High Frontier: A Private Asteroid Excavation Mission

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Karman+: To mine Near-Earth Asteroids (NEAs) to provide abundant, sustainable energy and resources for the space economy.

https://www.karmanplus.com/about/

Karman+: About us

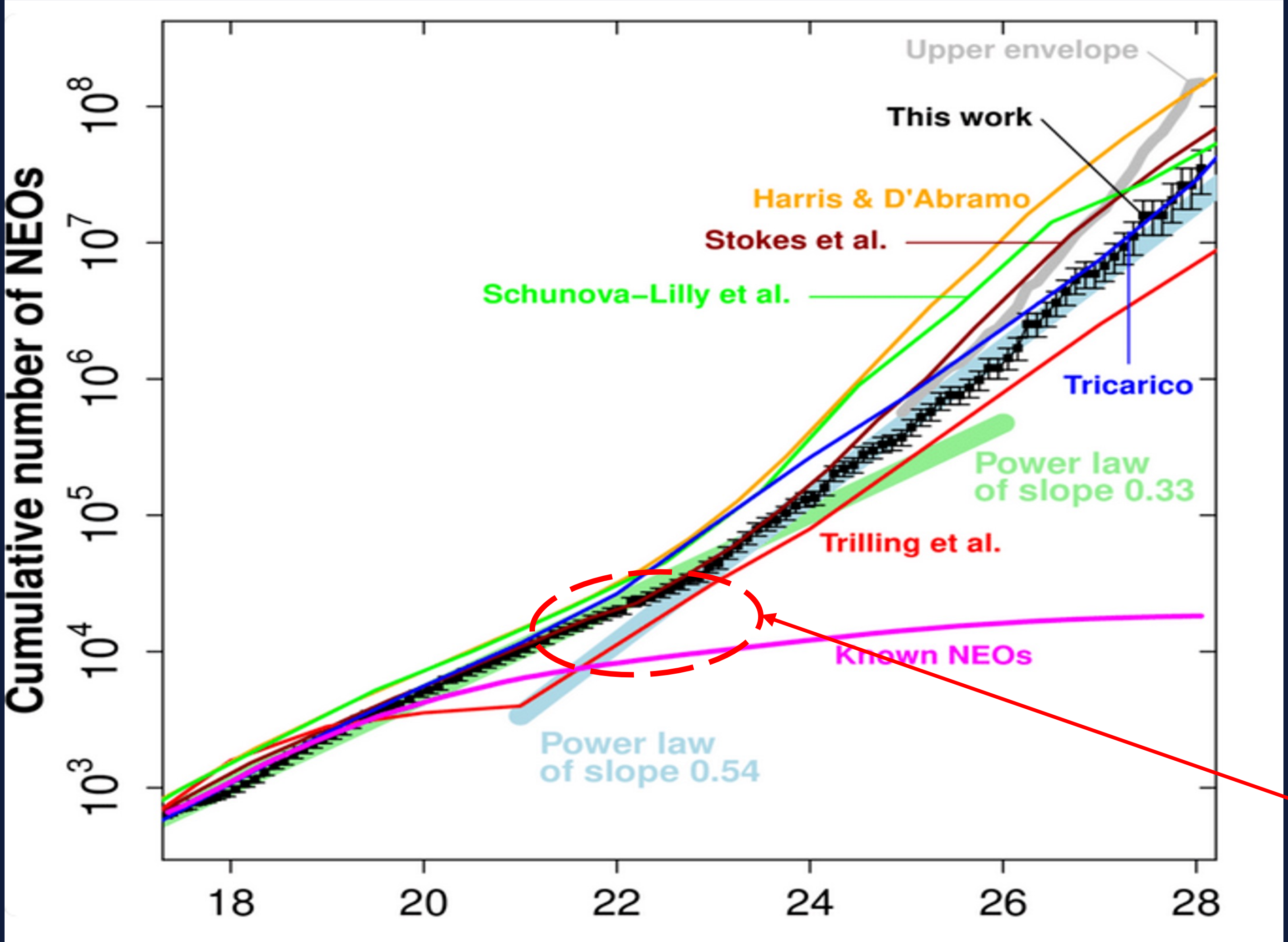
Denver-based

15 engineers, scientists, analysts, roboticists

12+ jobs currently posted
https://www.karmanplus.com/jobs/

Blend of space veterans from JPL, Lockheed Martin, SpaceX, iSpace, and others – including with asteroid mission experience (NASA OSIRIS-REx, NASA DART) – as well as from outside the space industry.

