Hopper Missions to Triton and Pluto using a Vehicle with In-Situ Refueling

A White Paper for the Planetary Science and Astrobiology Decadal Survey 2023-2032

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Key Points:

- Global surface mobility is the key to comprehensive exploration of the diverse surfaces of worlds such as Triton. We propose to do this with a rocket-powered “hopper” vehicle
- The Triton Hopper is a NASA Innovative Advanced Concepts (NIAC) project to design a mission to not merely land, but repeatedly fly across the surface of Triton, utilizing the volatile surface ices (primarily nitrogen) as propellant for a radioisotope-heated thermal rocket engine to launch across the surface and explore all the moon’s varied terrain.
- With a calculated range of 20 km per hop, equator-to-pole mobility can be achieved over a primary mission duration of 2 years.
- The same concept of using in-situ ices to refuel a radioisotope engine for global mobility would be applicable to other airless bodies in the solar system. Using Nuclear Electric Propulsion for the transfer vehicle, the same concept can be applied for a mission to the surface of Pluto.

The mission described would be either a flagship-class mission, or a component of a flagship-class mission that also includes science investigations of Neptune and its smaller moons.

Figure 1: visualization of Triton Hopper vehicle on the surface of Triton

1. Introduction

This white paper is drawn from a NIAC study of a conceptual design of a mission to the surface of Triton. The paper draws on two primary sources: Landis *et al.*, 2019 [1], and the Triton Hopper NIAC Phase II midterm report [2]. A final report [3] is in process.

Neptune’s moon Triton is a dynamic moon with a highly varied surface, a thin atmosphere, and geysers [3]. Triton is unique among the moons in the outer solar system in that it is most likely a captured Kuiper belt object (KBO), a leftover building block of the solar system, of a size slightly larger than Pluto. At a temperature of 33 K, the surface is covered in ices made from nitrogen, water, and carbon dioxide, and shows surface deposits of tholins, organic compounds that may be precursor chemicals to the origin of life. At a distance of over 30 astronomical units, it would be by far the most distant object ever landed on by a spacecraft, and the first detailed visit to a Kuiper-belt object.

Experience with rovers on Mars shows that mobility is invaluable to exploring a planet (or moon). Triton, and its slightly smaller twin Pluto, are large and show a wide diversity of structure: one landing spot will barely scratch the surface. Triton’s landforms are interesting from pole to

equator. Mobility across the surface on a global scale is an indispensable requirement for full understanding of these bodies.

The flight demonstrations of the Mars helicopter “Ingenuity” and the Titan helicopter “Dragonfly” will be the first confirmations of the value of airborne mobility on other worlds. However, helicopter and other wing-based flight systems are not applicable to airless worlds. We need a flight system that is capable of multiple flights above and across the surface that does not rely on the atmosphere.

The Triton Hopper (Figure 1) is a concept for a vehicle to not merely land, but to utilize the volatile surface ices (primarily nitrogen) as propellant for a radioisotope-heated thermal rocket engine to launch across the surface and explore all the moon’s varied terrain [2,3]. We call this vehicle a “hopper” because it is capable of making multiple rocket-propelled ballistic “hops” across the surface, allowing long-distance mobility and the ability to examine multiple sites of scientific interest.

Using the in-situ resources of a body has been shown by many to be key to long-term exploration. The use of in-situ collection of surface volatiles as propellant for hopper’s radioisotope thermal engine, will open up operations on not merely Triton and Pluto, but be an enabling technology for exploration of small bodies across the solar system

2. Triton Hopper Science

The case for science on Triton is being made by other white papers submitted in support of this decadal survey, and will not be detailed here. However, we note that any real understanding of Triton would necessarily be incomplete if done at a single landing site. Because of the wide diversity in surface landforms, we want to look at regions varying from the nitrogen geysers, to the chaotic “cantaloupe terrain” in mid latitudes, to the nitrogen-ice glaciers; terrain which spans locations from nearly the Triton pole to the equator. Triton is a Pluto analogue (or vice versa), and all the questions we have about landforms on Pluto also apply to Triton. Likewise, there would be great science value in a landed mission to Pluto, but any single location would tell us only a fraction of what we need to know about the diversity of Pluto. For Pluto, as with Triton, we need a mission that can access a multiplicity of locations ranging from the pole to the equator.

Figure 2: Triton hopper phase-II design, showing major subsystem components.

