

Prospector-1: The First Commercial Small Spacecraft Mission to an Asteroid

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ABSTRACT

Deep Space Industries (DSI) is developing a microspacecraft asteroid exploration mission named Prospector-1. The goal of this mission is prospecting for resources, particularly water, extractable from the surface of a volatiles-rich target asteroid. This mission objective implies not just surveying the water content of the surface, but penetrating to subsurface depths as well. In addition to water reconnaissance, Prospector-1 will also investigate the mineralogy and geotechnical characteristics of the asteroid using a proprietary instrument suite that is intended to be used on the asteroid surface.

In addition to representing what will potentially be the first private interplanetary mission yet undertaken, it is also expected that Prospector-1 will be the smallest and least expensive asteroid mission to date. The mission involves dispatching a small microspacecraft using all-chemical propulsion to an asteroid, followed by the use of water electrothermal propulsion for cruise, rendezvous, and proximity operations. A multi-week remote sensing campaign will map the surface and subsurface in visible and mid-wave infrared bands, in parallel with the generation of a water map of the asteroid at near-subsurface levels. Finally, the spacecraft will attempt to land on the asteroid surface to assess geotechnical characteristics of potential resource extraction sites, as well as to assert a presence and establish the first commercial base on a space object. This mission is being developed with an aggressive cost-cap in the tens of millions of USD and a schedule in single-digit years.

1. INTRODUCTION

Deep Space Industries (DSI) is a space resource and technology company with the ultimate goal of harvesting asteroids to industrialize the frontier. In the not too distant future, the abundance of raw materials in near-Earth asteroids will allow the production of salable products in space—such as fuel, air, water, and large structures—in quantities that are simply impractical to launch from the surface of the Earth, but which will nevertheless enable space development in a way that has not yet been possible.

While the company vision is long-term, its near-term roadmap and strategy begin small: leveraging the increasing capabilities of nano- and microspacecraft to undertake simple, cost-effective, and aggressively-scheduled asteroid exploration missions.

DSI's value chain and product line comprise the missing technologies needed to enable interplanetary small spacecraft missions—in particular, high-performance propulsion systems; reliable deep space communication systems; novel absolute and relative navigation technologies; and robust, radiation-tolerant

avionics. While DSI considers these to be exploration-enablers for its own missions, the company business model is also predicated on monetizing such technologies in the existing small satellite market, selling them into other customer programs to enhance activities in Earth orbit and beyond. Ultimately, DSI aims to satisfy a customer base today with products that can be serviced using in-space resources in the future.

1.1 Mission Context, Objectives and Constraints

As with any mining project, the first stage in the harvesting of space resources is prospecting. As early as the end of this decade, Deep Space Industries intends to launch Prospector-1: a microspacecraft that has the promise of being the first private mission to an asteroid, for the purpose of assessing the abundance of extractable resources—in particular, water and carbon dioxide—as well as performing geotechnical reconnaissance of the asteroid in order to understand its overall mineability. This mission intends to combine the best of flight-proven microsatellite systems with the cornerstone technologies being developed by DSI in order to accomplish space exploration at significantly

lower-cost than would have been achievable as recently as five years ago.

Selected fundamental objectives of the Prospector-1 mission include:

- undertaking the first private missions to a candidate asteroid for future mining operations;
- verification of commercially-viable returnable quantities of resources—in particular, water and carbon dioxide—from the candidate asteroid; and
- exploration of the geotechnical characteristics and mechanical properties of the target asteroid’s regolith—essentially, the asteroid’s “diggability”—to inform the design of extraction and processing equipment on subsequent missions.

Selected fundamental constraints of the Prospector-1 mission include:

- the mission must be developed to flight-readiness within three years;
- the target cost must be in the low tens of millions USD, the actual figure being confidential;
- the mission must be launch vehicle agnostic to the extent practical and able to be launched as a secondary payload; and
- the target asteroid visited by Prospector-1 must be the intended mining target for follow-on missions.

Prospector-1 can be viewed as the precursor mission for sub-scale and full-scale resource harvesting missions, which DSI refers to as its *Harvestor™* program. In our proposed mission sequence, a given asteroid would first be prospected using one or more small Prospector microspacecraft, after which a much larger Harvestor spacecraft would be dispatched to extract and process its resources. The low-cost Prospector missions are used to de-risk each mining target—if the particular asteroid is deemed to not be prospective for mining, the much larger capital investment to harvest it would not occur, and the company would move on to a different target. In this architecture, a fully-mature asteroid mining capability involves prospecting and harvesting multiple asteroids in parallel to achieve a high cadence of returned resources, with a Prospector dispatched to a new potential target in parallel with a Harvestor sent to the previously scouted one.

Of course, the matter of asteroid selection is central to the mission architecture and mission cadence described above, but discussion of target identification and down-selection is beyond the scope of this paper—and particularly represents a key proprietary aspect of DSI’s work. Intermediate steps depicted below are described in subsequent sections.

