, at an altitude <100,000 km. Tour must be flexible to return to location of any new plumes detected at an altitude of <20,000 km, phase angle <30 deg. If/when plumes are located image the source at a resolution of 100m or better acquire spectra of plume material at res of 2km or better.
T3. TRITON IONOSPHERE, ENERGY FLUX & NEPTUNE INTERACTION Determine the nature of the moon-magnetosphere interaction at Triton. How does it regulate the energy flux and ionosphere formation at Triton, and contribute to the heavy ion population and dynamics of Neptune's magnetosphere?	Measure the flow of plasma density, energy spectrum, flux, and composition around Triton for ions and electrons. Measure the electron density and the composition of the ionosphere, and how these vary with local/diurnal time. Measure the interaction of Triton with Neptune's magnetosphere including electric currents and electron beams, either directly or through beam-generated plasma waves	Thermal Plasma Spectrometer + Energetic Particle Instrument (PIMS), Magnetometer (fluxgate), Radio/Gravity Science Subsystem.	Particle instruments need instrument pointing parallel, anti-parallel and perpendicular to magnetic field, ~few hundred km altitude.
T4. TRITON ATMOSPHERE Determine the composition, density, temperature, pressure, and spatial/temporal variability of Triton's atmosphere.	Measure the temporal variability of atmospheric composition and density. Measure the atmospheric pressure and temperature from the base to the thermosphere, and as a function of local time. Measure the atmospheric escape rate. Search for and map surface telltales of atmospheric seasonal variability, such as wind streaks and seasonal layering. Map atmospheric transport; gas and haze composition/evolution. Map distribution of volatiles in order to map polar cap boundaries.	Ion and Neutral Mass Spectrometer. UV Imaging Spectrometer (Alice). Narrow Angle Camera (Ralph), Radio/Gravity Science Subsystem	Mass spectrometer to (near) ram, ~few hundred km altitude. Phase angles to at least 150 deg,~few hundred km altitude. 6-12 solar and stellar occultations distributed in latitude and (for the stellar occultations) in local time of day. At least 2 mass spec sampling approaches ~few hundred km altitude; more highly desired. 6-12 solar and stellar occultations distributed in latitude and (for the stellar occultations) in local time of day. At least 2 mass spec sampling approaches ~few hundred km altitude; more highly desired.

2. High-Level Mission Concept

2.1 Overview

As part of NASA's support to the National Research Council (NRC) and its Planetary Science and Astrobiology Decadal Survey 2023–2032: Panel on Ocean Worlds and Dwarf Planets, the Johns Hopkins Applied Physics Laboratory (APL) was assigned the task of developing a mission and flight system architecture suitable to perform a scientifically viable Triton Ocean World Surveyor (T-OWS) mission responsive to STM requirements formulated by the Science Champion, Candice Hansen-Koharcheck.

APL was specifically tasked to determine if T-OWS could fit within NASA's New Frontiers cost in FY2025 dollars using the Planetary Mission Concept Study (PMCS) ground rules for reserves. Architecture trade-space analyses as well as detailed point designs were to be performed by APL, however on a compressed schedule. This was due to the Ocean Worlds and Dwarf Planet's panel's needs. To meet the compressed schedule, APL performed high-level trades and high-level point designs, followed by parametric and historical cost estimating of the final mission architecture. APL assembled subject matter experts to perform concurrent engineering remotely due to the ongoing COVID-19 pandemic. The work was done in close coordination with the Science Champion and science team both actively engaged throughout the process in the design decisions leading to the T-OWS mission described in this report.

2.2 Concept Maturity Level (CML)

Upon completion of the T-OWS study, with point designs in place, the concept is at concept maturity level (CML) 4, as defined by Wessen et al. [2013][1] and described in Table 2-1. The architectures studied were defined at the subsystem level with estimates developed for mass, power, data volume, link rate, and cost using APL's institutionally endorsed design and cost standards. Due to the compressed timeline, less analysis of instrument detailed performance was performed because the instruments are well known. The study performed analysis of Triton's tour coverage of instruments to ensure the STM was satisfied.

Concept Maturity Level (CML)	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, and validation and verification (V&V) approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Table 2-1. *Concept Maturity Level Definitions.*

2.3 Technology Maturity

All flight system elements – subsystems and instruments – are currently at or above technology readiness level (TRL) 5. The instruments are TRL 6 or higher.

The instruments are all based on technology that either is highly developed or has already flown, as shown in Table 3-7 (Instrument Mass & Power). For the instruments, only engineering development necessary to accommodate the mission and the specific enhancements of performance would be required.

2.4 Key Trades

Multiple solutions were considered for each design decision, with final selections primarily motivated by the prioritization by cost and longevity. Key trade studies that drove the design are listed in Table 2-2.

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[1] Wessen, R., C. Borden, J. Ziemer, and J. Kwok, 2013, Space mission concept development using concept maturity levels, NASA JPL, AIAA SPACE 2013 Conference & Exposition, San Diego, California, September 10-12, 2013 http://hdl.handle.net/2014/44299

Area	Trade Space, Result (Bold)	Rationale
Three Axis Attitude Control	Redundant Reaction Wheels	Pointing of the instruments and Ka-Band antenna are satisfied using propulsive control, adds longevity to the mission with limited power
	Propulsive	
Launch Vehicles	SLS, Vulcan/6S, **Falcon Heavy Expendable**, Atlas V, Delta IV-Heavy	Expect that Falcon Heavy and Vulcan/6s will be nuclear rated and is mission enabling C3 of 80-85 km^2/s^2
High Energy Upper Stage	**Star 48BV**, Orion 50	Heritage design and limited mission design resources to investigate alternative
Propulsion System	COLD Prop Bi-Propellant (MMH/MON-25)	Lack of qualified 1lb thrusters would not allow three axis attitude control using COLD Prop allowing tank temps to reach –40C
	Dual Mode Earth Storable System (MMH/MON-3)	
Attitude Control during Cruise Phase	Three Axis	Use New Horizons model of unattended operation. Use medium gain antenna to support cruise phase. Added fuel to support.
	Spin Stabilized	
Number of Required RTG Clads	**136 (Mod 0 and Mod 1)**	Would require increasing the electrical efficiency of EPS system and looking at updating our thermal model beyond what is done at a ACE run
	128 (Qty 2 Mod 1's)	
Instrument Scan Platforms or Gimbals	Provide Instrument scan tables or gimbals	Instruments are required to be internal to the S/C structure to support thermal balance – pointing and scan must be accomplished by GNC under thruster control
	Eliminate instrument scan tables or gimbals	
RF Frequency Allocations	**Ka-Band and X-Band**	Single Ka-Band 34-m is the guidance of the Decadal Committee and meets the mission data throughput needs and S/C pointing requirements
	X-Band Only	
Supplemental Peak Power	Additional RTG Clads or Units	Battery was added to support peak needs of the mission
	Battery	
Bi-Propellant System Design	Redundant	Acceptable risk under a New Frontiers cost cap, e.g., Juno
	Single	

Table 2-2. *Key Trades.*

3. Technical Overview

3.1 Instrument Payload Description

The entire science payload is based on existing instruments, as shown in Fig. 3-1 and 3-2. None require new technologies, but some have modifications that improve their performance for this mission. The instrument complement includes some that are body mounted, some that are mounted internally to the spacecraft, and some to a fixed boom. Internal mounting is required for thermal balance reasons. The imagers and imaging spectrometers are mounted on the same side of the spacecraft and will be facing nadir during most low-altitude passes.

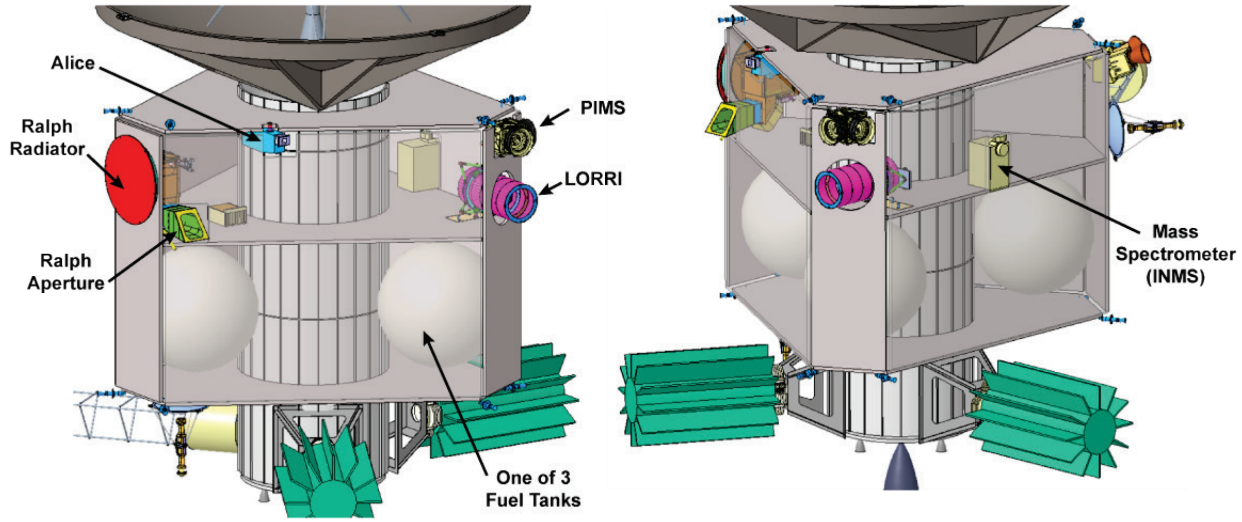


Figure 3-1. *Instruments and other spacecraft components are internally mounted within the spacecraft to use dissipated power for thermal heating of the spacecraft internal structure, particularly to maintain the necessary propulsion system temperature range, this is critical to the thermal design of the spacecraft.*

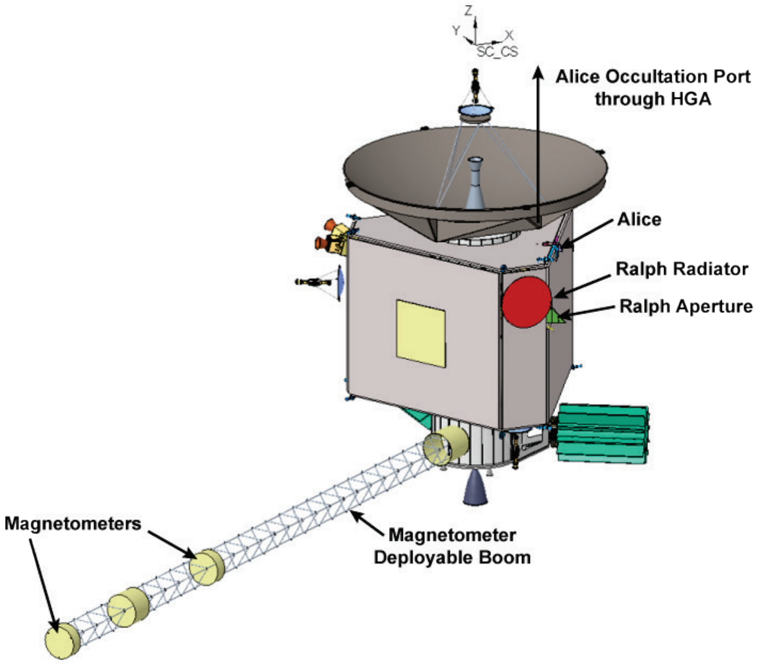


Figure 3-2. *Two Magnetometers mounted on 8.5-meter deployable boom, also shows in the Ka/X-Band HGA antenna to support radio and gravity science. The NGRTG are offset to allow for spinalization during cruise.*

Instrument	Type	CBE Mass (kg)	CBE Power (Watts)	TRL/Mission
Alice	Ultraviolet Imaging Spectrograph	7.2	4.4	9 / New Horizon
LORRI	Long-Range Imager	8.6	5	9 / New Horizons
Ralph	Multispectral Visible Imaging Camera, Linear Etalon Imaging Spectral Array	10.67	5.3	9 / New Horizons
PIMS	Plasma for Magnetic Sounding	6.4	15.06	6 / Clipper (IVO)
MAG	Fluxgate Magnetometer with boom	45.73	4.2	9 / Europa Clipper
INMS	Mass Spectrometer	23.3	10.3	9 / Cassini
Radio Science	Gravity + Atmosphere	Included with S/C	Included with S/C	6 / Europa Clipper
	Total	**101.9**	**44.26**	

Table 3-1. *Instrument Mass and Power.*

1. Science Champion requested the additional of 2 kg of mass be added to the Alice instrument for enhancements to performance.

