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ENHANCED GRAVITY TRACTOR TECHNIQUE FOR PLANETARY DEFENSE

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Abstract

Given sufficient warning time, Earth-impacting asteroids and comets can be deflected with a variety of different "slow push/pull" techniques. The gravity tractor is one technique that uses the gravitational attraction of a rendezvous spacecraft to the impactor and a low-thrust, high-efficiency propulsion system to provide a gradual velocity change and alter its trajectory. An innovation to this technique, known as the Enhanced Gravity Tractor (EGT), uses mass collected in-situ to augment the mass of the spacecraft, thereby greatly increasing the gravitational force between the objects. The collected material can be a single boulder, multiple boulders, regolith or a combination of different sources. The collected mass would likely range from tens to hundreds of metric tons depending on the size of the impactor and warning time available. Depending on the propulsion system's capability and the mass collected, the EGT approach can reduce the deflection times by a factor of 10 to 50 or more, thus reducing the deflection times of several decades to years or less and overcoming the main criticism of the traditional gravity tractor approach. Additionally, multiple spacecraft can orbit the target in formation to provide the necessary velocity change and further reduce the time needed by the EGT technique to divert hazardous asteroids and comets. The robotic segment of NASA's Asteroid Redirect Mission (ARM) will collect a multi-ton boulder from the surface of a large Near-Earth Asteroid (NEA) and will provide the first ever demonstration of the EGT technique and validate one method of collecting in-situ mass on an asteroid of hazardous size.

Background

A variety of techniques have been proposed to deflect asteroids and comets that could impact the Earth and cause destruction and loss of life. Efforts to deflect these hazardous Near-Earth Objects (NEOs) significantly benefit from early detection and precise orbit characterization. Warning times on the order of a decade or more significantly reduce the impulse, or velocity change (ΔV), needed to deflect an impacting NEO. Accurate knowledge of the object's orbit is needed to confirm that the object will indeed impact the Earth, which is possible with a sufficient number of accurate astrometric observations along with the possible addition of precise radar measurements or the presence of an in-situ spacecraft. As shown in Figure 1, the application of approximately one cm/s (0.022 mph) of ΔV a decade before impact is typically required to allow for a one Earth radius deflection. This would be the minimum impulse required to just avoid a worst case impact that hits the Earth "dead center." Additional ΔV would be required for margin against the orbit uncertainty or the NEO's orbit would need to be more of a grazing impact to assure that the object misses the Earth. This ΔV increases by approximately an order of magnitude within a year of impact, and surpasses a meter per second in the last months before impact.
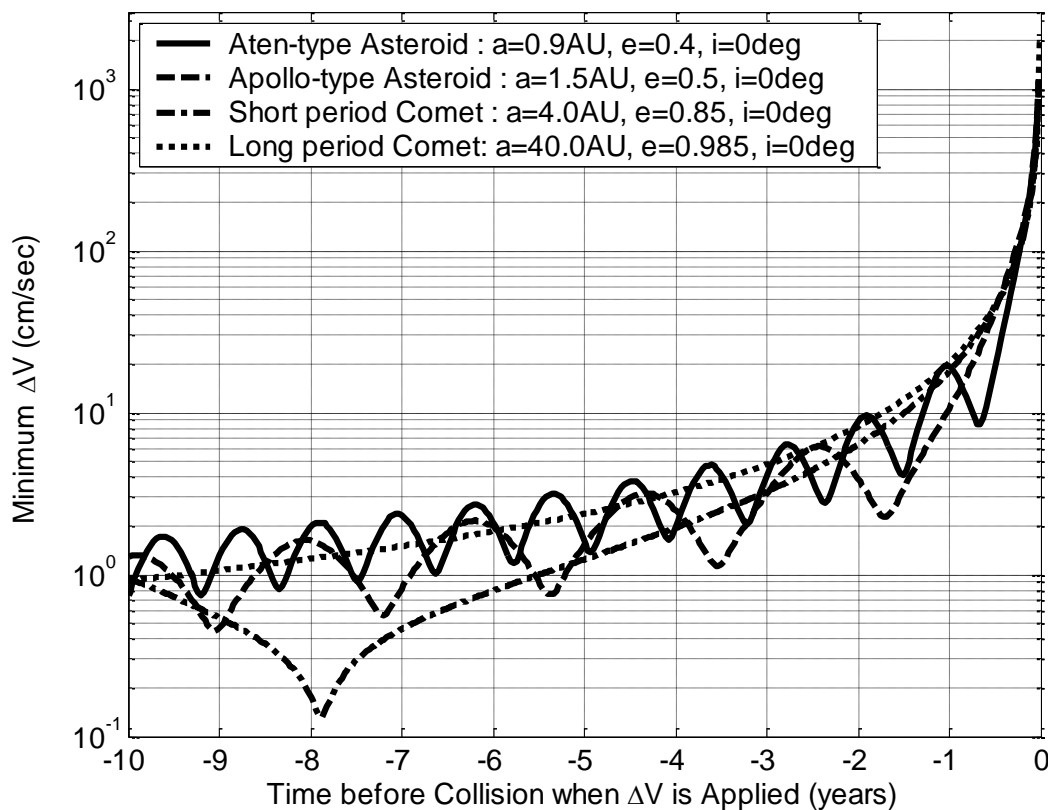

Figure 1: Estimated Minimum ΔV Required to Deflect Example Impactors by One Earth Radius for Pre-Perihelion Impact (Credit: Ref. [1]).

Planetary defense techniques that can provide large, rapid impulses, such as kinetic impactors and nuclear detonations, require the least amount of warning time, but their effectiveness is dependent on the NEO properties, which are likely uncertain and vary substantially between objects. Additionally, the application of a large, concentrated force has the potential to fragment the NEO due to the unknown structure and mechanical properties of the target. These fragments could still be dangerous if they

remain on an impacting trajectory with Earth. Techniques that can provide small, gentle impulses are much less likely to cause fragmentation, but typically require much longer interaction times (months to many years) to provide the necessary ΔV to deflect the impacting object. These "slow push/pull" techniques typically work by enhancing natural effects (e.g., albedo/thermal response modification via the Yarkovsky effect), by the ablation/expulsion of surface material, or by applying a contact or gravitational force. They are also effective against NEOs that are binary or even ternary systems. One consideration for these gradual deflection techniques is that when an impact with the Earth is confirmed, the exact impact point is still uncertain. This path of possible impact points, known as the "risk corridor," is altered during a deflection effort with the impact point moving across the Earth's surface as the impactor's trajectory is slowly changed (see Figure 2 for an example). Choosing how the deflection is accomplished has significant geopolitical considerations and will likely require the cooperation of multiple nations. Finally, definitive knowledge that an impact will actually occur is often difficult to determine from ground-based measurements and the probability of impact will likely not be a certainty before a deflection mission is undertaken.

The gravity tractor is a planetary defense technique that uses the gravitational attraction between a rendezvous spacecraft and the NEO to gradually alter the trajectory of an impactor [2]. With this approach, the spacecraft maintains separation from the NEO by using its thrusters to oppose the small gravitational attraction between the two bodies without pluming the NEO, which reduces the technique's effectiveness. The gravity tractor requires the use of a low-thrust, high-efficiency propulsion system, such as Solar Electric Propulsion (SEP), to balance the gravitational force while minimizing the propellant required for the deflection. With this technique, the NEO is accelerated in a very uniform manner with only extremely small tidal forces causing any internal structural stresses. One of the shortcomings of the traditional gravity tractor approach is that the applied force is exceedingly small and depends on the mass of the spacecraft. This results in many years or decades of operation to alter the impactor's trajectory and a decade or more of warning time.
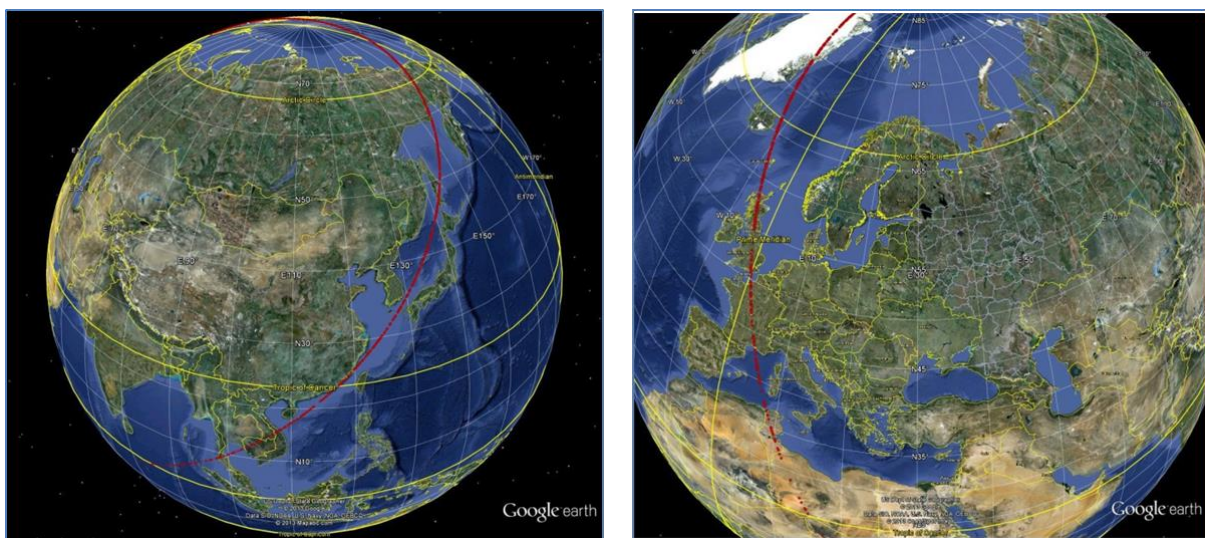
**Figure 2: Example Potential Impact Path or "Risk Corridor"
(Credit: NASA/JPL and Google Earth).**

Introduction

The National Aeronautics and Space Administration (NASA) is currently developing a mission concept known as the Asteroid Redirect Mission (ARM), which includes the goal of robotically returning a multi-ton boulder (typically 2-4 meters in size) from a large Near-Earth Asteroid (NEA), 100 meters or greater in size, to cislunar space using an advanced 50 kW-class Solar Electric Propulsion (SEP) spacecraft designated the Asteroid Redirect Vehicle (ARV). After the ARV returns to a lunar distant retrograde orbit (LDRO) in the mid 2020's, initial astronaut exploration and sampling of the returned material will take place as part of ARM. Subsequent human and robotic missions to the asteroidal material would also be facilitated by its return to cislunar space and would benefit scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the demonstration of mining of asteroid resources for commercial and exploration needs. The capabilities, systems, and operational experience developed and implemented by ARM and subsequent missions to the returned asteroidal material will advance NASA's goal of sending humans to deep-space destinations and eventually to surface of Mars. The robotic mission will also permit the demonstration of planetary defense techniques.

The robotic mission to capture a multi-ton boulder from the surface of a large NEA [3] is depicted in Figure 3. The maximum boulder mass that can be returned is currently limited by the ARV xenon propellant capacity (~10 t) and the target asteroids available with orbits that allow returns in the mid-2020 time period. The maximum returnable mass is currently estimated to be approximately 40 metric tons. The capture system design has focused on retrieving a boulder that is 1-4 meters in size (up to a mass of ~70 t), but the design can be scaled to accommodate significantly larger boulders. This option includes the opportunity to demonstrate future planetary defense strategies on a hazardous-sized NEA. Inspired by the mission requirement to collect a boulder from the asteroid and thus dramatically augment the rendezvous spacecraft mass with in-situ material, the idea of the Enhanced Gravity Tractor (EGT) technique was conceived.

Figure 3: ARM Robotic Mission (Image Credit: NASA/AMA, Inc.).