The Triton Hopper Project phase-II midterm study report [2] lays out a science traceability matrix for the main science questions and maps them into an instrument suite and concept of operations for a hopper mission. The science traceability maps three fundamental goals, and nine

supporting objectives to nine onboard instruments and supporting instrumentation and observations from the vehicle that delivers the hopper to Triton. The Triton Hopper science goals and objectives are:

- 1) Characterize the surface/subsurface properties of Triton at lander scale (micron to meter).
 - a) Observe the properties of surface materials and sub-meter-scale landing hazards at landing site, including sampling area. Connect local properties with those seen by remote sensing.
 - b) Characterize dynamic processes of Triton's surface and ice shell over the mission duration to understand exogenous and endogenous effects on the physiochemical properties of surface material.
- 2) Characterize surface/subsurface properties of multiple Triton terrains from pole to equator.
 - a) Observe the properties of surface materials at multi-meter scale during hops, landing hazards at landing sites, including sampling area. Connect local properties with transits and with those seen by remote sensing.
 - b) Characterize dynamic processes of Triton's surface and ice shell over the multiple landing sites and terrains to understand exogenous and endogenous effects on the physiochemical properties of surface material.
 - c) Observe atmosphere during hop excursions at different elevations, and over different geologic terrains, and as seasons change.
- 3) Assess the habitability of Triton via in-situ techniques, and search for biotic chemistry.
 - a) Characterize non-ice composition of Triton's near-surface material to determine whether there are indicators of organic or pre-biotic chemistry, chemical disequilibria and other environmental factors essential for life.
 - b) Determine chemical composition and nature of Triton's geysers, dark streaks, and plume materials.
 - c) Determine provenance of sampled materials.

A suite of instruments operated during both hops and at each landing site include:

- Descent-Excursion-Ascent camera for synoptic and transit imagery
- Panoramic and hyperspectral imaging suite (including “hand lens” imaging of cores samples)
- Accelerometers, seismometers, and possibly a magnetometer for geophysics
- Evolved gas experiment including multiple characterization of acquired samples
- Neutron, Gamma Ray, and Alpha Particle X-ray spectrometer for bulk chemistry
- Atmospheric and meteorology station for wind, temperature, pressure over time and space.

3. NIAC Phases

3.1 Phase I project

In the phase-I project, an initial engineering design of the spacecraft and mission was done, with the purpose of showing that the concept was feasible [4]. The Phase-I Triton Hopper design was able to achieve a hop of up to 5 km approximately once per month. A two-year mission would allow the 300-kg vehicle to accomplish a traverse distance of about 150 km and visit 30 sites.

The phase-I mission design showed that a Solar Electric Propulsion (SEP) vehicle using Aerocapture for arrival at Neptune would be capable of delivering the hopper vehicle, and the orbiter which supports the mission and serves as a data relay, with an 11-year cruise time from Earth to Neptune.

3.2 Phase II project

The phase-II project [5], analyzed improvements to the mission, utilizing a changed engine concept to improve performance to allow longer hops, and incorporated a number of trade-studies to optimize performance.

. The revised design showed that the vehicle could achieve the goal of allowing pole-to-equator exploration while increasing the science payload. The phase-II analyses also improved the delivery system by incorporating a Nuclear Electric Propulsion (NEP) system utilizing the recently-developed “Kilopower” reactor [6] as a primary energy source.

Triton is only one of many possible applications of the design of a vehicle able to use in-situ ices as fuel for a radioisotope thermal engine. Pluto, like Triton, has surface deposits of nitrogen ice, and the design for a Pluto-exploration hopper is very similar to the Triton Hopper design. Likewise, although not discussed here, the icy satellites of Jupiter and Saturn would be possible locations in which the in-situ refueled engine could enable near-global mobility.

4. Mission and Vehicle Design

4.1. Radioisotope engine with thermal storage

A mission envisioning global or near-global mobility using rocket-powered hops on the surface of Triton (or any such airless body) cannot be done using propellant brought from Earth; the amount of propellant required for multiple hops would quickly make the required mass ratio absurdly high. The key element that makes such multiple hops across the surface possible is the use of a radioisotope source to provide energy, and locally supplied (nitrogen) propellant that is gathered from the surface.

The propulsion energy is supplied by a conventional plutonium isotope heat source, the GPHS (“General Purpose Heat Source”) which is identical to those used in previous missions, including Pioneer, Viking, Voyager, Galileo, and Cassini mission to the outer solar system. The GPHS produces heat at a nominal temperature of up to 1200°C. This energy is then transferred to a thermal mass, which is used to heat the propellant

Nitrogen is passed through the heated thermal mass and then expanded through a rocket nozzle to produce the thrust needed for the hop [7]. A number of different possible materials were possible for the thermal mass; for the baseline case we assumed molten lithium, due to its high heat capacity and thermal conductivity, but several other choices (e.g., phase-change salts) also achieve similar performance.