The instruments in this study were selected to verify the feasibility of the measurements required to meet the science goals. Table 3-1 provides details on the payload mass and power. The radio frequency (RF) communications system provides the downlink rate necessary to return all required data, with margin.

3.2 Orbiter Flight System

The flight system would consist of a single T-OWS spacecraft that enters the Neptune/Triton system after a 16-year cruise. The Neptune orbit capture would require approximately 240 days. During cruise the spacecraft would be spin stabilized with periodic periods of 3-axis control for high data rate or ΔDOR. Refer to § 3.3 for the proposed timeline and trajectory. The spacecraft uses its large chemical propulsion system for the Neptune/Triton/ΔV maneuvers, and later for orbit adjustment tour ΔV maneuvers. The flight system would employ three-axis stabilization during orbital operations and feature the following: body-fixed Earth-pointing high- and medium-gain antennas HGA/MGA and body-fixed payload suite, X- and Ka-band science data downlinks, one Mod 0 and one Mod 1 next-generation radioisotope thermoelectric generator (NGRTGs) to provide power, pressure regulated dual mode system propulsion system for Neptune Orbit Insertion (NOI), orbit maintenance, and attitude control.

The flight system would be dual string with cold spares and a 3.1-m-diameter HGA. The main propulsion system is single string and is appropriate for a New Frontiers mission risk. The equipment layout and thermal design are intended to minimize heater power required. All of the bus equipment and much of the payload share a highly insulated single enclosure. Fig. 3-3 illustrate the payload and equipment layouts, respectively. Fig. 3-4 shows the flight system block diagram and Table 4 represents the neutral mass summary of the T-OWS spacecraft.

Subsystem	CBE	Cont.	MEV
Avionics	14	10%	15
Guidance, Navigation & Control	25	10%	28
Power	154	10%	170
Harness	50	10%	55
Thermal	54	15%	62
RF Communications	61	15%	68
Propulsion	148	7%	158
Mechanical	162	15%	186
Spacecraft Bus Total	**667**	**11%**	**741**
Payload	**102**	**10%**	**112**
Flight System Dry Mass (CBE, cont., MEV)	**769**	**11%**	**853**
Hydrazine Mass + Oxidizer (CBE, cont., MEV)	**1381**	**15%**	**1588**
Neutral Mass (CBE, MEV), kg	**2150**		**2441**
Dry Mass MPV, kg			**1109**
Dry Mass Margin, kg			**213**
Dry Mass Margin, %			**44%**

Table 3-2. *Flight System Neutral Mass Summary.*

All of the bus equipment and much of the payload share a highly insulated single enclosure. Fig. 3-3 illustrates the payload and equipment layouts, respectively. Fig. 3-4 shows the flight system block diagram, and Table 3-2 represents the neutral mass summary of the T-OWS spacecraft. Table 3-3 shows the power modes of the T-OWS spacecraft, and Table 3-4 shows the overall flight parameters of the spacecraft and mission.

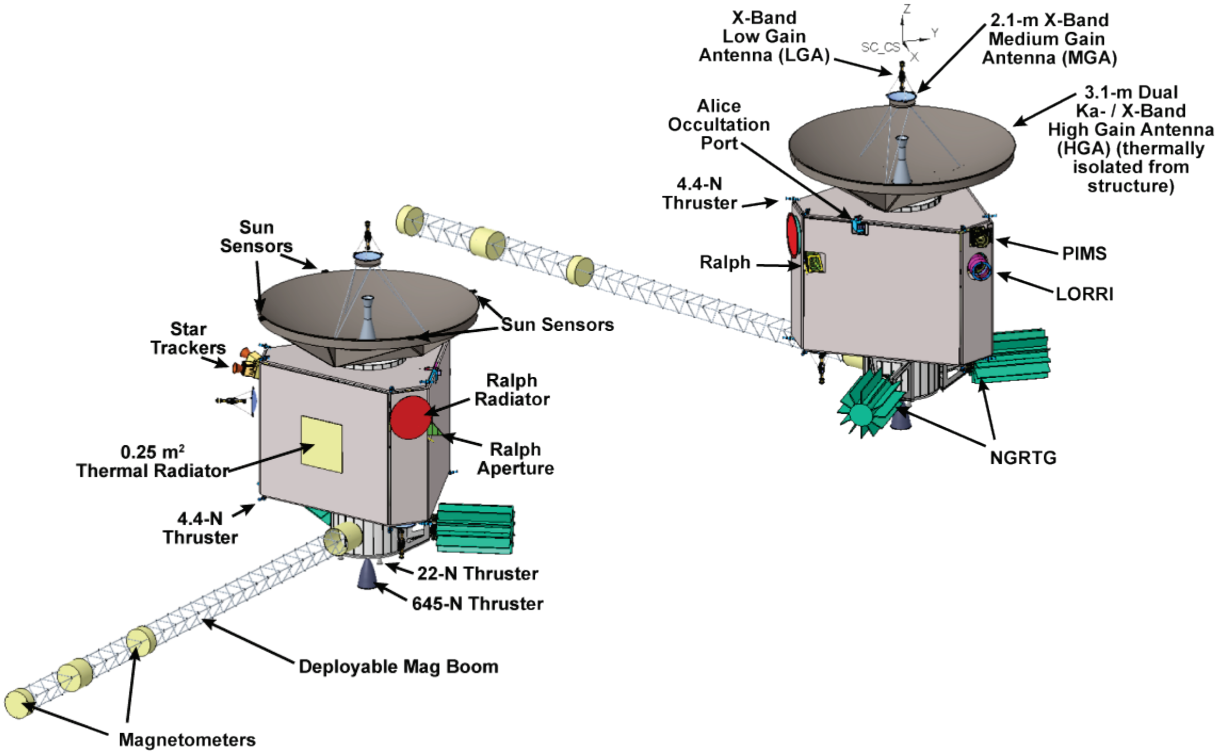
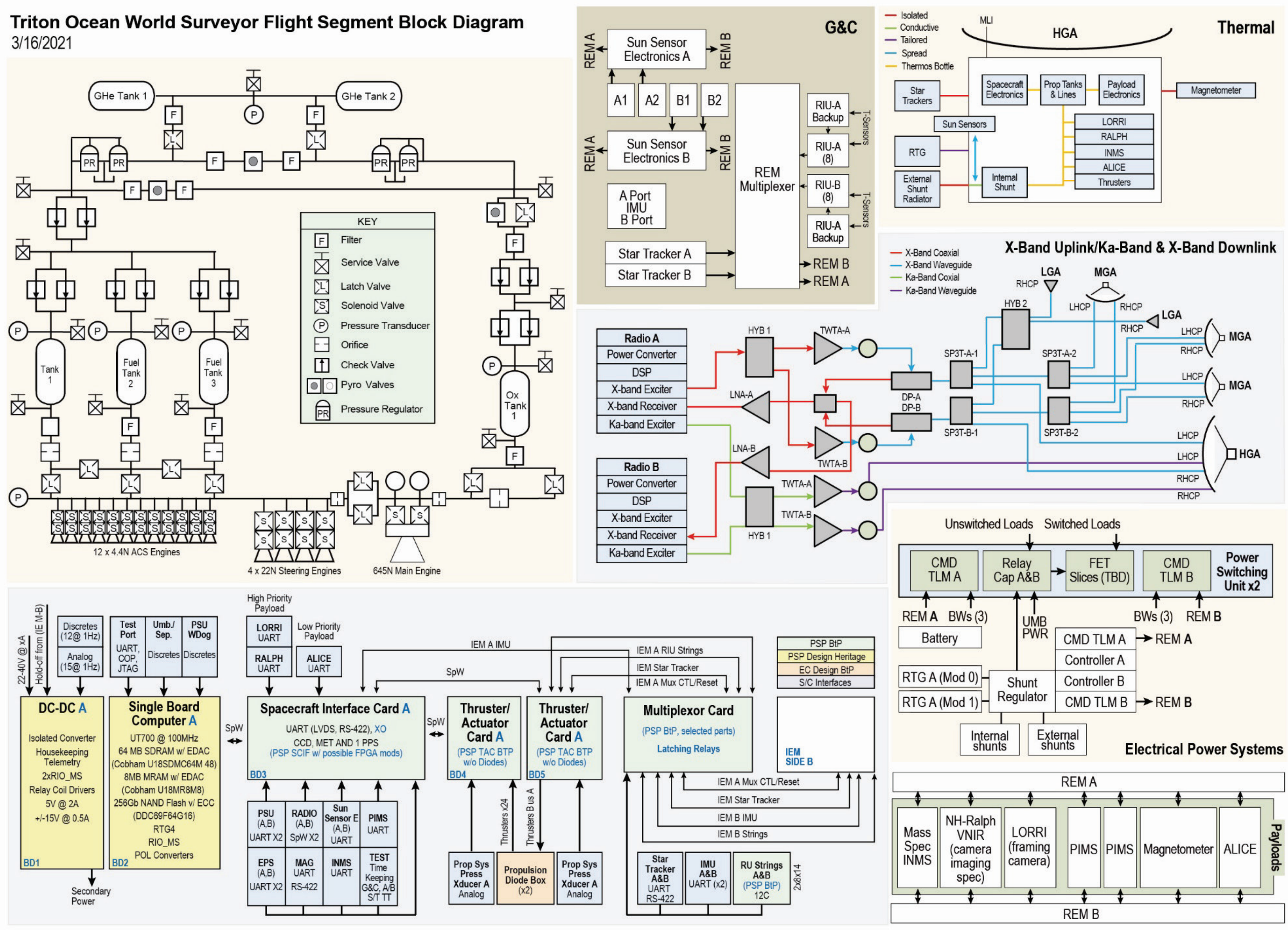