EGT uses mass collected in-situ to augment the mass of the spacecraft, thereby greatly increasing the gravitational force between the objects. The collected material can be a single boulder, multiple boulders, regolith or a combination of different material types using a variety of collection techniques, including the use of a separable spacecraft to "harvest" the material. Since the material would not need to be returned to Earth for an actual deflection mission, significantly more mass could be collected to provide mass augmentation than can be achieved during the ARM robotic mission. The mass of the collected material for actual planetary defense effort would likely range from tens to many hundreds of metric tons based on the size of the impactor and warning time available. Depending on the SEP system's capability (i.e., power, thrust, and propellant) and the mass collected, the EGT approach can reduce the deflection times by a factor of 10 to 50 or more over the standard gravity tractor method, thus reducing the deflection times of several decades to years or less. The ARM robotic mission will provide the first ever demonstration of the EGT technique on a hazardous-sized asteroid and validate one method of collecting in-situ mass.

Due to the collisional nature of how NEAs are created, the presence of retrievable material is a virtual certainty. Although the EGT does require some period of interaction with the target, the vast majority of the time is spent in the gravity tractoring mode, which is done without direct contact. This paper describes a simple, single spacecraft EGT methodology to explain the basic concept. There are many possible approaches and synergies that could significantly increase the effectiveness of the EGT that are available for further investigation. For example, the use of one or more separable spacecraft to collect and aggregate asteroidal material, along with an enhanced, higher power version of the ARV to act as the EGT "tug," would greatly increase the effectiveness of the technique and provide additional mission robustness. Additionally, the efforts to extract and retrieve resources from large asteroids for future exploration and commercial mining efforts would greatly increase our capability to obtain the necessary mass for an EGT deflection effort against a future Earth impactor. Finally, the ability of multiple spacecraft to orbit the target in formation to provide the necessary velocity change can further reduce the time needed by the EGT technique to divert hazardous NEOs. These are just a few examples. Many other ideas, including combining EGT with other deflection techniques, are possible.

Concept of Operations

Once in the proximity of a hazardous NEO, the EGT operations consist of five phases: 1.) initial orbit determination; 2.) characterization; 3.) material collection; 4.) tractoring; and 5.) final orbit determination. Having a spacecraft near the asteroid allows for very precise orbit determination and confirmation that the threat is an impactor prior to any interaction with the asteroid. If an impact is confirmed, the spacecraft can facilitate a refinement of the ΔV required in order to avoid a direct impact or any gravitational keyhole passages [4] that could result in an Earth impact during a subsequent encounter. Orbit determination can begin hundreds of kilometers from the asteroid and continue throughout the characterization phase. The characterization phase will begin during the initial approach and provide a detailed gravity field, shape model, and imagery of the asteroid. The imagery will be used to identify boulders and other asteroidal material to be collected. Gravity and shape models will be used by the spacecraft's guidance and navigation system during the collection phase.

Material collection operations will depend on the spacecraft capabilities, as well as the targeted material to be collected. Depending on the type of asteroid, pre-launch knowledge and imagery of the surface, the size of the asteroid, estimates of required ΔV, warning time, and the amount and type of material (single boulder, multiple boulders, regolith, etc.) can vary. While this paper will not discuss in detail all of the possible capture mechanisms and operations, it should be noted that it is desirable to have a robust collection capability to sufficiently augment the mass of the spacecraft.
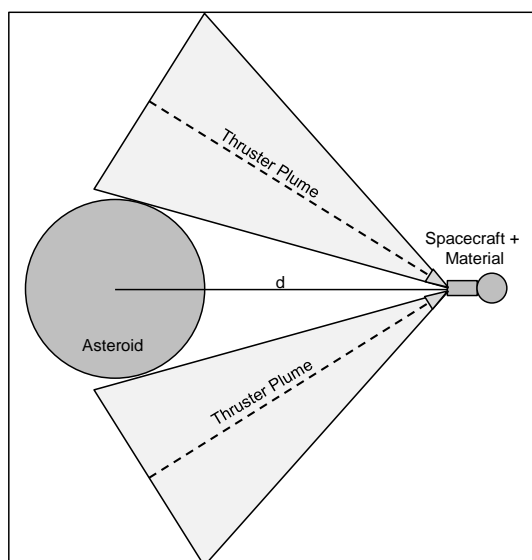

Figure 4: In-line Tractoring Method.

After collecting and securely restraining the asteroidal material, the spacecraft enters the tractoring phase. The EGT tractoring operations are similar to the standard gravity tractor with the spacecraft maintaining a constant distance (d) from the asteroid, countering the gravitational attraction by thrusting away from the asteroid with an equal force. Station-keeping to maintain the desired orbit for any EGT method requires active navigation and awareness of the spacecraft's relationship to the asteroid.

One way to achieve this standoff is having the spacecraft maintain a position along the asteroid's orbital velocity vector [2]. This in-line method, as shown in Figure 4, provides a simple navigation strategy with constant line of sight to the asteroid for range and position measurements. The thrust can then be adjusted to maintain the desired position. However, this method also requires canting of the thrusters in order to avoid pluming the asteroid. This requires additional propellant along with higher thrust to account for the cosine losses and thus increased power for electric propulsion (EP) system, or increased distance from the asteroid which would reduce the gravitational attraction and thus increase the deflection time.

Other methods have been proposed to increase the efficiency of tractoring. One of the most prominent is the spiral method [5]. Figure 5 depicts this method in which the spacecraft enters a halo-like orbit around the asteroid's velocity vector, creating a spiraling orbit when viewed in a sun-centered frame. This allows the spacecraft to decrease the distance (d) to the asteroid and increase the gravitational attraction while avoiding pluming the surface or requiring canting of the thrusters. By eliminating canting and setting the orbital period such that the centripetal acceleration counters the off-axis components of the gravitational force, the thrust required is equal to the net force along the velocity vector ($\vec{v}$). This allows the full thrust capability of the spacecraft to be utilized in the deflection of the asteroid. The maximum deflection force is now a function of the mass that is collected and the minimum distance to the asteroid is set by risk posture, with thruster characteristics (e.g., plume angle, maximum cant angle, etc.) being a secondary consideration. While there are cosine losses introduced by the spacecraft not being aligned with the velocity vector because the resulting gravitational force is along the NEO-to-spacecraft line, these loses are

overcome by the increased force as the spacecraft decreases the range to the asteroid which has inverse square relationship.
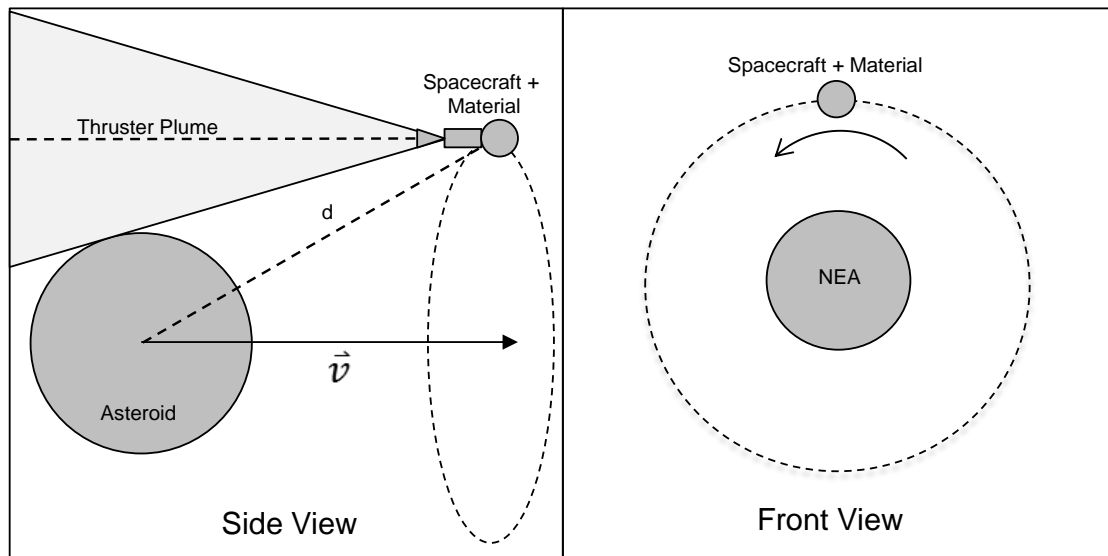

Figure 5: Spiral Tractoring Method.

Asteroid Redirect Mission EGT Demonstration

The ARM robotic mission [3] would demonstrate the EGT spiral method and one method of collecting material from a hazardous-sized NEA. Due to the mission objective of returning the collected boulder to the Earth-Moon system, this mission will not have the time nor mass collection capability to impart a ΔV of the magnitude that would be required for an actual deflection mission. However, all phases of the EGT operations will be demonstrated, including producing a deflection which is large enough to measure either with the vehicle still in the asteroid's vicinity [6] or via ground-based radar measurements if possible.

Assuming the target asteroid hasn't been visited by a precursor mission, which would provide shape and gravity models as well as detailed imagery, the ARV will spend approximately 14 days during initial approach to transition from a 1,000 km acquisition point to 100 km range. During this time, initial shape and gravity models will be developed and imagery will be gathered to begin identifying potential landing sites. Over approximately the next five weeks, a series of six fly-bys will be conducted with a close approach range of one km and relative velocities decreasing from a meter per second to approximately 0.1 m/s. The first four fly-bys are targeted over different latitudes to build a detailed gravity model and gather <10 cm resolution global imagery. A two week hold will be used to process the data and imagery and identify potential collection sites to be targeted during the final two fly-bys. A final two-week hold will then be used to identify and prioritize three collection sites. Three sites are chosen to protect against the unknowns of the surface and boulder characteristics. A total of five collection attempts and three dry-run sequences over different collection sites have been budgeted.

The collection process begins with a series of dry-runs that are used to test and demonstrate the navigation and control systems. The ARV will rely on optical Terrain-Relative Navigation (TRN) that will track landmarks that are mapped during the fly-

bys. The first dry-run will start at a range of 5 km and follow a passively safe trajectory to an altitude of ~200 m. During this dry-run, both the LIDAR and TRN systems will be able to develop solutions that will be tracked prior to the execution of a pre-planned maneuver at the end of the dry-run. Once the navigation system performance is demonstrated, the second dry-run will follow the same passively safe trajectory but then continue to descend down to an altitude of 50 m. At that altitude, the ARV will match spin rates with the asteroid and maintain a stationary position relative to the target boulder for 10 minutes to demonstrate the TRN filter and the control algorithms that will be required for the final descent.

The final descent will again follow the same passively safe trajectory down to 50 m altitude at which point the ARV will maintain a local vertical descent through touchdown. During the final 20 m, use of the thrusters that plume toward the surface will be limited to attitude control only with no vertical velocity control in order to minimize any disturbance to the surface. At touchdown, the residual velocity will be attenuated by the Capture and Restraint System (CRS) [7]. While on the surface, as depicted in Figure 6, the CRS will provide stability while a small downward thrust is maintained in order to increase the downward force in the extremely low-gravity environment. Two robotic arms with microspine grippers with anchoring drills [8] will then grasp the boulder prior to the CRS providing a mechanical push-off that will separate the boulder from the surface, breaking any cohesion, and provide an initial ascent without pluming the surface. Once the ARV and boulder are clear of the surface, a propulsive maneuver will be performed to achieve a slow drift from the asteroid while the boulder will then be secured and a series of small maneuvers will be performed to determine the mass properties of the combined boulder and ARV.
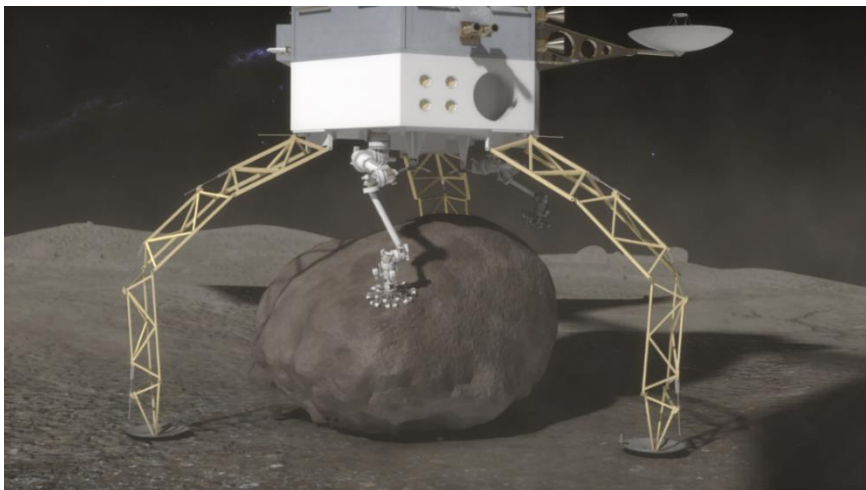

Figure 6: Capture System during Capture Operations (Image Credit: NASA/AMA, Inc.).