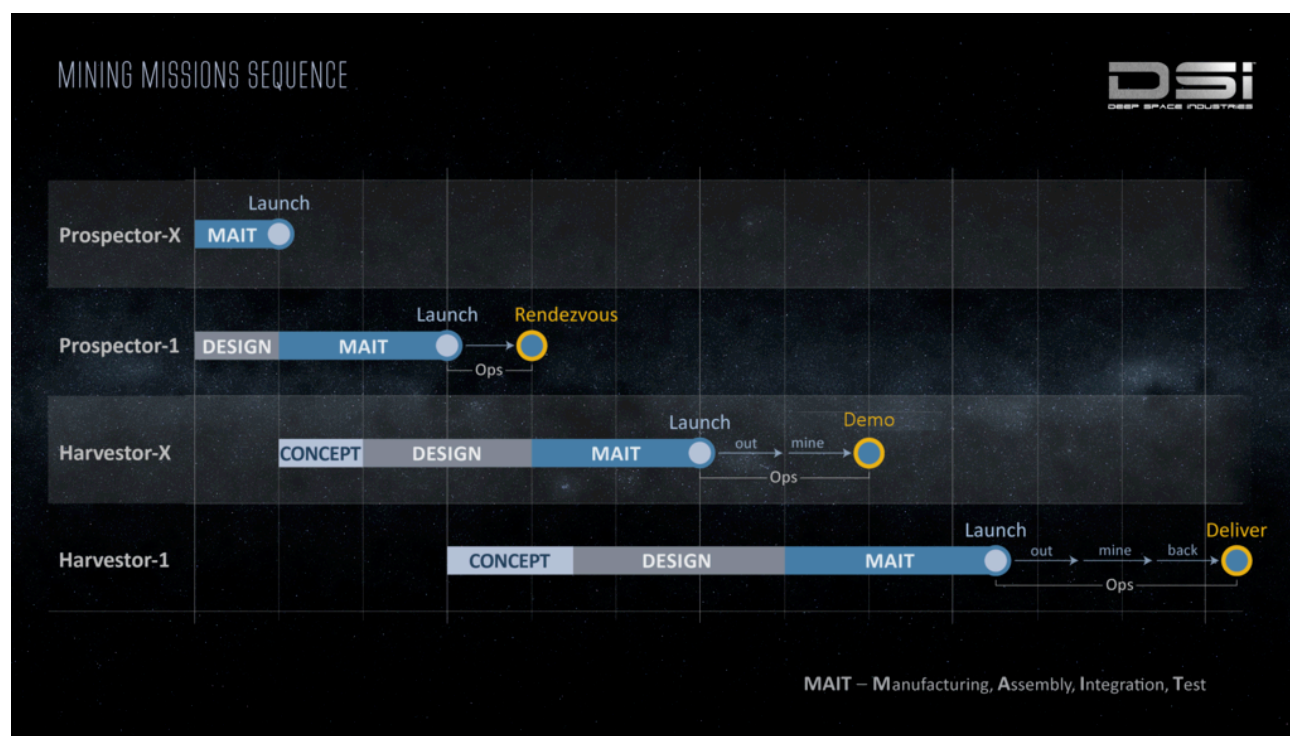


Figure 1: Deep Space Industries Mission Roadmap – Prospector-X (launching in 2017) will be the first precursor risk-reduction mission flown by DSI.

2. PROSPECTOR-1 OVERVIEW

The Prospector-1 spacecraft concept is depicted in Figure 2 and Figure 3, with a summary of key characteristics and specifications presented in Table 1. Prospector-1 combines the best of high-heritage nano- and microsatellite technologies with cornerstone DSI technologies to enable an extremely low-cost, yet highly capable small spacecraft exploration platform. While DSI is developing this spacecraft for asteroid prospecting, the intent is also to offer the platform commercially for other customer missions, which may range from high-performance Earth-orbit missions to low-cost exploration missions to the Moon or Mars.

2.1 Spacecraft Platform

Prospector-1 is an approximately 30 kg dry mass, 50 kg wet mass spacecraft that employs an approximately 50 cm tall hexagonal platform, with a single primary load path through its central axis for launch and interplanetary injection. The structure is simple, with avionics in discrete enclosures mounted peripherally around a central propellant tank and harnessed circumferentially, with body panels serving as secondary structure to house solar panels, as well as externally-mounted instruments and thrusters.

The spacecraft uses three sets of four thrusters arranged in quad-pack configurations, which serve the combined purpose of reaction control system (RCS) and interplanetary maneuvering system (IMS). These thrusters—part of the DSI-developed *Comet* design family—use water as propellant, which is intrinsically inexpensive, inert, launch-safe, and, most significantly, uses the most abundant and key resource that can be derived from in-situ asteroid materials. Each *Comet* thruster uses a simple design that expels superheated water vapor at close to 1000 °C to produce thrust, achieving approximately 200 s specific impulse. Whereas commercial DSI missions employ single thruster configurations, Prospector-1 thrusters each use a manifold to feed individual thruster heads. Each thruster in a given quad is throttlable, and each also offers extremely fine impulse resolution and control. DSI has invested in water propulsion in recognition of the future importance of having propulsion systems that can be serviced using propellant derived from space resources.

Prospector-1 uses a distributed network device architecture based around a single CAN bus. The system employs functional redundancy rather than actual redundancy, with the role of the flight computer reduced as compared to more common central computer, or star, architectures. The Prospector-1 flight

computer is being custom-developed for deep space missions in concert with its power system, under a partnership that is expected to be announced by the time of this paper's presentation.

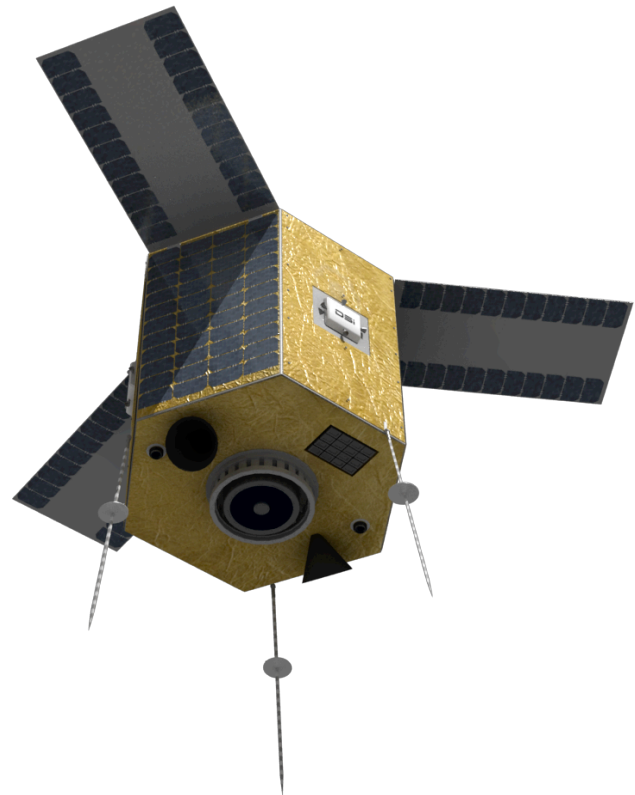


Figure 2: Prospector-1 Spacecraft – Depicting primary optical aperture, neutron spectrometer, star trackers, proximity operations cameras, and injection stage adapter.