Figure 3-3. *Triton Ocean World Surveyor Spacecraft External Equipment Layouts (INMS instrument not shown). The spacecraft will be completely blanketed with 0.015 estar MLI and is also not shown.*

Figure 3-4. *Block Diagram.*



Subsystem / Instrument	Science	ΔV Prep	ΔV	Radio Science	Data Link	Safe	Cruise	Battery Charge
Payload Instruments MEV (W)	54	4	7	8	2	2	2	2
CDH MEV (W)	18	18	18	18	18	36	18	1
GNC MEV (W)	70	69	60	69	70	69	69	66
EPS MEV (W)	45	45	45	45	45	45	45	45
TT&C MEV (W)	15	51	51	56	83	50	51	15
Propulsion MEV (W)	26	93	98	26	26	26	26	26
Total MPV Power (W) (w/harness losses)	301	368	366	292	322	313	279	204
Power Shunt (W)	2	4	32	19	7	8	28	66
Excess Power (W)	23	0	0	15	0	5	18	56
RTG Available Power (W)	326	326	326	326	326	326	326	326
Battery Power Draw (W)	0	46	72	0	0	0	0	0
Depth of Discharge (%)	0	28.5	16.7	0	0	0	0	0

Table 3-3. *Flight System Power Modes.*

Flight System Element Parameters	Value/Description
General	
Design Life, Years, Cruise	17
Design Life, Years, Neptune/Triton	17 + 2 = 19
Design Life, Years, Extended Mission	19 + 1 = 20
Structure	
Structure Material	Aluminum
Number of Articulated Structures	None
Number of Deployed Structures	One (magnetometer boom)
Thermal Control	Single passive “thermos bottle” design
Type of Thermal Control Used	Mostly passive thermal control with heaters and louvers utilized to protect the minimum temperature of the system
Propulsion	
Systems	Pressure Regulated Dual Mode
Chemical Total Propulsion ΔV	2102 m/s
Chemical Propulsion ISP & Thrust	315s; 645N
Chemical Propulsion Thrusters & Tanks	Four 89 cm inner diameter tanks, one oxidizer tank 12 × 4.4 N; 4 × 22 N; and one main 645 N
Chemical ACS Propulsion ΔV	Cruise 56 m/s; Tour 150 m/s
Chemical ACS Propulsion Isp	220 s (steady-state)
Attitude Control	
Control Method	Three-axis and spin stabilized using thruster control
Control Reference	Solar (safe), stars (all other modes)
Pointing Control Capability, arcsec	18 arcsec
Pointing Knowledge Capability, arcsec	216 arcsec
Agility Requirements (maneuvers, scanning, etc.)	20°/s
Articulation	All elements body-fixed
Sensor and Actuator Information (precision/errors, torque, momentum storage, etc.)	Five fine Sun sensors, two star trackers with <25-arcsec accuracy, single Scalable Space Inertial Reference Unit (SSIRU)
Command and Data Handling	
Flight Element Housekeeping Rate	≤20 kbps
Data Storage Capacity	256 Gb
Maximum Storage Record Rate	>2 Mbps
Maximum Storage Playback Rate	>2 Mbps
Power	
Power Source	Mod 0 and Mod 1 NGRTG
Beginning of Life and End of Life Load Power Capability	538 W at launch; 325 W at 21 years post-launch

Table 3-4. *Flight System Element Parameters.*

3.2.1 Attitude Control System (ACS)

The T-OWS guidance, navigation, and control (GNC) provides a three-axis-controlled platform that satisfies all requirements set by science, navigation, communication, and propulsion. All GNC components are available commercial off-the-shelf (COTS) with multiple potential vendors.

3.2.2 RF Communications

The T-OWS telecommunications system will feature a fully redundant design, including two radios, all necessary redundant RF cabling and switching, and two Ultra Stable Oscillators (USOs). The radios are connected to a suite of antennas: two low-gain antennas (LGAs), two medium-gain antennas (MGAs), and one high-gain antenna (HGA). The HGA is a 3.1-m dish, with heritage from the Europa Clipper HGA. The USOs are in an active cross-strapped configuration; both clocks will be powered on and available to provide clocking to the radios. The USOs provide the radios with a precision clock source capable of radio science, as well as standard communications exchange. The Ka-band transmission will be supported by a 20-W amplifier, and the X-band will be supported by a 12-W amplifier.

The T-OWS spacecraft will communicate to the DSN's family of 34-m beam waveguide (BWG) antennas. Upon arriving at Neptune/Triton, the Ka-band downlink will provide a 4.1- to 12 kbps link with margin to the DSN. This will allow 4.26-Gbit of compressed image data to be return in 17 days of the 23.5 day orbit of Triton.

3.2.3 Chemical Propulsion System

The chemical propulsion subsystem is a pressure-regulated dual mode hydrazine system that provides ΔV capability and attitude control for the spacecraft. The system consists of one (1) 645-N bipropellant dual mode apogee main engine, four (4) 22-N (5-lbf) hydrazine monopropellant thrusters used for steering, and twelve (12) 4.4 hydrazine monopropellant thrusters used for ACS and components required to control the flow of propellant and monitor system health and performance. The propellant and oxidizer are stored in in four identical tanks with two pressurant tanks.

The steering and ACS thrusters are of the catalytic monopropellant hydrazine type; when the thruster valves open, propellant flows through the thruster into a catalyst bed, where the hydrazine spontaneously decomposes into hot gases, which then expand through a nozzle and exit the thruster, producing thrust. For the purposes of this study, mission-averaged performance data for the MESSENGER-heritage Aerojet Rocketdyne MR-106E 22-N thrusters were used, but alternate options exist.

The propellant and pressurant will be stored in a titanium tank manufactured by Northrop Grumman. The remaining components used to monitor and control the flow of propellant will be selected from a large catalog of components with substantial flight heritage on APL and another spacecraft.

3.2.4 Avionics Architecture

The Triton Ocean World Surveyor avionics architecture is designed for block redundancy with full interface cross-strapping. The avionics hardware is separated into two primary housings: the Redundant Processor Module (RPM) and the Redundant Electronics Module (REM). This approach is consistent with previous APL spacecraft programs and will take advantage of extensive heritage hardware.

3.2.5 Redundant Processor Module

Command and data handling (C&DH), GNC, and spacecraft fault protection functions will be performed in a single radiation-hardened, quad-core, GR740 processor. A cold redundant processor and solid-state recorder (SSR) will serve as backup and can be placed in a warm-spare state as needed. The Avionics Redundancy Controller (ARC) will continually monitor the status and health of the single board computer (SBC) and SSR systems and switch or change power states of the equipment if necessary.

The SSR board will form eight 32-Gbit memory banks for a recorder size of 256-Gbit. This design leverages existing technologies developed for the Parker Solar Probe mission.

3.2.6 Redundant Electronics Module

The REM consists of the Spacecraft Interface Card (SCIF), the Thruster/Actuator Controller (TAC), and the Multiplexer Card. The REM incorporates cross-strapped redundancy for payload and navigation interfacing as well as SpaceWire links to the RPM through a nine-port SpaceWire router. The SpaceWire and payload routing will be performed by an RTG4 field-programmable gate array (FPGA) onboard the SCIF.

3.2.7 Power

The Electrical Power Subsystem (EPS) provides power generation, regulation, and distribution for the vehicle through all mission phases. Fig. 3-5 represents a block diagram of the EPS. The subsystem is designed to provide a 30% margin in all load cases (Table 3-3).

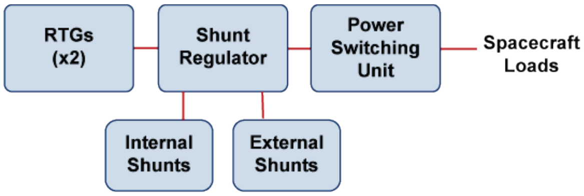


Figure 3-5. *Electrical Power System Block Diagram.*

3.2.8 Power Generation

One (1) Mod 0 and one (1) Mod 1 NGRTGs provide power to the vehicle. Together the NGRTGs provide 538 W when initially loaded with fuel and are estimated to provide 325 W at the end of the mission (after) distribution, regulation, and switching losses, available power at power switching unit output assuming the NGRTGs are loaded 2 years[2] before launch. The NGRTGs are provided by NASA and will be installed at the launch base. Spacecraft testing will be achieved using NGRTG simulators, which are similar in form, fit, and function to the RTGs, but the thermocouples are heated using electrical heaters.

3.2.9 Mechanical

The mechanical design of the spacecraft consists of one main section: that primarily houses the propulsion tanks (hydrazine) and the two NGRTGs, as well as accommodating all of the other components, including the instruments. The Ka-Band antenna is thermally isolated form the main section and is used during flyout as a thermal shield for the main section.

The nadir side of the upper section accommodates the nadir-facing instruments with their fields of view (FOV) unobstructed. The magnetometer boom also deploys off the main section and points anti-nadir. The +Z face of the upper section accommodates most of the antennas, HGA, MGA, and one LGA (the other LGA is located adjacent to the launch vehicle interface facing −Z). The antennas are stacked on each other in a configuration that was used on New Horizons.

Eight reaction control engines are located on each main section (12 total). The four on the lower section are positioned toward the −Z to maximize separation from the engines on the upper section.

3.2.10 Thermal

The T-OWS thermal design accommodates the range of mission solar distances. All instruments are thermally isolated from the spacecraft and blanketed to minimize heater power usage. For the spacecraft bus, T-OWS uses the same approach as New Horizons. All spacecraft hardware including instrument electronics and propulsion module components are thermally coupled together and covered with VDA Kapton multilayer insulation, using electronics waste heat to maintain temperature. The spacecraft bus will maintain a constant internal heat dissipation, providing a set thermal load to the system. As electronics boxes are turned off, makeup heaters will be enabled to maintain the bus temperature. Heat pipes will be selectively utilized to transport the concentrated heat from the traveling wave tubes (TWTs) and PPU to a nearby radiator for rejection to space. Louvers maintain the spacecraft core between 10°C and 50°C as the external environment varies because of solar distance, along with bus internal heat variations.

The NGRTGs are mounted on brackets in a ring around the propulsion module section. Although the NGRTGs are thermally isolated from the structure via the titanium brackets, enough heat soaks back into the structure to help maintain the propulsion tank within the limits of 15–50°C with only a small amount of heat need to keep the tank from freezing. Special internal shunt heaters could be enabled inside the spacecraft bus and on the propulsion tank should extra heat be needed. The structure design requires 200 W from shunting and/or component dissipations to keep the thermos bottle design over 15°C at end of mission (EOM).

3.2.11 Flight Software

The TOWS flight software (FSW) is built upon software successfully flown on multiple APL missions, including the most recent Parker Solar Probe. The FSW uses a layered architecture to encapsulate functionality into multiple distinct applications. This ensures that functionality is self-contained and readily maintainable.

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[2] The timeline of 2 years prior to launch for fueling the NGRTGs is for the purposes of calculating the degradation rate of the fuel source over the course of the mission lifetime.