With the boulder restrained and the mass properties updated, as depicted in Figure 7, the ARV begins to transit to an initial EGT spiral orbit. Much like the boulder collection dry-runs, prior to entering the final EGT orbit the ARV will demonstrate the EGT operations in an orbit with a range of one kilometer. This initial orbit will be held for about a week to demonstrate the TRN acquisition, control algorithms, and station-keeping operations. The ARV will then transition to the final EGT orbit which will have a minimum altitude of one asteroid radius. During the EGT orbit, the ARV will track landmarks through the onboard TRN over two imaging arcs that occur just after

crossing the terminator plane onto the illuminated side of the asteroid and just prior to crossing the terminator plane into eclipse. These imaging arcs will allow the system to precisely determine the ARV's state and calculate any required updates to maintain the desired EGT orbit.

Figure 7: ARV with Captured and Restrained Boulder ready for EGT Operations (Image Credit: NASA/AMA, Inc.).

This final orbit will be held for a pre-determined amount of time ranging from approximately 30-90 days depending on the target asteroid and collected boulder mass. This will provide a small deflection, limited by the propellant and time constraints of the ARM robotic mission, while not drastically altering the trajectory of the hazardous-sized target. The ARV will then maneuver to a stand-off location where it will wait an additional four to five months for the deflection to propagate. This will allow the asteroid to achieve advantageous Earth alignment for deflection verification, which will be accomplished using ground ranging to the ARV combined with precise ranging from the ARV to the asteroid. Once the deflection is verified to beyond a three-sigma uncertainty, the ARV and captured boulder will begin the transit to back to the Earth-Moon system. Depending on the target asteroid's future Earth approaches and tractoring time available, there may be the opportunity to observe the deflection using Earth-based radar, allowing the ARV to begin the return transit prior to verification.

Comparison of Traditional and Enhanced Gravity Tractor Techniques

Compared to standard gravity tractor operations, without augmenting the mass [2,5,9], the EGT is more effective, and thus, requires less time to achieve the same amount of deflection. Since the gravitational acceleration imparted on the asteroid is independent of the asteroid mass, a simple consideration would expect the benefit to be constant and equal to the ratio of the spacecraft mass to the mass of the spacecraft plus collected material up to the point that the gravitational force reaches that maximum thrust capability of the SEP system. However, Figures 8 and 9 show that the deflection time benefit provided by EGT over gravity tractor is not just a function of collected mass and SEP power available for thrusting, but also the asteroid size. This is a result of the characteristics of the propulsion system. Assuming a constant asteroid density, as the asteroid size increases the thrust required to counteract the gravitational attraction increases. This increase in required thrust is provided by increased mass flow through the propulsion system and therefore more propellant usage. Including this propellant and accompanying increased tankage in the mass of the spacecraft introduces an asteroid size dependency in the ratio of the EGT to the GT systems which produce the slopes seen in the figures.

As shown in Figure 8, almost 30 times less time is needed for a 200 m spherical asteroid (assuming a density of 2 g/cm^3) with a 50 kW EGT system that has a 4,000 kg dry mass and 500 t of collected material. As the asteroid increases in size, the propellant required increases the mass of the GT at a proportionately higher rate than the EGT. This leads to the slow reduction in benefit seen. However, even at these lower power levels the EGT can reduce deflection times by one to two orders of magnitude for smaller asteroids, which are much more numerous and harder to target with kinetic impactor techniques because of their size. Figure 9 shows that using the EGT with a 300 kW SEP system and 500 t of collected mass provides almost a factor of 50 reduction in deflection time for a 300 m diameter asteroid. If the collected mass is reduced to 100 t, the EGT is still almost 10 times more efficient. As asteroids get larger, these numbers decrease, but even for a 500 m asteroid, the EGT method with 500 t of material can reduce the deflection time by a factor of approximately 15.

The impact of SEP power and thrust can easily be seen by comparing Figure 10 with Figure 11, which provide an estimate of the EGT deflection time (years) and propellant (metric tons of xenon) required for a given diameter asteroid. The gravitational force is proportional to the product of the asteroid mass and the combined mass of the spacecraft and collected material, and it is also equal to the thrust required to maintain the relative standoff position and thus impart the ΔV on the asteroid. As one or both of these masses increase to the point the gravitational attraction equals the maximum thrust capability of the spacecraft, the spacecraft then must move further away from asteroid to decrease the attraction to a point where it can be balanced by the thrust. This decreases the efficiency of the tractoring and provides a limit that can be seen as the lines converge. This also leads to the observation that for larger asteroids the EGT does not provide a benefit over the standard gravity tractor without additional thrust capability. This asteroid size is a function of the vehicle thrust. For a 50 kW system with a nominal dry mass of 4,000 kg that provides 1.63 N of thrust, this limit is reached with a 650 m diameter asteroid (assuming a density of 2 g/cm^3). Keeping these assumptions while increasing the power to 300 kW and the thrust to 9.78 N, the limit is increased to over 1000 meters.

There are a few additional, and more subtle, aspects of this comparison. One is the minimum allowable range from the spacecraft to the asteroid. For the plots shown, a minimum range of one asteroid radius above the assumed spherical asteroid's surface was maintained. When this range is combined with the assumed plume divergence half angle of 20 deg., the cosine losses of the gravitational attraction that are inherent to the halo orbit method are set and add another dependence on the asteroid's radius. Another is the dependency of the SEP specific impulse (I_{sp}) on the throttle setting. This analysis assumed standard SEP throttle curves and a SEP system consisting of four thrusters that can produce a total 1.63 N. At maximum thrust, the SEP operates at maximum efficiency, however as the SEP is forced to operate at lower throttle settings, the I_{sp} decreases. As the asteroid size increases, more thrust is required and the SEP thrusters can be used closer to their optimal efficiency which leads to the dips seen in Figures 10 and 11, most notably in the standard GT time curves. While these variables do have some impact on the EGT effectiveness, they are much smaller than the overall thrust level of the spacecraft or the ability to collect more mass, which is seen by the dips almost disappearing once the EGT collects a mass of 50 metric tons or more.
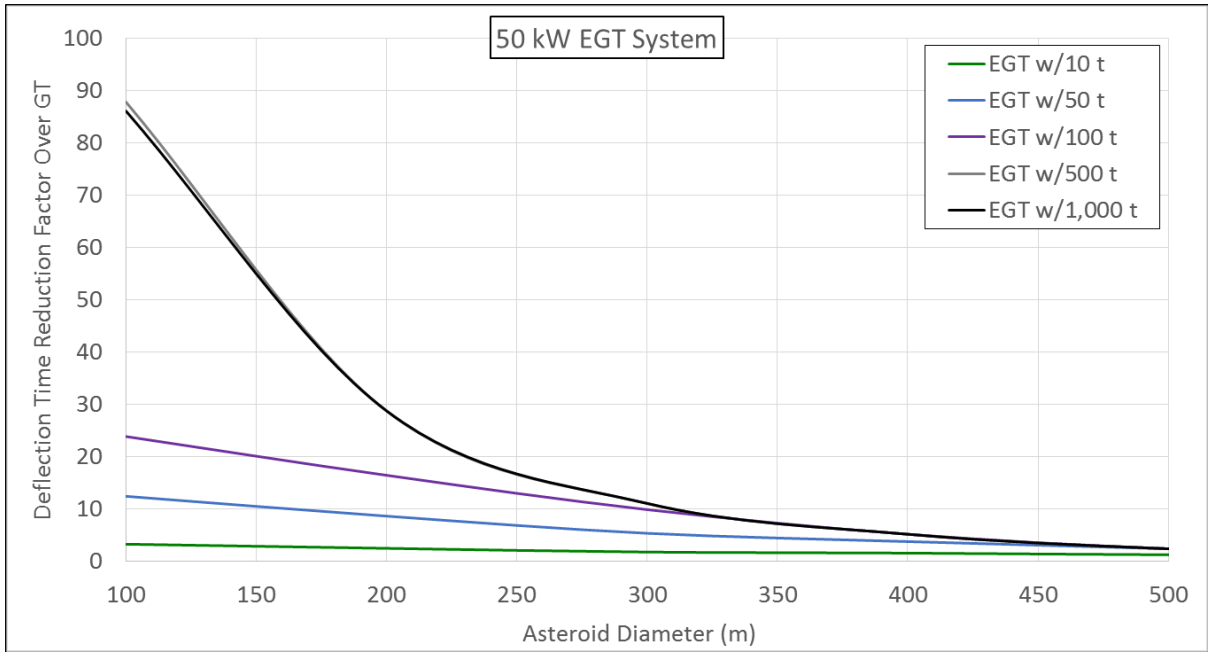
**Figure 8: EGT Deflection Time Reduction Factor Compared to
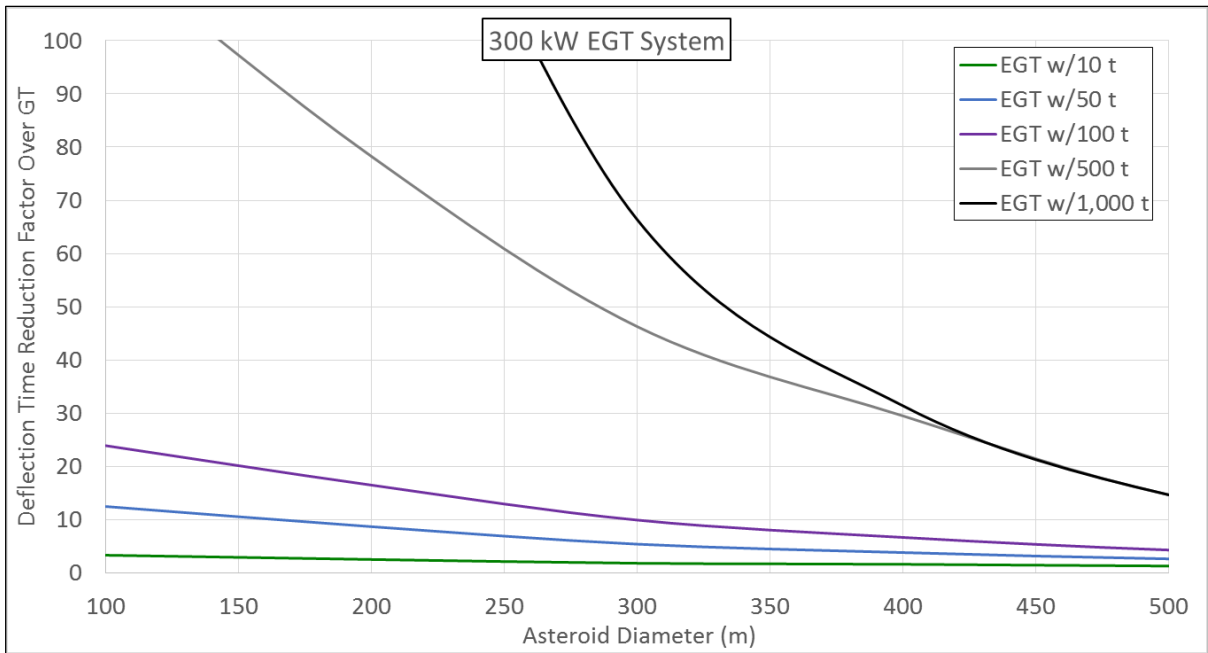Standard Gravity Tractor for 50 kW SEP System.**

**Figure 9: EGT Deflection Time Reduction Factor Compared to
Standard Gravity Tractor for 300 kW SEP System.**

It can be observed in Figures 10 and 11 that the amount of SEP propellant required for the EGT is relatively insensitive to the amount of mass collected. Expanded scales for asteroids up to 400 m are shown in Figures 12 and 13. Figure 12 shows that even a 50 kW EGT system can allow deflection times of less than a year for impactors up to ~175 m in diameter. The standard gravity tractor requires 18 years for a 100 m impactor (red line in upper left-hand corner). Figure 13 shows that the xenon propellant for the EGT is significantly lower than the standard gravity tractor, due to the EGT operating at a higher thrust and I_{sp}. The current ARV with a maximum I_{sp} of

