PLANETARY RESOURCES' COMMERCIAL APPROACH TO ASTEROID MINERAL EXPLORATION.

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Introduction: Near-Earth asteroids (NEAs) have long been considered a potential source of valuable in-space resources for the utilization and expansion of the space economy. In the early 2020s, Planetary Resources, Inc. (PRI), a commercial space resources company headquartered in Redmond, WA, intends to embark on the first commercial mineral exploration of NEAs for the specific purpose of assessing the economic viability of available water as a source of propellant for in-space customers. The extraction of water from carbonaceous asteroids for propellant has the potential to lower launch costs, easing access to space.

Mission Philosophy: In its approach to asteroid mining, PRI draws parallels from the terrestrial mineral resource industry, which operates on multi-decadal lifecycles comparable to that required for asteroid mining. The "exploration" phase of a mine lifecycle includes up to a decade of reconnaissance and appraisal that involves understanding the availability of the resource, the geotechnical properties of the deposit, and the resulting value. There is so little currently known about carbonaceous asteroids that any commercial mission must address fundamental scientific questions about the asteroid before designing a mining operation.

Target Selection: While the 2018 arrivals of the *OSIRIS-REx* and *Hayabusa2* spacecraft to carbonaceous NEAs will advance the community's understanding of these bodies, the carbonaceous chondrite collection indicates the potential for wide diversity among their parent bodies. This also includes the possibility of a target that is not economically viable, necessitating a multiple-target approach to mitigate risk to mission success. As such, PRI has established a target selection funnel for identifying the top asteroid mission candidates from a pool of 17,000+ NEAs. The process hinges on selection via three key properties:

1. Value: C-complex or X-complex typing favored for higher potential of bearing water.
2. Accessibility: diameter, Orbit Condition Code, valid Earth-to-asteroid trajectories are available in the Exploration phase (2020-2022).
3. Exploitability: sufficient transport trajectories exist (Earth-asteroid & asteroid-Earth) to make mining economically viable within the active mine phase (2030-2040).

These criteria are continuously applied as more NEAs are discovered or characterized to identify up to six exploration targets from the entire set.

Objectives: PRI will send a robotic spacecraft to each of the targets to perform a survey that addresses the following key objectives:

1. Confirmation of the available water and estimation of the grade and tonnage of the resource.
2. In-situ sampling and liberation of the water resource from the NEA's bulk material.
3. Evaluation of the NEA's thermal, mineralogical, and mechanical properties to inform next steps.

From these objectives, the scientific questions that the spacecraft must answer are not dissimilar from those of a science-driven mission. Some of these questions include: What does the NEA look like? How much water is present? What happens when you touch it? What are its chemical, physical, and geological properties?

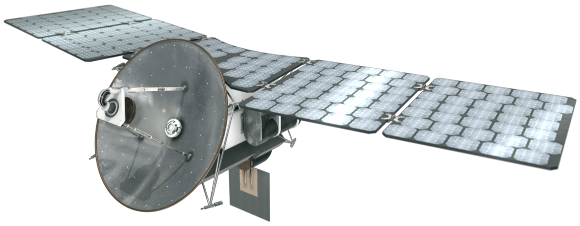
Payload: To address the mission objectives, the payload on each spacecraft will include a broadband visible imager, a near-infrared spectrometer, and a set of four deployable, instrumented penetrators, each carrying an accelerometer and a water liberation experiment. The resulting measurements are outlined in **Table 1**.

Table 1. Payload and corresponding measurements.

Instrument	Measurement
Broadband Visible Imager	- shape - rotation state - visible imagery for geology and navigation
Near-infrared Spectrometer	- global and regional water abundance/distribution - thermal inertia
Instrumented Penetrator	- regolith strength - water liberation - temperature of water liberation
Radio Science	- mass

Spacecraft: The mission requires multiple spacecraft to rendezvous with targets scattered throughout near-Earth space. Identical small ESPA-class spacecraft allow all spacecraft to share the same launch, greatly decreasing cost for a mission of this complexity (**Figure 1**). Low-thrust propulsion makes NEA targets more accessible while allowing all spacecraft to depart for their own targets when starting from C_3=0 parabolic orbit provided by the launch vehicle.

Figure 1. Spacecraft rendering.



A general challenge of this small-spacecraft, multi-target approach is the limitation of resources available to each spacecraft, which can negatively impact the data return. The mission combats this with both autonomy and onboard data processing (when possible). The mission concept of operations is illustrated in **Table 2**.

Resource Assessment: Traditionally, ore grade (wt%) and tonnage (mass) are estimated using drill cores. In PRI's approach, the primary spacecraft data used to assess the amount of water on targets are sparse, spatially distributed point measurements of the 3-µm water/hydroxyl absorption feature. A library of representative meteorite spectra coupled with thermogravimetric analysis of their wt% water will permit a quantitative interpretation of NIR spectral data for the abundance of water on the target. We are developing a statistical method that uses the spectral library to simulate plausible hydrated mineral distribution data, which is then used to infer grade and tonnage. The penetrators will be used to confirm the presence of subsurface water and our ability to extract it from the bulk asteroidal material.

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Table 2. The concept of operations for PRI's mineral exploration mission.

Phase	Description	Duration
Launch	Launch vehicle imparts sufficient energy for all spacecraft to reach edge of Earth's sphere of influence	2 hours
Commissioning	Ensure each spacecraft is performing nominally & calibrate instruments	30 days
Cruise	Use propulsion system to execute thrust profile to rendezvous with each asteroid target	<2.5 yr
Approach	Characterize asteroid sufficiently to travel within the radius it gravitationally dominates	30 days
Preliminary Survey	Use a series of flybys to measure the asteroid mass and shape; handover to relative navigation.	25 days
Map	Create global maps of hydration and imagery used to identify Regions of Interest (ROIs)	65 days
Recon	Collect more detailed information about ground-selected ROIs	32 days
Deploy	Deploy in-situ instrumentation packages below the surface; relay data to ground	52 days
Margin	Margin to account for unforeseen circumstances	90 days