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ASTEROID REDIRECT MISSION PROXIMITY OPERATIONS FOR REFERENCE TARGET ASTEROID 2008 EV$_5$

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NASA's Asteroid Redirect Mission (ARM) is composed of two segments, the Asteroid Redirect Robotic Mission (ARRM), and the Asteroid Redirect Crewed Mission (ARCM). In March of 2015, NASA selected the Robotic Boulder Capture Option[1] as the baseline for the ARRM. This option will capture a multi-ton boulder, (typically 2-4 meters in size) from the surface of a large (greater than ~100 m diameter) Near-Earth Asteroid (NEA) and return it to cis-lunar space for subsequent human exploration during the ARCM. Further human and robotic missions to the asteroidal material would also be facilitated by its return to cis-lunar space. In addition, prior to departing the asteroid, the Asteroid Redirect Vehicle (ARV) will perform a demonstration of the Enhanced Gravity Tractor (EGT) planetary defense technique[2]. This paper will discuss the proximity operations which have been broken into three phases: Approach and Characterization, Boulder Capture, and Planetary Defense Demonstration. Each of these phases has been analyzed for the ARRM reference target, 2008 EV$_5$, and a detailed baseline operations concept has been developed.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is developing the first-ever robotic mission to visit a large near-Earth asteroid (NEA), collect a multi-ton boulder from its surface, and redirect it into a stable orbit around the Moon. NASA's Asteroid Redirect Mission (ARM) is composed of two segments, the Asteroid Redirect Robotic Mission (ARRM), and the Asteroid Redirect Crewed Mission (ARCM). The ARM is part of NASA's plan to advance the technologies, capabilities, and spaceflight experience needed for a human mission to the Martian system in the 2030s. The ARM is designed to address the need for flight experience in cis-lunar space and provide opportunities of for testing the systems, technologies, and capabilities that will be required for future human deep space operations. A principle objective of the ARM is to develop a high-power Solar Electric Propulsion (SEP) vehicle, and demonstrate long-duration SEP operations in interplanetary space, which is critical for deep-space exploration missions. A second prime objective of ARM is to conduct a human spaceflight mission involving in-space interaction

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with a natural object in order to provide the systems and operational experience that will be required for eventual human exploration of Mars, including the Martian moons Phobos and Deimos.

In March of 2015, NASA selected the Robotic Boulder Capture Option[1] as the baseline for the ARRM. This option will capture a multi-ton boulder, (typically 2-4 meters in size) from the surface of a large (greater than ~100 m diameter) NEA and return it to cis-lunar space for subsequent human exploration during the ARCM. Further human and robotic missions to the asteroidal material would also be facilitated by its return to cis-lunar space. In addition, prior to departing the asteroid, the Asteroid Redirect Vehicle (ARV) will perform a demonstration of the Enhanced Gravity Tractor (EGT) planetary defense technique[2]. The design of the proximity[3] and surface[4] operations was a major focus of the pre-Phase A study, but in order to continue to mature these designs, asteroid 2008 EV_5 was chosen as the ARRM reference target to allow for more detailed planning.

The proximity operations have been broken into three phases: Approach and Characterization, Boulder Capture, and Planetary Defense Demonstration. Each of these phases has been analyzed for 2008 EV_5 and a detailed baseline operations concept has been developed in order to support requirements closure and move the ARRM into Phase B. This paper provides an overview of these operations.

