AAS 24-301

HIGH FRONTIER - A PRIVATE ASTEROID EXCAVATION MISSION: DESIGN AND DEVELOPMENT ANALYSIS

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Karman+ is developing a mission called High Frontier to a near-Earth asteroid for kilogram scale regolith excavation. Our first mission is taking on a number of mission design and navigation challenges. Solar electric propulsion will perform the Earth escape spiral and interplanetary cruise. To reduce ground resource dependencies during cruise, optical navigation will be processed by an autonomous navigation system. Descent to the asteroid will use simultaneous localization and mapping to maneuver "touch-and-go" use of excavation equipment. This paper will go over the design, tools, and techniques under development and analysis in preparation for a preliminary design review.

INTRODUCTION

Karman+ is aiming to excavate regolith from carbonaceous asteroids, which is a soft mixture of hydrated clays, nitrogen, methane, iron, cobalt, magnesium and a wide range of other trace elements.[1,2] As the first step towards that goal, we are currently developing a regolith mining mission, named High Frontier, to an uncharacterized near-Earth asteroid. Launch is planned for the fourth quarter of 2026 with the primary mission objective of multi-kilogram scale extraction from the asteroid's surface.

Karman+ is taking on a number of mission design and navigation challenges during its first mission. The spacecraft will use a solar electric propulsion (SEP) Hall-Effect Thruster (HET) to perform its Earth escape spiral and interplanetary cruise. High Frontier will launch as part of a rideshare into low Earth orbit (LEO). The spacecraft will perform a time optimized spiral escape prior to its interplanetary voyage. To reduce dependency on ground communication resources, during interplanetary cruise the spacecraft will perform optical navigation which will be processed by an autonomous navigation system. Novel excavation equipment designed for kilogram scale extraction in zero-g will be demonstrated.

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The High Frontier Preliminary Design Review (PDR) is scheduled for October 2024. This paper provides context of the mission, insights on requirements, and supporting analysis for PDR preparation. The paper focuses on the mission design, navigation, and GNC elements of the High Frontier program.

First an overview is provided of the mission and spacecraft for context on trades and requirements. Methods to provide a sufficient interplanetary SEP cruise in support of optical navigation and asteroid rendezvous are detailed next. Covariance analysis model rationale are described next with examples relevant for operational considerations. The "Autonomous System" section scopes the onboard autonomous navigation and guidance methods and the prototyping that enables the tight development timeline. The simultaneous localization and mapping (SLAM) PDR simulation status is described with an example. In June 2024 a selection of the High Frontier excavation equipment occurred, with the results briefly described. Lessons learned during the initial analysis tool build-up and component selection from the perspective of a privately funded small team are shared. This is the first paper which details Karman+'s High Frontier mission design, navigation, and GNC process, status, and future work.

SPACECRAFT AND MISSION OVERVIEW

Mission Overview

With High Frontier Karman+ will demonstrate that asteroid regolith extraction is scalable and that we have arrived at the critical inflection point of technical progress and innovation to open the "*Regolith Age*".[3] To show the commercial viability of asteroid regolith extraction, the first mission's objectives have been bounded with the following criteria:

1. Rendezvous with a near-Earth asteroid
2. Capture regolith from the surface at kilogram scale
3. Maintain a total mission cost (spacecraft operations, launch, research and development, etc) of $20 million
4. Provide scientific data on the asteroid, including surface imaging and select physical measurements.

Karman+ will launch a spacecraft to LEO in Q4 2026, where a spiral Earth escape starts. Once interplanetary cruise begins, optical navigation used onboard the spacecraft will enable autonomy. The rendezvous with the asteroid is targeted for Q4 2027 through Q1 2028. Stationkeeping will be performed while building an onboard asteroid map. The spacecraft will descend to the asteroid using SLAM and perform excavation demonstration one during a touch-and-go (TAG) maneuver. It will then ascend back to stationkeeping where results are downlinked and a mass estimation maneuver is performed. Once the excavation demonstration one critical telemetry is downlinked, the spacecraft will complete additional TAG excavation with alternate equipment and use a science instrument developed at the University of Tokyo, the Surface Dielectric Analyzer (SDA).

The missions Deep Space 1,[4] Hayabusa,[5] Hayabusa2,[6] OSIRIS-REx,[7] and Psyche[8] offer inspiration and lessons for High Frontier to reduce risk while advancing the state of the art during the interplanetary cruise and asteroid interfacing phases. Deep Space 1 was a SEP spacecraft which demonstrated "AutoNav", using beacon asteroids for navigating interplanetary cruise and then for multiple flybys. Karman+ draws on Deep Space 1 based techniques to scope autonomy during the interplanetary cruise. Hayabusa and Hayabusa2 showed SEP spacecraft utilizing stationkeeping at an asteroid, before performing TAG asteroid sampling. The High Frontier mission will similarly perform stationkeeping at the asteroid during proximity operations. OSIRIS-REx used "natural feature tracking" (NFT) optical navigation for descent and TAG asteroid sampling. NFT navigated by way of an onboard catalog of landmarks extracted from a detailed shape model built with ground based Stereophotoclinometry (SPC). Motivated by our desire for reduced communications and more autonomy, the High Frontier spacecraft will autonomously map the asteroid onboard using visual SLAM. The Psyche spacecraft is the only SEP Hall-Effect thruster mission to operate beyond the Earth's sphere of influence. High Frontier has a Hall-Effect thruster, making the Psyche work detailing the margin policies, sequencing processes, development experience, modeling, and flight preparations relevant. While High Frontier will begin its mission from LEO, the SMART-1[9] mission, which completed a spiral from geosynchronous transfer orbit (GTO) injection to a lunar orbit with a Hall-Effect thruster, provides insights concerning radiation single event upsets and safe mode important for Karman+ to consider for a successful SEP Earth escape.

Flexibility to the target mining asteroid is a key aspect of the High Frontier mission. Karman+ has completed scoping work to determine potential target asteroids for mining operations, resulting in a shortlist of some tens of potential target asteroids for High Frontier. Among other physical qualities, the target would ideally be a carbonaceous asteroid with a rotation period slower than the 2.2 hour spin barrier to maximize the likelihood of finding loose unconsolidated material on the asteroid surface.[10]

For the Karman+ asteroid mining operations to reach profitability, the target asteroids must be reachable both in terms of deltaV and time of flight to minimize spacecraft mass and operations duration. As the High Frontier spacecraft design advances, the team will down select targets to meet its capabilities. The quality of the selected target asteroid's physical characteristics must be balanced against the deltaV, time of flight, and launch window constraints. High Frontier is targeting carbonaceous asteroids but is robust to all other types except M-types due to their harder surface material. Similarly, asteroid rotation rates accepted will be based on spacecraft design constraints for surface velocity. To develop the potential asteroid target list, initial trajectory assessments are performed with Lambert trajectories.

Karman+ is developing SEP trajectories while refining toolsets to account for specific operation constraints. Karman+ is also expanding capabilities to analyze optical navigation techniques, plan asteroid proximity operations, and increase analysis fidelity generally. Because of the uncertainty on the final asteroid target, excavation equipment is being prepared for a variety of surface conditions. The developments thus far are on a path to meet the mission objectives.

Spacecraft Design

Karman+ is pursuing a development path involving a close relationship with a spacecraft bus provider. The payload developed by Karman+ enables interplanetary operations, asteroid proximity operations, and asteroid excavation. The spacecraft bus is a modification from a LEO/GTO/GEO focused bus design. The Psyche mission pursued a similar path for the spacecraft, with a MAXAR based spacecraft bus as a base, with NASA/JPL requirement based alterations to enable its asteroid exploration.[11] Karman+ expects its entire payload to be contained within one region of the finalized spacecraft. This allows Karman+ to provide a "bolt on" payload and facilitate testing prior to spacecraft integration delivery. Described in this section are the current pre-PDR spacecraft design selections for High Frontier.