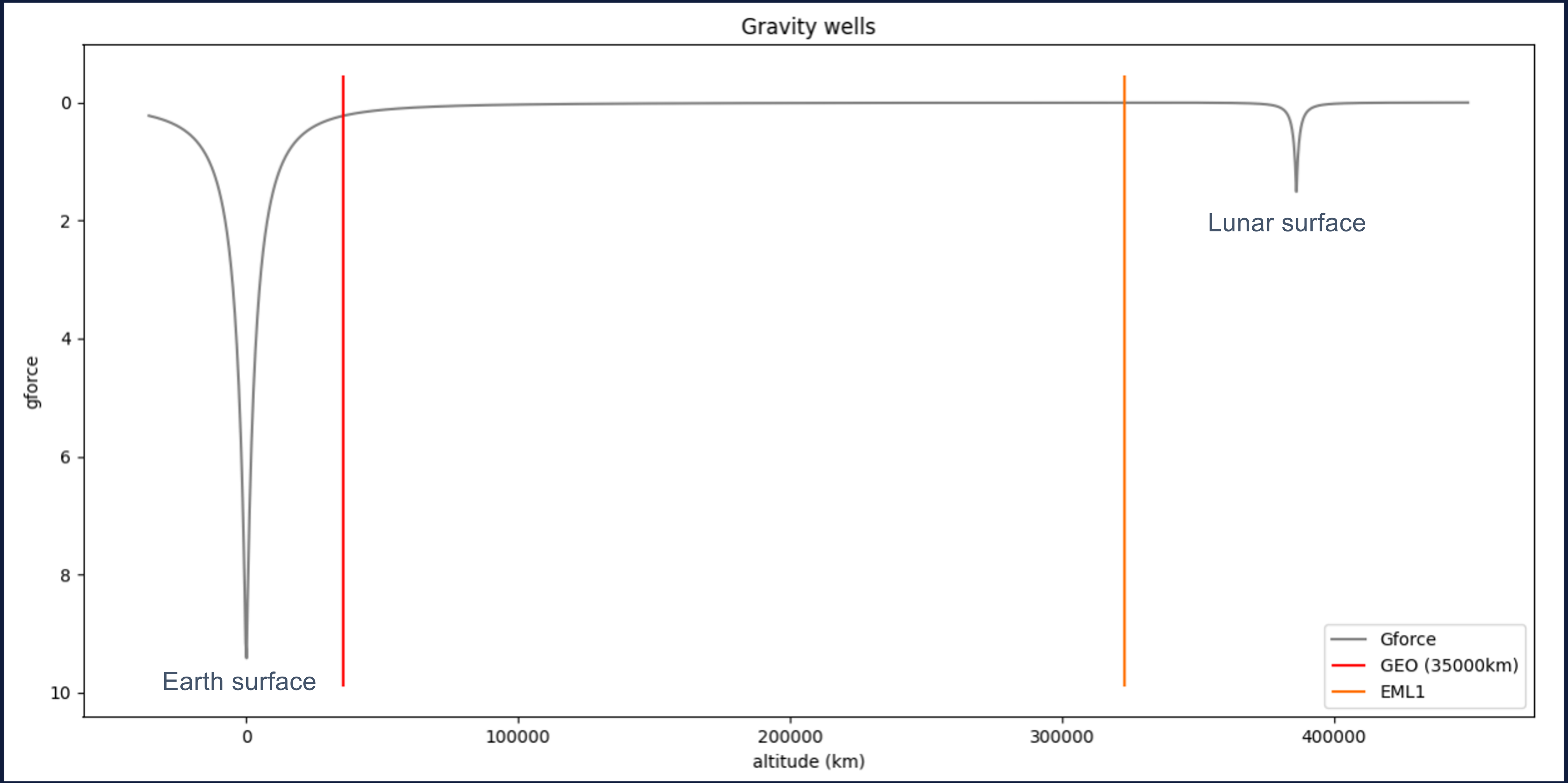
Asteroid regolith will enable economic activity in orbit with accessible resources at **scale.**



Many thousands of NEAs in our sweet spot of ~200m+ diameter yet to be discovered.

Source: [1]

Asteroid regolith will enable economic activity in orbit with **accessible** resources at scale.



Building a bridge to the Regolith Age

0. Exploration

Establish company, team, technical focus, approach, feasibility analysis

Exit criteria: Critical path established, K+1 Mission defined (High Frontier)

COMPLETED

1. TAG

Multiple small s/c missions for mass return to cislunar.

Exit criteria: Master/scale (1) Deep Space and (2) Mining in zero-G
$/kg trend to $10,000

IN PROGRESS

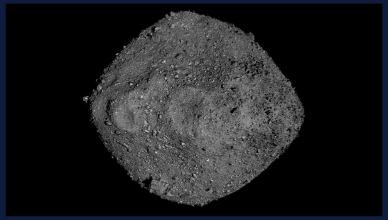


Image credit: NASA

2. Mine & Tug

Processing at asteroid, including s/c components.

Exit criteria: Master/scale (3) ISRU w/ advanced regolith products.
$/kg trend to $100

SBSP Image credit: Karman+

3. Whole buffalo

Use and move entire asteroids to build massive structures.

Exit criteria: Transformative, including heavy manufacturing and energy (SBSP).
$/kg trend to $0.01

Image credit: Amazon Studios

4. Expanse

Move Earth-centric operations to asteroids, including main belt.