Figure 3: Prospector-1 Spacecraft – Depicting main solar panels, scanning antenna array, reaction control thrusters, and landing penetrator legs

Table 1: Prospector-1 Overview

Characteristic	Specification / Description
Spacecraft mass (post injection)	29 kg dry mass 49 kg wet mass
Spacecraft Size	Hexagonal form factor 54 cm x 47 cm x 50 cm (27 cm wide faces)
Cruise Propulsion	Water electrothermal propulsion (DSI <i>Comet</i> thrusters) 200 s specific impulse 1000 m/s delta-V on-board
Power generation	Three deployed and three body-mounted solar arrays 120 W nominal (main solar panels at 1AU solar distance)
Tracking, telemetry and command	Scanning X-band antenna system DSN-compatible ranging transponder Minimum 3.1 dB link margin at worst-case range / orientation Minimum 1 kbps at worst case range / orientation
Attitude determination and control	Dual star tracker configuration Three reaction wheels RCS propulsion shared with primary propulsion Arcminute-level attitude control
Guidance and navigation	Ranging transponder for absolute navigation Optical (IR) navigation for relative navigation Stereo optical navigation for proximity operations
Command and data handling	Distributed network CAN architecture Single computer and high-speed data recorder
Payloads	VIS/MWIR Camera (0.5 m spatial resolution @ 10 km range) Neutron spectrometer Instrumented landing legs, magnetometer, gravimeter

The Prospector-1 design uses three deployed and three body-mounted solar arrays using triple-junction cells for power generation. The spacecraft is able to produce keep-alive power in any attitude, and uses an approximately 24 V to 28 V 7s3p internally-redundant battery pack for energy storage and load-levelling. The spacecraft power system uses a battery bus with series peak-power tracking (PPT) at the individual panel level to maximize power production from each array across a range of temperatures, while also decoupling the array and battery voltages. Each array is operated at its optimum voltage for power production, and stepped down to the battery (bus) voltage. Peak power trackers are synchronized to operate in polyphase to reduce bus voltage ripple and conducted electromagnetic interference. The spacecraft power management system protects all spacecraft loads from overcurrent events such as single event latchup (SEL) with resettable solid-state switches.

Prospector-1 uses a DSN-compatible ranging transponder for tracking, telemetry, and command (TT&C) in X-band—nominally 7.2 GHz uplink, 8.4 GHz downlink—combined with a scanning antenna that offers nearly full hemispherical coverage with high-gain upon acquisition of signal from Earth. This

combined system permits a robust communications and navigation solution with a single beam-steering antenna system. The Prospector-1 transponder also supports hardware-decoded commands which enable system reset (“firecode”) functionality, and a DSI-developed interface node which allows all subsystems on the satellite platform to be commanded directly over the command link, removing the need for a dedicated computer to intermediate device-level communications.

While its ranging transponder provides absolute navigation, an infrared camera sharing optics with the primary spacecraft science imager provides a longer-range navigation solution in the far infrared for target localization—in order to remain independent of approach angle with respect to a dark target asteroid—while a smaller stereo navigation camera set provides close-range proximity operations navigation, and, most significantly, serves as the terminal guidance approach for landing.

Attitude determination and control is enabled using Sinclair Interplanetary star trackers and reaction wheels, with the *Comet* propulsion system providing the dual role of maneuvering and wheel desaturation. In the event of wheel failure, the propulsion system can serve as the primary attitude control system. Two star

trackers are employed to ensure availability and provide improved roll accuracy. Arcminute-level attitude control has been demonstrated on multiple missions with this hardware suite.

2.2 Spacecraft Instruments

Prospector-1 carries several different payloads. First, a set of three cameras sharing common optics are used for (1) imaging in visible (VIS) bands (red/green/blue) using a Bayer-filtered CCD detector; (2) a mid-wave infrared (MWIR) high spectral resolution instrument for imaging the $3.1\text{ }\mu\text{m}$ water absorption band; and (3) a far-infrared (FIR) detector that is used for longer-range navigation purposes.

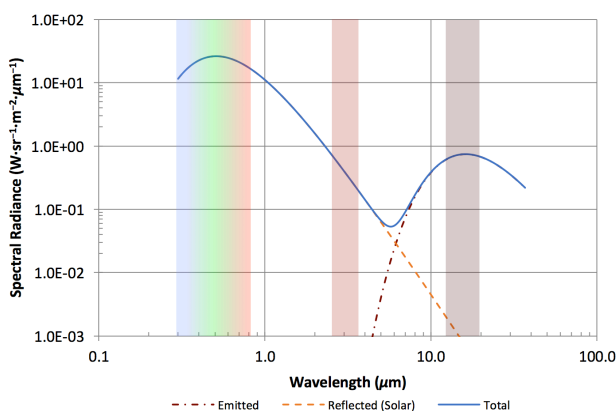


Figure 4: Prospector-1 – Spectral bands of interest, overlaid on blackbody-calculated (170 K) asteroid radiance. Visible, mid-wave IR (water absorption band), and far-IR (for navigation) of particular interest.