Karman+ key decisions influencing the bus design are total deltaV capacity, propulsion type, risk posture, and solar array configuration. The nominal deltaV capability will be 14 km/sec. With 14 km/sec deltaV, it is expected that a time optimal Earth escape spiral from LEO could be pursued while leaving the interplanetary phase around 6 km/sec. Karman+ currently reserves about 1 km/sec of deltaV for asteroid operations including proximity operations and excavation attempts. The amount of fuel allotted to asteroid operations will be refined and can be traded against the fuel for interplanetary cruise and asteroid approach. Xenon was selected as the fuel of choice, as it should provide some deltaV capacity benefits over krypton. A fringe benefit of the xenon selection is that it was chosen for all beyond Earth SEP missions[12] which may make their experiences more applicable to the High Frontier spacecraft.

Karman+ has decided to use a single solar array to reduce the required size for a workable, hazard free area for excavation available on the asteroid. A single solar array can be perpendicular to the asteroid surface as the excavation occurs. A drawback is that the asymmetrical design makes solar radiation pressure a significant disturbance. To deal with reaction wheel desaturations, Karman+ is opting for a "momentum management roll." To desat, the spacecraft will roll about the thrust axis so that once completed the solar radiation pressure will produce torque on the solar array in the opposite direction than before the roll. It is expected that the EP engine will be able to maintain thrusting during the momentum management roll.

The mission risk posture considers the limited lifetime of the High Frontier mission. Karman+ is tailoring its radiation and fault tolerance to ensure spacecraft survival without overly limiting hardware selection or driving redundancies increasing mass. Karman+ has begun performing radiation testing for components of high interest instead of limiting to components that come qualified from vendors. There is an acceptance of having limited single fault tolerance. Extra hardware carried can also account for some additional desired capacity instead of traditional pure redundancy.

The Karman+ payload final mass goal is 60kg. The payload package provides deep space communication, select GNC sensors, a dedicated computer, excavation equipment, and supporting avionics and structures for those devices. The deep space communication system includes a high gain antenna (HGA) and the ability to perform two-way coherent radiometric communications. A potential payload layout is shown in Figure 1.

Its GNC sensors include one narrow angle camera (NAC), one wide angle camera (WAC), and a laser range finder (LRF). The WAC needs to be in focus at 1km to the target asteroid and have a field of view of minimally 20 degrees. For the interplanetary cruise autonomy desired during the mission, it has been determined that the NAC must be able to detect objects with an apparent magnitude up to 11.5. This capability will increase the availability of potential asteroids to use during "beacon navigation", detailed later. For observing apparent magnitude 11.5 objects, depending on the final spacecraft design, the trades for integration time and coadding frames will be considered. A NAC with an optical resolution of 50 $\mu\mathrm{rad}$ increases the accuracy for determining the location of the beacon asteroids and their observation. The achievable navigation accuracy scales linearly with the optical resolution. Such an optical resolution also benefits the asteroid surface mapping, while allowing a reasonable stationkeeping distance. A NAC total field of view of around 5 degrees is desired. A camera which starts the mission with very low read noise and dark current is desired, as it is known that radiation exposure which will occur during the Earth spiral escape can significantly increase those noise sources.

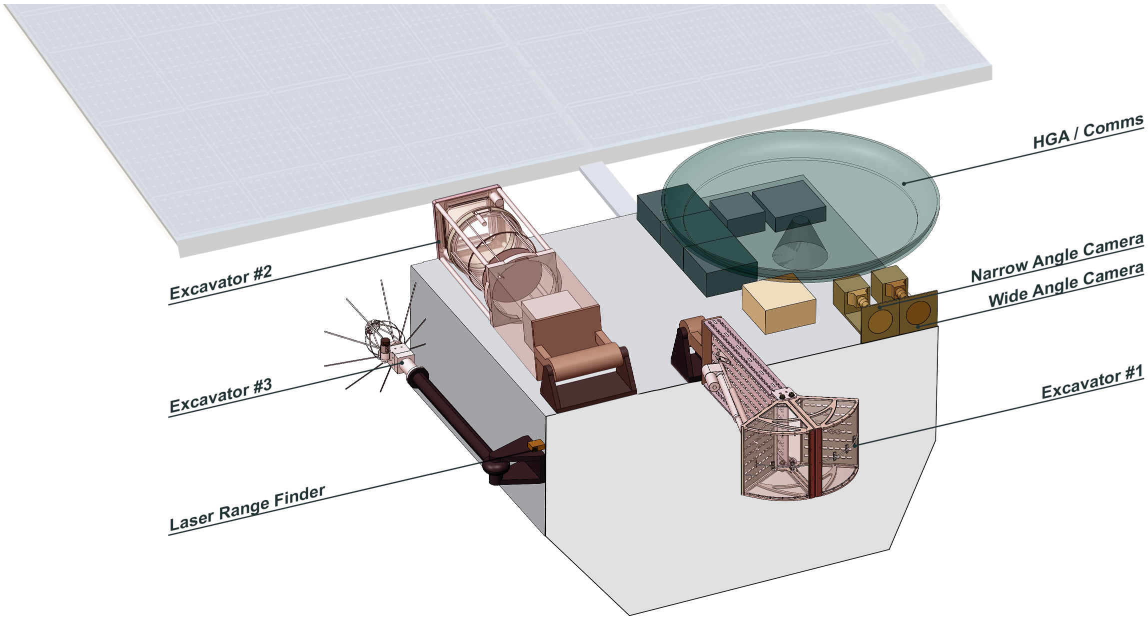

Figure 1: Karman+ Payload Layout Example

An LRF will provide direct line of sight distance measurements to the asteroid. This provides initial scaling of the asteroid for combination with the optical measurements of the asteroid, then helps to maintain proximity operations with stationkeeping. The Jenoptik DLEM 20LE[*] is the current baselined LRF. Karman+ brought a DLEM20LE through total ionizing dose (TID) and proton dosing tests, while in modes relevant to the mission use cases. The DLEM20LE survived the testing and initial post dosing testing showed acceptable performance was maintained.

Within the Karman+ payload a dedicated computer is responsible for its activities. This computer is primarily responsible for performing the interplanetary and asteroid operations guidance and navigation calculations, controlling the payload communication, GNC, and avionic devices, and interfacing with the bus. Performing SLAM is the driving capability for the payload computer performance. Avionics for a power distribution unit, switches, serial interfaces, thermal control, and harnessing for the payload devices are within the Karman+ scope as well.

The excavation system is baselined to have three excavation tools which will be detailed later. Critical excavation system logic is maintained within its own controllers. The payload computer will provide the excavation system details on the estimated time to the asteroid surface and relevant spacecraft system information. Excavation system cameras will record their performance and success.

The commercial spacecraft bus will provide the near Earth communication system, the electric propulsion system, power system staples such as gimballed solar arrays, the spacecraft computer, and the remaining GNC equipment necessary. The near Earth communication system of the bus will serve as the interplanetary low gain antenna (LGA). The bus' computer has the logic and controls for implementation of thrusting, attitude, base fault management, and other spacecraft life maintenance activities. To ensure sufficient state knowledge and control, four reaction wheels, two star trackers, and two IMUs will be used. For Earth operations, a GPS system would be available. The

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[*] `https://www.jenoptik.us/products/lasers/laser-distance-sensors/dlem`

reaction control system (RCS) thrusters are maintained by the bus with their placement approved by Karman+ to meet asteroid proximity and excavation operations.