3,000 seconds and propellant capacity of 10 t would permit deflections of asteroids approaching 300 m depending on the amount of propellant needed to reach the target. Increasing the I_{sp} while still providing sufficient thrust levels would be needed to reduce the propellant loads required, which likely become prohibitive, along with deflection time for the larger asteroids with lower SEP power. Going to higher power SEP systems, which is the goal of future human exploration architectures, can increase the size of asteroid targets as shown in Figure 11. Finally, it should also be noted that the above analysis did not assume a specific orbit and therefore did not adjust the power and thrust available based on solar range. The power and thrust levels stated are the assumed power and thrust levels during the entirety of the EGT operations.
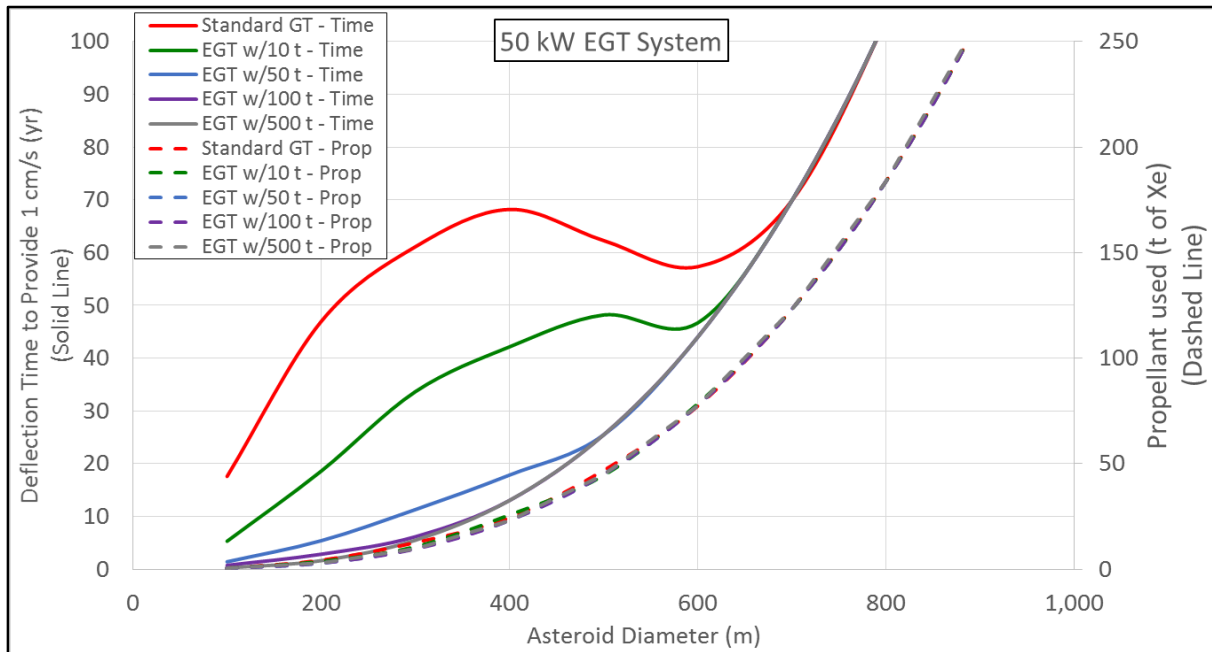

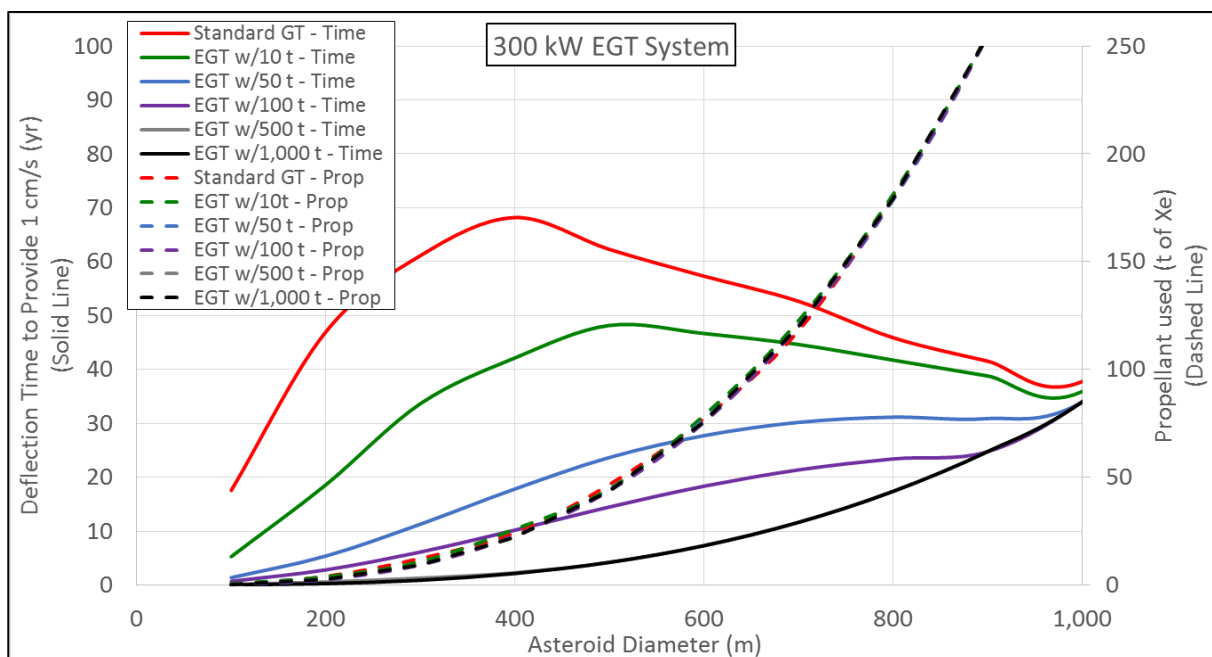**Figure 10: EGT Deflection Time and Propellant for 50 kW EGT System.**

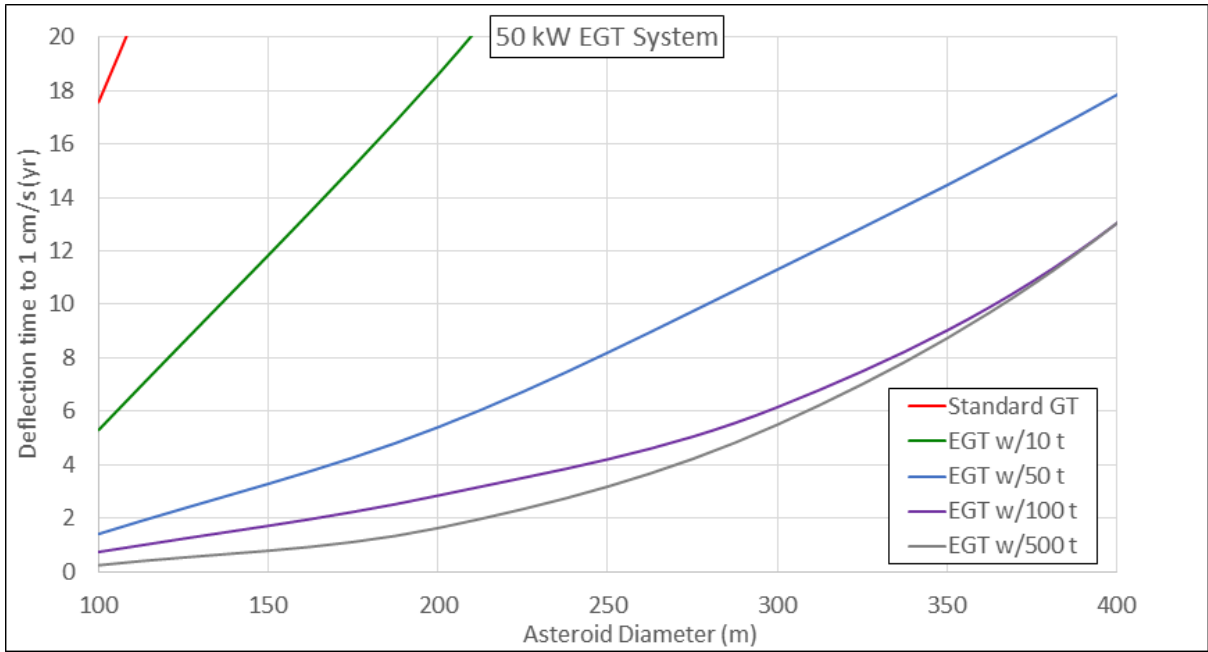**Figure 11: EGT Deflection Time and Propellant for 300 kW EGT System.**

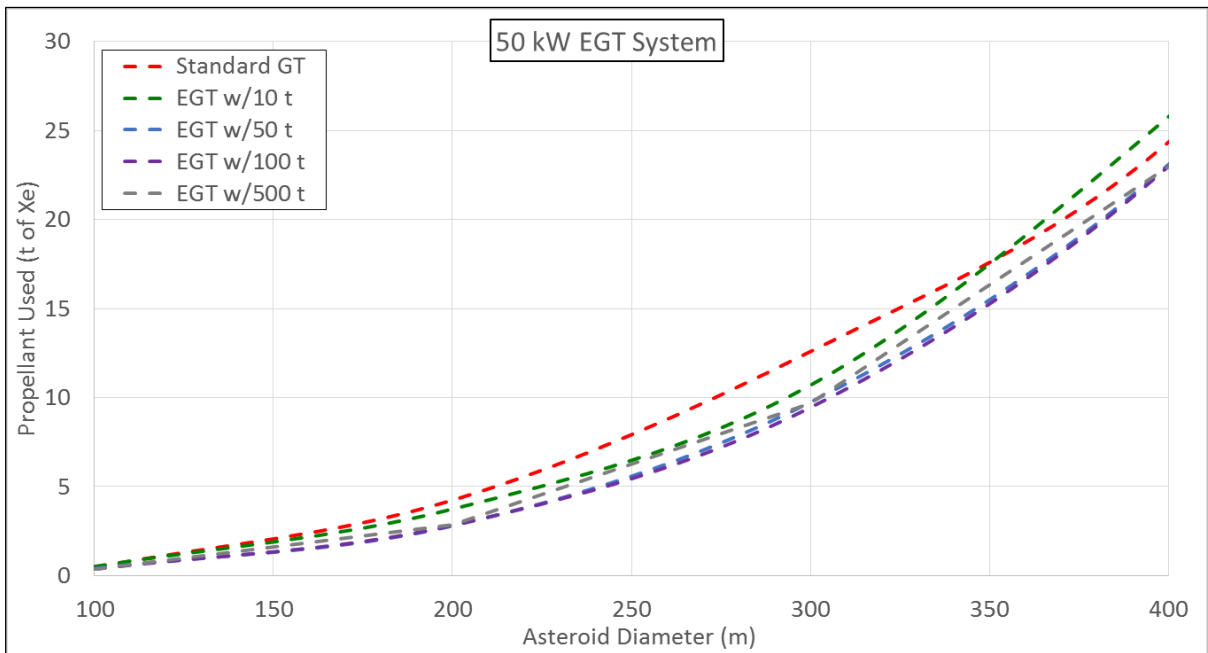**Figure 12: Expanded Scale of Deflection Time for 50 kW EGT System.**

Figure 13: Expanded Scale of Propellant Required for 50 kW EGT System.

Mass Collection Options

From all the data collected over natural bodies greater than 100 m in size, such as natural moons and asteroids, there are an abundance of boulders and regolith littered on their surfaces [10,11,12,13]. Hence designing a spacecraft that is capable of in-situ mass collection is a natural choice for deflecting asteroids using the EGT method. The in-situ utilization of the native asteroid also has the obvious advantage of avoiding the launch and delivery to the asteroid of a spacecraft with the equivalent mass of the EGT.