The spacecraft also carries a highly-compact neutron spectrometer, which can be used at relatively long-range as well as near the surface to detect the presence of hydrogen—and, by inference, water—at the asteroid. This spectrometer will map the depth and distribution of water on the target asteroid, and the data will be co-registered with imagery from the VIS/MWIR instrument to create a comprehensive water map of the target asteroid.

Lastly, the spacecraft carries a set of instrumented landing legs, with accelerometers and thermocouples, as well as a three-axis magnetometer for geotechnical reconnaissance at the surface. At the end of its remote sensing survey, Prospector-1 will attempt to land at a prospective water-rich site on the asteroid, at a relatively low rate of centimeters-per-second, using its thrusters to apply downforce and using its landing penetrators to measure the compression and shear strength of the local asteroid regolith. Once settled on the surface—and with the ability to provide down-force

via thrust, since asteroid “landing” is more akin to “rendezvous”—temperature and local magnetic field measurements will be recorded. Landing will be attempted in sunlight and in-pass. This final sequence of measurements is expected to be end-of-life activities, as the spacecraft is not expected to survive long once on the surface. However, with that said, the intent is to have the spacecraft beacon key health telemetry whenever its panels are illuminated once on the surface if it remains able to do so.

Instrument development partnerships for Prospector-1 are expected to be announced by time of this paper’s presentation.

3. MISSION CONCEPT

Whereas previous sections described the Prospector-1 spacecraft and instruments, in this section we describe the overall concept of operations. Prospector-1 is currently being built between DSI’s offices in California and Luxembourg City. The intent is to achieve flight-readiness within three years.

3.1 Near-Earth Asteroids

Asteroids are primitive inner solar system bodies that are the primary source of meteors. In popular culture, they are monolithic silicate rocks in the asteroid belt, but in reality, asteroids are extremely diverse. Many are darker than charcoal, some are completely desiccated and are held together by Van der Waals forces, and others have surfaces that are the same density and hardness as a dust-bunny [1]. The asteroids of greatest interest to asteroid miners contain water and other volatiles—low temperature sublimating compounds—that promise to dramatically change space infrastructure as we know it.

C-Cadre, primarily C-, D-, and P-type, asteroids contain carbonaceous materials and water. Some C-type asteroids on the outer edge of the main belt have been detected completely covered in ice [2]. The surfaces of these asteroids are cold enough for ice to exist on the surface, even in vacuum, and some microgravity geology can act as a concentrating mechanism. C-cadre asteroids that are closer to the sun are compositionally the same as these main-belt objects, but the surfaces are too warm for ice to ever exist [3]. Surface minerals can still be aqueous—molecularly bound within silicates—and ices can exist beneath a thermally insulating layer of regolith [4].

Asteroids are a complex geochemical and geotechnical environment for Prospector to explore. The science campaign begins as soon as Prospector can identify the

target against the background stars, which is anticipated to be 10 km from the target.

3.2 Target Selection

One of the perceived challenges with asteroid mining is associated with target selection. However, with more than 14,000 near-Earth asteroids discovered to date, and with discovery rates only increasing, DSI has already identified several highly attractive targets for its first prospecting mission. In fact, DSI has identified enough targets so as to enable more flexibility regarding launch and Earth departure than typical for any interplanetary mission.

DSI has developed an extensive target selection and evaluation process that considers, among other aspects, the outbound and return opportunities and velocity change requirements for each target, the maximum Earth-asteroid and Sun-asteroid ranges for power generation and communication purposes, the orbit condition code of each target, whether the target has been spectrally characterized or offers an opportunity for spectral characterization, whether the target is volatile rich, i.e. a carbonaceous chondrite or generally C-cadre, and whether the target is sufficiently large that an industrial quantity of material, particularly water, has high odds of being recoverable from the object. DSI has actively worked with commercial and government customers for future resources to establish a viable product which must be proven to exist and be recoverable from a target.

3.3 Launch, Commissioning, Earth Departure, and Cruise

Prospector-1 has been designed to be launched as a secondary payload and injected to its target asteroid directly from low-Earth orbit. While there are any number of intermediate parking orbits that would be preferable for interplanetary injection, not the least of which is a hyperbolic trajectory outbound using direct throw of the launch vehicle, in order to manage costs and maximize launch opportunity, it was considered an unacceptable risk to assume the mission would be able to start anywhere else than low-Earth orbit. However, a LEO initial orbit offers the advantage of allowing spacecraft commissioning prior to injection at relatively close range using commercial ground stations.

Prospector-1 and its injection stage would be delivered to LEO as secondary payloads. No dedicated small launch vehicle is assumed, though it is also not precluded by DSI's mission architecture, and a dedicated small launch would be extremely attractive if any of the emerging providers are flying in the near-

future. The spacecraft would be commissioned in LEO months prior to injection to ensure that the spacecraft is fully functional prior to Earth departure. Prospector-1 is depicted with its injection stage in Figure 5.