The bus electric propulsion system includes a 2-axis gimbal to maintain thrusting through the center of mass. An example of an appropriate thruster for the Karman+ mission is the Busek BHT-6000[*]. In addition to its nominal capabilities, its inclusion in the NASA Gateway program means the level of rigorous testing desired for an interplanetary spacecraft's thruster has already begun. The BHT-6000 testing for NASA Gateway is using xenon propulsion.[13] Should the BHT-6000 be the final selected thruster, having xenon propulsion would make its Gateway testing especially relevant to Karman+.

TRAJECTORY DESIGN

Trajectory design for the High Frontier mission is broken into two main phases, the Earth escape trajectory and the interplanetary trajectory which will rendezvous with a target asteroid. Although the bus provider would provide Earth operations, Karman+ needs a model of the spiral escape for deltaV tracking, escape timing, and initial conditions for the interplanetary trajectory. Karman+ uses the MONTE[14] software to simulate a basic velocity direction burn until Earth escape conditions are achieved. The thruster duty cycle settings are being used as a stand in for operational constraints which would impact escape timing. The escape simulation is being enhanced with logic to look for eclipses and set burn start and stop times accordingly. The plan for the Earth phase trajectory is to deal with the majority of any escape inclination deficiencies during the interplanetary segment to save deltaV. QLaw[15] or other targeting methods may come into play as the design is refined or more operational constraints are considered. At this point in preliminary design preparations, the focus has been on having representative spiral escape conditions and a functional pipeline from spiral escape to beginning interplanetary trajectory.

The interplanetary SEP trajectories are being developed with the MONTE capability MCOLL. MCOLL uses collocation and mesh refinement techniques to determine an optimal trajectory with minimized error for the polynomial degree, segments, and tolerances set. The user can set a variety of constraints on boundaries, paths, and points. MCOLL allows multiple legs which can have different optimization priorities, thrusting definitions, multibody gravity, solar radiation pressure, and other scenario considerations. MCOLL has been verified against the JPL Mystic program, which was used to design the trajectories of the Dawn and Psyche spacecraft.[16]

The trajectories under development all use an 80% duty cycle. This accounts for spacecraft activities that will necessitate thrusters being off, such as HGA communications. The duty cycle also accounts for margin for inefficiencies in the thrusters as well as the very early phase of the mission development. MCOLL will identify trajectories which make use of optimal coast, periods with no nominal thrusting, but during thrust periods will restrict the thrust capability to 80%. Future work will reduce the duty cycle closer to asteroid approach to account for additional spacecraft activities, and adjustments to the trajectory after the asteroid has been sighted. Prior to flight, the Psyche mission margined trajectory design to have an 80% duty cycle between Earth and Mars, and up to a 50% duty cycle during Psyche approach and orbital operations.[17] As the spacecraft design advances and the final target asteroid is selected, Karman+ may opt to increase the duty cycle as prior interplanetary SEP missions have done.[18]

Initial SEP investigations for a target asteroid of interest have simplified assumptions such as

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[*] `https://www.busek.com/bht6000`

Sun gravity as the only active force, an initial state matching Earth's, and a final state matching the asteroid. Trajectory coverage checks over a range of timeframes including launch window and desired arrival window are performed. Priority for further investigation is given to asteroids which are found to have trajectories over a larger portion of the timeframes, trajectories over the period with lower nominal deltaV needs, and asteroids which have physical characteristics preferred for the broader Karman+ company mission. Higher fidelity trajectories are then designed starting from an Earth escape spiral exit state and using multibody gravity and solar radiation pressure.

Once a higher fidelity trajectory has been developed, it is used to investigate various rendezvous and approach scenarios. These scenarios are based on the specifics of the asteroid, the spacecraft NAC capabilities, and the spacecraft trajectory approach conditions which occurred with the minimal constraints previously described. Taken together, these set distances from the asteroid to set constraints on the solar phase angle, an offset distance of the spacecraft along the asteroid-sun line but otherwise matching asteroid state, relative velocity, and combination constraint scenarios. The results of prior runs are used to seed more complex runs, as an initial guess to help ease convergence. When adding approach and rendezvous constraints, we also investigate the MCOLL parameters which were used for the initial guess and the modified approach scenario. Specifically, the number of segments, polynomial degree, mesh type, mesh conditions, and tolerances will influence whether a solution is found. Figure 2 shows an example SEP rendezvous trajectory approach phase to a potential mining target asteroid. It was developed with MCOLL to minimize fuel use while meeting desirable solar phase angle and asteroid relative velocity restrictions.

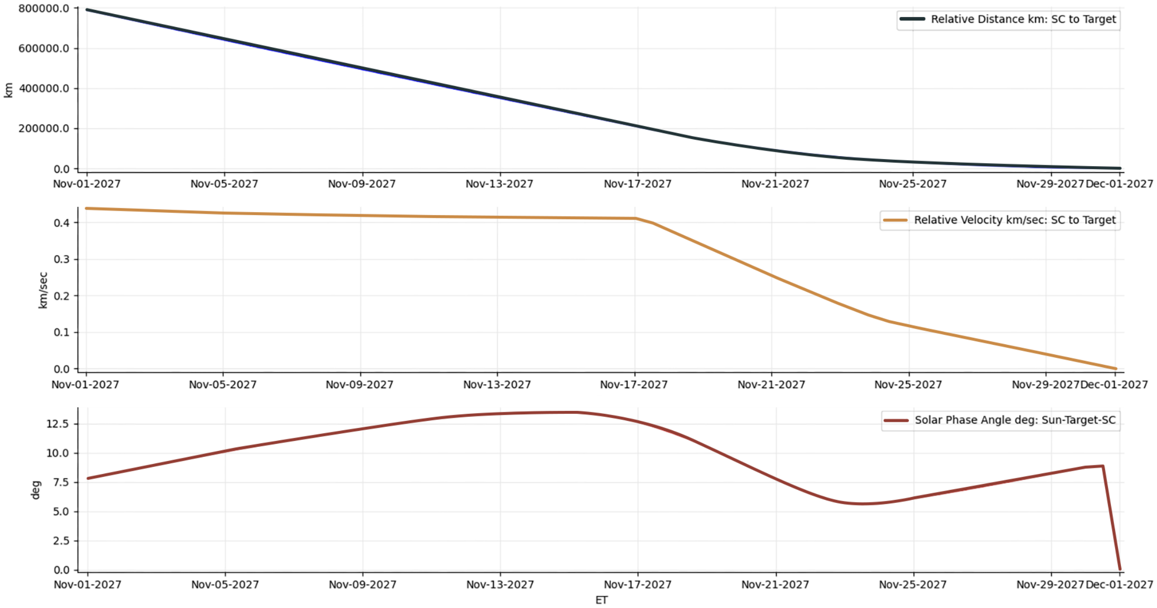

Figure 2: Example Asteroid Rendezvous Trajectory, Final 30 Days of Approach. Top: Relative distance of SC to Target, (km). Middle: Relative velocity of SC to Target, (km/sec). Bottom: Solar Phase Angle (Sun-Target-SC), (degrees)

As more is learned about the system, polynomials for the thruster force and mass flow rate performance can be included directly into MCOLL to further increase fidelity. By default, duty cycle is a scaling of the available thruster capability; over time, this will be replaced with additional forced coast segments to account for the spacecraft activities. As asteroid targets are down selected, operational preferences will refine additional constraints in the "modified approach" to balance mission margins, system capabilities, and desired arrival timelines.