Karman+ technical focus

Deep Space Missions

Robotic, low-cost and reliable

Mining in Microgravity

Excavating regolith

Asteroid ISRU

Extracting and processing regolith at the asteroid

K+ mission 1: **“High Frontier”**

Tech and Capability demo mission

Mission complete in 2027
$20 million

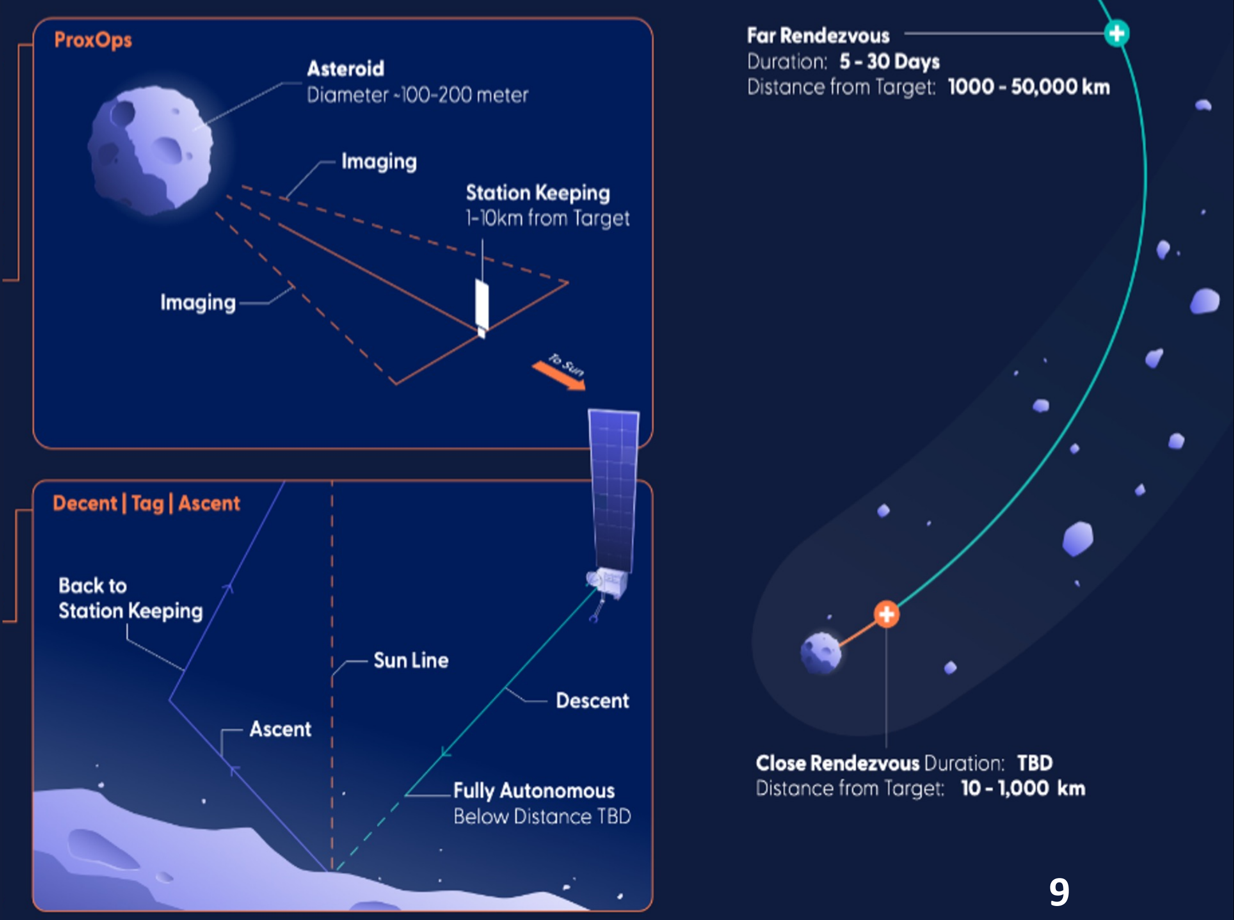
Mission objectives:

1. Rendezvous with near-Earth Asteroid
2. Capture sample from surface at kg-scale
3. Transmit data confirm sample capture

Extended mission objective:
Multiple attempts to land on surface and test excavation and performance and autonomous operations

Current preliminary design and concept of operations:

- Launch a SEP spacecraft ~700/750 kg to Low Earth Orbit in H2 2026
- Perform a spiral Earth escape
- Begin interplanetary cruise ~550kg
- Throughout cruise use optical navigation onboard the spacecraft to enable autonomy
- Rendezvous with the mining target asteroid, targeting Q4 2027
- Perform station keeping while building an onboard asteroid map
- Descend to the asteroid using simultaneous localization and mapping
- Perform excavation demonstration 1 during a touch-and-go maneuver
- Ascend back to station keeping
- Perform a mass estimation maneuver
- Downlink results
- Perform additional TAG excavation with alternate equipment
- Use a University of Tokyo developed dielectric analyzer science instrument



Tech focus: **Deep Space Missions**

Goal:

- **Adaptable and generalizable mission design**

Identified archetype asteroid:

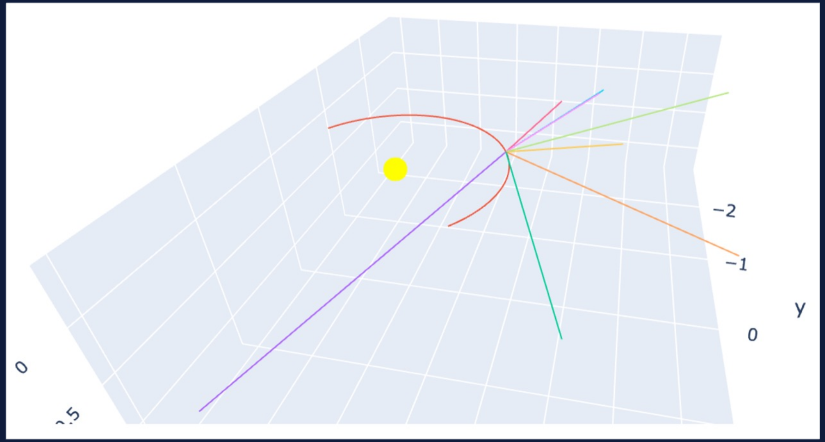
- C-type NEA 150-300 m in diam. (relative frequency, interesting resources, we have sample data!)