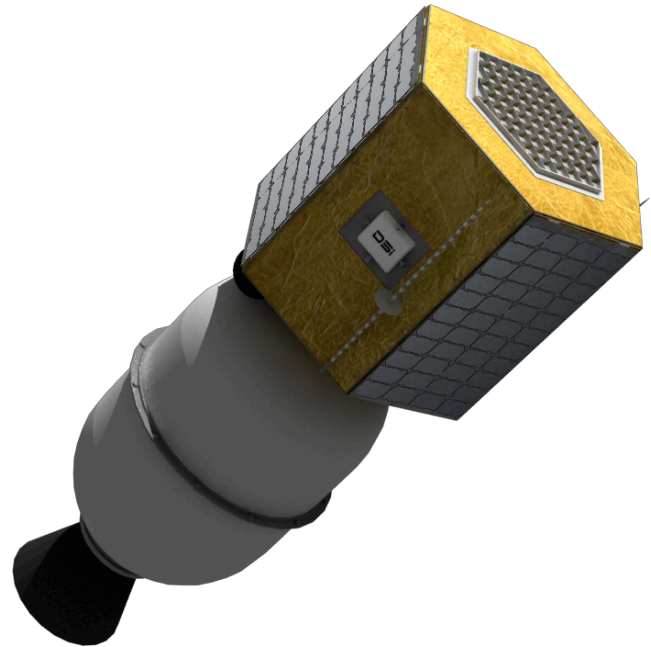


Figure 5: Prospector-1 with injection stage and stowed panels

A high-energy, dedicated chemical injection stage is used for Earth departure. This avoids the expensive, high-power, and high operations tempo otherwise associated with an electric propulsion spiral injection—particularly from LEO or GTO, which adds the additional challenge of frequent passage through the Van Allen radiation belts. However, while designed to use impulsive chemical injection, Prospector-1 is also designed to be largely decoupled from its Earth departure propulsion so as not to preclude any number of options—e.g. a dedicated solar electric stage dispatched from GEO, a larger carrier spacecraft transporting Prospector as a subspacecraft or hosted payload, or direct throw from a dedicated smallsat launcher. This is also done in the interest of offering Prospector as a platform to other commercial or government customers wishing to procure a high-performance exploration platform without precluding a different launch or Earth departure arrangement.

Following Earth departure, the spacecraft cruises to the asteroid with its main panels on the sun. After an initial drift period post-injection, Prospector-1 will perform a series of course corrections using its *Comet* water thrusters. As both the Sun and Earth remain in the same hemisphere during cruise, Prospector's scanning antenna is used to acquire Earth while its main solar

panels remain trained on the sun. The X-band transponder on Prospector-1 also permits high-accuracy absolute range and range-rate information during cruise.

3.4 Rendezvous and Stationkeeping

The Prospector-1 mission plan involves the spacecraft being able to localize its target asteroid in interplanetary space using its far infrared camera. Even with an orbit condition code of zero, position uncertainty of the asteroid requires acquisition at long-range by the spacecraft, though with close operator-in-the-loop supervision. In general, target asteroids are chosen to maximize position and acquisition certainty, with DSI's evaluation cost function favoring asteroids that remain near Earth during Prospector-1's mission duration to maximize operator-in-the-loop capability and minimize required spacecraft autonomy.

From a propulsive standpoint, rendezvous is a relatively benign maneuver—in fact, a series of small maneuvers—which in most cases are smaller than mid-course adjustments needed by the spacecraft. Target asteroids are so small that it is more useful to imagine Prospector-1 co-orbiting the sun nearby the asteroid, rather than capturing into orbit. While maintaining a sunlit position with respect to the asteroid, Prospector-1 is considered to have arrived at its target when a stable stationkeeping range of approximately 10 km is achieved. Again, it is important to note that 10 km is long-range relative to an asteroid with mean dimensions in the tens to hundreds of meters.

3.5 Science Campaign

A high-level illustration of Prospector-1's acquisition and science (water-mapping) campaign is presented in Figure 6. During this remote sensing phase, a combination of sub-resolution visual imagery, mid-

wave IR imagery around the $3.1\text{ }\mu\text{m}$ water absorption band, and neutron spectroscopy will combine to create an extremely high-resolution volatile map of the target asteroid.

The broad sequence from target acquisition, to the creation of a complete hydrogen (water) map, to descent and landing, is summarized as follows:

1. Identification of asteroid against background stars.
2. Proximity course corrections, acquisition of long-range ($\sim 10\text{ km}$) stationkeeping.
3. Early-stage asteroid images returned, major surface features identified.
4. Thermal neutron counter receives confirmation of hydrogen in near-subsurface.
5. Reduction of stationkeeping range with continued imaging.
6. Position hold at medium-range ($\sim 1\text{ km}$) from target.
7. High resolution imaging.
8. Begin north-south drift maneuver for hydrogen mapping.
9. Creation of hydrogen map from differential thermal neutron count as asteroid rotates beneath Prospector-1; co-registration of hydrogen with visible and MWIR imagery.
10. Initial landing site selected; begin descent at sub-meter-per-second velocity using optical and inertial navigation.
11. Continue high resolution imaging on approach.
12. Constant-velocity touchdown, in-pass, in-sunlight; fast acquisition of telemetry from landing leg telemetry and beaconing of key data through X-band transponder.