REFERENCE TARGET: 2008 EV_5

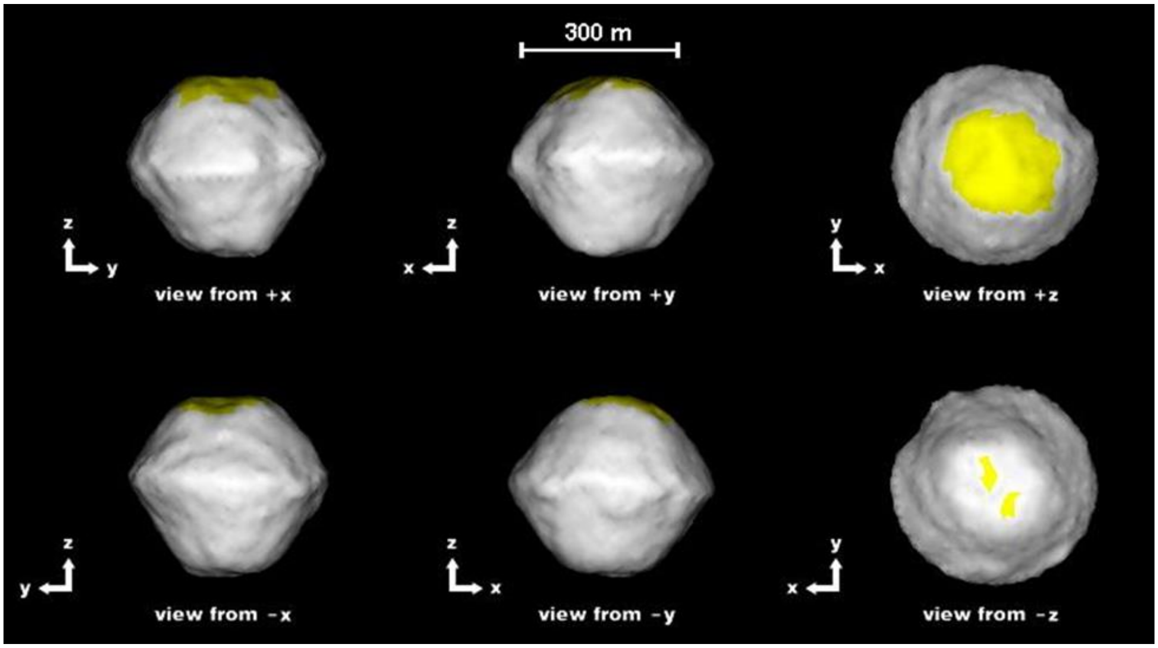


Figure 1. 2008 EV_5 shape model from radar observations. Yellow shading indicates areas that were not viewed by radar[5].

The near-Earth asteroid (341843) 2008 EV_5 was discovered on March 8th, 2008 by the Mt. Lemmon Survey in Tucson, Arizona. Follow-on radar observations where made with Arecibo and Goldstone in December of 2008. These observations show a retrograde spinning spheroid with dimensions of 420 m x 410 m x 390 m +/- 50 m, a rotation period of 3.725 hr +/- 0.001 hr[5], and an optical albedo of 0.095 +/- 0.035[6]. Shown in Figure 1, 2008 EV_5, was chosen as the reference target of the ARRM based on its assumed classification, orbital mechanics, and radar observations from which the presence of boulders can be inferred. Other NEAs currently in consideration are (101955) Bennu, (162173) Ryugu, and (25143) Itokawa. As NEAs in accessible orbits continue to be discovered, they will be analyzed for ARM applicability and this list could expand. A final target selection will not be made until a year prior to launch which is currently set for December 2020.

2008 EV_5 has been classified as a carbonaceous, or C-type, asteroid which are of high interest to both science and in-situ resource utilization (ISRU) communities due to their potentially high water content. More specifically, the ARM Formulation Analysis and Support Team (FAST) has stated that 2008 EV_5 is likely most similar to CR meteorites with CI, CM, and CK meteorite analogs also being a possibility[6]. Having a fairly Earth-like orbit and close approach timing within the ARM timeline allow for a return mass of over 20 t with the current ARV capabilities and ARRM mission timeline. This translates to a spherical equivalent boulder of approximately 2 to 3 m in diameter when considering the expected density range.