The lithium thermal storage mass is contained in a cylindrical containment vessel containing 25 kg of lithium. The nitrogen flows through 540 1.5-mm diameter tubes, each 40 cm long, to three operating nozzles. Due to the reactivity of lithium, the preferred alloys for the lithium heat pipes are molybdenum-based alloys [8], such as Titanium Zirconium Molybdenum (TZM), which has high melting point, a high thermal conductivity (110 W/mK at 1000°C), high strength, and is compatible with lithium at high temperatures.

In the center of the thermal block is a hollow in which four General Purpose Heat source (GPHS) bricks are inserted. The GPHS blocks contain the Pu-238 isotope, each one providing about 245 Watts from the radioactive decay of encapsulated plutonium oxide fuel, with a half-life of 87.7 years [9]. GPHS blocks are designed to be robust against mishaps ranging from launch failure to atmospheric entry, and have been used for missions ranging from Pioneer through the Mars Curiosity mission.

The thrust of a hop is done in two segments, a first burn to loft the vehicle into its ballistic trajectory, followed by a coasting period, and then a second burn to bring the vehicle to a soft landing. Specific impulse achieved is about 161 seconds at the beginning of thrust, dropping down to about 108 seconds at the end of the second thrusting period, for an average specific impulse of 127.5 seconds.

4.2 Propellant collection

Although the atmosphere of Triton is thin (about 1/70,000th of the Earth's surface pressure), we determined that the vehicle could be refueled by gathering and compressing nitrogen from the atmosphere. However, since the surface deposits are nitrogen snows and ices, in the phase-II design, we baselined collecting propellant in the form of cores from the surface deposits, rather than from the atmosphere. After some analysis and testing of the properties of nitrogen ice, we determined that ice cores could be obtained with a hollow-core drill, similar to the tools used to obtain glacial ice cores on Earth. The drill will thus do double-duty, serving to gather propellant and to produce scientific coring for stratigraphic studies of the ice.

Figure 2 shows the design of the hopper, with the coring drill shown at the front.

The ice core is inserted into the collection-chamber canister, and the chamber then closes (Figure 3). The canister is heated while maintaining a pressure sufficient to liquify the nitrogen ($\sim 63\text{K}$, $>0.125\text{ atm}$), at which point a pressure feed system drains liquid nitrogen into the (low temperature) fuel tank, where it is allowed to cool back into solid form. The process is repeated as needed until the main tank reaches capacity. When the capacity is reached, the tank is then heated to the storage pressure and temperature. The collection canister serves a primary science function as well, as several analysis instruments either observe the sample inside it or draw some of the sample (gas, liquid, and/or solid) into the chemical analysis suites.

The propellant in the tank is stored as pressurized gas, simplifying the propellant feed, and avoiding the difficulties of two-phase flow in the heat exchanger. As the propellant is exhausted, the drop in pressure and resultant expansion of the propellant remaining in the tank drops in temperature due to Joule-Thomson cooling. The point where the cooling reaches the liquidus point marks the end of the thrust period. We determined the optimum pressure and temperature to be around 21 MPa (3000 PSI) and 300K temperature, at which about 10% of the initial propellant load remains in the tank at the end of thrust. This residual propellant can be reheated and used for a second, short distance hop, if it is desirable to make a fine adjustment to the landed location.

Figure 3: Propellant fill schematic

The design study showed that either a solar electric propulsion stage, using aerocapture for orbital insertion, or a nuclear electric propulsion (NEP) system would be capable of delivering the vehicle to Triton orbit insertion. Due to the recent development of the “Kilopower” reactor [6], a small nuclear reactor which was recently demonstrated with the “KRUSTY” experiment [10], we

4.3 Delivery and Operations

The design study showed that either a solar electric propulsion stage, using aerocapture for orbital insertion, or a nuclear electric propulsion (NEP) system would be capable of delivering the vehicle to Triton orbit insertion. Due to the recent development of the “Kilopower” reactor [6], a small nuclear reactor which was recently demonstrated with the “KRUSTY” experiment [10], we

baselined the NEP vehicle for the mission, adapting a vehicle design from an earlier design study of a Kuiper Belt Object mission [11]. An advantage of the NEP transfer vehicle is that, since aerocapture in the Neptune atmosphere is no longer required, the vehicle concept can be used for small airless bodies such as Pluto or Charon, and is no longer restricted to moons orbiting a gas-atmosphere primary.