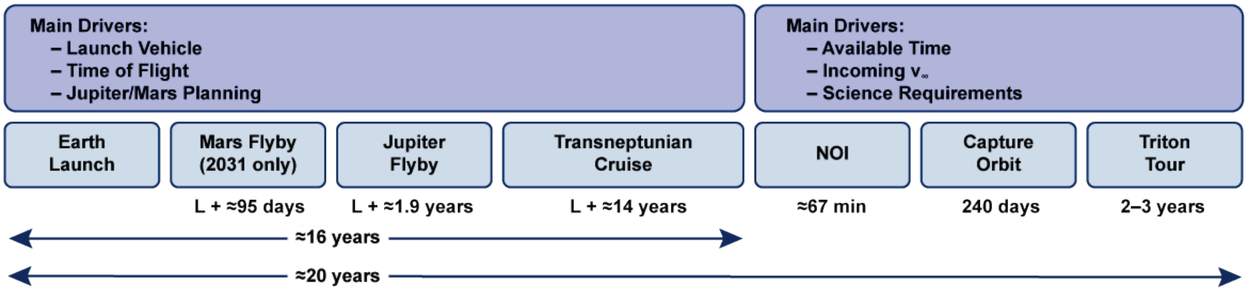

Figure 3-6. *Mission Overview.*

3.3 Concept of Operations & Mission Design

Neptune interplanetary trajectories for orbital campaigns are challenging due to the competing characteristics of RTG power degradation with time, Neptune's extreme heliocentric distance (30 AU), and the time-penalties associated with ΔV reduction, e.g., gravity assists and a sufficiently slow Neptune approach velocity for chemical orbit capture. However, we find that enabling 20-day interplanetary launch opportunities in 2030 and 2031 are possible by using a direct-to-Jupiter gravity assist (JGA), as well as a preceding Mars flyby (2031 only) combined with modern high-energy launch vehicle offerings available in the next decade. This approach balances time-of-flight and ΔV by using zero heliocentric revolutions while still taking advantage of fortuitous gravity assist geometry. The availability of the Falcon Heavy Expendable (FHE) launch vehicle (or potentially a Vulcan + 6 solid) augmented with a STAR 48 BV kick-stage provide sufficient launch mass capability to enable this interplanetary transfer strategy and satisfy the operational time constraints of the RTG. Past the 2031 opportunity, unfavorable Jupiter phasing prevents subsequent launch opportunities until after 2040.

The prime launch period opens on 10 Jan 2030 with a mission-driving maximum C_3 of 80.4 km^2/s^2 and closes on 29 Jan 2030 with a broken plane maneuver 7 months after launch. The backup launch period occurs 13 months later, starting on 2 Feb 2031 and closing on 21 Feb 2031 with a maximum C_3 of 74.6 km^2/s^2 and includes a Mars gravity assist 3 months after launch. However, because the backup drives the total post-launch ΔV, this case is used as the reference trajectory for the mission concept and is shown in Fig. 3-7.

The JGA takes place about two years into interplanetary transfer and delivers the payload to Neptune about 14 years later. Upon arrival, a ~1.3 km/sec main engine burn lasting about 67 min places the spacecraft on a 240-day elliptical orbit at Neptune that enables a tour qualitatively like the one described in the PMCS study *Neptune Odyssey: Mission to Neptune-Triton System (Aug 2020*).

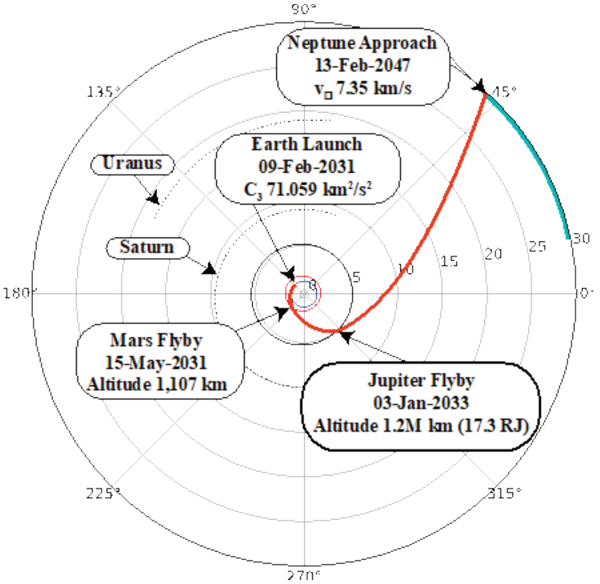

Figure 3-7. *Interplanetary Trajectory.*

3.3.1 Interplanetary Trade Space

The selection of the prime and backup interplanetary transfers was based on a patched-conics broad search over a feasible region of gravity-assisted interplanetary opportunities in the 2030–2035 timeframe. To enforce project constraints, including presumptions on maximum budget and available launch performance for New Frontiers-class missions, the broad search did not consider trajectories based on the Space Launch System (SLS), solar electric propulsion, or inner solar system cruise phases. These constraints resulted in a more narrowed search based on a direct-to-Jupiter strategy and Mars gravity assists to limit C_3 while providing a substantial time-of-flight benefit. Pre-selection of this sequence was influenced by the preliminary findings of the Ice Giants Pre-Decadal Survey Mission Study Report[3], Dr. Kyle Hughes dissertation studies[4], and prior experience designing Neptune Odyssey. In addition, Saturn and Uranus were not considered as gravity assist candidates due to their unfavorable phasing during the period of interest.

Post-NOI mass is a convenient optimization construct of the broad search process and is calculated in accordance with Fig. 3-8. The objective of the broad search shown in Fig. 3-9 was to minimize post-NOI mass and maintain a C_3 at or below the capabilities of the considered launch vehicles. The maximum time of flight was constrained to remain within the maximum expected lifetime of the RTG. Finally, the Neptune injection ΔV was constrained to remain within the capabilities of the chemical main engine and capture in an orbit from where a Triton flyby with a v_∞ compatible with that of the Odyssey mission concept.

3.3.2 High-Fidelity Analysis

The 2030 and 2031 trajectories were selected from the above criteria and optimized in a high-fidelity, *n*-body integrated model. As depicted in Fig. 3-10, the high-fidelity analyses of the launch period for both the 2030 and 2031 opportunities result in 20-day windows with maximum C_3 of 80.4 km^2/s^2 and an overall post-injection ΔV below 1.3 km/sec, well within the bounds of current propulsion system capabilities.

While the C_3 requirements for the 2030 opportunity are within the capabilities of a Delta-IV launch vehicle, the higher C_3 for the 2031 opportunity pushes the vehicle selection to a Falcon Heavy Expendable augmented by a STAR 48BV kick-stage.

A high-fidelity analysis was conducted on the finite-burn losses that result from the low-altitude/long-duration NOI burn. As a result, it was determined that a main engine with a 150 lbf of thrust capability and a velocity tracking NOI implementation would be required to maintain ΔV losses

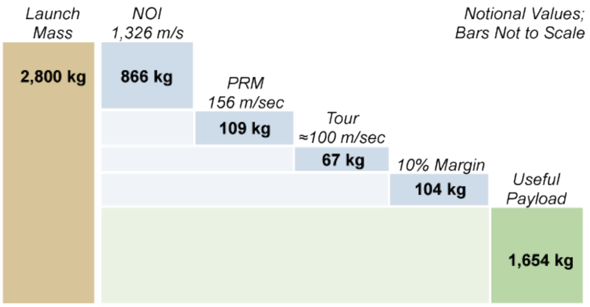

Figure 3-8. *Breakdown of Mass Consumption by Mission Phase.*

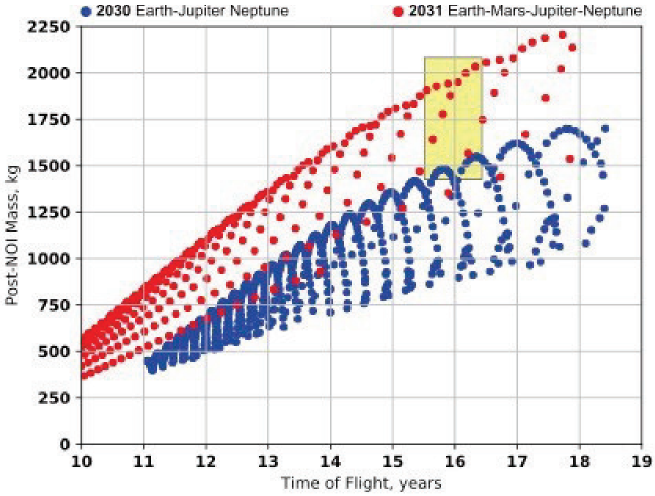

Figure 3-9. *Post-NOI mass for 2030 and 2031 opportunity launching on a Falcon Heavy Expendable.*

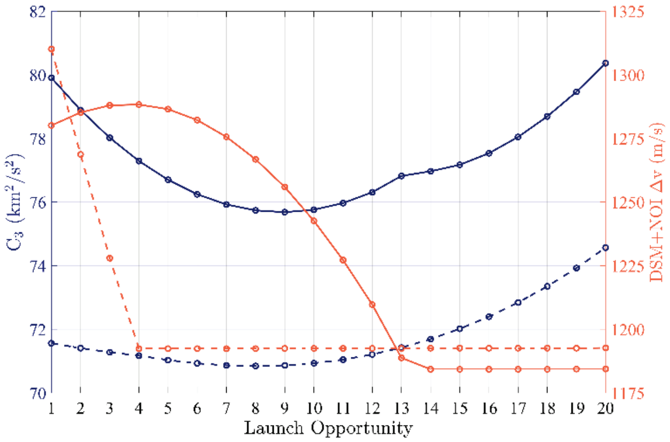

Figure 3-10. *Launch Period Analysis. Solid lines correspond to the prime launch opportunity and dotted lines correspond to the backup launch opportunity.*

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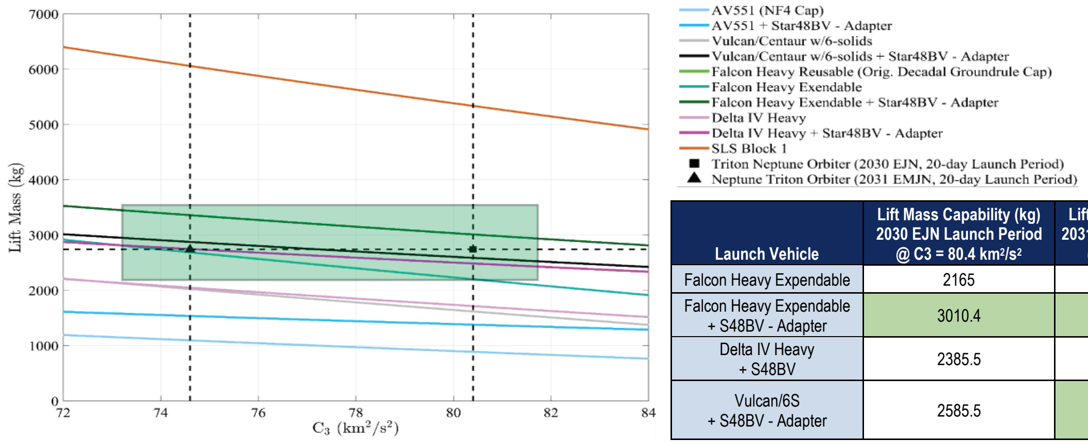
[3] National Aeronautics and Space Administration, Ice Giants Pre-Decadal Study Final Report, prepared by the Jet Propulsion Laboratory, July 2017

[4] Hughes, K.M. Gravity-assist trajectories to Venus, Mars, and the ice giants: Mission design with human and robotic applications, PhD thesis, Purdue University, 2017.