COVARIANCE ANALYSIS

In addition to trajectory development, MONTE is also used for covariance analysis. Covariance analysis allows an investigation into the effects of various error sources and measurement cadence on the uncertainty of parameters of interest along a nominal trajectory. A batch filter is used to estimate system model parameters with a simulated trajectory and measurements. Nominal values are not changed from the *a priori*; the *a posterior* covariance still provides the statistical relationships of and between estimated parameters. Using MONTE for both trajectory design and covariance analysis allows direct and easier integration of the analysis pipeline.

The spacecraft state uncertainty is of primary interest, both the current state uncertainty ("knowledge") and the predicted mapped state uncertainty ("dispersions"). The SEP system thrusting is the major source of spacecraft state uncertainty. The error models for the system are in the early stages of development. For the time being, EP navigation error models based on the Psyche mission preflight models are used in covariance analysis. This is considered reasonable as Psyche is also an interplanetary mission with gimballed Hall-Effect thrusters, as Karman+'s thruster will be, and its comparable cruise operation cadence. The SEP thruster model error main case values and estimation strategy Karman+ is using are summarized in Table 1. The method and values are based on preflight Psyche covariance modeling.[8] As the Karman+ design advances, the methods used by Psyche to refine their error model values will be followed to update the High Frontier EP error modeling.

Table 1: Preliminary Covariance Thruster Model Error and Estimation Strategy

EP Error Model	Per-arc bias (3σ)	Stochastic uncertainty (3σ)	Stochastic batch
Thrust Magnitude	2.3%	0.5%	24 hours
Thrust Pointing	0.3°	1.5°	12 hours
Single Thrust Group	All burns are in a single group with a priori uncertainties and batch length common for the magnitude scale and thruster RA/Dec pointing parameters		

The measurement uncertainty expectations for High Frontier are also under development. For radiometric tracking, Karman+ system is baseline X-band two-way coherent Doppler and range tracking. Karman+ is not working with the Deep Space Network (DSN) or European Space Agency (ESA) tracking networks, but is exploring partnerships with commercial networks. Due to limited information of non-DSN/ESA network performance, Karman+ has opted to use DSN representative values for Doppler and range measurements and scaling the error levels. Table 2 shows the Karman+ radiometric categories and error levels. These values will be updated as more information about the eventual High Frontier communication network for interplanetary cruise is obtained.

Table 2: Preliminary Radiometric Measurement Error Values

Measurement Type	DSN Measurement Error Value Expected	Assumed Scaled Value for Alternative Networks
X-band 2way Coherent Doppler	0.0056 Hz (0.1 mm/sec)	X10
X-band 2way Coherent Range	7.022 RU (1 m)	X20, X100

Interplanetary missions will frequently use Delta-Differenced One-way Ranging (DDOR) measurements to provide highly accurate off-Earth line of sight measurements for the spacecraft. Unfortunately, Karman+ is not expecting DDOR measurements for its mission. Optical navigation measurements will be the only source of off-Earth line of sight measurements. Karman+ will use optical navigation of asteroid "beacons", onboard the autonomous system and as part of the ground navigation. Beacon navigation is described in more detail in subsequent sections. For covariance analysis of the beacon navigation performance, Karman+ has a stand-in camera simulating as 12MP, 150mm focal length, 2.7 um pixel pitch, and beacon asteroid sighting uncertainty of 0.1 pixels.

An example of these error models on the spacecraft state uncertainty 1-week prediction mapping is shown in Figure 3. In Figure 3 the "Baseline" case has weekly Doppler, range, and beacon asteroid optical measurements; the "Optical Only" case has weekly beacon asteroid optical measurements only. All other models and errors between the two cases are identical. The sawtooth pattern which is observed in Figure 3 is due to the measurement cadence, with dips aligning when measurements are taken. The large dip in predicted state uncertainty seen in the Baseline case, is from a period of optimal coast within the trajectory. Without the errors caused by thrusting, the radiometric measurements resolve the spacecraft state uncertainty significantly better than performing asteroid beacon optical navigation. During periods of thrusting, the 1-week prediction mapping for the spacecraft state uncertainty are of the same order of magnitude.

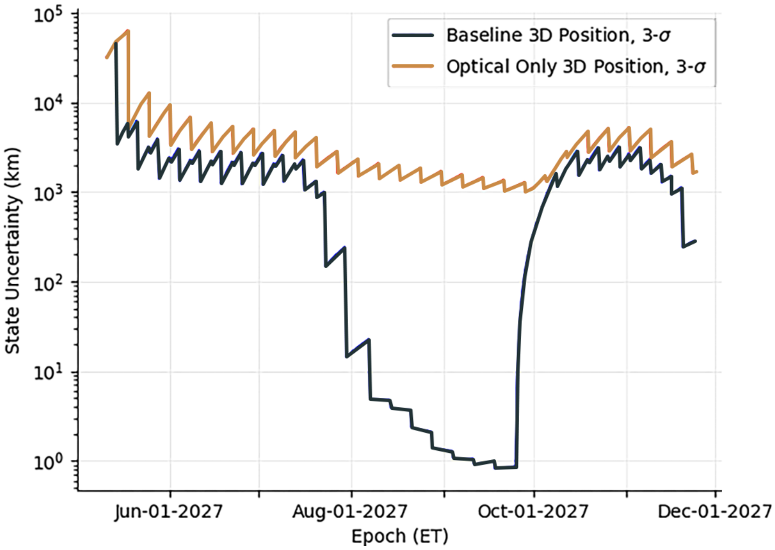

Figure 3: 1-week mapped spacecraft state position uncertainty (3σ). Baseline Case: Doppler, Range, and Beacon Asteroid Optical Measurements. Optical Only Case: Weekly Beacon Asteroid Optical Measurements

Comparing covariance cases with different error modeling provides important insight about mission sensitivities. Figure 4 shows a comparison of cases of interest for a spacecraft position uncertainty 1-week prediction mapping, during a thrusting period approximately one month before target asteroid arrival, and shortly after a series of asteroid beacon optical measurements were performed. This is a period of interest as it is just before observations of the target asteroid would be possible. The Baseline case and Optical Only case of Figure 4 are the same as those in Figure 3. Comparing the Baseline case and the "Doppler and Range Only Msr" case shows how the optical measurements aid the state uncertainty predictions. Figure 4 also shows that for the 1-week uncertainty mapping performed, the prediction ability with optical only nearly matches that of the radiometric only solution. In particular, Figure 4 shows a glimpse of how degraded EP maneuver errors ("x2 EP Maneuver Errors" case) can cause more prediction uncertainty even with radiometric measurements, than better characterized EP maneuver errors prediction uncertainty with optical navigation measurements only. Covariance studies such as these will be used to test sensitivities of trajectories in an informed manner. From the nominal trajectory position, the spacecraft will be perturbed based on the covariance results, and rerun to determine if the target asteroid can still be met within the allowed deltaV bounds.