13

Mass for an EGT deflection mission can be collected in the form of boulders, rocks, or regolith from the asteroid surface using a variety of options with the goal of collecting as much mass as needed to maximize the effectiveness of the technique and minimize operational complexity and risk. To achieve this, several collection options are conceptualized.

Concept 1 – Collecting a Single Boulder

In the ARM robotic mission concept, the capture system is being designed to capture a single coherent boulder with a maximum mass of 70 metric tons. The collection of a single boulder of this size and mass is adequate for a demonstration mission, but future planetary defense missions would benefit from being designed to capture a larger, more massive boulder in order to achieve the necessary deflection in a given warning time. The ARV capture system is scalable to larger boulders, with a boulder on the order of 10 meters in size required to provide approximately 1,000 metric tons of in-situ mass.

Concept 2 – Collecting Multiple Boulders

The second concept is a natural extension of the boulder collection functionality demonstrated by the ARM robotic mission – being capable of collecting multiple boulders. Since the boulders are scattered on the asteroid surface, the spacecraft still picks up one boulder at a time. During the characterization phase, the spacecraft surveys the asteroid surface and maps out the locations of the target boulders and the associated local terrains. A number of boulders are selected based on the estimated sizes and masses, and the sequence of collection is determined. During the collection phase, the spacecraft approaches and lands at the first boulder site, and after one boulder is secured proceeds to hop to the next boulder, and so on. In the micro-gravity environment in the vicinity of an asteroid, hopping between boulders is not expensive in terms of fuel consumption. For example, it takes as little as approximately 0.28 m/s of ΔV to escape the gravity well of asteroid 2008 EV_5, which is approximately 205 m in radius, and hopping on the surface takes far less ΔV than that. This concept is illustrated in Figure 14.

The single spacecraft design reduces mission complexity compared to concepts involving multiple spacecraft. However, there are significant challenges associated with this concept. First, the spacecraft has multiple capture mechanisms, and each of them has to function individually without interference. Depending on the size of the boulders, this can be challenging. Second, maintaining proper attitude to capture a boulder with other boulders without precisely known mass properties in tow is a challenging problem. Again, depending on the size of the boulders, the spacecraft may have to be tilted when approaching and capturing a different boulder, which may be limited physically because of the large solar arrays. Third, the Guidance, Navigation, and Control (GN&C) can be challenging. The dynamics associated with hopping combined with robotic capture mechanisms with large masses and the presence of large solar arrays are complicated. The sensor fields of view may become obscured by captured boulders, so additional maneuvers such as reorientations may need to be performed before approaching the subsequent boulders. Finally, significant portions of these operations will have to be performed autonomously due to the inherent communication delays.
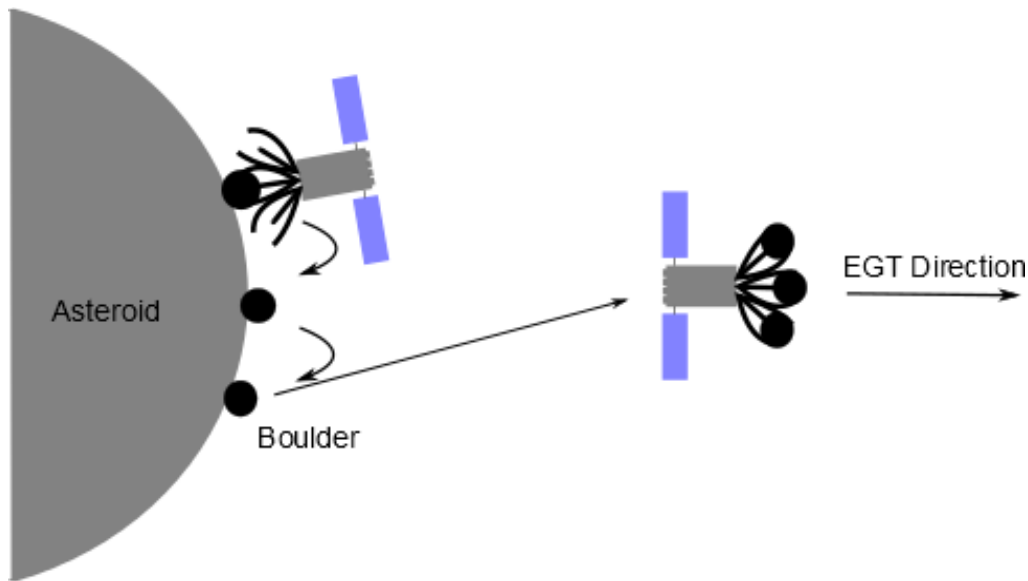
Figure 14: Illustration of Single Spacecraft Picking up Multiple Boulders.

Concept 3 – Separable Collection Spacecraft and SEP Tug

The third concept attempts to address some of the challenges associated with using a single spacecraft to pick up multiple boulders by utilizing two spacecraft. The main SEP spacecraft, or "mother ship" does not go down to the asteroid's surface. This spacecraft is designated as a SEP tug and remains in proximity to the asteroid. A smaller spacecraft is designed for the single purpose of collecting regolith or capturing boulders and ferries between the surface and the SEP tug and transfers the acquired material to the mother ship. The collection spacecraft can be equipped with a smaller capture mechanism and does not require the large solar arrays that are needed by the SEP tug to power the ion engines. Therefore, it can be smaller, less massive, and more maneuverable than a single spacecraft that must perform both the collection and tractoring functions. This concept is illustrated in Figure 15.

The SEP tug will need to station-keep at some acceptable distance from the asteroid and must have the capability to receive and store the regolith and/or boulders delivered by the collection spacecraft. The SEP tug can hover over the collection sites to provide accessibility for material transfer or it can hover over the polar region to minimize the propellant required for matching the rotation of the asteroid while hovering, provided that the asteroid is a single-axis rotator. After enough mass is collected, the SEP tug moves into position for EGT.

The smaller and specialized collection spacecraft greatly reduces the challenges associated with the surface operations, including maneuvering and collecting the asteroidal material. However, there are challenges with this concept, most of which lie in the GN&C aspects and repetitive automated rendezvous and docking (AR&D) required by the concept. The collection spacecraft has to dock with the SEP tug in order to transfer the material, and the SEP tug has to be able to receive and store the material in the micro-gravity environment. This requires that the two spacecraft must be controlled precisely so that no collision occurs and the material is successfully

transferred to the SEP tug. Rather than just storing the collected material, this concept also introduces the possibility of processing asteroidal material to extract propellants, such as magnesium or sulfur, which could be used by the SEP tug during tractoring operations. This would be particularly valuable for larger asteroids that require several hundred tons of propellant to be delivered to the asteroid.
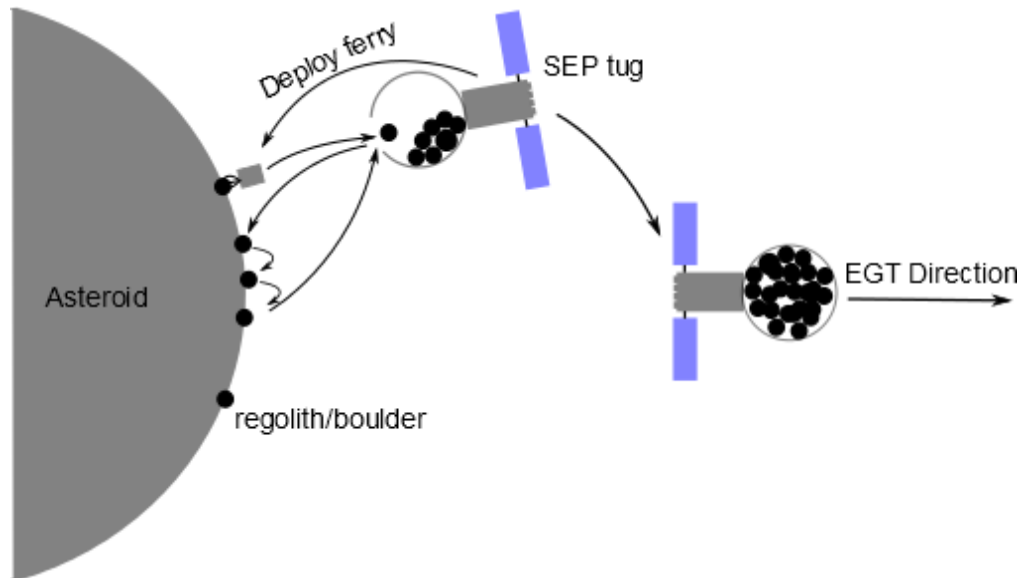

Figure 15: Illustration of Separable Collection Spacecraft and SEP Tug.

Concept 4 – Multiple Collection Spacecraft and SEP Tug

The fourth concept deploys multiple collection spacecraft to collect asteroidal material and deliver it to the SEP tug. These collection spacecraft are likely smaller than the one envisioned in the second concept acquiring less mass during each collection operation. However, by having spacecraft scattered in a swarm fashion on the surface, this concept can access multiple areas simultaneously and can be more efficient in accumulating masses than a single collection spacecraft. In addition, having multiple collection spacecraft provides redundancy to ensure success of the mission. This concept faces the same GN&C and AR&D challenges as with the single collection spacecraft concept with the additional constraint of scheduling delivery of material to the SEP tug by multiple spacecraft. This concept is illustrated in Figure 16.

There are multiple variations and ways of implementing and combining these three basic concepts. Successful attempts to harvest asteroidal resources by NASA's ARM and commercial entities (e.g., Planetary Resources, Deep Space Industries, and Kepler Energy and Space Engineering) will also have tremendous synergistic benefits for the successful implementation of material capture for a the EGT technique. Learning the basic techniques for mining material from larger NEAs will help improve the reliable operations needed to allow this approach to be successfully implemented for a future planetary defense effort.
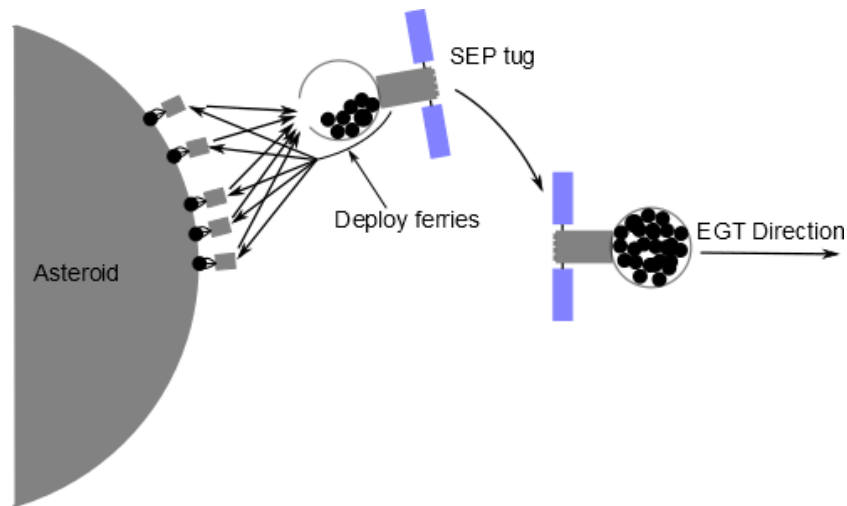
Figure 16: Illustration of Multiple Collection Spacecraft and SEP Tug.

Other EGT Operational Concepts

This section briefly discusses several other EGT concepts of operations that are of interest. These concepts assume that a SEP system is still the primary source of thrust that facilitates the deflection of the asteroid. When using a SEP tug for EGT, it is very important the SEP thruster plume not impinge on the asteroid. This requires that the SEP engines are either canted [2] or the EGT is offset radially from the asteroid velocity vector [5,9]. As discussed previously, canting the SEP engine reduces the efficiency and the effectiveness of the EGT due to thruster cosine losses, and thrusters that minimize plume divergence greatly benefit all operational concepts. Offsetting the EGT using the spiral tractoring technique also introduces cosine losses of the gravitational pull in the along-track direction. The concepts discussed here aim to improve upon the existing EGT concepts in the literature by alleviating some of the aforementioned shortcomings, by utilizing solar sails and tethers. Detailed analyses of these concepts will be presented in a future publication [14].