Probabilistic thinking for target selection "compono" (right)

Launch vehicle flexibility

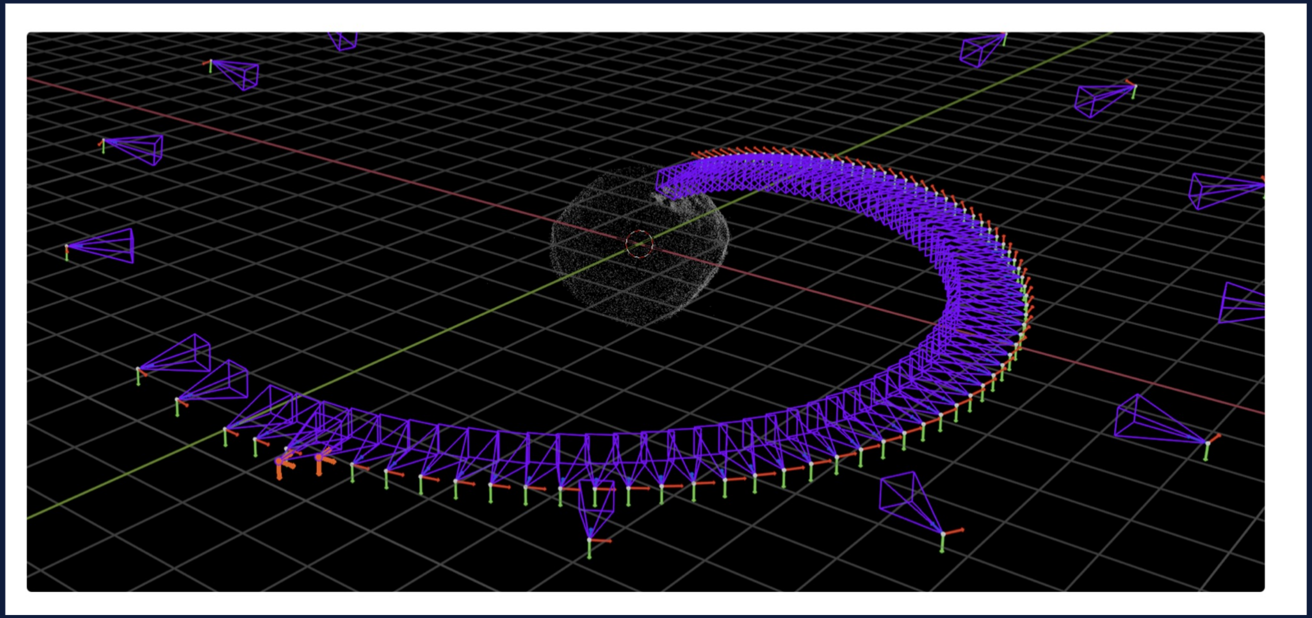
- An emerging market of higher energy rides
- presents challenges and opportunities –
- flexibility is critical (orbit, launch window, mass)

Tech focus: **Deep Space Missions**



Goal:

- **Mission autonomy** so we can remove reliance on the ground and explore asteroids with little/no prior data



Vision navigation technology::

- Beacon Nav (top right)
- Simultaneous Location and Mapping (SLAM) (bottom right)

Highlight: autonomous cruise

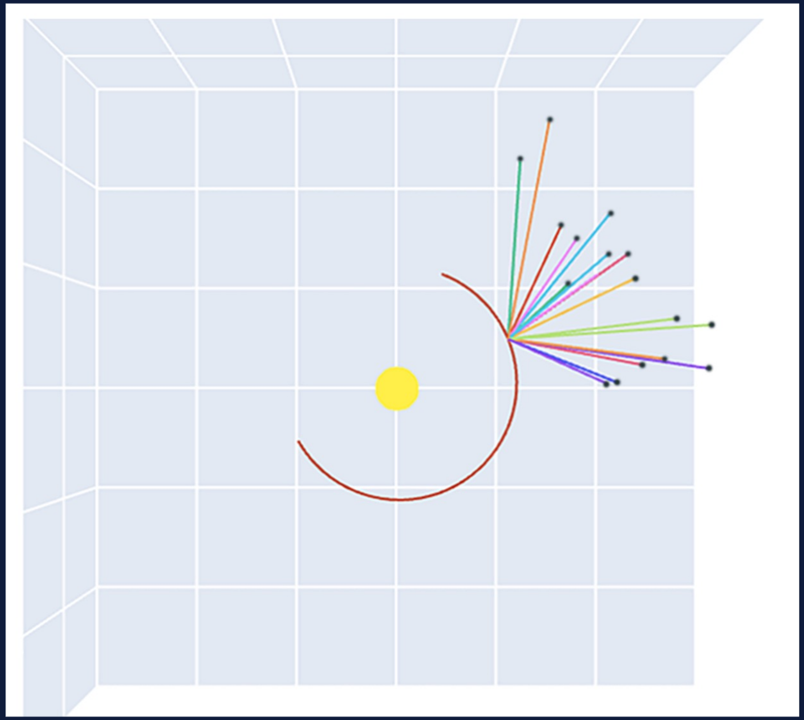
- Deep Space 1 demonstrated onboard SEP trajectory adjustments during interplanetary cruise[2,3,4,5]