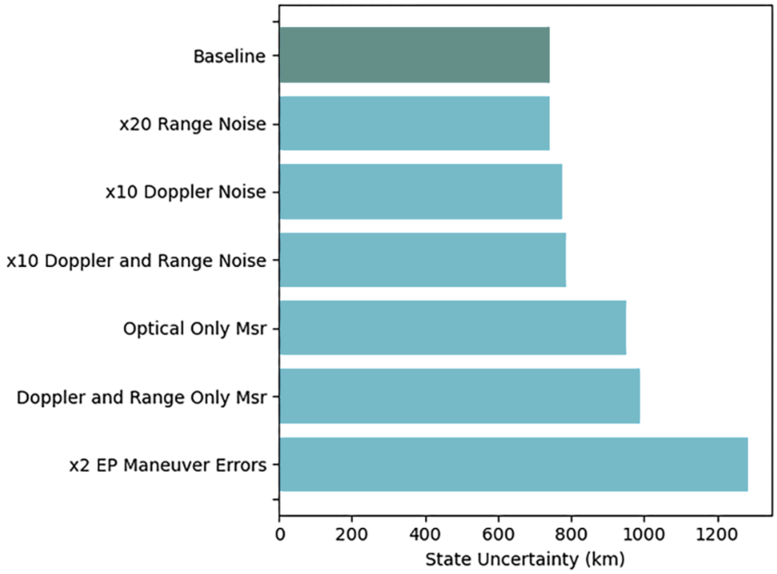

Figure 4: Sensitivity comparison of 1-week mapped spacecraft state position uncertainty (1σ)

AUTONOMOUS SYSTEMS

Karman+ has opted to scope additional autonomous systems beyond the necessities for fault management and the final moments of asteroid excavation operations. These onboard autonomous navigation and guidance methods will enhance robustness to potential ground communication complications, and provide a starting point for follow-on missions to expand upon. The autonomous system areas are trajectory adjustments, cruise navigation, and asteroid proximity operations.

Trajectory Adjustments

The necessity of autonomous trajectory adjustment must be contextualized with the practices of other SEP interplanetary missions. For cruise operations, Psyche preflight plans detailed nominally having four-week command sequence segments to be maintained on the spacecraft. As one four-week command sequence is being executed, another would be developed by the ground team based on spacecraft performance, orbit determination, and mission needs. The Psyche team may perform navigation updates at a two-week development cycle to accommodate DSOC pointing requirements.[17] Psyche cruise tracking should be approximately once to twice a week, with orbit determination occurring throughout the build sequence period. Hayabusa, during cruise, was allowed to thrust for three weeks with a ground defined thrust command sequence. After three weeks, a one-week ballistic period with three tracking passes would occur and orbit determination was performed, for an uplink of a new three week thrusting sequence to the spacecraft.[5] Neither Psyche nor

Hayabusa had the capability for trajectory replanning from the thrust command sequences which the ground provided. These missions show that it is possible to allow a SEP spacecraft to use ground designed thrust commands for several weeks without update during interplanetary cruise. Karman+ will keep onboard a four-week thrust sequence at a minimum.

An outlier among interplanetary missions is Deep Space 1. Deep Space 1 was the first interplanetary SEP mission and a technology demonstration. Through its AutoNav program, it performed onboard optical navigation based state estimates and trajectory replanning. The optical navigation details for Deep Space 1 which Karman+ draws from will be described further in the subsequent section. Key aspects of the Deep Space 1 trajectory replanning which Karman+ plans to follow are focused in this section.

Karman+'s initial plans for onboard trajectory modification mirror the Deep Space 1 in not being concerned with the ability to reoptimize a SEP trajectory onboard. Instead, a ground designed nominal trajectory and thrust profile would be kept onboard, to make use of the expectation that in interplanetary space the spacecraft should only deviate within a linear region about the nominal trajectory. This allows a linear targeting controller to determine if the thrusting needs adjustment to meet the mission targets, such as the one used by Deep Space 1.[19] The mission thrust can be broken up into segments for processing by the linear controller. In flight operations, a natural choice for thrust segment boundaries would be any forced coasting for spacecraft activities such as communications. If the target state tolerance is violated, the linear controller can iterate over thrusting segments adjusting until the target tolerance is met or no additional thrusting segments remain. When there is convergence, the new thrusting plans will overwrite the prior thrust plan; otherwise, the previous thrusting plan will be maintained. An example of the onboard logic flow is shown in Figure 5.

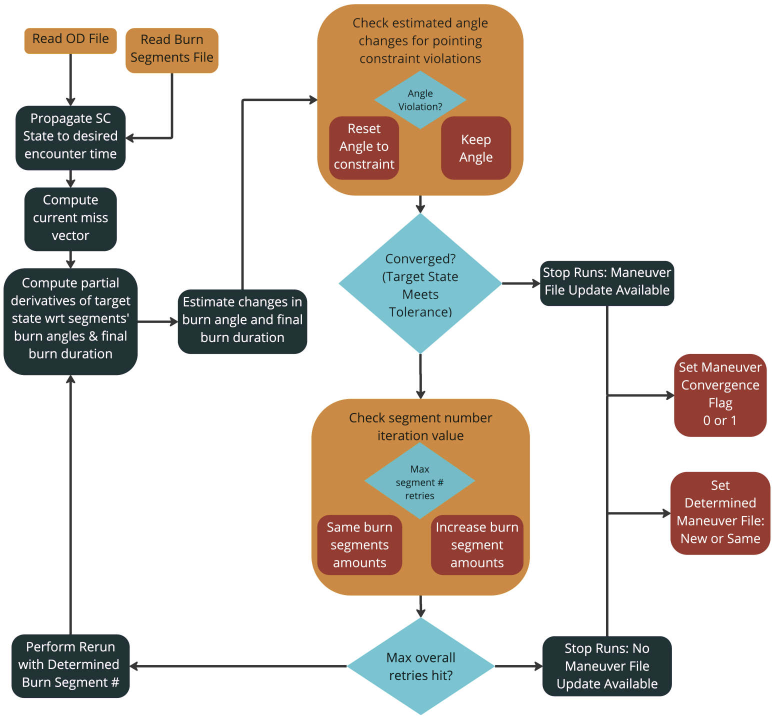

Figure 5: SEP Trajectory Adjustment Onboard Logic Option Compatible with Linear Controls

Results from covariance analysis will help inform the level of deviation which can be considered acceptable for the given trajectory. Tuning is necessary so that the system is not overly strict; otherwise, more fuel than is needed to meet the mission goals may be used. If events require a reoptimization of the trajectory, the ground team would uplink a new nominal trajectory to the spacecraft to use. This could be necessary due to events such as a safe mode, a determination that the spacecraft thruster is performing differently than expected, or if the observed location of the target asteroid is significantly different than expected. Given the High Frontier concept of operations, and prior SEP mission experiences, an onboard trajectory adjuster is desired but is not considered mission critical. The onboard linear trajectory adjustment scheme is an upcoming area of prototyping for Karman+.

Asteroid Beacon Navigation

Optical measurements to well known "beacon" asteroids can be used to estimate the inertial state of the spacecraft by position resection. Deep Space 1 utilized such a method during its cruise with extreme success.[4] We used the "kinematic approximation" method of Broschart et. al.[20] to initially derive navigation camera requirements from our desired cruise navigation performance. We chose 11.5 as our magnitude sensitivity requirement, because it resulted in sufficient close range, visible beacon asteroids, with good triangulation geometry, and without requiring a narrow solar exclusion angle for the camera. Figure 6 demonstrates the more optimal resection geometry afforded by a more sensitive camera. We believe navigation accuracy of 1000km or better will be achievable with our resulting camera.