Figure 17 shows the concept of attaching a solar sail to the EGT spacecraft. The Solar Radiation Pressure (SRP) naturally pushes the EGT away from the sun, and thus, offsetting the EGT from the asteroid velocity vector. The solar sail can also be tilted so that a force component can be generated in the along-track direction to supplement the tugging force. The position of the EGT relative to the asteroid is an equilibrium resulting from balancing three external forces, gravity, SEP thrust, and SRP. An appropriate equilibrium can be established by trading the combined spacecraft mass, the size of the solar sail, as well as the solar sail tilt, given the thruster plume divergence angle.

Using multiple EGTs in formation can drastically improve the efficiency of the asteroid deflection. For example, Wie [5] showed that placing *n* spacecraft in a halo gravity tractor orbit is *n* times more efficient in deflecting an asteroid. However, this requires tight control of the spacecraft positions to prevent them from colliding with each other as well as the asteroid's surface. This issue can be mitigated if the spacecraft can be naturally separated. Figure 18 illustrates such a concept, which is a view of a 3-EGT scenario from behind the asteroid in the along-track direction. It can be seen that each of the three EGTs is attached to a solar sail, and by tilting the solar sails about the

17

along-track vector, the forces in the cross-track direction separate the spacecraft naturally. These EGT spacecraft do not fly in a halo orbit in front of the asteroid. Instead, they are naturally held at their respective equilibria due to balance of external forces.

The effectiveness of the EGT operations is greatly dependent on the gravity component in the along-track direction. Thus, it is preferable to keep the mass close to the asteroid. Figure 19 illustrates a concept that keeps the augmenting mass on a tether. The augmenting mass can be placed much closer to the asteroid to increase the gravitational pull, to the limit of the SEP thrust capability, with much less mass while the SEP tug can be placed further from the asteroid for increased safety margin. Similar to the approach shown in Figure 17, a solar sail is used to provide the radial offset, and it can be tilted to augment the tugging force. The dynamics associated with the tether in the micro-gravity environment can be complicated, and need to be carefully analyzed.
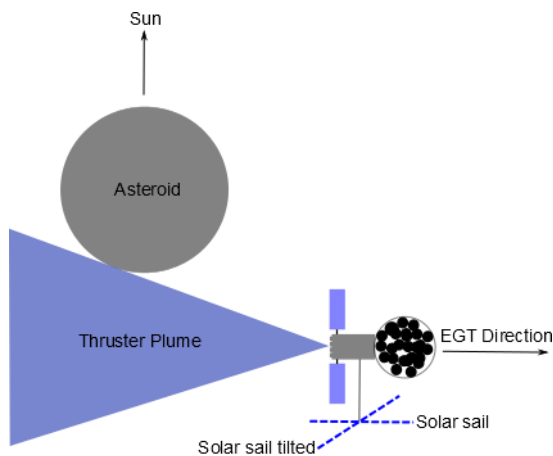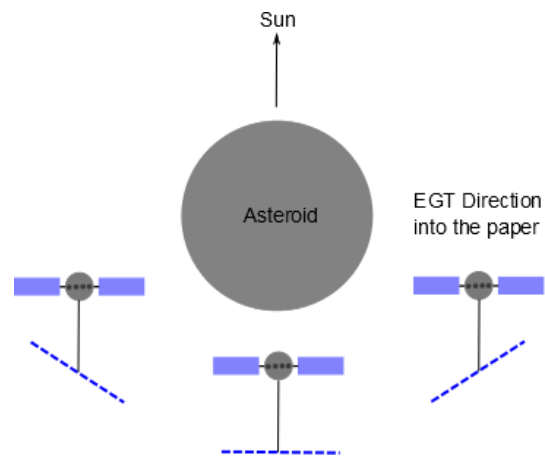

Figure 17: Single EGT with a Solar Sail.   **Figure 18: Multiple EGTs on Solar Sails.**

Figure 20 shows a concept where the EGT is in-line with the asteroid velocity vector. This concept requires the SEP engines to be canted to prevent the plume streams from impinging the asteroid surface. This reduces the effectiveness of the gravity tractor due to the cosine loss of the SEP thrust in the along-track direction. For example, Lu [2] showed a concept where the effective thrust for tugging the gravity tractor is only half of the total available thrust due to canting the SEP engines 60 degrees from the along-track direction. The concept here aims to reduce the cosine loss. As shown in Figure 20, the augmenting mass is attached to a tether, and kept close to the asteroid, while the SEP tug is kept farther away in the in-track direction. Because of the increased distance from the asteroid to the SEP tug, the SEP engines do not need to be canted as much as in the case where the SEP tug is closer to the asteroid, assuming the thruster plume angle remains the same. Clearly, this concept increases the efficiency of the EGT operation. Here, the mass can be kept closer to the asteroid than the scenario where the spacecraft and the augmenting mass are collocated. Thus, the same effectiveness of EGT can be obtained with a smaller mass. The challenge of this concept lies in the complicated dynamics associated with tethers in the micro-gravity environment. The complexity of station-keeping the mass and the interaction between the mass and the SEP tug need to be carefully investigated.
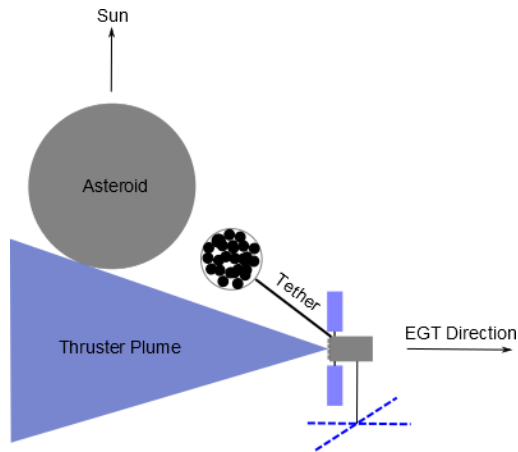
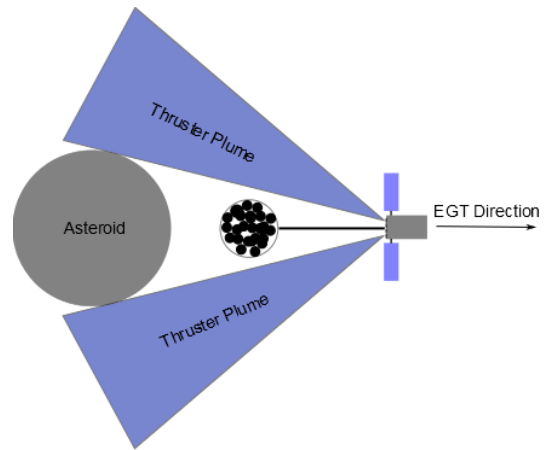**Figure 19: Single offset EGT on a Solar Sail with Tethered Mass.**

Figure 20: Single in-line EGT with Tethered Mass.

Collection Site Selection

It is postulated that most of the boulders and regolith on the surface of an asteroid may be deposited by impacts from other small bodies [11]. For example, Küppers [11] shows that the boulders on the surface of asteroid Lutetia are mostly concentrated around the central crater in Baetica region, as shown by the images taken by the OSIRIS camera onboard Rosetta. This is consistent with the simulated distribution of boulders ejected from that crater. It is also theorized in Thomas [15] that Shoemaker crater is the source of most boulders on asteroid 433 Eros. Boulders can also be created by thermal stresses. A larger structure can be fractured by the larger temperature gradients caused by crossing the terminator plane repeatedly [12]. If these theories are correct, it is likely that most boulders should be loosely resting on the surface, with the forces keeping them on the surface being only the low gravity and cohesion.

Selection of boulder sites depends on many factors, which include lighting, communication links, asteroid rotation, etc. Here we touch upon the comparison of the sites on various latitudes in facilitating the boulder extraction only. All asteroids rotate in some fashion, with some tumbling (e.g., Toutatis) and others rotating around a single axis (e.g., Itokawa, 2008 EV$_5$, and Bennu). For a tumbling asteroid, it is difficult to characterize the pros and cons of going to various sites on the surface. However, for the principal-axis rotators, it is evident for the few well observed asteroids such as Itokawa and Eros, many of the boulders congregate in the equatorial regions [10,12]. This can be explained by the slow process in which the boulders shift to the equatorial regions due to the extremely small but persistent centripetal acceleration. Thus, the abundance of boulders makes the equatorial regions more favorable than others. In addition, the centripetal acceleration is the strongest at the equatorial regions, which can facilitate picking up boulders. For example, Figure 21 shows a comparison of the gravitational and centripetal accelerations at various latitudes on a fictitious spherical asteroid with a 250 m radius and a density of 2 g/cm^3. The boulder is 20 metric tons, and the spacecraft is 9.7 metric tons (wet mass) at 20 m above the surface when capturing the boulder. It can be seen that if the asteroid rotates more rapidly than approximately once every 2.4 hours, in the equatorial regions, once the

cohesion is broken, the spacecraft can fly away with the boulder naturally without the need for external forces due to the centripetal acceleration being greater than the gravitational acceleration (green and red curves). The benefit of the centripetal acceleration diminishes as the collection site moves up in latitude. If boulder to surface cohesion is low, which can be expected for a boulder resting on the surface, there are likely regions on the surface where collection operations could be greatly simplified.
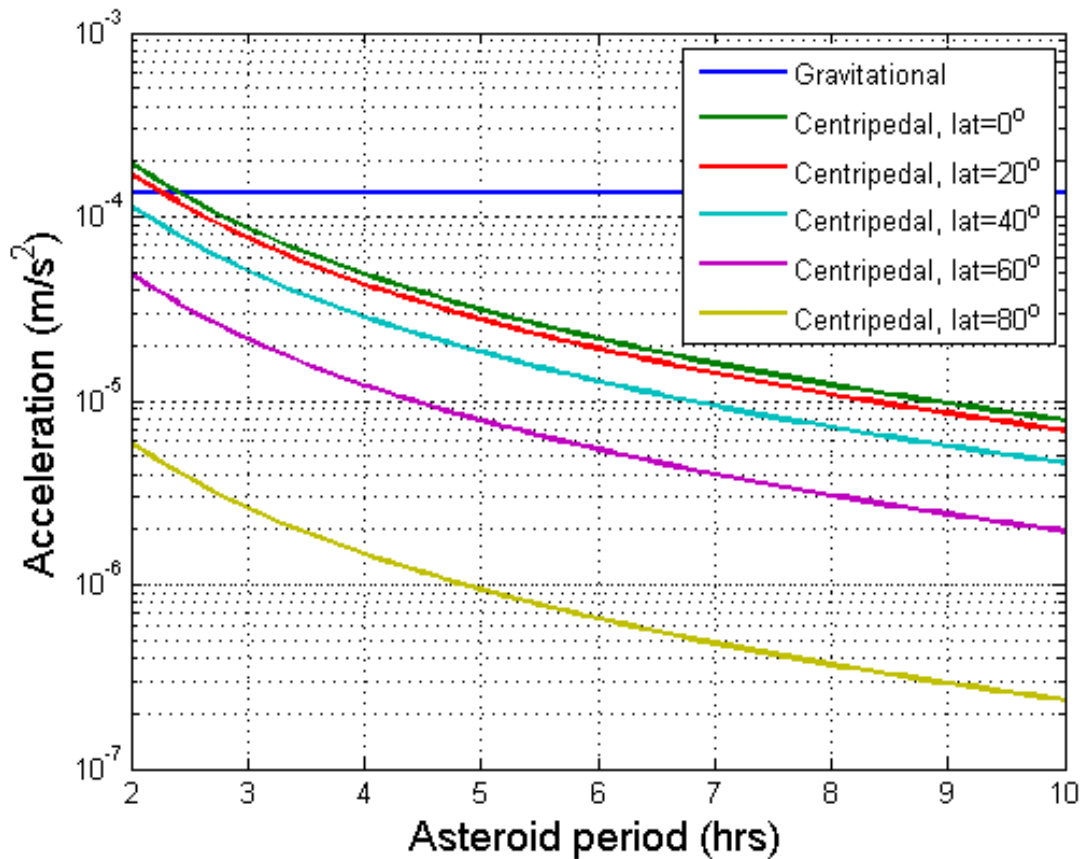

Figure 21: Comparison of Gravitational and Centripetal Accelerations.