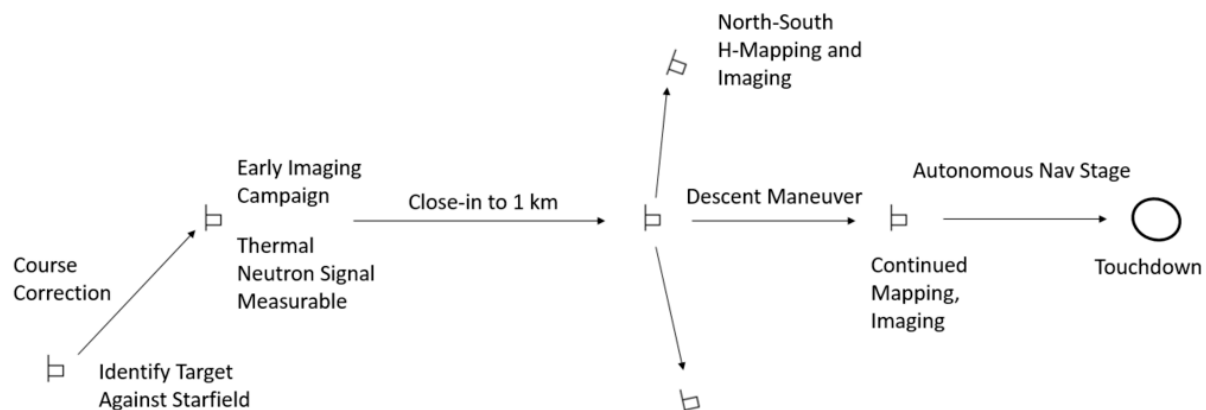


Figure 6: High-level sequence of Prospector-1 hydrogen mapping campaign

3.6 Remote Sensing and Neutron Survey

The Prospector-1 approach to neutron spectroscopy is sufficiently different from prior art that it bears further elaboration. Neutron spectrometry for the Moon, or for large asteroids such as Vesta and Ceres, has been historically done by performing hundreds of low-altitude mapping orbits. Asteroid neutron counting requires a different approach, where the asteroid rotates “beneath” the spacecraft, and the neutron count rate differs as new regolith is revealed on the dawn horizon while old material is hidden at asteroid-dusk. This method of horizon edge-mapping is expected to create a very high resolution map of hydrogen abundance, which is the marker for water, when co-registered with visible and mid-wave infrared imagery.

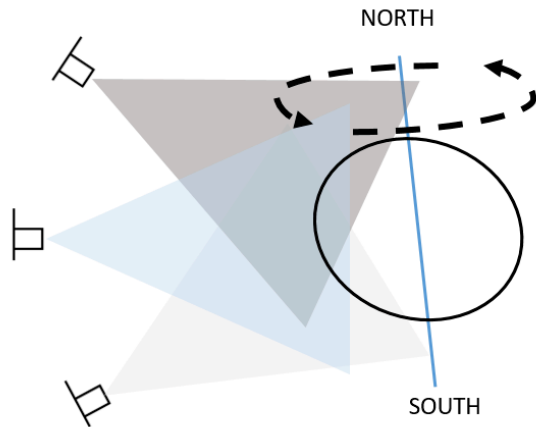


Figure 7: North-South drift creates a different dawn-dusk edge profile, adding a vertical component to the hydrogen map

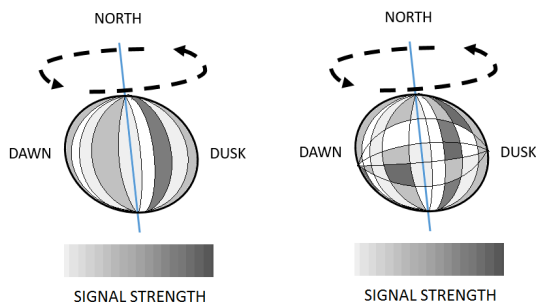


Figure 9: Hover perspective hydrogen map (left) vs north-south transition map. The initial hydrogen map will only have longitudinal resolution. As Prospector drifts north-south in the asteroid’s inertial reference frame, the map takes on a vertical component.

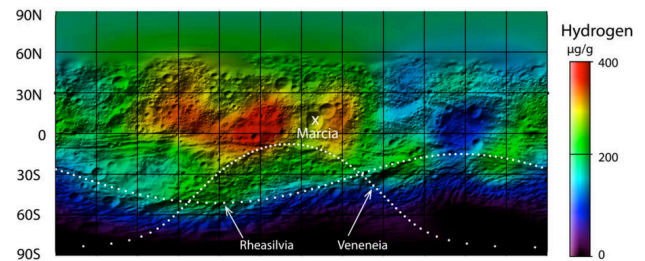


Figure 8: Example hydrogen map created from thermal neutron counting by the Dawn spacecraft on Vesta. A difference in count-rate of thermal and epithermal neutrons determines the moderator-quality of the regolith, which is indicative of hydrogen percentage [5].

3.7 Descent, Landing, and Geotechnical Reconnaissance

Prospector-1’s propulsion system has been sized to enable three months of proximity operations assuming a worst-case target asteroid size and range. There is expected to be ample time to perform the remote sensing survey described above. However, at end of mission, ostensibly the riskiest part will be attempted: trying to land the microspacecraft on the surface of the asteroid. There are two objectives to attempting to put down on the surface—the non-technical objective is to assert a presence and secure tenure at the asteroid for future mining; the technical purpose is to perform geotechnical reconnaissance.

The objective of the geotechnical reconnaissance is fundamentally to assess “diggability”. It is of limited value to know bulk volatile composition without understanding the mechanical and mineralogical characteristics of it, since it is the mechanical and other properties of the regolith that will inform the design of mining equipment. Put a different way: Prospector-1’s remote sensing will prove that the resources of interest are there, while touching down will tell us how difficult those resources will be to interact with and extract.

During the descent, the neutron counter should experience a change in relative signal strength indicative of water percentage heterogeneity of the regolith. The hydrogen map generated in Phase 9 will give an expected regional hydrogen percentage to the mapping resolution. If that expected signal strength differs relative to range during the descent, then Prospector-1 will have determined whether or not water is distributed relatively homogeneously or in concentrated pockets in the near subsurface.

At a controlled centimetre-per-second level velocity, Prospector-1 will attempt to put down. Accelerometers will measure the failure force of the regolith, after which shear and friction forces dominate and will also be measured. Once the spacecraft has come to a rest on the surface—assuming it does—temperature and magnetic measurements will be performed and beacons, along with imagery, while the spacecraft is still able. It is expected this is where Prospector-1 will remain: as the first permanent commercial station on an asteroid.

4. PRECURSOR MISSIONS AND ENABLING TECHNOLOGIES

Development of Prospector-1 is already underway at Deep Space Industries. However, there are several key partnerships and essential, cornerstone technologies that remain to be proven. DSI has planned a series of technology demonstration activities, through R&D activities and commercial activities, to reduce risk for Prospector-1.