Other interplanetary SEP missions have used operation cadences for ground teams to modify trajectories as needed

- Karman+ will use an onboard linear corrector[3] for optional thrust adjustments
  - Thrust segments defined between non-thrusting comms periods
  - Determine the target miss distance
  - If needed/allowed, use existing thrusting plans to modify one or more thrust segments

Highlight: beacon navigation

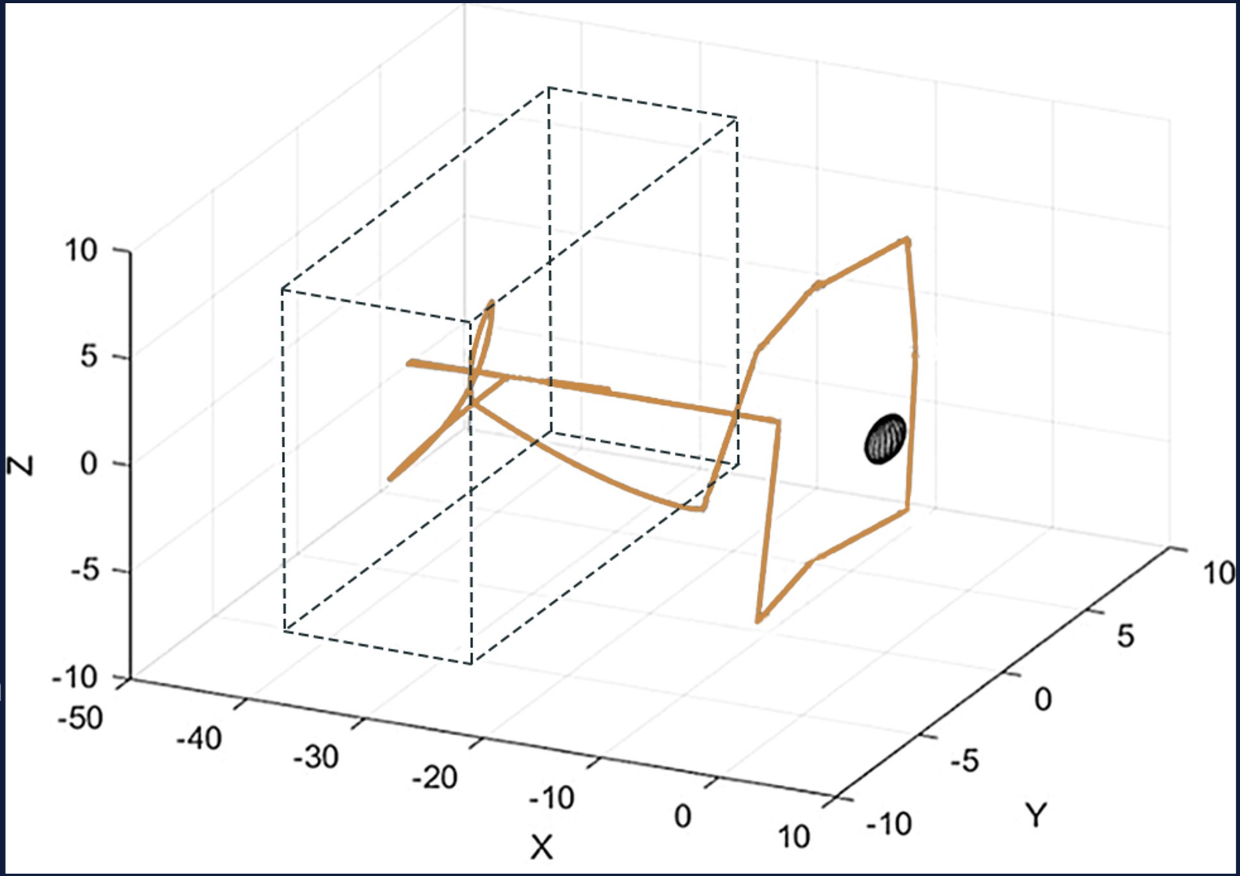
- Beacon Asteroid Navigation Covariance Analysis:
  - Karman+ adapted kinematic methods for beacon asteroid navigation[6] for determining the spacecraft inertial state with optical navigation
  - The covariance analysis models the Karman+ camera and performs beacon asteroid navigation with nominally 0.1 pixel measurement errors in the observed images



Example of available asteroid beacons with the Karman+ camera able to observe apparent magnitude 11.5 objects