Operational Challenges of Mass Augmentation

One significant operational challenge of the EGT method involves collecting the augmentation mass at the NEO. However, analysis that has been performed for the ARM robotic concept to date [6,7] and the commercial interest in asteroid mining indicates that collecting many tons of mass from the surface of an asteroid is feasible and further analysis and concept development is warranted. The concept of operations currently being considered would provide the first demonstration of mass collection of the magnitude needed to successfully conduct an EGT deflection. Other collection techniques such as electromagnets, large quantity regolith collection, multiple boulder collection systems, and others have been envisioned and require further study and development.

The ARM robotic segment concept assumes that capture operations occur while the collection site is illuminated by the sun due to the reliance on optical navigation sensors and the desire to keep the ARV from experiencing an eclipse due to power, thermal, and potential charging issues. This constraint combined with the reliance on

20

optical navigation during descent and the desire to maintain a passively safe trajectory as long as possible, sets a spin rate limit for accessible asteroids at a little over 3 hours [6]. However, if a mission were solely focused on planetary defense, different designs could easily be envisioned that would remove or limit the reliance on optical navigation and/or allow the spacecraft to operate through an eclipse period that would relax this spin rate limit.

Finally, another concern about the spin rate is the existence of collectable material at the target. On small, fast rotators, the centripetal acceleration can exceed the surface gravitational forces leading to shedding of surface material and forming a monolithic body without any available material to collect. As shown in Figure 22, very few large asteroids have been observed to be spinning at a rate above the rubble pile "speed limit" rotation period of approximately 2.3 hours [16]. A low cohesive strength of only 25 Pa can explain this observation. This leads to the conclusion that the vast majority of the large asteroids have the capability to retain surface material, and that material is likely to be loosely bound to the parent asteroid and readily collectable, thus making EGT a credible deflection technique for hazardous-sized impactors.
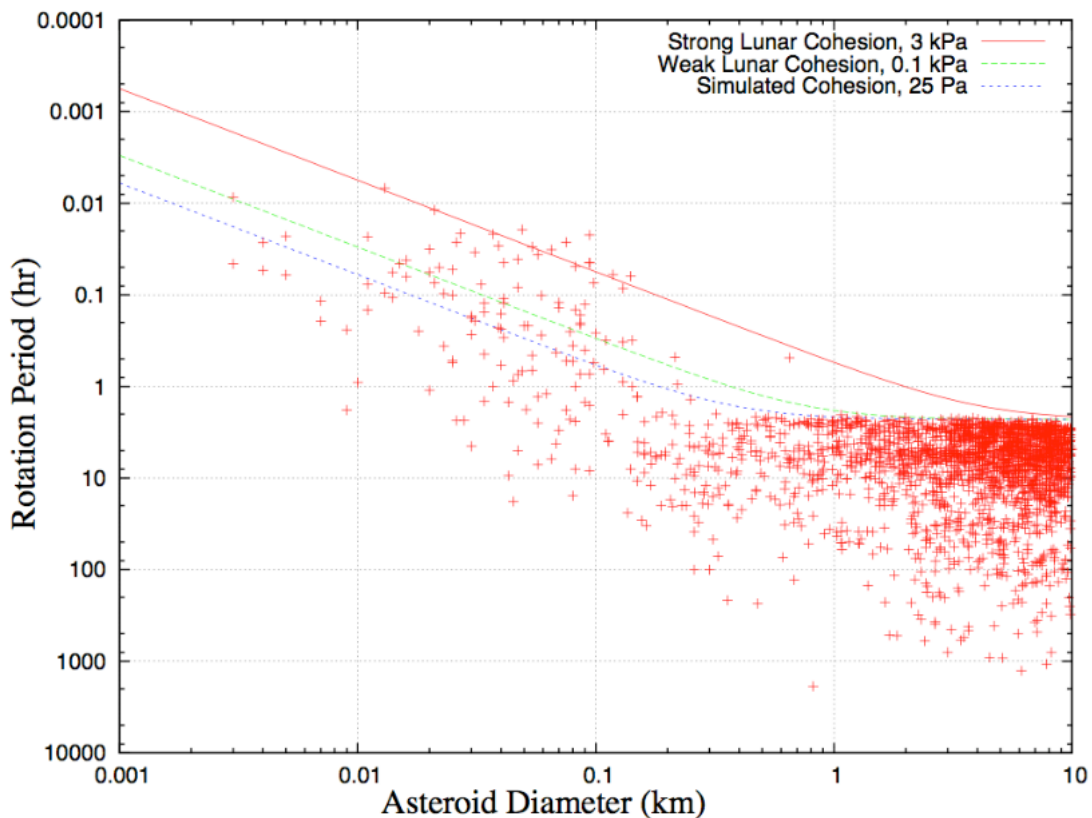

**Figure 22: Asteroid Size vs. Rotation Period Distribution
(Image Credit: Paul Sánchez and Dan Scheeres – Ref. [16]).**

Applicability to Hypothetical Threat "2015 PDC"

We analyzed the ability of a 50-kW spacecraft like the ARV to deflect the 4th IAA Planetary Defense Conference hypothetical asteroid "2015 PDC" using the enhanced gravity tractor technique. There are two major challenges in this scenario for a gravity tractor. First, assuming that launch or departure from the Earth-Moon system is not

possible earlier than spring 2017 (about a year after final observations are made), the impact date of September 2022 defined in this scenario leaves only 5.5 years to reach the asteroid and impart enough impulse to deflect it. This would be challenging for any slow-push/pull approach. Second, the asteroid orbit aphelion of 2.65 AU limits the available sunlight during parts of the diversion to only about 15% of the 1 AU insolation. This severely limits the power available for any technique that utilizes the solar power. Nevertheless, we found that there are some plausible solutions in which an ARV-class EGT can deflect the hypothetical asteroid 2015 PDC in the available time.

The only physical characteristic of the asteroid known at time of launch is the absolute magnitude, H = 21.3 ±0.4 (assumed to be one-sigma uncertainties). Depending on the albedo and density of the asteroid, this could correspond to a spherical-equivalent diameter from less than 100 m to more than 500 m, and a mass from less than 1 million tons to more than 100 million tons. The asteroid is more likely to be in the lower third of this range unless it has both a very dark albedo and the error in H makes it brighter than nominally predicted. As a test case we defined an asteroid with H = 21.7 (i.e. +1σ), albedo = 0.3, and density of 2.5 g/cm^3 corresponding to a stony asteroid with a mass of 1.7 million tons. This is smaller and less massive than the most likely values, but within a reasonable range. The spherical equivalent diameter would be 110 m, but we assumed a 2:1:1 ellipsoid of the same volume as the predicted sphere, with dimensions of ~87 x 87 x 175 m. This non-spherical assumption is important because it influences how close to the asteroid the spacecraft can be, and the gravitational force is proportional to the square of the separation distance. We applied a constraint that the spacecraft should remain at least 100 m beyond the maximum dimension of the asteroid to avoid collision, corresponding to a minimum spacecraft-to-asteroid radius of 187 m when not thrusting, and radius when thrusting of about 200 m using the halo orbit approach defined in [9] and described earlier in this paper. Dense asteroids can be easier to move than larger low-density asteroids of the same mass, and spherical asteroids are easier to move than elliptical ones, because the gravity tractor can orbit closer to the center of mass and generate more gravitational force.

The force that can be applied to the asteroid is potentially limited by two factors. First is the available thrust from the spacecraft, based on the available power and the capacity of the propulsion system. Second is the gravitational attraction between the asteroid and the spacecraft plus collected augmentation mass. In most cases we investigated, gravitational attraction was the limiting factor, so it is more effective to collect as much mass as possible from the asteroid, up to an assumed limit of 1000 metric tons. It should be noted that this mass is greater than the current ARM robotic boulder capture system design requirement, so a modified capture capability would be necessary. This produced a net tractor force of approximately 1.0 N using the following equation from [9]:

$$F_N(\rho, z) = \frac{GM_{ast}m_{sc}}{(\rho^2 + z^2)^{\frac{3}{2}}} z \quad (1)$$

F_N – Thrust required to remain in the halo, also the thrust that the spacecraft applies to the asteroid-ARV system.

G – Gravitational constant

M_{ast} – Mass of the asteroid

m_{sc} – Mass of the spacecraft with any mass augmentation

ρ – Radius of the halo orbit from the trajectory centerline

z – Offset distance of the halo orbit from the center of mass of the asteroid

It is assumed that the ARV spacecraft departs the Earth-Moon system with a characteristic energy (C_3) of 2.0 km^2/s^2. This can be achieved by a spacecraft orbiting in high Earth orbit using a lunar flyby, or by a direct launch from Earth to escape on NASA's planned heavy-lift launch vehicle known as the Space Launch System (SLS). The transit to the asteroid, shown in Figure 23 in green, takes 1,000 days and has a single 40 day coast period (shown in purple), though 10% power margin and a duty cycle of 95% allow for additional thruster off periods. Upon arriving at the asteroid on March 12, 2020, a three month long period of reconnaissance and mass collection is allocated before beginning the EGT operations. By thrusting for the next 824 days, the ARV is capable of deflecting the asteroid from the subterranean 2,790 km Earth periapsis radius (i.e., an impact) to 6,930 km allowing for a miss of 560 km altitude from the surface. In Figure 24, the trajectory of the ARV while thrusting with the asteroid is shown in green and the trajectory of 2015 PDC after deflection and subsequent Earth close approach is shown in purple. Given the very narrow miss distance margin, this scenario defines the limit of what this 50 kW-class vehicle can accomplish with the warning time and impactor orbit provided in the scenario and highlights the fact that more warning time and better remote characterization of impactors are highly desirable, particularly for slow-push/pull techniques.
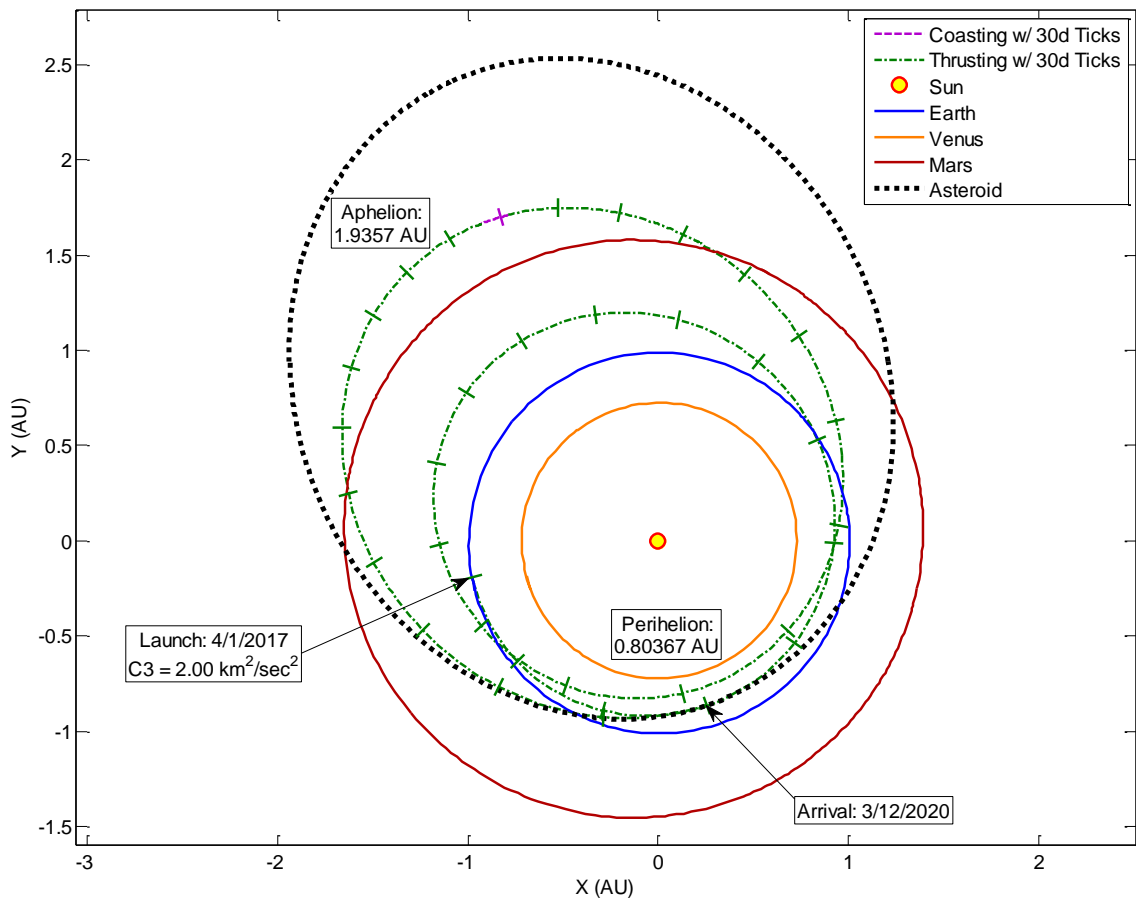