The presence of boulders was also a key factor in the decision to select 2008 EV_5 as the reference target. Using the Arecibo radar images from December of 2008, it is possible to identify six boulders that are approximately 10 m in scale on the surface of 2008 EV_5. With the limitations of the radar viewing, boulders could only be identified on roughly half of the surface, leading to the assumption that there are likely ten such 10 m scale features on 2008 EV_5. With the inclusion of the radar scattering data which suggests millions of 10 cm scale cobbles, along with a conservative power law size frequency distribution, it is estimated that there are ~3,000 1-5 m boulders and ~360 2-3 m boulders on 2008 EV_5[6].

ASTEROID REDIRECT VEHICLE OVERVIEW

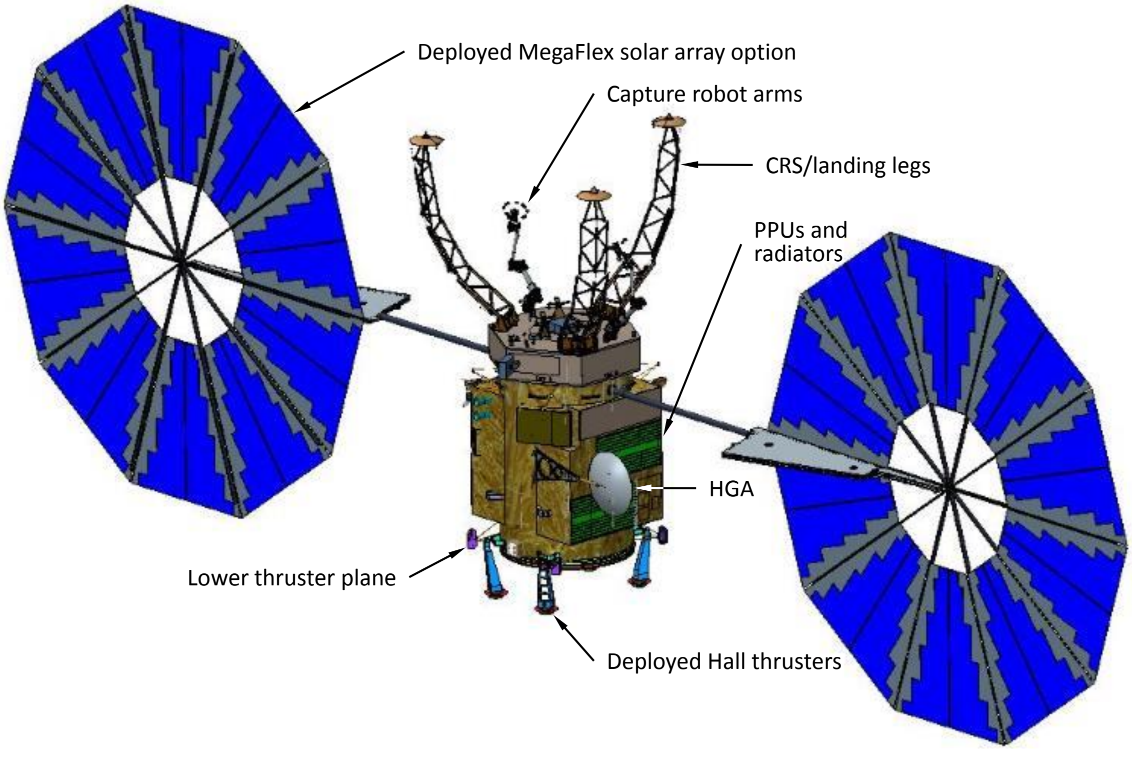


Figure 2. Notional Design of the Asteroid Redirect Vehicle.