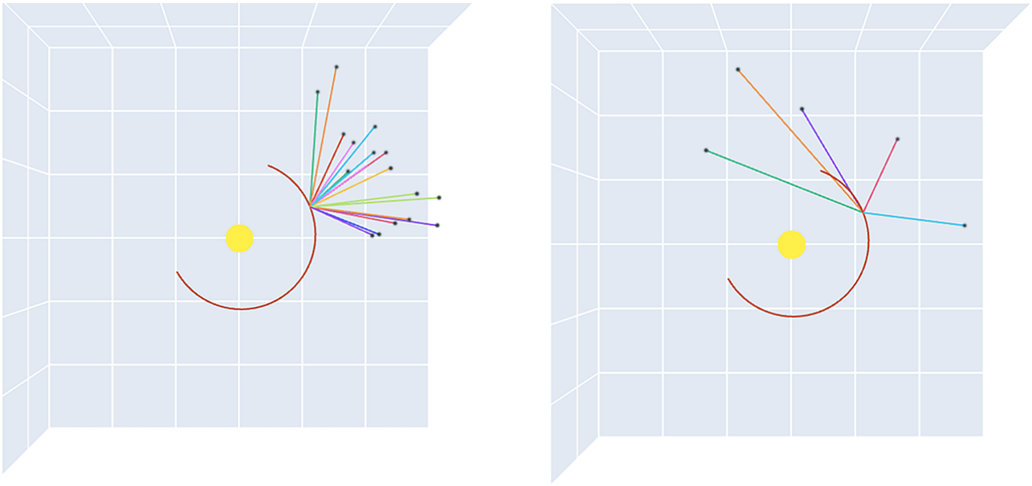

Figure 6: (Left) visible beacons for an example orbit epoch, if sensitive to magnitude 11.5. (Right) visible beacons for the same epoch if sensitive to magnitude 10.5. The resulting worse resection geometry, and requirements for narrow solar exclusion angle, motivated the requirement to specify a more sensitive camera.

The ability to perform beacon asteroid optical navigation sets a variety of requirements for the imaging, timing, and attitude control capabilities. An absolute time reference on the order of 1 second (1σ) is desired given the average asteroid beacon velocity and the direct relationship between an absolute time knowledge error and an error in the navigation solution. Image processing necessary to perform onboard optical beacon navigation include image sensor non-uniformity correction, background estimation, source extraction, and centerfinding. In order to accurately determine the inertial line of sight to beacon asteroids, we must first compute the astrometric solution from the observed star field. The astrometric star pattern match also provides information for the photometric calibration from observed camera counts which aids in beacon asteroid discrimination.

The beacon asteroid observations would occur in small batches, approximately every week, when the spacecraft has stopped thrusting. The time required for beacon observations will primarily be paced by the slew and settle time of the spacecraft, and secondarily by the amount of time required to detect the beacon asteroids against the star field. Limitations of our spacecraft bus pointing stability limit our ability to capture and detect faint beacon asteroids in a single, long image exposure. We are investigating several options, including closing the attitude loop around our narrow angle camera, co-adding multiple short exposure images, and the MPC method[21,22] successfully used on Deep Space 1 to extract sources in long exposure imagery with significant smear.

Karman+ has begun implementation, simulation, and night sky testing of the beacon navigation algorithms for early validation of our performance predictions. We tested our non-uniformity correction, source extraction, and astrometric fit and camera calibration pipeline against night-sky imagery collected with a camera that we had irradiated to our expected TID level, which demonstrated the expected increase in non-uniformity and dark noise levels. The results of the image correction process is shown in Figure 7. We are estimating the dark frame correction with a multi-frame technique because we do not plan to fly a mechanical shutter on our camera.

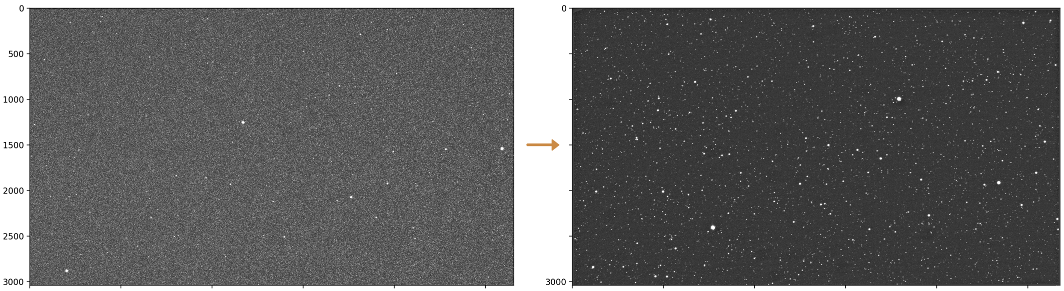

Figure 7: (Left) raw image from a sensor irradiated to our expected TID level, demonstrating expected non-uniformity and dark noise. (Right) the same image after multi-frame non-uniformity, dark frame, and flat field correction

We first do frame-to-frame matching of the brightest sources, while the spacecraft executes a small, low rate, inertial relative slew. The stack of resulting co-registered images is used to separate the fixed pattern noise from moving source signals. We follow this by a tile-based background estimation / flat field correction, similar to the methods used by standard astrometric software packages like SExtractor[*] and PhotUtils[†]. This process reveals thousands of visible sources per image at our expected sensitivity level. We do an initial coarse astrometric fit using a pairwise hashing algorithm of the brightest handful of sources in the image. From the initial coarse fit, we can then more precisely fit the remaining catalog objects to the image, and compute the camera intrinsic calibration and extrinsic rotation to the celestial reference system. This process is followed by a photometric calibration to convert from observed digital counts to catalog magnitudes. Finally, we can do multi-frame tracking of all observed sources to further discriminate our desired beacon asteroid from other visible sources both present or not in the onboard star catalog.

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[*] `https://sextractor.readthedocs.io/en/latest/`

[†] `https://photutils.readthedocs.io/en/stable/`

We take the dozen or so beacon line of sight measurements collected over the short no-thrust segment and compute the spacecraft position and velocity over the segment using a non-iterative closed form optimal resectioning formulation[23] with RANSAC to identify outliers. The individual estimates for each segment and the inlier observations are used to bootstrap an iterative nonlinear batch least squares estimator, that will additionally estimate average thrust acceleration across each week to two week long thrusting arc between beacon observation batches.

Within the batch estimator, modeling will include multibody gravity effects, solar radiation pressure accelerations likely assuming a spherical spacecraft, and accelerations from prior spacecraft thrusting events are made available from a history file. Future thrusting accelerations can be modeled based on the onboard sequences and projected spacecraft mass. The onboard beacon asteroid ephemeris files and the beacon image measurements will be used to converge upon a spacecraft state solution. This methodology was proven successful during the Deep Space 1 missions AutoNav demonstration.

We have completed an initial implementation of an end-to-end simulation and processing pipeline for beacon navigation, that is depicted in Figure 8. We start with a high fidelity simulation of the trajectory from MONTE and generate radiometrically accurate images for each planned observation epoch. The images are fed into our pipeline of source extraction, astrometric fit, beacon discrimination, and position/velocity resectioning, and batch trajectory estimation. We compare the resulting trajectory and thrust level estimates to the original high fidelity simulation, and are preliminarily showing good agreement. In the future, we plan to continue adding fidelity to this simulation, including additional calibration and other noise source errors.

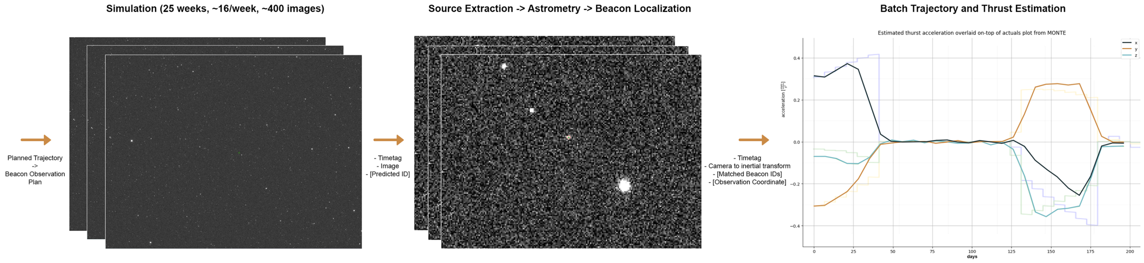

Figure 8: Depiction of our preliminary beacon navigation validation testing pipeline.