Launch Vehicle	Lift Mass Capability (kg) 2030 EJN Launch Period @ C3 = 80.4 km²/s²	Lift Mass Capability (kg) 2031 EMJN Launch Period @ C3 = 74.6 km²/s²
Falcon Heavy Expendable	2165	2675
Falcon Heavy Expendable + S48BV - Adapter	3010.4	3354
Delta IV Heavy + S48BV	2385.5	2645
Vulcan/6S + S48BV - Adapter	2585.5	2873

Figure 3-11. *Launch Vehicle Selection.*

within an acceptable level. The main results from the gravity loss analysis are summarized in Table 3-5 and assume an I_{SP} of 300 sec and a notional mass of 2,500 kg.

As depicted in Fig. 3-12, the second half of the NOI burn would not be visible from Earth. However, prior experience with partially occulted large burns indicates that this lack of visibility is not a major concern. In addition, the baseline capture sequence was analyzed for ring avoidance and it was found that no ring hazards exist during injection.

3.3.3 Neptune-Triton Tour

After NOI, the spacecraft would target a Triton flyby with an inbound v_∞ of 3.68 km/sec, compatible with the 2020 Odyssey tour shown in Fig. 3-13, where a collection of resonant transfers would provide near-global coverage of northern and southern Triton latitudes in both hemispheres as evidenced by the ground tracks shown in Fig. 3-14.

Within two to three years, the spacecraft would perform 35–45 science-oriented flybys of Triton, followed by a series of fast resonant orbits that would reduce Neptune-relative periapsis ultimately resulting in atmospheric entry at Neptune for spacecraft disposal that complies with Planetary Protection requirements.

A navigation analysis performed in collaboration with JPL for this study found that even the fastest Triton-to-Triton transfers were navigationally feasible. The overall ΔV requirements for the mission, driven by the backup launch opportunity, are shown in Table 3-6.

Engine Thrust	Inertial	Velocity Tracking
100 lbf (~444 N)	1,649.6 m/s 1.97 h	1,379.8 m/s 1.72 h
150 lbf (~667 N)	1,416.6 m/s 1.17 h	1,288.3 m/s 1.09 h
300 lbf (~1,335 N)	1,247.2 m/s 0.53 h	1,214.6 m/s 0.52 h

Table 3-5. *Finite Burn Analysis.*

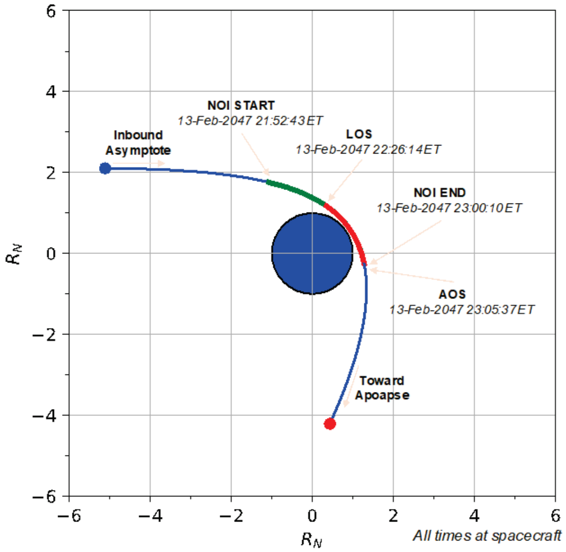


Figure 3-12. *NOI Burn Geometry.*

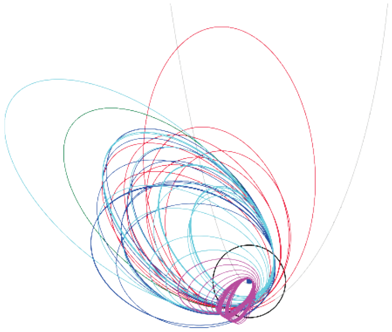


Figure 3-13. *Neptune Odyssey Tour.*

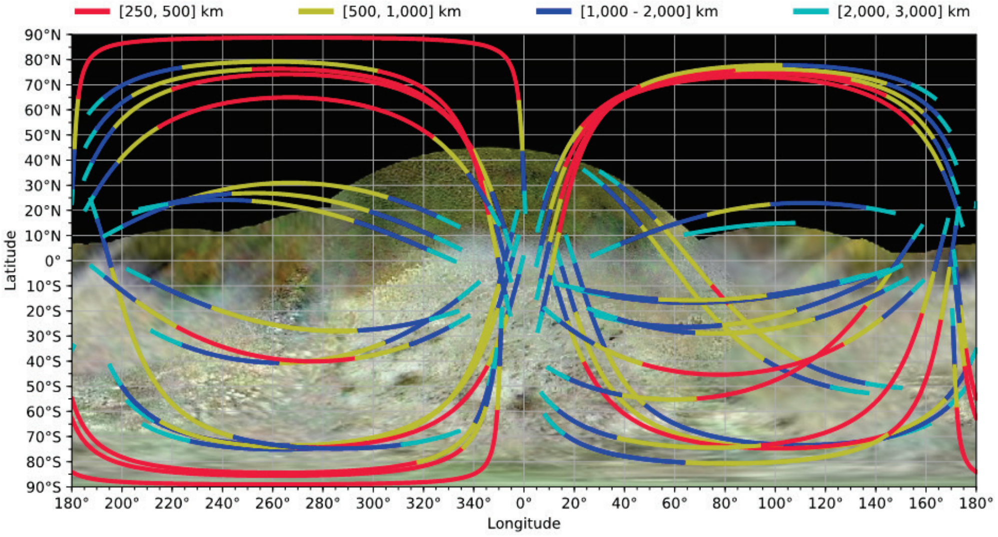


Figure 3-14. ***Altitude-Colored Ground Tracks of Neptune Odyssey.***

Maneuver Name	ΔV (m/s) *Deterministic*	ΔV (m/s) *Statistical*	ΔV
Launch Cleanup		20	**20**
Mars bias/targeting		50	**50**
Mars powered flyby	118		**118**
Jupiter Targeting		20	**20**
Neptune Targeting		20	**20**
NOI	1,300		**1,300**
NOI Cleanup		25	**25**
PRM	150		**150**
Tour deterministic	100		**100**
Tour statistical		50	**50**
Disposal	121		**121**
ACS		56	**56**
Unallocated Margin	72		**72**
Total	**1,861**	**241**	**2,102**

Table 3-6. *ΔV Budget.*

3.3.4 Neptune Triton Orbital Phase

Fig. 3-15 illustrates an orbital tour which is 23.5 days in duration for a 4:1 resonance orbit as described in the Neptune Odyssey 2020 PMCS final report. The orbital tour is then divided into "day" epochs and are allocated to various spacecraft modes indicated by different colors of "X".

Once orbital insertion is accomplished, the two-year science mission begins which includes several spacecraft power modes including: Science, Radio Science, Delta V Prep, Delta V Maneuver, Battery Charge, and Data Link Mode. Two of these modes Delta V Prep and Delta V Maneuver require a battery to support due to a short duration high power demand. These combined two modes, indicated in red, are a total of 61 minutes, a battery charge mode is indicated in orange.

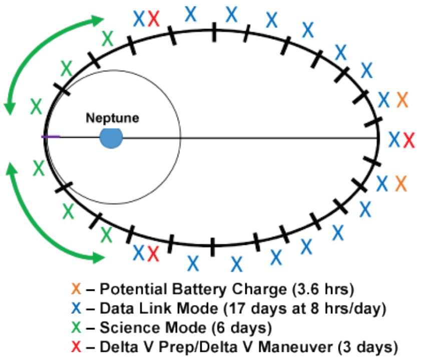


Figure 3-15. *Notional Neptune Orbit with Triton Flyby Coverage CONOP to accommodate science operations, orbital maintenance and battery charging*

Science Mode/Radio Science Mode are indicated in green. During the six days in this mode, the spacecraft is using payloads to collect measurements and images.

For data transmission, the spacecraft is in Data Link Mode. Data Link Mode days are indicated in blue. A total of 17 days is allocated to transmit the science data volume back to the DSN BWG ground stations. DSN dedicates 8-hour/day to receive this mission data.

Parameter	Value	Units
Triton Orbit Parameters (apogee, perigee, inclination, etc.)	45E or 225E 5-8N 250-2700km	Subsolar (lon) Subsolar (lat) Flyby Altitudes (km)
Mission Lifetime	252	mos
Maximum Eclipse Period	N/A	min
Launch Site	KCAS	
Total Flight Element #1 Mass with contingency (includes instruments)	1109	kg
Propellant Mass without contingency	1381	kg
Propellant contingency	15	%
Propellant Mass with contingency	1588	kg
Launch Adapter Mass with contingency	100	kg
Total Launch Mass	2667	kg
Launch Vehicle	FH Expendable w/STAR 48 BV	Type
Launch Vehicle Lift Capability @$80.4 m^2/s^2$	3110	kg
Launch Vehicle Mass Margin	1112	kg
Launch Vehicle Mass Margin (%)	44	%

***Table 3-7.** Mission Design Table.*

	Cruise	Orbit Capture	Radio Science	Science Return
Downlink Information				
Number of Contacts per Week	1	7	6	7
Number of Weeks for Mission Phase, weeks	812	40	104	104
Downlink Frequency Band, (GHz)	8.2	8.2	8.2	31.8
Telemetry Data Rate(s), kbps	0.05	.5	-	4.1 to 12
Transmitting Antenna Type(s) and Gain(s), (dBi)	MGA/26	HGA/45	MGA/26	HGA/57.3
Transmitter peak power, (W)	12	12	12	20
Downlink Receiving Antenna Gain, (dBi)	68.1	68.1	68.1	78
Transmitting Power Amplifier Output, (W)	12	12	12	20
Total Daily Data Volume, (MB/day)	1.5	14	-	118 to 345
Uplink Information				
Number of Uplinks per Day	1	1	1	1
Uplink Frequency Band, (GHz)	7.8	7.8	7.8	7.8
Telecommand Data Rate, (kbps)	.05	.05	-	2
Receiving Antenna Type(s) and Gain(s), (dBi)	MGA/25.8	MGA/25.8	MGA/25.8	HGA/45

***Table 3-8.** Mission Operations & Ground Data Systems.*

3.4 Risk List

T-OWS risks are identified using APL's standard risk management process (Table 3-9). The risks are dominated by external factors; all risk factors under program control have had mitigation plans included in the baseline concept (e.g., limited technology development required). The external dependencies (launch vehicle NEPA approval and radioisotope power system (RPS) production) are critical items that would need to have development plans tied to the program milestones.

T-OWS has identified the RTG clad production rate as a significant risk.