Once orbital insertion is achieved at Triton, potential landing sites are photographed from orbit to identify and verify an initial landing site. A solid rocket then performs the deorbit to initiate the descent of the hopper toward the surface. Figure 4 shows the hopper with the solid rocket motor attached. Following the deorbit burn, the hopper vehicle then detaches from the solid rocket, and uses the radioisotope thermal engine to make the initial soft landing.

5. Triton Hopper Design Results

Table 1 shows the mass summary, showing both the hopper itself, and also the hopper with the solid-rocket stage for the initial descent of the vehicle from Triton orbit. Basic dry mass of the vehicle, not including the solid rocket stage, is 440 kg; (~550 kg assuming growth allowance of 30%). This compares favorably to other similar landed systems; for example, the Mars Curiosity mission has a rover mass of roughly 900 kg. Including the descent stage, the mass delivered to Triton orbit by the transfer vehicle is about 900 kg (compare to Curiosity rover's entry mass of nearly 2000 kg).

Figure 4. Triton hopper with solid rocket for deorbit

The baseline vehicle, with no performance margin added and without assuming vehicle mass growth, achieves about 33 km per hop. Incorporating margins and growth, the realistic distance achievable per hop is 21 km, which is still a considerable improvement over the 5 km baselined in the initial design.

5.1 Operations (Conops)

The core drilling and fueling process takes about 3 days, not including margin. This allows a hop once per Triton day (141 hours, about every 6 Earth days).

Since the transfer vehicle remains in orbit, a high-resolution camera is used to plan each jump. This planning is used to ensure that the landing spot for each hop is smooth, level, and free of large (>50 cm) boulders. Orbital

MEL Summary: Case 3 Triton Hopper CD-2019-12			
	Hopper	Solid Stage	TOTAL
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Total Basic Mass(kg)
Science	31.6	0.0	31.6
Attitude Determination and Control	8.2	0.0	8.2
Command & Data Handling	11.5	0.0	11.5
Communications and Tracking	6.5	0.0	6.5
Electrical Power Subsystem	23.3	0.0	23.3
Thermal Control (Non-Propellant)	41.5	0.0	41.5
Propulsion (Chemical Hardware)	154.3	51.6	205.9
Propellant (Chemical)	79.4	265.3	344.7
Propulsion (EP Hardware)	0.0	0.0	0.0
Propellant (EP)	0.0	0.0	0.0
Structures and Mechanisms	83.7	12.9	96.6
Element Total	440.1	329.7	769.8
Element Dry Mass (no prop,consum)	360.7	64.5	425.1
Element Propellant	79.4	265.3	344.7
Element Mass Growth Allowance (Aggregate)	65.0	6.4	71.4
Additional System Level Growth (For 30% tot)	43.2	12.9	56.2
Total Wet Mass w/ 30% Growth	548.3	349.1	897.3

Table 1. Mass summary

infrared spectroscopy will verify that surface deposits of nitrogen ice (or snow) are available for refueling. The orbital imagery will also give geological context for the science, and will be used to search for targets of special interest, such as nitrogen geysers, which may give clues as to the deeper interior of the moon.

In the case that the hopper lands at a location that does not have nitrogen ice available on the surface, the residual propellant in the tank can be used to make a secondary hop to a more suitable location for propellant harvesting.

At the maximum hop distance of 20 km, the desired mission criteria of 2400 km (*i.e.*, Triton pole to equator) is achieved in the nominal prime mission duration of 2 years.

A mission to the surface of Triton is likely to be flown as part of a mission to observe Neptune [3]. During the 2-year primary mission of the hopper, the transfer vehicle will support the hopper mission in orbit as a radio relay, and as a platform to take high-resolution images of potential landing sites. Following this initial mission, a sufficient number of detailed surface observations will have been made that the vehicle is no longer required for close support of continued operation of the hopper. The transfer vehicle can then leave Triton orbit, and can be used as a vehicle to study Neptune and its ring system, as well as making fly-bys of other satellites.

The same concept could be adapted to other icy worlds. In particular, use of the Nuclear Electric Propulsion for the transfer vehicle (discussed in greater detail in other white papers submitted to the decadal survey) means that the same vehicle concept can be used for a hopper vehicle to explore Pluto.

6. Conclusions

Global mobility is the key to comprehensive investigation of bodies with a large number of diverse surface features, such as Neptune's moon Triton. The hopper concept utilizing in-situ materials for propulsive jumps to enable multiple landing sites is a game-changing capability for the exploration of icy bodies. The NIAC study describes a high-value mission with a large complement of science instruments capable of global (pole to equator) coverage of the surface within a primary mission span of two years.

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