4.1 Precursor Missions: Prospector-X

Before undertaking Prospector-1, DSI is currently developing a precursor mission for low-Earth orbit with the intent of flight-demonstrating several key Prospector-1 technologies. This mission, referred to as Prospector-X (the “X” denoting “experimental”), funded by the government of Luxembourg as part of their SpaceResources.lu initiative, will demonstrate

several key subsystems of Prospector-1, notably including its power system, command and data handling system, tracking, telemetry and command system, optical navigation, water-based propulsion system, and (TBC as of this writing) one of its key science payloads.

The Prospector-X nanosatellite (Figure 10) is a CubeSat scheduled for launch in Q3 2017. The mission will be assembled and tested in DSI’s European office, located in Luxembourg City.

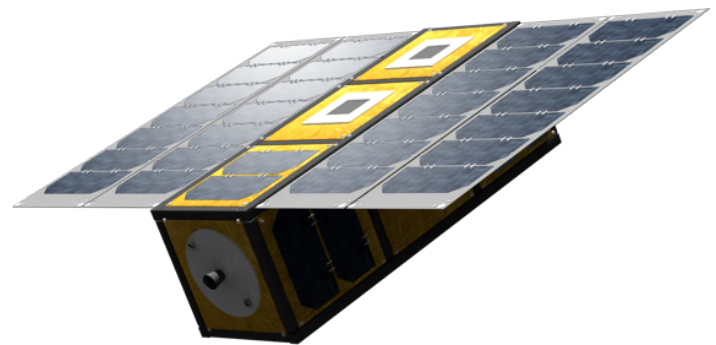


Figure 10: The Prospector-X Pathfinder Nanosatellite

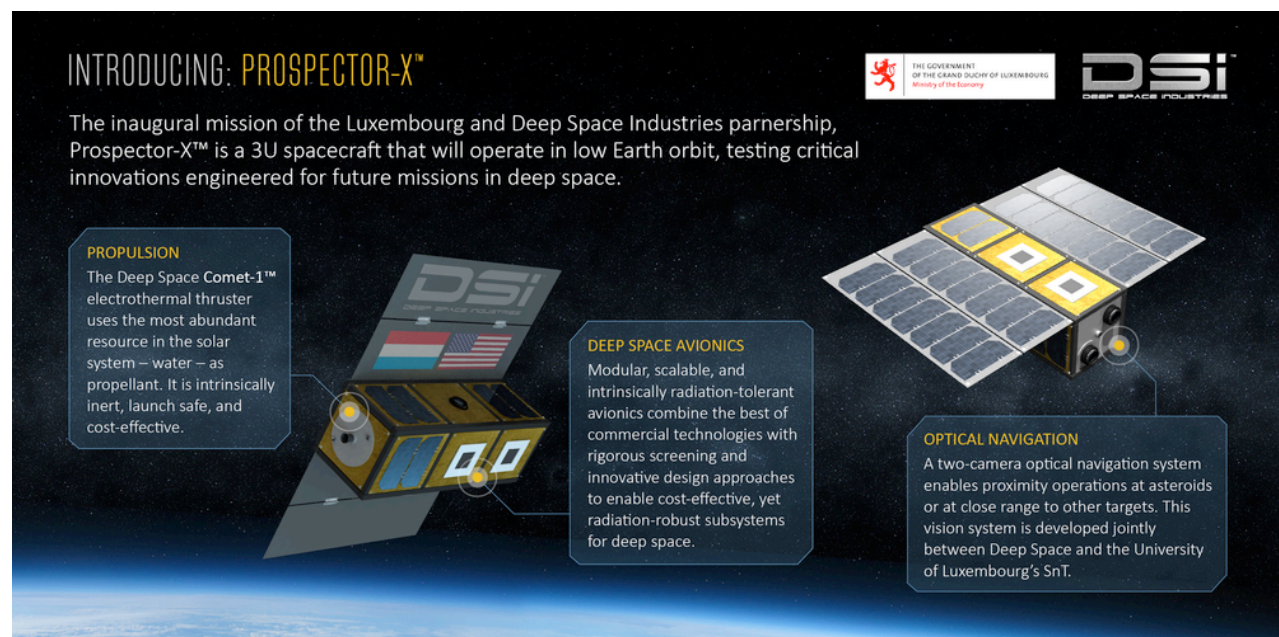


Figure 11: The Prospector-X nanosatellite, funded by the Government of Luxembourg

4.2 Precursor Missions: HawkEye 360

Recently, Deep Space Industries was awarded the mission prime contract on the HawkEye 360 Pathfinder mission. HawkEye 360 is developing a constellation of formation-flying micro-satellites in low Earth orbit (LEO) to execute a unique radio frequency (RF) spectrum monitoring and geolocation capability. The company's analytics engine generates reports on signals that can be used to track and monitor global transportation networks, detect distress alerts, assist with emergencies and much more. By implementing this exciting new concept, HawkEye 360 will provide highly accurate maritime domain awareness, establish a spectrum inventory, and develop insight into how signals are being used globally. Preparing for its product launch, HawkEye 360 is poised to address pressing needs of commercial and government customers worldwide.

Deep Space Industries—who is leading the mission with its manufacturing partner, the UTIAS Space Flight Laboratory—is notably contributing the same *Comet* water-based propulsion systems to each of the HawkEye satellites as it will be flying on Prospector-X, Prospector-1, and other commercial missions. Taken together with the deep expertise within DSI on small spacecraft formation flight, Deep Space Industries was awarded the HE360 contract in a competitive bid and is currently building the first three satellites of their constellation. The targeted launch is Q3 2017, similar to Prospector-X. A single HawkEye 360 microsatellite is shown in Figure 12, with a cutaway showing DSI's *Comet-1* thruster in Figure 13.