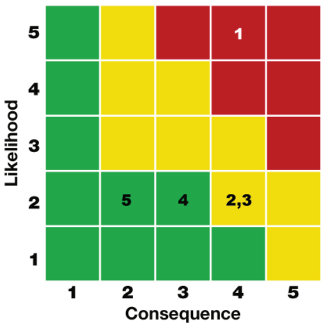


***Figure 3-16.** Summary of T-OWS risks. See table below for details*

NASA RPS and the Department of Energy (DOE) have agreed to a constant rate of production rate of a range from 10–15 clads per year. However, less than 15 clads starting in FY21 will not allow for two fully fueled Mod 0 and Mod 1 to be ready in time for spacecraft integration. This risk can be easily mitigated if NASA and DOE immediately step-up production to 15 clads through FY2029. Any shortfall in production would require exceeding the constant rate of production to work off the shortfall. T-OWS believes that short term raises in production can be accomplished without the need for additional manufacturing infrastructure.

#	Title	Risk Statement	Consequence	Likelihood	Risk Score	Mitigation
1	RTG Clad Production Rate	IF RPS does not come to maximum production of 15 or more clads per year starting in FY21 and maintain that until delivery in FY28, THEN the needs of Triton Ocean World Surveyor and other approved missions may not be met.	4	5	**20**	Slip the launch to 2031 with no viable backup launch date, reduce the number of clads needed
2	Launch Vehicle NEPA Approval	IF LV NEPA certification is delayed, THEN there could be a launch delay. • Atlas V has prior NEPA certification • Falcon Heavy NR need NEPA certification	4	2	**8**	NASA and LV provider must work diligently to acquire certification in a timely manner
3	Electrical Power & Thermal Control	IF RPS delivers a Mod 0 and Mod 1 RTG with reduced performance than the Feb 2021 PMCS ground rules, THEN the mission may have insufficient power and thermal control.	4	2	**8**	Reduce the number of instruments and significantly increase electrical and thermal efficiency of design
4	Ka-Band Antenna Pointing	IF the Ka-Band HGA antenna alignment and end-to-end pointing budget exceeds 0.06°after in-flight calibration, THEN the mission may have significantly less science return.	3	2	**6**	May require additional antenna calibrations error over temperature to quantify error.
5	Total Thruster Cycles During 3-Axis Control	IF the total thruster cycle count on the 4.4N thrusters is high due to dead-band maintenance during 3-axis control, THEN the mission may lose the ability to point the Ka-Band antenna and optical instruments	2	2	**4**	Change design to accommodate smaller thrusters, add additional thrusters and phase usage, pay for +500K cycle thruster qualification

Table 3-9. *Risk List.*

4. Development Schedule & Schedule Constraints

4.1 High-Level Mission Schedule

The program development schedule (Fig. 4-1) is constrained on both ends. The start date of 1 Jan 2023 is specified by the study guidelines. Orbital dynamics and the JGA constrain the latest possible launch window to Feb 2031. A second possible launch window was also identified to ensure a backup opportunity ~13 months earlier. Therefore, the program phasing is constrained as shown in Tables 4-1, 4-2, and 4-3 and Fig/ 4-1, with 85 months between Phase A start and launch. The phase durations compare favorably to Parker Solar Probe, a mission of comparable development (more technology development but less overall complexity). However, the program is constrained to 2.4 months of schedule margin on the critical path. The critical path follows the propulsion subsystem through system integration and testing (I&T) to RTG integration at the launch site. The critical path schedule margin is set at the minimum recommended by APL guidelines. Additional margin could be allocated with an earlier start date, or by a more aggressive (shorter in duration) Phase A plan. Shortening Phase A is feasible because of the limited amount of technology development for the mission.

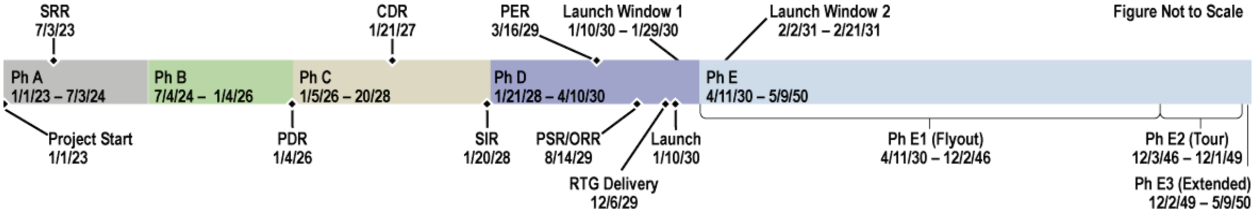


Figure 4-1. *High-Level Mission Schedule.*

Project Phase	Approximate Duration
Phase A – Conceptual Design	18
Phase B – Preliminary Design (excl. Phase B Bridge)	18
Phase C – Detailed Design	25
Phase D – Integration & Test	24
Phase E – Primary Mission Operations	244.5
Start of Phase B to PDR	18 mo.
Start of Phase B to CDR	31 mo.
Start of Phase B to Delivery of All Instrument	43 mo.
Start of Phase B to Delivery of All Flight Elements	43 mo.
System Level Integration & Test	19 mo.
Project Total Funded Schedule Reserve	98 mo.
Total Development Time Phase B–D	62 mo.

Table 4-1. *Key Mission Phase Durations.*

Mission Level Milestones	Date
System Requirements Review (SRR)	7/3/2023
Preliminary Design Review (PDR)	1/4/2026
Critical Design Review (CDR)	121/2027
System Integration Review (SIR)	1/20/2028
Pre-Environmental Review (PER)	3/16/2029
Pre-Ship Review (PSR)/Op. Readiness Review (ORR)	8/14/2029
RTGs Delivery Need Date	12/6/2029
Launch	1/10/2030

Table 4-2. *Mission-Level Milestones.*

	Duration	Start	Finish
Launch Window 1	20 days	1/10/2030	1/29/2030
Launch Window 2	20 days	2/2/2031	2/21/2031

Table 4-3. *Launch Opportunities.*

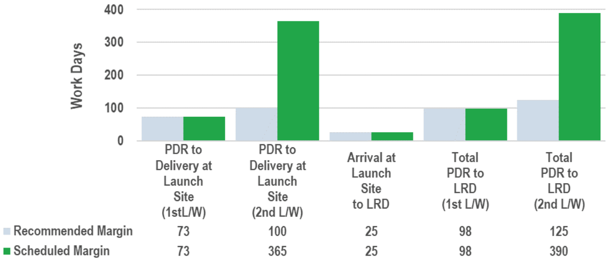


Figure 4-2. *Schedule Margin.*

4.2 Technology Development Plan

No new technology is required to support the T-OWS mission.

4.3 Development Schedule & Constraints

No long-lead-time procurements would be required.

RPS production of fuel clads must be maintained at 15 clads per year starting in FY2021 to accommodate a Mod 0 and Mod 1 NGRTG and Dragonfly. It will take significant schedule to meet NEPA requirements). There is no alternative to RTG power to support the T-OWS mission.

Launch can occur no earlier than 2029 because of the availability of flight-qualified NGRTGs Mod-1 (source: PMCS Ground Rules, November 2019).

Launch Window #1 is 10 Jan 2030 to 29 Jan 2030, if a slip occurs. Final Launch Window is 2 Feb 2031 to 21 Feb 2031. Jupiter does not come back into phase until after 2040.

5. Mission Life Cycle Cost

5.1 Introduction

T-OWS is defined at a concept maturity level (CML) of 4. The primary objective of the T-OWS cost analysis is to determine, according to NASA budgetary criteria, if the concept could be reasonably proposed as a competitive New Frontiers mission.

Adjusted for inflation, the projected Pi-Managed Mission Cost (PIMMC) cap, which covers Phases A–D, will be $1,090.1M in fiscal year 2025 (FY$25) dollars. The estimated T-OWS PIMMC cost of $1,066.7M FY$25 – including a baseline cost of $742.8M FY$25and $323.9M FY$25 in cost reserves – is under the cost cap. PIMMC reserves are calculated as 50% of Phase A–D estimated costs, excluding RPS costs. The resulting reserves are substantially more compared to those proposed for New Frontiers missions. The estimated PIMMC cost does not cover the Falcon Heavy Expendable launch vehicle and services, but does include a budgetary estimate for the STAR 48BV upper stage.

Using the Aerospace Mission Cost Estimating Tool MOCET, Phases E–F costs are estimated as $850.8M FY$25 – $680.6M plus cost reserves of $170.2M (25% of the baseline Phase E–F costs). That puts the total estimated life-cycle cost for the T-OWS mission at $1,909.9M FY$25. DSN aperture fees, estimated as $23.5M FY$25, are not included in the mission life-cycle cost.

5.2 Mission Ground Rules & Assumptions

- Estimating ground rules and assumptions are derived from the PMCS ground rules dated Feb 2021.
- Cost estimates are reported in FY$25, with conversions based on the NASA New Start Inflation Indices issued Dec 2020 (NNSII 2020).
- Mission costs are reported using the Level-2 work breakdown structure (WBS) described in NPR 7120.5E.
- Instruments will be delivered to the flight system from US organizations funded by NASA that have relevant expertise and experience from past instrument deliveries.
- The spacecraft will be built, integrated, and tested in-house by the implementing organization.
- The T-OWS concept requires power from one NGRTG Mod 0 and one NGRTG Mod 1; the PMCS ground rules state that those two units will be available for a 2030 launch. Phase A–D cost for the two units is $95M, calculated as $70M for the more expensive Mod 1 unit, plus $25M for what the Guidelines call "an additional unit" – in this case, an NG RTG Mod 0. The PIMMC cost also includes a fee of $26 million to cover RPS NEPA launch compliance activity.
- The T-OWS concept includes a Falcon Heavy Expendable launch vehicle. Based on Mar 2021 Decadal Studies Q&A, the launch vehicle is assumed to be available in time for a 2030 launch. The launch vehicle and services will be provided by and paid for by NASA. Cost for a STAR 48BV upper stage, as well as $26M FY$25 to cover NEPA activity, is also included.
- The T-OWS concept is based on mature hardware and software designs, nearly all of which have been demonstrated successfully on NASA space missions. For example, with the exception of PIMS, which is proposed for the IVO Discovery mission, previous versions of the T-OWS instruments have manifested on New Horizons, Parker Solar Probe, or Cassini. Likewise, spacecraft subsystems and components are based on hardware and software (both flight and ground) flown on NASA missions. Accordingly, all systems are at or above TRL 6, and no technology development activities are required.

5.3 Cost Methodology

Table 5-1 summarizes the methodologies used to generate Phase A–D costs.