Highlight: station keeping and mapping

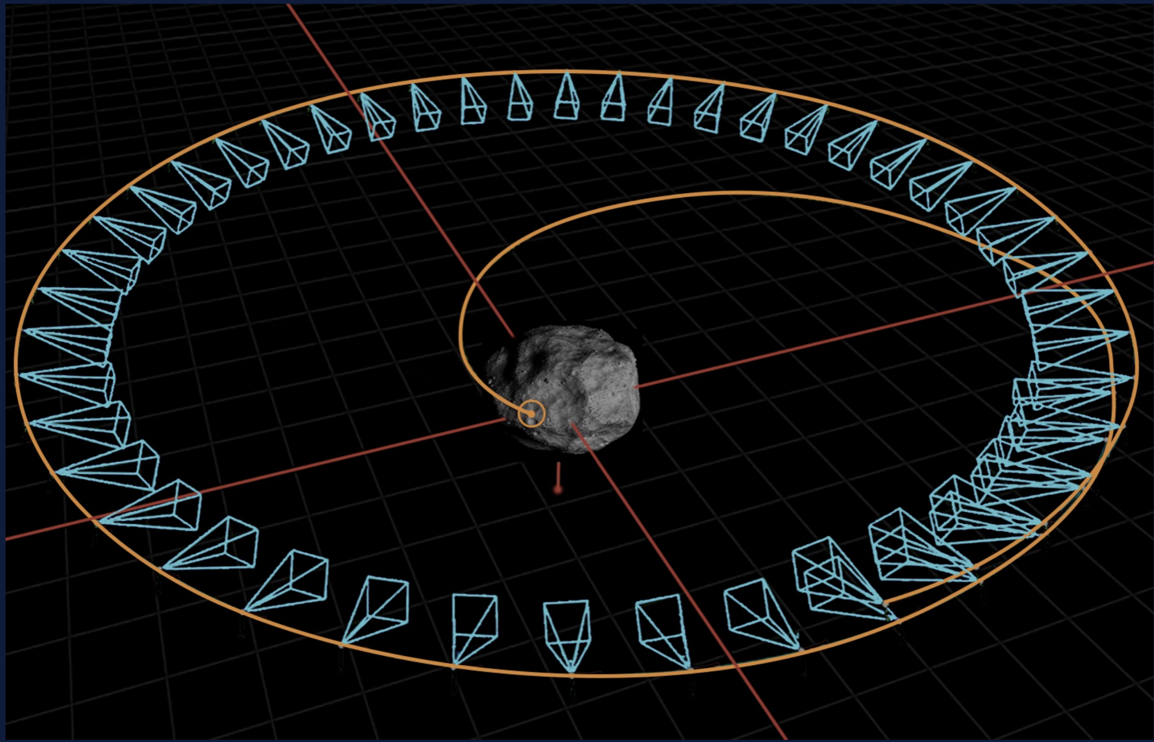
- Spacecraft will autonomously maintain relative distance and inertial offset to asteroid safe position 5 km sunward and within 1 km of the asteroid sun line.
- Asteroid will be characterized using narrow field of view camera from safe standoff distance (~1 km)
  - Maintaining relatively constant inertial offset and pha angle
  - Ground sample resolution of 2-5 cm
- Target landing site will be specified relative to map built during this phase, from limited subset of downlinked imagery.



Spacecraft maintaining a station keeping boundary from the asteroid along the sunline. Higher resolution imagery at varying lighting angles can occur at dedicated stations closer to the asteroid

Highlight: Closed Loop Rendezvous, Proximity Operations and Descent

- **Onboard map using SLAM during descent, avoiding high resolution mapping operations and extensive downlink/uplink.**
- Target selection and closed loop guidance and control occur during RPO/Descent simulation
  - Blender is used for image simulation and Cycles for independent/flexible OpNav simulations.
  - Closed loop guidance and control have navigation prototypes and mechanisms to migrate to flight code.
  - Process and results verified against analytical models and measurements of full formation mapping/SLAM.
- Descent is a diagonal path to match tangential surface and desired vertical velocity at contact.



Asteroid Fixed Frame View of the End-to-End Closed Loop Simulation of SLAM Based Landing Site Matching Descent Trajectory Execution. The yellow line starting from the right hand side is the descent trajectory from the surface mapping standoff location.

Tech focus: Deep Space Missions

Goal:

- **Low cost**

COTS + approach: Radical diligence (test /question everything mindset)

- Identify performance capability and all paths to that.

Streamlined s/c platform and systems across multiple missions.

Spacecraft Design Overview

The spacecraft bus is a modification from a GEO focused bus design.

- Key platform components include: EP thruster w/ 2 axis gimbal, reaction wheels, RCS thrusters, star trackers, IMUs, GPS, near-Earth comms/LGA

Supporting a payload for interplanetary operations, asteroid proximity operations and asteroid excavation.