With the expectation of limited radiometric tracking, asteroid beacon navigation information is considered more critical to the High Frontier mission than trajectory adjustment ability. The spacecraft team can use the beacon asteroid observations in ground navigation. Optical navigation imagery will provide off-Earth line of sight information that is not likely to be otherwise available. It is possible that High Frontier will be the first spacecraft outside the sphere of influence for the ground communication network selected. Optical navigation imagery and state estimates from the spacecraft will provide additional robustness for the mission if the quality of radiometric data is degraded more than expected or other difficulties are experienced.

Asteroid Operations Autonomy

Because of the stringent beacon navigation requirements on hardware and processing, it was found unnecessary to require additional sensitivity for target asteroid observation and rendezvous. The initial navigation to the target asteroid occurs with identical methods to beacon navigation described previously when it is a point source in the image. As the spacecraft is significantly closer to the asteroid, the navigation accounts for the multi-pixel sizing of the asteroid as it begins to appear as a “blob”. Once at the target asteroid, the spacecraft will map the asteroid in stages from stationkeeping positions. Autonomous onboard navigation will be used to maintain the desired asteroid relative position and velocity. The asteroid operation sensors are the navigation cameras and a laser range finder. Notionally, the asteroid will be characterized using the NAC from a safe stand off distance. The primary stationkeeping gate is expected to be approximately 5km sunward from the asteroid due to the likely onboard cameras and the desired resolution and lighting conditions of target asteroid images. The spacecraft will be allowed to drift within 1km tolerance box around the stationkeeping center. The angle off the sunline of the stationkeeping position may be adjusted so that with the 1km box allowance variation in shadows over the asteroid surface would be observed. For higher resolution imagery, the spacecraft can move closer to the asteroid up to 1km standoff and move between a series of positions to vary the image angles, as depicted in Figure 9. At the end of closer standoff mapping or should the need arise otherwise, the spacecraft will autonomously return to the 5km stationkeeping position. Even at 1-5 km distance, little gravitational perturbation disturbance from the bodies is expected due to the size of the targeted asteroids for the High Frontier mission.

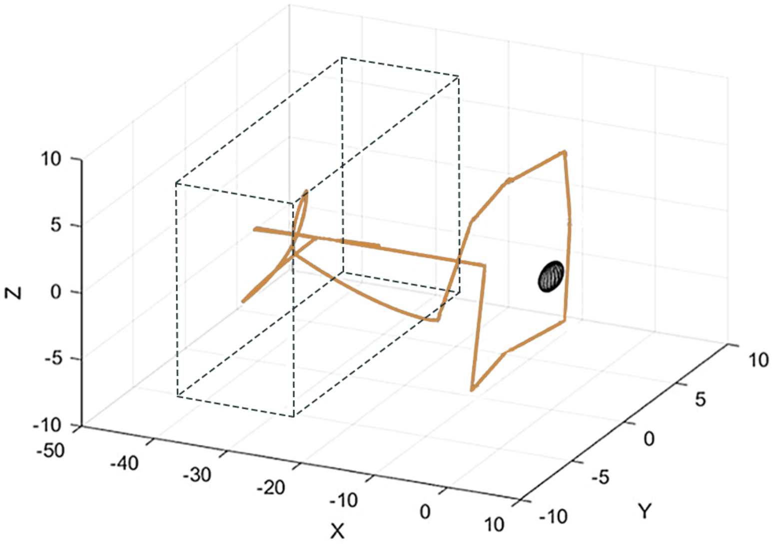

Figure 9: Spacecraft maintaining a stationkeeping boundary and performing asteroid imagery at varying lighting angles

An onboard map will be developed in support of SLAM, to be used for descent to the surface. A limited subset of downlinked imagery will be sent to the ground for determining potential target landing sites without large hazards and the final target site. At a 1km imaging position, the notional narrow angle camera condition allows ground sampling resolution of 2-5cm.

The descent trajectory departure point will be from the standoff position of 1km. Because the NAC is not in focus at ranges closer than 1km, the WAC will be the primary imager for descent. The spacecraft will initiate the descent burn with the EP thruster. The descent burn will be timed so that at its completion the target site will be illuminated in the manner providing the best possible navigation solution with respect to the map built. The descent trajectory is nominally a diagonal path to match tangential surface velocity and desired vertical velocity at contact. As the spacecraft descends, it will continue to map finer scale features with the onboard SLAM capability. This concept of operations is motivated to avoid more extensive high resolution mapping operations and extensive downlink and uplink needs.

In preparation for PDR, a closed loop rendezvous and proximity operations (RPO) descent simulation with image processing, target selection, and closed loop guidance and control has been developed. Image simulation is performed with Blender (Cycles).[24,25] For optical navigation simulations, the Cycles path tracer was also used as a stand alone USD Hydra Render Delegate, independent of Blender, to allow additional flexibility. This allows interoperability with other open source renders and toolkits with USD Hydra rendering delegate plugins. We have created a plugin for Blender to allow easier dynamic rendering within a closed loop simulation along with overlaid visualization of navigation results, and are additionally leveraging the "Geometry Nodes" capability of Blender to generate synthetic, procedurally generated asteroids. The RPO closed loop guidance and control models have navigation code prototypes with mechanisms to progressively migrate to flight code. The closed loop RPO simulation development was verified against an analytical model. The analytical model had the full formation of the mapping/SLAM with analytical measurements instead of image processing, to facilitate earlier covariance analysis and Monte Carlo work.

From the minimal images downlinked, the team will select a point on an image of interest as a target site. The image coordinate is related to a 3D point in the onboard map frame by intersecting the pixel selection with the approximate surface of the SLAM point cloud. The type of intersection and level of reconstruction chosen will influence how well localized the image point will be in the depth direction. With an initial target location selected, additional imagery for that region could be downlinked from the onboard stored higher resolution images with much finer angular separation. During the descent phase, the SLAM solution is predicting the trajectory of the spacecraft in the asteroid frame. It estimates where the trajectory will intersect the surface, comparing the hit point with the aim point, and projects the results into the desired camera current or future frame. Because of the expected size of the target and the limited gravity disturbances which they can cause, the descent burn targeting guidance can be fairly straightforward. Currently, a two burn guidance targetor is used. In operations, there are opportunities for trajectory corrections using the RCS thrusters.

In the inertial frame, the survey mapping occurs at a fixed point and the spacecraft descent occurs in a straight line. In the asteroid fixed frame, because of the asteroid's rotation, the survey mapping appears to be a circular orbit and the descent is curved. This is shown in Figure 10, where the spacecraft descends to reach a target landing location selected from a reference image. The example landing site selection reference image and the selected landing site on the 3D surface model is shown in Figure 11. In Figure 11, the circle diameter is 14cm, corresponding to a single pixel in the particular survey orbit imagery used for the location selection. The final contact error of 0.3m corresponds to approximately 2 pixels distance in the original survey frame image where the target position was designated. This is just a preliminary result against a closed-loop model with low fidelity dynamics, however it demonstrates feasibility of our RPO navigation approach, including interaction with ground based site selection, under downlink bandwidth and other operations constraints.