Figure 23: ARV Trajectory to Asteroid 2015 PDC (green/purple); Asteroid 2015 PDC initial Orbit (black); Earth Orbit (blue).
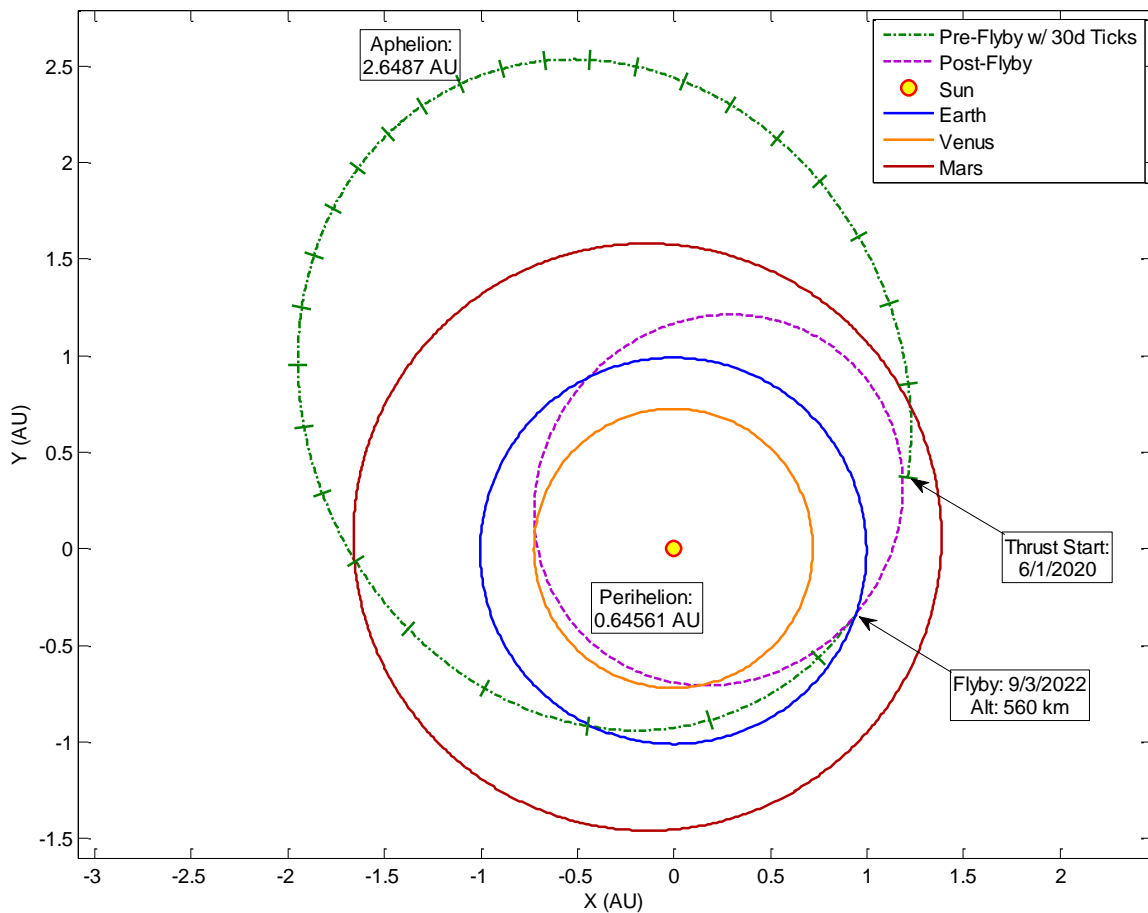
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**Figure 24: ARV Deflection of Asteroid 2015 PDC Thrusting Arc (green);
Trajectory of 2015 PDC after Deflection and Subsequent Earth
Close Approach (purple); Earth Orbit (blue).**

As mentioned, the variables that affect the deflection are the time allowed to deflect and the maximum thrust that can be applied. The SEP system aboard the ARV is capable of 1.63 N of thrust and could be augmented with additional thrusters to upgrade the system, which would allow for a potentially shortened thrusting duration to reach the asteroid. Additionally, either larger arrays or new cell technology could take the maximum power at one AU to a higher level than the assumed 50 kW capability. More array power would allow the thrusters to operate at the maximum allowed halo thrust when farther from the Sun and would also allow for a shortened thrusting duration to the asteroid. Either of these vehicle modifications coupled with earlier detection would allow the ARV to be applicable to larger NEAs.

Warning Time and Compatibility with other Planetary Defense Options

As shown previously, a significant advantage of the EGT is that it can drastically reduce the deflection time compared with the standard gravity tractor. Although sufficient warning time is needed as is the case with all slow-push/pull techniques, EGT is a viable option when the warning time is measured in years, and not decades as is needed for the standard gravity tractor approach utilizing only the mass of the spacecraft. Figure 25 shows the approximate regimes of primary applicability of the four types of planetary defense techniques: civil defense, kinetic impactor, the

traditional gravity tractor, and a nuclear explosive device. The EGT technique can significantly overlap the regime of the kinetic impactor, especially if a SEP spacecraft like the ARV has been developed and operated or if it has actually been launched and can be expediently refueled in space.
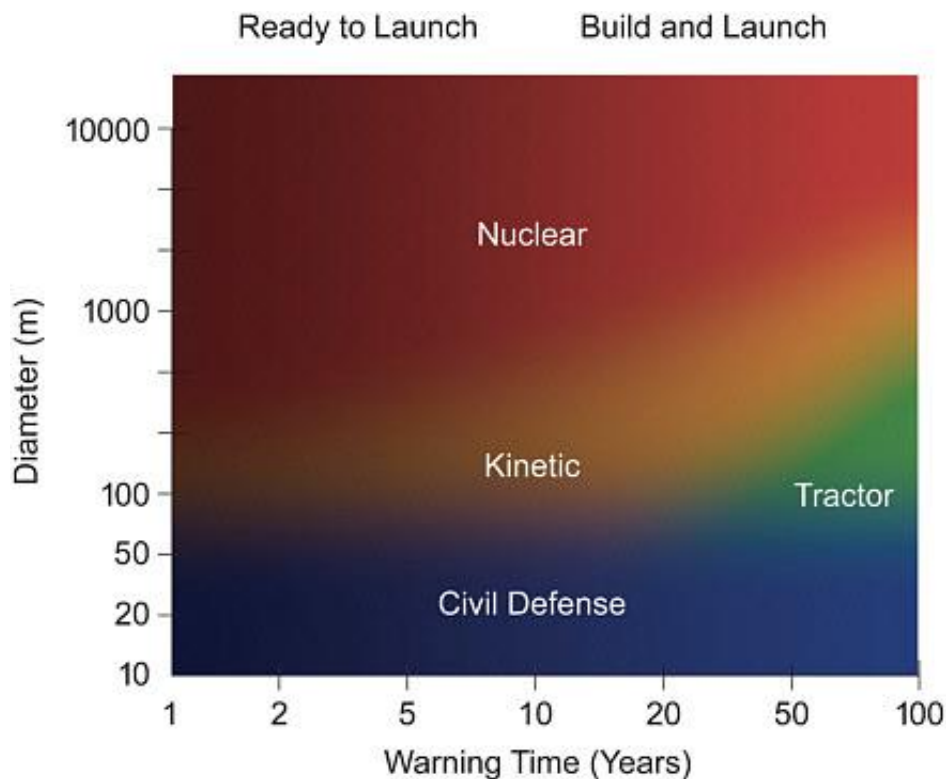

Figure 25: Approximate Regimes of Primary Applicability of four Types of Planetary Defense Techniques (Image Credit: Tim Warchocki – Ref. [17]).

The pros and cons and the typical mission scenarios and constraints of classic techniques for planetary defense such as nuclear blast, kinetic impactor and gravity tractor have been well documented in literature, while the EGT is quite a new concept. It is also a very flexible tool in the hands of policymakers when they have to choose the reaction strategy. The simplest mission scenario for the EGT is that it is chosen as the primary reaction strategy as soon as the asteroid threat is discovered and sufficiently characterized: the spacecraft is launched, it collects mass from the asteroid, and performs the EGT deflection.

However, the EGT is also very much complementary to the kinetic impact and nuclear explosion techniques. Indeed, assuming that policymakers decide to implement a kinetic impact approach or opt to deliver a nuclear explosive device, if the primary mission does not perform with full success and is not completely successful in deflecting the impactor or leaves smaller parts of the original asteroid still with a risk of impacting the Earth, the EGT can provide trajectory corrections to the impactor or can collect mass from the smaller asteroid fragments and perform the EGT technique on them.

Additionally, in principle the EGT spacecraft can also provide in one single mission (one single spacecraft) the nuclear option. The spacecraft could also carry a nuclear explosive device and deploy it after collecting mass from the asteroid for subsequent

tractoring. Depending on the warning time and the characteristics of the impactor, policymakers will have to decide if the nuclear explosion option should be performed right away, or if the EGT can be performed first. If the nuclear explosion is taken as the first mitigation technique, the EGT can maneuver to safe distance while the explosion takes place, and then come back to check if the primary option worked properly, and perform corrections through the EGT technique on the main body and/or any smaller fragments that might still have a risk of impacting with the Earth.

It is likely that in the future there will be multiple ARV buses ready to launch and already operational in space, for example to deliver logistics supplies to astronauts in cislunar orbit, where the first ARV has placed the redirected asteroidal material, or to deliver cargo to the Mars neighborhood. Since the EGT technique builds on the ARV bus, the fact that there could be multiple ARV-derived buses available would make the EGT a ready to launch option. So ready that it might already be in space and simply be repurposed for its critical new mission of planetary defense. Finally, with the ability to be refueled, the ARV itself could be used as a kinetic impactor augmented by the mass collected during normal asteroid mining and processing operations.

Summary

The Enhanced Gravity Tractor technique is a novel, innovative variant of the traditional gravity tractor that can significantly reduce the deflection time required to be an effective planetary defense approach. Using mass collected in-situ, which would likely range from tens to hundreds of metric tons depending on the size of the impactor and warning time available, allows for significant augmentation of the tractoring mass and greatly increases the gravitational force between the objects.

NASA's ARM robotic segment will provide the first ever demonstration of the EGT technique and validate collecting a multi-ton boulder in-situ. For an actual mission to deflect an Earth impactor, the collected material could be a single boulder, multiple boulders, regolith or a combination of different sources. There are many ideas for mass collection techniques and operational augmentations that can increase the effectiveness and reduce the operational risks associated with the EGT technique, and several have been highlighted in this paper. Depending on the impactor's characteristics, the propulsion system's capability and the mass collected, the EGT approach can reduce the deflection times by more than two orders of magnitude. Although the EGT still requires a significant warning time to reduce the required ΔV for the deflection, the ability to alter the trajectory more rapidly allows the EGT technique to be applicable to a greater range of impact threats. The ability for multiple spacecraft to orbit the impactor in formation can increase the ΔV than can be applied and further reduce the time needed by the EGT technique to divert hazardous NEOs.

Finally, the spacecraft necessary to successfully conduct an EGT deflection can also support other planetary defense techniques in a coordinated manner to maximize the successful deflection of a future Earth impactor. Advancements in SEP propulsion, autonomous vehicles, and robotic systems applicable to human and robotic exploration, commercial asteroid mining, and the used of space-based resources can synergistically help provide a robust defense against future Earth impacts.

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