- Optical Navigation system (WAC, NAC, graphics processor), HGA/deep space comms, excavation technology

Tech focus: **Mining in Microgravity**

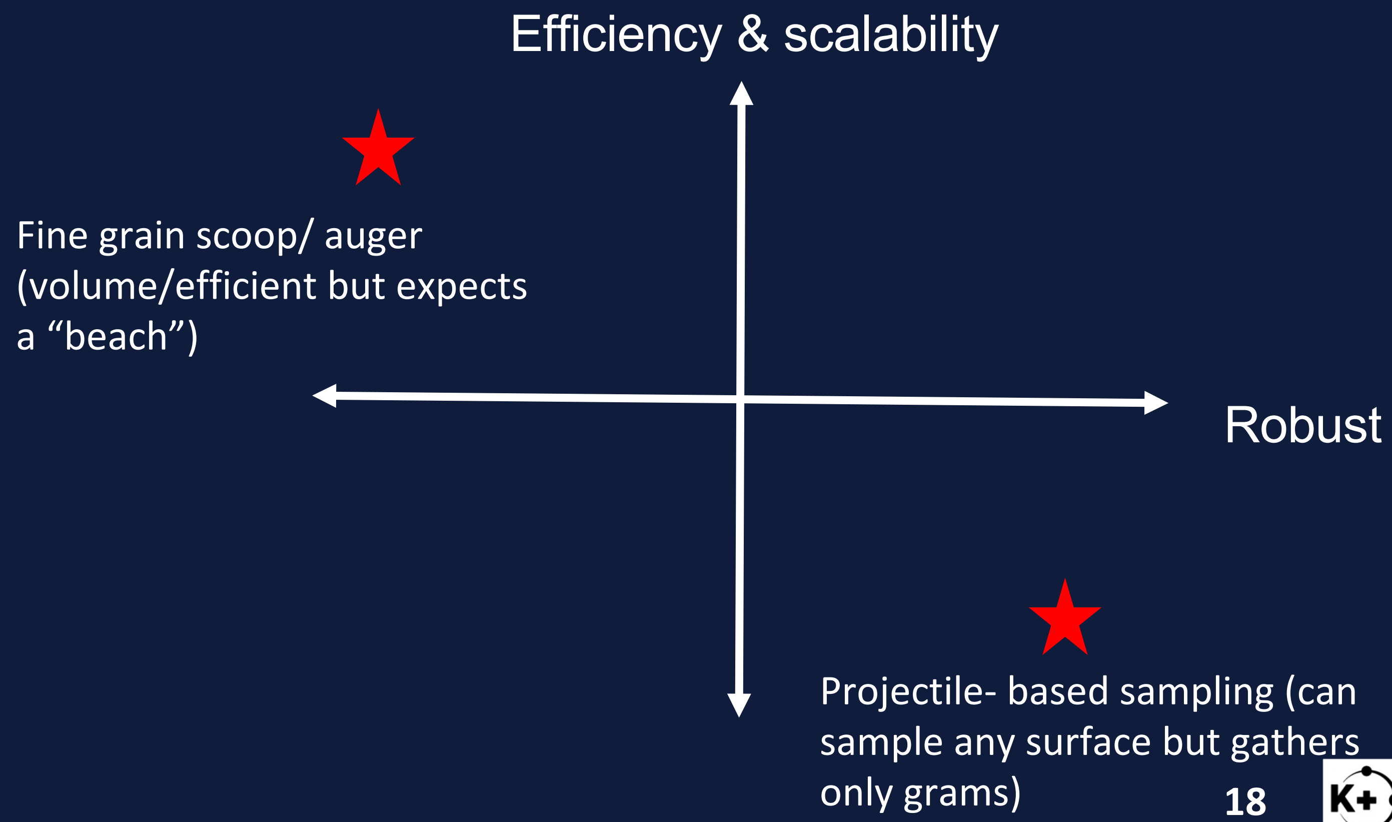
Future state:

- Scalable (1000s kgs)
- Robust to varied and unknown surface conditions
- Extreme field conditions (temp, micrograv)
- Rapid technology advancement