At the landing site, a touch and go (TAG) maneuver is executed, during which the excavation equipment detailed in the subsequent section will be active. The touch portion will last at most 30 seconds, after which the spacecraft will execute an ascent burn, then return to its stationkeeping location. The main spacecraft autonomous behavior during the excavation will watch over whether

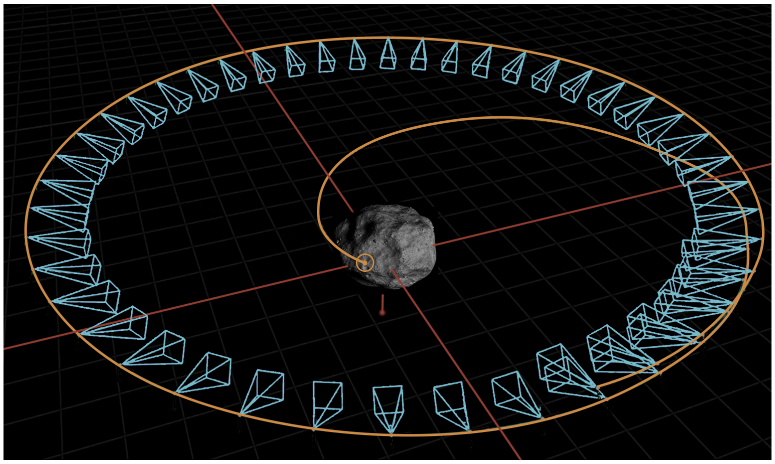

Figure 10: Asteroid Fixed Frame View of the End-to-End Closed Loop Simulation of SLAM Based Landing Site Matching Descent Trajectory Execution. The yellow line starting from the right hand side is the descent trajectory from the surface mapping standoff location.

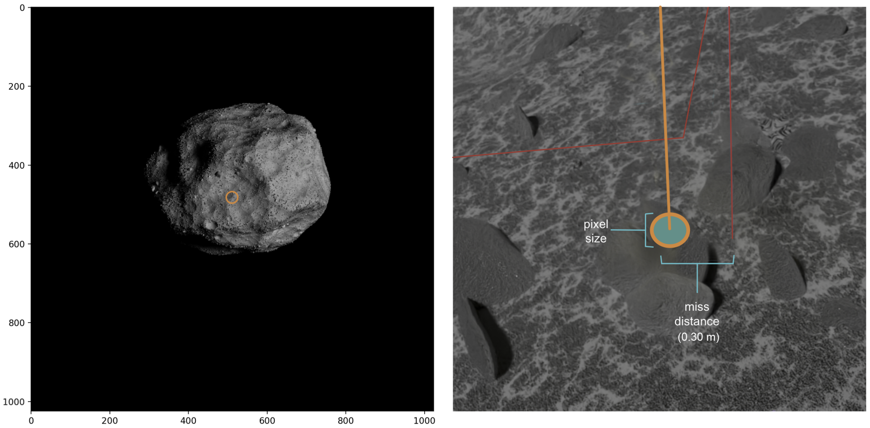

Figure 11: Landing Site Selection Reference Image (left) and Landing Site 3D Surface Map with SLAM Targeter Miss Distance (right)

the spacecraft is tipping over more than the allowed 10 degrees and can initiate an early abort ascent to stationkeeping.

EXCAVATION SYSTEMS

During the High Frontier TAG, Karman+ custom designed mechanisms will be used to perform the excavation of regolith. These designs aim to mine regolith in the kilogram scale in a short period of time. To have a system agnostic to the unknown asteroid surface, a range of novel options were under development, such as those in Figure 12.

Excavation prototypes were made and a test campaign was developed as part of the down-selection process. The test campaign was a proving ground for prototype excavation methods and concepts. The testing consisted of a battery of physical test setups paired with simulations and analysis tools to verify results and estimate performance in mission conditions not reproducible

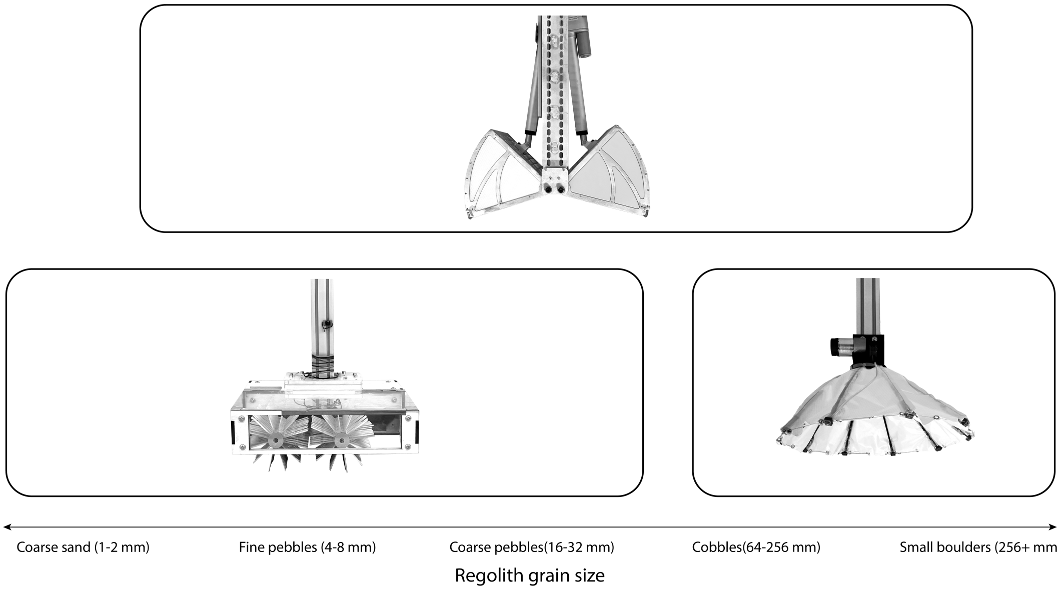

Figure 12: Excavation method concepts mapped against regolith granule size

physically. Simulants of regolith and rocks of C and S type asteroids were procured and creative alternative materials for representing excavation target behaviors were sourced to broaden testing regimes. A simulation environment to extrapolate granular effects in a zero-g environment was developed. A testbed was designed to compensate for the Earth gravity environment for physical tests of prototypes under conditions more relevant to their final use case. Through the excavation testing, some of the excavation techniques were modified or hybridized together.

At the conclusion of this campaign, three excavation methods were selected to provide a broad range of capabilities: a compliant gripper that can pick up small boulders, a clam shell that can grab and crush, and a brush wheel that can continuously mine smaller grains. The brush wheels are laterally compliant, allowing them to pull regolith inwards with adjacent brush wheels rotating in opposite directions. The clam shell is similar to traditional Earth excavation equipment, with a dual sided clamp down shovel scoop. The compliant gripper uses biomorphic inspiration, with a set of tendrils with claws/hooks lining its interior, and a membrane around those limbs. The compliant gripper will latch onto regolith boulders and wrap around the material as much as possible, with the membrane helping to prevent materials from slipping between tendrils. As each of the three concepts are further advanced, the spacecraft team and excavation team will iterate to refine capabilities and requirements for the High Frontier spacecraft.

CONCLUSION

This work represents the first thorough detailing of the Karman+ High Frontier mission development in support of an October 2024 PDR. Considerable progress has been made across the program, with areas needing refinement well understood. Analysis tools and prototyping has begun across critical areas for mission design, navigation, autonomous systems, and excavation systems. Integrated analysis pipelines have been utilized from an early stage across teams for rapid advancements. Initial hardware selection, development, and testing has started and shown viable options to support the mission. As vendor relationships are finalized, thorough calibration activities will occur to refine the preliminary analysis described. High Frontier builds on established technologies and methods of prior spacecraft, while pursuing the advancements described in this work to demonstrate how we intend to scale deep space missions at cost. Karman+ is well on its way to meet the mission objectives of High Frontiers and kicking off the Regolith Age.

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