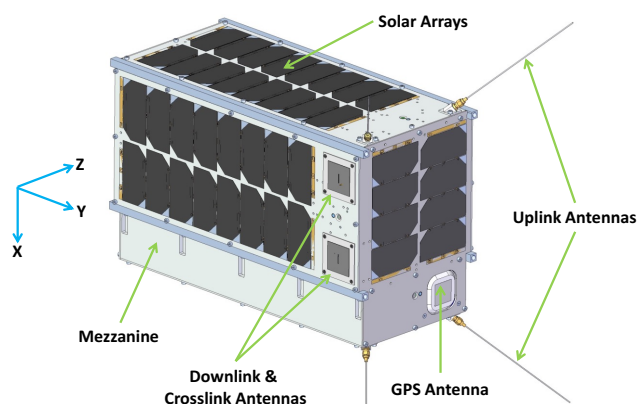


Figure 12: HawkEye 360 Satellite Concept – each spacecraft is a small approximately 10 kg microsatellite, with roughly 40 x 30 x 20 cm dimensions.

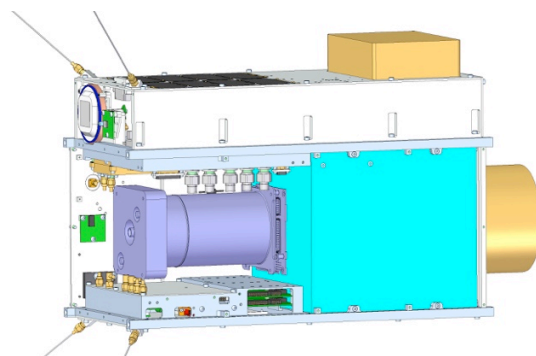


Figure 13: HawkEye 360 Spacecraft Cutaway with Extended DSI Comet-1 Thruster (Purple)

4.3 DSI Comet Thruster Line

The common, cornerstone technology shared across all DSI missions—from its ambitious *Prospector-1* asteroid mission, to its risk-reduction *Prospector-X* precursor, to the first three HawkEye 360 microsatellites launching in 2017, is the DSI-developed *Comet-1* water electrothermal thruster.

Comet-1 is an electrothermal thruster that uses an extremely high-temperature chamber to heat and exhaust superheated water vapor to produce thrust. The thruster is intrinsically simple and robust, and most significantly, uses the most inexpensive and ubiquitous propellant available on Earth and elsewhere in the solar system: water. This thruster is depicted in **Figure 14**, with a functional block diagram of the thruster presented in Figure 15.

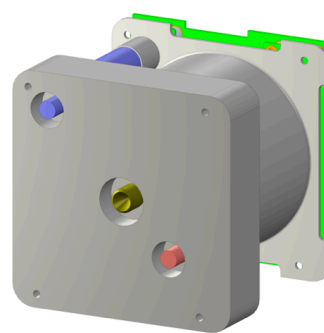


Figure 14: 1U Water Electrothermal Thruster

While *Comet-1* is ultimately intended for a small microsatellite developed by DSI, the base unit being employed by HawkEye 360 and Prospector-X is CubeSat-compatible, in response to the ever-growing number of users and customers in the CubeSat space.

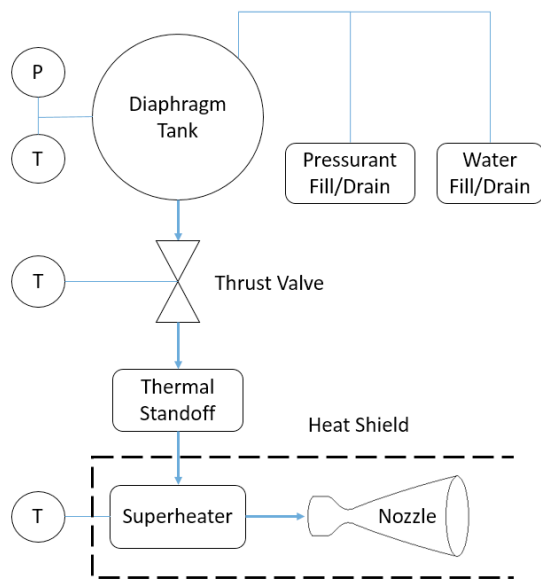


Figure 15: Comet-1 Simplified Functional Block Diagram for Prospector-1

Additionally, while the Prospector-1 implementation employs a bladder tank and pressurant to feed water into each thruster manifold, the smaller thrusters flying on DSI's missions next year employ a proprietary feed system that entirely avoids high-pressure components on launch. This enables, among other benefits, a propulsion system that is completely safe for delivery, deployment, and even fueling on board the International Space Station.

Comet-1 is so-named as the first in a line of *Comet* thrusters for a reason. Additional propulsion technologies on DSI's roadmap include both solar thermal and helicon electric water thrusters, all fed by a common propellant management approach. As stated early in the paper: DSI is endeavoring to create an ecosystem of products today that can be supplied by space resources in the future. And the future of space resources is water.

5. CONCLUSIONS

Deep Space Industries was founded with a bold ambition to industrialize the frontier by harvesting space resources: derived from space, for use in space, for the betterment of humankind and the expansion of life in general. The vision is large, but the implementation begins small: with extremely low-cost, small spacecraft to prove that asteroid resources are indeed prospective. At the same time, DSI is generating both key technologies and a spacecraft platform that

others can use for a wide variety of Earth orbit satellite applications and low-cost space exploration missions.

From the small beginning of Prospector-1, DSI will attempt to set the stage for the exploration of space using small spacecraft in general. It is among our foundational beliefs that we are living at the most exciting time for space exploration: in which a larger number of smaller, lower-cost missions will enable a new understanding of the solar system, and usher in a new era of space exploration that is more open to a larger number of commercial and government actors.

In short, Deep Space Industries is attempting to stand on the shoulders of what the small satellite community has accomplished to date and take the next obvious step for this community: beyond Earth.

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