Balance of robustness vs efficiency/scalability

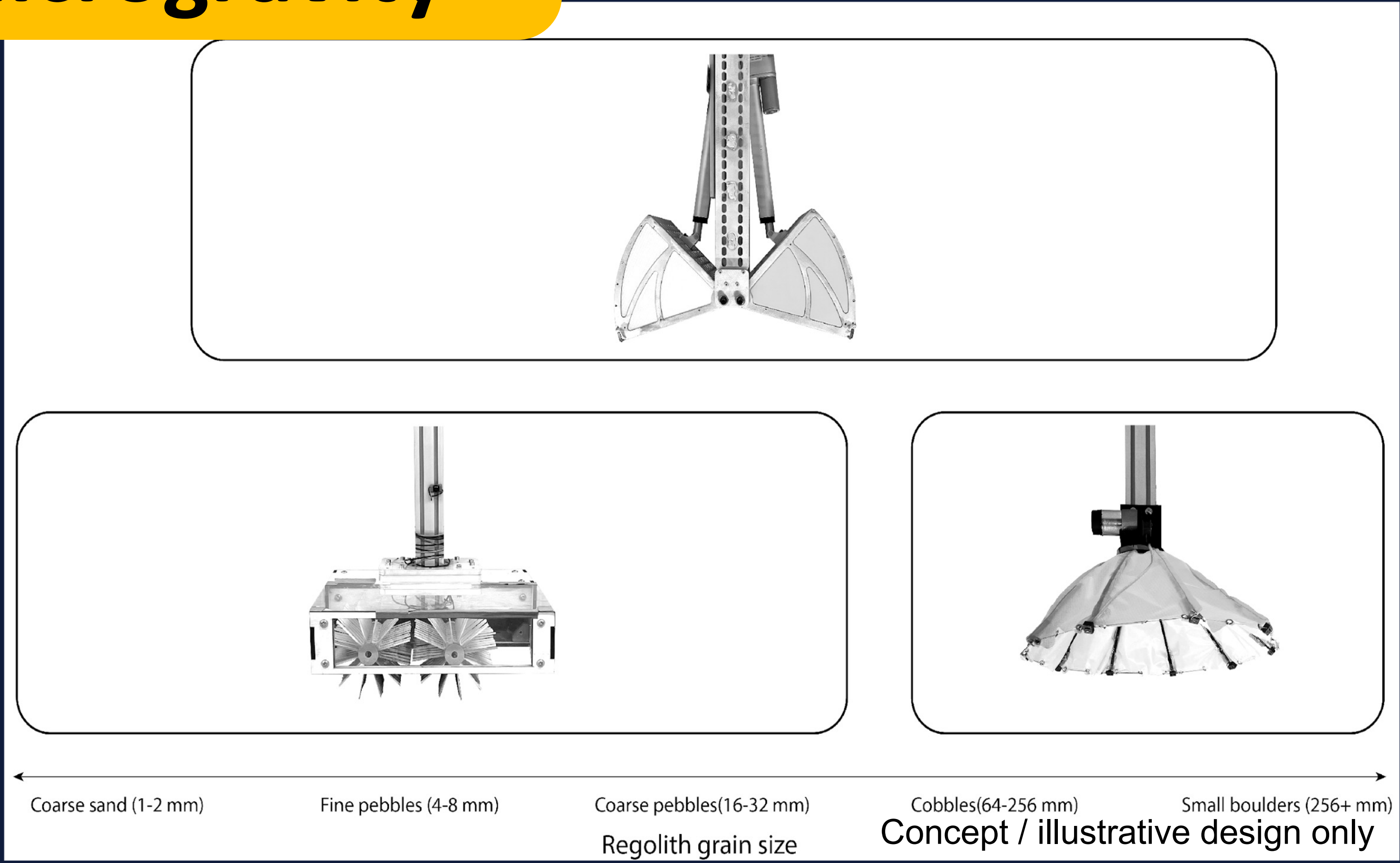
Testing:

- Novel test suite
- Blend sims w/ physical tests
- Approx to microgravity
- Little known granular dynamics
- LIttle known regolith strength
- Little known regolith composition



Tech focus: Mining in Microgravity

- A range of excavation options was developed to be resilient to the unknown asteroid environment (shown conceptually at right)
- TAG GNC requires maximizing flexibility to excavation methods and keeping spacecraft safe
  - The touch portion will be up to 30s
  - Autonomous ascent will occur early if the spacecraft tips more than 10 degrees.



Tech focus: Asteroid ISRU

Future state:

- Propulsion use case
- Extract, refine (probably in transit from asteroid)
- Deliver to customers in Earth orbit

Issued an RFP for science instrumentation → HF science payload: Surface Dielectric Analyzer

東京大学
THE UNIVERSITY OF TOKYO

Developing our own high-fidelity asteroid simulant in partnership with TU-Berlin.

- Test extraction and storage/transport methods
- Prelim testing of use cases for propellent and additive manufacturing feedstock

Call to action

- Register for updates on the website: https://www.karmanplus.com/k-company-update-q1-2024/

- Open to partnerships / collaboration on the focus areas:
  - Deep space
  - Mining in microgravity
  - Asteroid-based ISRU

References:

[1] Heinze, A. N., Larry Denneau, John L. Tonry, Steven J. Smartt, Nicolas Erasmus, Alan Fitzsimmons, James E. Robinson et al. "NEO population, velocity bias, and impact risk from an ATLAS analysis." The Planetary Science Journal 2, no. 1 (2021): 12.

[2] S. Bhaskaran, J. Riedel, S. Synnott, and T. Wang, “The Deep Space 1 Autonomous Navigation System: A Post-Flight Analysis,” AIAA/AAS Astrodynamics Specialist Conference, Denver CO, Aug 2000.

[3] S. D. Desai, S. Bhaskaran, W. E. Bollman, C. A. Halsell, J. E. Riedel, and S. P. Synnott, “The DS-1 Autonomous Navigation System: Autonomous Control of Low Thrust Propulsion System,” AIAA Guidance, Navigation, and Control Conference, New Orleans, LA, August 1997. (AIAA-97-3819).

[4] S. Broschart, N. Bradley, and S. Bhaskaran, “Kinetmatic Approximation of Position Accuracy Achieved Using Optical Observations of Distant Asteroids,” Journal of Guidance, Control, and Dynamics, Vol. 56, No. 5, 2019, pp. 1383–1392.

[5] J. Riedel, S. Bhaskaran, S. Synnott,W. Bollman, and G. Null, “An Autonomous Optical Navigation and Control System for Interplanetary Exploration Missions,” AIAA, Washington DC, 1996.

[6] S. Broschart, N. Bradley, S. Bhaskaran. “Kinetmatic Approximation of Position Accuracy Achieved Using Optical Observations of Distant Asteroids” Journal of Spacecraft and Rockets 56.5 (2019), 1383-1392[18] A. Madni, N. Bradley, D. Cervantes, D. Eldred, D. Oh, D. Mathews, and P. C. Lai, “Missed Thrust Requirement for Psyche Mission,” AIAA Propulsion and Energy Forum, Virtual, 2020.