HIGH FRONTIER: THE FIRST ASTEROID EXCAVATION MISSION.

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Introduction: Karman+ is a commercial venture that seeks to mine space resources from near-Earth asteroids to provide abundant, sustainable energy and resources in space and for Earth. Asteroids can contribute substantially to resource availability while also reducing harmful externalities, although uncertainties remain related to asteroid material characteristics and the cost effectiveness of deep space mining [1]. We stand convicted that these uncertainties are not obstacles to asteroid mining but do require bold efforts to address. Our first mission, High Frontier, addresses these challenges head on. The mission is funded and targets a late 2026 launch with the following objectives:

1) Rendezvous with a near-Earth asteroid;
2) Capture regolith from the surface at kilogram scale;
3) Maintain a total mission cost (s/c, operations, launch, R&D, etc) in the range of $20-30 million; and
4) Provide scientific data on the asteroid, including surface imaging and select physical measurements.

This is a technical demonstration mission and its objectives focus on commercial viability. Namely, with High Frontier we seek to address the cost-effectiveness of deep space mining missions as well as the scalability of regolith excavation. We use the term excavation with particular emphasis given the distinction of kilogram-scale capture in contrast with small-scale scientific sampling.

Our effort builds on collaboration with the scientific community as well as lessons learned and data captured from previous space missions, including: asteroid interaction missions such as OSIRIS-REx (NASA), Hayabusa 1 and 2 (JAXA), DART (NASA), Lucy (NASA), small-sat deep space missions like CAPSTONE (NASA), survey missions such as Gaia and Euclid (ESA), and the growing number of public and private lunar missions.

Regolith Age: These previous efforts show that asteroid mining is feasible and with High Frontier we will further demonstrate that it is scalable and that we have arrived at the critical inflection point of technical progress and innovation to open the Regolith Age.

Asteroid regolith will enable economic activity in orbit at scale. We are targeting regolith excavated from carbonaceous asteroids, which is a soft mixture of hydrated clays, nitrogen, methane, iron, cobalt, magnesium and a wide range of other trace elements [2,3]. We intend to process this regolith to liberate water and other consumables for customers in Earth orbit. High Frontier is the first step on our roadmap to provide these at a cost less than $10,000 per kg. Today's buyers would include GEO satellite operators, the U.S. Space Force, public space agencies from around the world, and incumbents and startups providing logistics services in orbit.

Beyond these immediate use cases, asteroid regolith as feedstock for space-based additive manufacturing, will be a pivotal component of the infrastructure essential for the growth of the space economy and it opens the doors for more ambitious efforts such as space-based solar power [4,5].

Lower cost per kilogram. Space missions are normally designed as highly complicated, risk-averse, bespoke projects, driven by sprawling requirements. Our roadmap is focused on executing multiple simple, robotic, low-cost missions that make incremental steps in three core technologies that we develop internally:

- Zero-G mining;
- Regolith processing; and
- Autonomy.

High Frontier sets the pace for this by demonstrating that a low-cost deep space mission that captures kilograms of material can be developed and flown for under $30 million in less than 3 years. Meanwhile, we are actively seeking collaboration on research for creating ceramics in space from asteroid regolith [6].

Spacecraft and Mission Design: We have developed a mission architecture that exploits the likelihood that there are thousands of rubble-pile like near-Earth asteroids that are yet to be discovered [7], including those reachable with delta-V budgets less than is required to reach and return from the lunar surface [8]. By establishing a fundamental mission and spacecraft design around this segment of asteroids we will be able to replicate and scale this mission as more asteroids are discovered and characterized, including by the Rubin Observatory [9]. To support this targeting analysis, we have developed an extensive data ingestion and modeling engine, *compono,* to evaluate and filter candidate asteroids.

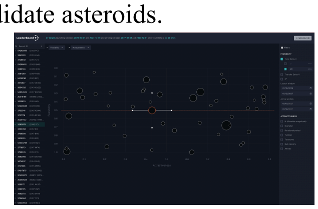

Figure 1. Screenshot of the Karman+ "leaderboard" produced by *compono* for target asteroid analysis.

ConOps: The High Frontier Concept of Operations (ConOps) is to: attain an initial Low-Earth Orbit via a rideshare launch, execute a "spiral-out" maneuver to reach Earth escape velocity and enter into a heliocentric orbit, continue on an interplanetary cruise, during which we plan to test “autonav” capabilities following heritage established by Deep Space 1 [10], Deep Impact [11], and Stardust [12] missions, rendezvous with the target asteroid, maintain stationkeeping to further characterize it and identify candidate landing sites, descent to the surface and capture kg-scale regolith, and communicate sample data to Earth. The extended mission would include multiple descent maneuvers to explore excavation and autonomous technologies that allow us to scale operations in subsequent missions. Furthermore, we issued a Request for Proposal (RFP) to carry independent scientific instruments and have selected two proposals for measuring asteroid composition and permittivity that we are refining further as part of our payload.

We considered prospecting missions that would remotely capture data, but ultimately determined that given the importance and uncertainty of asteroid regolith attributes [1], we must demonstrate the ability to excavate material at scale. We also recognize that while we must deliver regolith payload to an Earth orbit, as an initial mission such a return approach could not be conducted in a cost- and time-effective manner and would prohibit the faster, more iterative approach we believe is necessary to advance our multi-mission roadmap. High Frontier thus hits the right balance of cost and cadence while still demonstrating deep space capability, rendezvous with an asteroid, and scalable excavation.

Spacecraft platform and systems. We have a preliminary platform design that will have a dry mass of less than 500 kg powered by a Solar Electric Propulsion (SEP) system. The platform will have structural, avionics, and communications systems capable of long-duration deep space missions. The integrated payload includes excavation assembly and a navigation system with cameras and onboard image processing capacity to support optical navigation via triangulation using “beacon” asteroids and our mapping and relative navigation maneuvers during Proximity Operations. We plan to use optical navigation to perform these tasks.

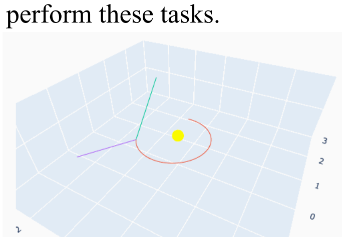

Figure 2. Illustration of the use of asteroid beacons (sitelines in purple and green) for navigation during interplanetary cruise (s/c trajectory in red).

Excavation: Given the extreme conditions we expect, including micro-gravity, and surface conditions that will be completely unknown prior to arrival at the asteroid, excavation technology represents an important and complex path of research and development. The excavation assembly we are developing will be optimized for C-type asteroids but will have to be robust to a variety of surface conditions and asteroid types. It will also need to perform across a diverse range of grain sizes and strengths and of course, successfully capture kilograms of material. We are developing a novel battery of analyses, simulations, and physical tests required to mature this technology given the expected extreme conditions in the field.

Call to engagement. We value transparency and collaboration as we develop this mission, such as with the referenced science payload RFP. We have also partnered with researchers to help us identify and characterize target asteroids and here again we seek possible collaborations for this. Furthermore, given the uncertainties related to material science and the compelling opportunities for research into regolith processing, we are keen to collaborate with interested parties to develop this aspect of the asteroid mining value chain and help bring about the Regolith Age.

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