WBS	WBS Description	Baseline Estimating Method	Comments on Cross-Checks, etc.
01, 02, 03	Program Management (PM), Systems Engineering (SE), Safety & Mission Assurance (S&MA)	Cost factor applied to sum of estimated costs of Instruments (WBS 05), Spacecraft (06), and System Integration & Test (10).	Cost factor derived from analysis of cost histories of medium-to-large APL and NASA center missions. The factor is sufficient to fund nuclear launch compliance analyses and top-level planetary protection assessments.
04	Science	Science: bottoms up estimate. SOC & other software: analogies.	3% of Phases A–D costs.
05	Instruments	Instrument Oversight: Cost factor based on past APL missions applied to estimated instrument costs. Instruments: Higher of reported costs of heritage instruments and results from NASA Instrument Cost Model (NICM9).	Assumption is that all instruments will be TRL 6 at the start of Phase A. Non-recurring funds should be sufficient to perform activities like updating parts lists and instrument repackaging. Selection of the higher of two estimates for each instrument results in a conservative cost estimate.
06	Spacecraft (S/C)	S/C Hardware: Average of subsystem cost estimates from TruePlanning parametric model (MEV inputs), NH S/C cost history, and cost/kg calculations using NH costs. Bi-propulsion subsystem cost based on MESSENGER history & current vendor component pricing. S/C FSW Development: Staff-month estimate derived from PSP and recent APL missions. RPS: 2 NGRTGs priced per PMCS guidelines.	S/C Hardware: MEV-based TruePlanning estimate is most conservative. Triton Ocean World Surveyor S/C is similar to APL's NH S/C except for additional RPS, larger HGA and Ka-band telecommunications, bi-prop in place of mono-propulsion. Cost-per-kg calculations with T-OWS CBE masses accounts for additional hardware at subsystem level. FSW assumes reuse of PSP architecture and modules.
07	Mission Operations	Detailed engineering estimate of personnel based on planning, training, and pre-flight activities.	Estimate originally generated for more complex Neptune Triton Orbiter concept.
08	Launch Vehicle & Services	Primary LV&S: GFE) provided by NASA at no charge to implementing organization. STAR 48BV stage: Northrop Grumman budgetary estimate included assuming that implementing organization will pay for stage. NEPA Launch Compliance Fee.	T-OWS requires Falcon Heavy Expendable from SpaceX or possibly a Vulcan-Centaur from ULA. NASA will have launched at least two Falcon Heavy's by 2030.
09	Ground Data Systems	Detailed engineering estimate of personnel, IT & comms hardware, and software licenses & development.	Estimate originally generated for more complex Neptune-Triton Orbiter concept.
10	System Integration & Test	TruePlanning estimate.	Cost factor cross-check.

Table 5-1. *Cost Overview.*

To ensure that hardware cost estimates are robust, both instrument and spacecraft hardware costs reflect both parametric results and full cost histories of analogous hardware.

5.3.1 Estimated Phase A–D Costs

Phase A–D costs are summarized in Table 5-2. As the last line of the table shows, the estimated Phase A–D cost with 50% reserves is approximately $20M under the New Frontiers PIMMC cap after adjustment for inflation.

WBS	Description	Phases A–D Estimated Cost (FY25$M)	Basis, Comments
N/A	**Phase A**	**$ 4.5**	**Based on NF 4 budget after inflation adjustment**
01, 02, 03	**PMSEMA**	**$ 80.2**	**Historical factor (15.5%) based on large missions; accommodates nuclear launch, planetary protection**
04	**Science**	**$ 26.0**	**Science team, SOC development, SciBox updating**
05	**Payloads**	**$ 174.9**	**Roll-up**
	Instrument Mgmt	$ 13.7	Oversight cost factor based on APL mission experience
	Instruments	$ 161.2	For each of 7 instruments, higher cost estimate of either NICM9 or historical analogy
06	**Spacecraft**	**$ 295.1**	**Roll-up**
	Hardware	$ 182.4	Average of TruePlanning parametric cost estimate, applicable NH history, and a cost-per-kg estimate based on NH history. ROM estimate for bi-propulsion subsystem
	FSW Development	$ 17.7	Flight software, autonomy rules & testbed SW
	RPS	$ 95.0	GFE price for NGRTG Mod 0 & additional NGRTG unit
07	**Mission Ops (B-D)**	**$ 25.0**	**Neptune Odyssey BUE plus $8.5M for launch ops**
08	**Launch Vehicle & Services**	**$ 69.8**	**Roll-up**
	Falcon Heavy Expendable	No Charge	Launch vehicle & services provided by NASA, cost excluded from PIMMC
	STAR 48BV Upper Stage	$ 43.8	Northrop Grumman budget estimate (under review), assumes upper stage procured by implementing organization
	NEPA Launch Compliance	$ 26.0	NEPA Launch Compliance Fee required for RPS launch
09	**Ground Data Systems (GDS)**	**$ 15.0**	**Neptune Odyssey BUE**
10	**System Integration & Test (I&T)**	**$ 51.7**	**Incl. testbeds. 11% of WBS 05 + 06 estimated costs**
Baseline (w/out reserves)		**$ 742.8**	**Roll-up**
Cost Reserves (50%)		**$ 323.9**	**50% of Baseline costs, excluding mission price of 2 NGRTGs**
PIMMC with Reserves		**$1,066.7**	**Under New Frontiers PIMMC Cap of $1,079.5**

Table 5-2. *Estimated Mission Phase A–D Cost (in FY$25 millions).*

5.3.2 Instrument Cost Details

Details on estimated instrument costs are shown in Table 5-3, with instruments ordered by priority of achieving mission science. The estimated cost of all recommended instruments is $158.8M (FY$25). That excludes the $13.5M for Instrument Management. Instrument cost estimates range from $9.9M for the delivery of one UV Imaging Spectrometer to $50.8M for delivery of a rebuild of the Cassini INMS.

Instrument Description	Abbreviation	Analogy Instrument	Analogy Cost	NICM9 Parametric Cost Estimate (50th pctl.)	Baseline Estimated Cost (FY25$M)	Cumulative Instrument Cost (FY25$M)
Narrow Angle Camera (NAC)	NAC	NH/LORRI	$ 14.1	$ 23.6	$ 23.6	$ 23.6
Magnetometer (Fluxgate), incl. boom	MAG	Galileo MAG (w/boom)	$10.8	$12.2	$ 12.2	$ 35.8
Multispectral Vis-NIR Imaging Spectrometer	RALPH	NH/RALPH	$ 49.0	$ 48.0	$ 49.0	$ 84.8
Plasma Instrument for Magnetic Sounding	PIMS	IVO PIMS	$ 12.0	$ 15.6	$15.6	$100.5
Ion and Neutral Mass Spectrometer (INMS)	INMS	Cassini/INMS	$ 31.1	$50.8	$50.8	$ 151.3
UV Imaging Spectrograph	ALICE	NH/ALICE	$ 9.9	$ 9.1	$9.9	$ 161.2

Table 5-3. *Estimated Instrument Costs (WBS 05, in FY$25 millions). WBS 05 also includes “Instrument Management & Oversight” activity with an estimated cost of $13.7 million.*

5.3.3 Spacecraft Cost Details

Spacecraft costs (Table 5-3) include three elements: (1) spacecraft hardware; (2) flight software (FSW) development; and (3) RPS procurement. Element (1) is estimated in three ways, and the results averaged. Element (2) is based on APL analogies, including PSP. Element (3) is a calculation based on RPS pricing ground rules.

The first of the three hardware estimates is derived by New Horizons (NH) actuals. The overall T-OWS design strongly reflects its NH heritage design; however, its $148.7M is only a starting point for T-OWS hardware development. T-OWS replaces the NH mono-propulsion subsystem with a bi-propulsion subsystem. NH does not include Ka-band transmitters. T-OWS borrows its 3.1-m HGA design from Europa Clipper, versus NH's smaller 2.1-m HGA. And, NH's electrical power system controlled an RPS whose output is about 40% of T-OWS. Given these changes, the NH is a low estimate.

A second estimate is calculated by summing the products of multiplying T-OWS' CBE masses by the cost-per-kg of NH spacecraft subsystems (or, in the case of T-OWS' bi-prop subsystem, by the cost-per-kg of the MESSENGER bi-prop subsystem, another bi-prop subsystem designed around a Leros 1b engine). The resulting hardware estimate is $159.3M.

The final estimate is generated using T-OWS MEV inputs and the PRICE Systems' TruePlanning estimating framework. The framework pertaining to space missions has been calibrated with NASA robotic spacecraft cost and technical data. The resulting estimate is the highest of the three at $173.1M. Averaging the three estimates at the subsystem level (except for the omission of the NH structure and propulsion subsystem costs) yields the total cost of $168.2M shown in the fourth row of Table 5-4.

Description	Estimated Cost (FY25$M)	Basis, Comments
Hardware	$ 182.4	Roll-up. Estimates incl. in average are in tab
Structures & Mechanical	$20.0	Estimated cost, 11% of S/C hardware costs, excl. NGRTGs, typical for in-house APL S/C
Harness	$ 3.1	
EPS. Less NGRTGs	$45.0	TP (MEV) est.: T-OWS EPS controls 2 NGRTGs (BOL Power: 538We).
Avionics	$25.4	Reuse of CORESat build-to-print boards proven on Parker Solar Probe. SBC processor updated to UT700 to reduce processor utilization.
RF/Telecomm	$36.4	Redundant X- & Ka-band; 3.1-m HGA, rebuild of proven Frontier software radios. T-OWS includes 2 USOs.
Propulsion (BiProp)	$35.2	ROM estimate based on MESSENGER & concept costs of vendor-supplied bi-prop subsystem with (1) Leros 1b engine; (16) 1-lb & (8) 5-lb thrusters; 4 standard ATK tanks.
GNC	$13.8	Star trackers, sun sensors, 1 SSIRU, control software.
Thermal Control (TCS)	$3.5	Thermos bottle' design. Assumes no reuse of NGRTG waste heat.
Flight Hardware Subtotal	**$200.1**	
Flight Software (FSW)	**$17.7**	**Engineering estimates covering flight software, autonomy development, and testbed software**
RPS (Next Gen RTGs)	**$95.0**	**One each of NGRTG Mod 0 and NGRTG Mod 1**
Total WBS 06	**$ 295.1**	**Total Spacecraft, incl RPS**

Table 5-4. *Estimated Spacecraft Costs (WBS 06, in FY$25 millions).*

5.3.4 Cost Confidence

According to the mission risks presented in § 3.4, primary mission risks relate to the RPS and heavy-lift launch vehicles, specifically, their availability and performance. If either is not delivered on schedule, the mission cannot launch successfully in 2030. Additional engineering studies would be required to identify if and how hardware and software could be added or modified to achieve threshold performance levels if the RPS or the heavy lift launch vehicles do not perform to specifications.

Given the design, manufacturing, and flight heritage of the mission hardware and software, their cost risks can be characterized as no higher than medium. In that case, and anticipating that future evolution of the mission concept will be evolutionary and not radical, cost growth is unlikely to exceed the 35% observed by Aerospace Corp. in all but the worst-case situations. With 50% cost reserves, the cost as estimated should be achievable on a New Frontiers budget. Fig. 5-1 compares estimated T-OWS Phases A–D costs against actual costs reported for the New Horizons and Juno missions, as well as APL's MESSENGER, PSP, and VAP missions.

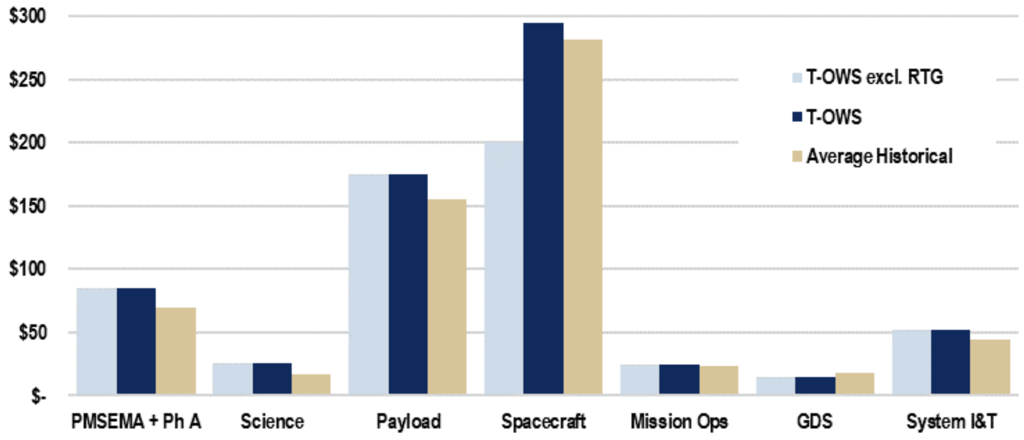


Figure 5-1. *Comparison of Estimated Triton Ocean World Surveyor Costs Versus Costs of New Frontiers and APL Missions. Costs shown in FY$25 million*

The magnitude and distribution of T-OWS cost estimates are comparable to the successfully conducted missions shown in the figure.

5.3.5 Phases E–F Cost Estimate

Phase E–F costs were estimated using the Aerospace MOCET model. MOCET is a parametric cost model based on a dataset of NASA space missions. It requires the estimator to specify the type of mission, destination, and duration and type of activity. The result is the estimated cost by activity, covering all costs except for DSN aperture fees.

The T-OWS cruise to Neptune includes a decade-plus quiescent cruise period. After consultation with the APL mission operations lead for New Horizons, the monthly cruise cost ($1.3M) calculated from the 3-year NH quiescent cruise replaced the significantly higher MOCET result.

Table 5-5 shows the details MOCET results. Consistent with guidance, 25% cost reserves are added to the baseline cost.

Using the JPL aperture fee tool and the concept of mission operations for an early 2030 launch, DSN aperture charges were estimated as $23.5M in FY$25, but not included in the mission life-cycle cost.

Phase	Description	Activity Start Date	Activity Duration (Months)	Estimated Cost (FY25 $M)	Notes
D	Early Ops & Checkout (Ph D)	1/10/2030	1	$ 3.3	MOCET: Large Outer Planet Mission
E	Post-Launch: Phase E Only		237	$ 654.5	MOCET: Large Outer Planet Mission
	Initial Cruise/Start Phase E	2/9/2030	25	$ 73.1	
	Prep for 6/5/32 JGA	3/6/2032	3	$ 15.0	
	Jupiter Gravity Assist (JGA)	6/5/2032	3	$ 15.0	
	Transneptunian (Quiescent) Cruise	9/4/2032	136	$ 180.9	NH Monthly Cruise Cost ($1.3M)
	NOI Preparation (3 years prior to NOI	1/5/2044	36	$ 188.8	Ramp-up starts 3 years prior
	NOI	1/7/2047	10	$ 52.3	10 month insertion activity
	Triton Tour	11/7/2047	24	$ 129.5	
F	Phase F	11/8/2049	8	$ 22.8	Disposal & Data Archiving
	End of Mission	7/1/2050	—	—	
	Post-Launch: Phases D, E, F		246	$ 680.6	
	Cost Reserves			$ 170.2	25% cost reserves
Total Post-Launch with Cost Reserves				**$ 850.8**	

Table 5-5. *Estimated Mission Phase E–F Costs (in FY$25 millions).*

5.4 Results & Conclusion

Table 5-6 shows that the estimated life-cycle cost of the T-OWS mission, as currently conceived, is $1,910M with robust reserves to return valuable science during a two-year prime science mission after an 18-year cruise. The total Phase A–D PIMMC is $1,059.1M – $20M under the adjusted 2025 New Frontiers PIMMC cost cap. Moreover, so long as NASA can deliver the required launch vehicle and RPS by 2030, the mission should be able to launch on schedule and within budget.

Description	Estimated Cost (FY25$M)
PIMMC (A–D) Baseline	$ 742.8
PIMMC (A–D) Reserves	$ 323.9
Total PIMMC Development Cost	**$ 1,066.7**
Phases E–F Baseline	$ 680.6
Phases E–F Reserves	$ 170.2
Total Phases E–F Cost	**$ 850.8**
A–F Baseline	$ 1,418.3
A–F Reserves	$ 491.5
Life-Cycle Cost	**$ 1,917.5**
DSN Aperture Fees	$23.5

Table 5-6. *Estimated Mission Life-Cycle Cost (in FY$25 millions).*

Appendix A: Acronyms & Abbreviations

ACE	APL Concurrent Engineering
ACS	Attitude Control System
AO	Announcement of Opportunity
APL	(Johns Hopkins) Applied Physics Laboratory
ARC	Avionics Redundant Controller
BOE	Basis of Estimate
BOL	Beginning of Life
BUE	Bottom-Up Estimate
BWG	Beam Waveguide
C/A	Close (Closest) Approach
C&DH	Command and Data Handling
Catbed (Heaters)	Catalyst Bed (Heaters)
CBE	Current Best Estimate
CDR	Critical Design Review
CER	Cost Estimating Relationship
cFE	Core Flight Executive
CFDP	CCSDS File Delivery Protocol
CG	Center of Gravity
CLPS	Commercial Lunar Payload Services
CML	Concept Maturity Level
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off the Shelf
ΔDOR	Delta Differential One-Way Ranging
ΔV	Delta (Change in) Velocity
DART	Double Asteroid Redirection Test
DC/DC	Direct-Current to Direct-Current (Converter Card)
DD	Dust Detector
DMA	Direct Memory Access
DOE	Department of Energy
DOR	Differential One-Way Ranging
DSN	Deep Space Network
DSS	Digital Sun Sensor
DTE	Direct to Earth

DTM	Digital Terrain Model
DVR	Digital Video Recorder
EC	Electrical Conductivity
EFH	Expendable Falcon Heavy
EOL	End of Life
EOM	End of Mission
EPC	Electronic Power Conditioner
EPS	Electrical Power Subsystem
ESA	European Space Agency
EVMS	Earned Value Management System
FOV	Field of View
FPGA	Field-Programmable Gate Array
FSS	Fine Sun Sensor
FSW	Flight Software
FY	Fiscal Year
G&C	Guidance and Control
GDS	Ground Data System
GFE	Government Furnished Equipment
GNC	Guidance, Navigation & Control
HGA	High-Gain Antenna
I&T	Integration and Test
I^2C	Inter-Integrated Circuit
IBR	Integrated Baseline Review
IEM	Integrated Electronics Module
IIF	Instrument Interface (Card)
IMU	Inertial Measurement Unit
INMS	Ion & Neutral Mass Spectrometer
IR	Infrared
IT	Information Technology
IVO	Io Volcano Explorer (Proposed Discovery Mission in Step 2)
JGA	Jupiter Gravity Assist
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KBO	Kuiper Belt Object
L/W	Launch Window

LEOP	Launch and Early Operations Phase
LGA	Low-Gain Antenna
LNA	Low-Noise Amplifiers
LORRI	(New Horizons) Long Range Reconnaissance Imager
LRD	Launch Readiness Date
LRM	Low-Reflectance Material
LRR	Launch Readiness Review
LV	Launch Vehicle
LVS	Low-Voltage Sensor
Ma	Million Years
MA	Mission Assurance
MAG	Magnetometer
MatISSE	Maturation of Instruments for Solar System Exploration
MEL	Master Equipment List
MEOP	Maximum Expected Operating Pressure
MER	Mars Exploration Rovers
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MEV	Maximum Expected Value
MGA	Medium-Gain Antenna
MIGS	Mission Independent Ground Software
MIMU	Miniature Inertial Measurement Unit
MLI	Multi-Layer Insulation
MMH	Monomethylhydrazine
MOC	Mission Operations Center
MOCET	(Aerospace Corp.) Mission Cost Estimating Tool
MON-3	Mixed Oxides of Nitrogen (Nitrogen Tetroxide)
MOps	Mission Operations
MOR	Mission Operations Review
MRAM	Magnetoresistive Random-Access Memory
MRR	Mission Readiness Review
MSL	Mars Science Laboratory
MUX	Multiplexer
MY	Million Years
NAC	Narrow Angle Camera
NASA	National Aeronautics and Space Administration

NEPA	National Environmental Policy Act
NG	Next-Generation (RTG)
NH	New Horizons
NICM	NASA Instrument Cost Model
NIR	Near Infrared
NOI	Neptune Orbit Insertion
NPR	NASA Procedural Requirement
NRC	National Research Council
NRE	Non-Recurring Engineering
OPAG	Outer Planets Assessment Group
ORR	Operational Readiness Review
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith EXplorer
PDR	Preliminary Design Review
PER	Pre-Environmental Review
PDB	Propulsion Diode Boxes
PDU	Power Distribution Unit
PIMMC	Principal Investigator Managed Mission Cost
PIMS	Plasma Instrument for Magnetic Sounding
PM	Project Management
PMCS	Planetary Mission Concept Studies
PMSEMA	Project Management, Systems Engineering, Mission Assurance
PPS	Pulse Per Second
PPU	Power Processing Unit
PSP	Parker Solar Probe
PSR	Pre-Ship Review
PSI	Planetary Science Institute
PSU	Power Switching Unit
Q&A	Question & Answer
RDM	Radiation Design Model
RF	Radio Frequency
RIO	Remote Input/Output
RIU	Remote Interface Unit
ROM	Rough Order of Magnitude
RPM	Rotations/Revolutions per Minute
RPS	(NASA) Radioisotope Power System(s)

RS	Radio Science
RTG	Radioisotope Thermoelectric Generator
RW	Reaction Wheel
S/C	Spacecraft
S&MA	Safety & Mission Assurance
SBC	Single Board Computer
SCIF	Spacecraft Interface
SE	Systems Engineering
SEER	System Evaluation and Estimation of Resources
SEIS-SP	Seismic Experiment for Internal Structure-Short Period
SEP	Solar Electric Propulsion
SIR	System Integrations Review
SMSR	Safety and Mission Success Review
SOC	Science Operations Center
SOR	Science Operations Review
SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch
SPS	Sun Pulse Sensor
SRAM	Static Random-Access Memory
SRR	System Requirements Review
SRU	Shunt Regulator Unit
SSIRU	Scalable Space Inertial Reference Unit
SSR	Solid-State Recorder
STM	Science Traceability Matrix
SWAP	(New Horizons) Solar Winds Around Pluto
SWAPI	(IMAP) Solar Winds and Pickup Ions
T-OWS	Triton Ocean World Surveyor
TAC	Thruster/Actuator Card
TCM	Trajectory Correction Maneuver
TID	Total Ionizing Dose
TOF	Time of Flight
TRL	Technology Readiness Level
TT&C	Tracking, Telemetry and Control
TWTA	Travelling Wave Tube Amplifier
UMOD	Uranian Model
USO	Ultra-Stable Oscillator

UV	Ultraviolet
UVIS	Ultraviolet Imaging Spectrometer
V&V	Validation & Verification
VAP	Van Allen Probes
VDA	Vacuum Deposited Aluminum
Vis/NIR	Visible and Near-Infrared (Imaging Spectrometer Instrument)
VLT	Very Large Telescope
WBS	Work Breakdown Structure
WT	Traveling Wave Tube