The Asteroid Redirect Vehicle, shown in Figure 2, consists of the Solar Electric Propulsion Bus and Capture Module. NASA has selected an acquisition strategy for the SEP Bus which will leverage U.S. commercial capabilities. This procurement process is currently in the early stages with Phase 1 Studies planned to be awarded in early 2016. The SEP Bus will include 50 kW-class solar arrays which will provide ~40 kW to the NASA developed SEP system which consists of the Power Processing Units (PPUs) and Hall Thrusters. The commercially provided bus will also house the communications system including the high-gain antenna (HGA), attitude and reaction control systems (RCS), and other standard spacecraft systems. While the outcome of the procurement process will impact the final design of these systems, for the purpose of initial operations planning, it was assumed that the RCS system includes 16 hydrazine thrusters that provide 22 N each. It was also assumed that the four nadir pointing thrusters are mounted at the top of the bus and canted 45 deg. to reduce any pluming of the asteroid surface.

The Capture Module is comprised of the Contact and Restraint Subsystem (CRS), the Robot Subsystem, or capture arms, and the Rendezvous and Proximity Operations (RPO) Subsystem. The CRS consists of the three legs and contact pads that will attenuate initial asteroid contact, provide stability during surface operations, execute an initial push-off from the surface during ascent, provide final restraint of the collected boulder, and provide the opportunity to collect regolith samples from the surface around the boulder through sample collectors on the contact pads. The Robot Subsystem consists of two independent seven degree-of-freedom robotic arms with Microspine[7] end-effectors that will provide initial capture of the boulder during ascent and maintain contact through final restraint by the CRS. Finally, the RPO Subsystem consists of three optical cameras and a 3-D lidar. The narrow field-of-view (NFOV) and medium field-of-view (MFOV) cameras are mounted on the side of the SEP Bus on a 2-Pi gimbal, while the wide field-of-view (WFOV) and lidar are nadir pointing and mounted in the center of the capture module. These sensors will be used during the Characterization Phase for asteroid and boulder mapping and in the Boulder Capture and Planetary Defense Phases for Terrain-Relative Navigation (TRN).

For the purpose of the initial assessments, it was assumed that the ARV had a dry mass of 4,820 kg with a capacity to hold a maximum of 5,000 kg of xenon and 400 kg of hydrazine. These baseline values will continue to evolve as the design progresses and SEP Bus provider is selected.

OPERATIONS

The current baseline mission, shown in Figure 3, begins with a late 2020 launch on a Delta IV Heavy, Falcon Heavy, or NASA’s Space Launch System (SLS) launch vehicle, followed by an outbound cruise phase. Once the ARV arrives at 2008 EV$_5$, there are 230 days of proximity operations that are followed by an inbound cruise that will return the ARV and boulder to the ARCM destination orbit in time for a late 2025 ARCM. Following the ARCM, the ARV will transfer to a long-term stable Lunar Distant Retrograde Orbit (LDRO). The ARCM orbit is yet to be defined and could potentially be the LDRO, eliminating this final transfer.

The outbound and inbound cruise phases[8] utilize the SEP system for both main propulsion and attitude control with each leg being approximately two years in duration, depending on the launch date and launch vehicle. The outbound leg will deliver the ARV to the vicinity of the target asteroid at which point the RCS will be used throughout the entirety of the proximity operations with the exception of the planetary defense demonstration. The Approach and Characterization Phase comprises the first 100 days of the proximity operations which will be spent mapping the surface to develop shape and gravity models, identify landmarks for TRN, and select target boulders.

With the targets selected and prioritized a series of dry-runs will be performed prior to the Boulder Capture operations. The allocation of 50 days allows for up to three separate capture attempts should the first not be successful. Once the boulder is collected and restrained, the ARV will demonstrate the Enhanced Gravity Tractor (EGT) planetary defense technique[9], producing a small but measureable deflection of the target asteroid prior to starting the inbound transit. Following ARV insertion into the ARCM orbit, two crew in an Orion will launch on an SLS, dock with the ARV, and conduct two EVAs to collect samples and measurements from the boulder prior to returning to Earth. These EVA's will also demonstrate crew interactions with asteroidal material. The following sections will provide more detail on the proximity operations phases.

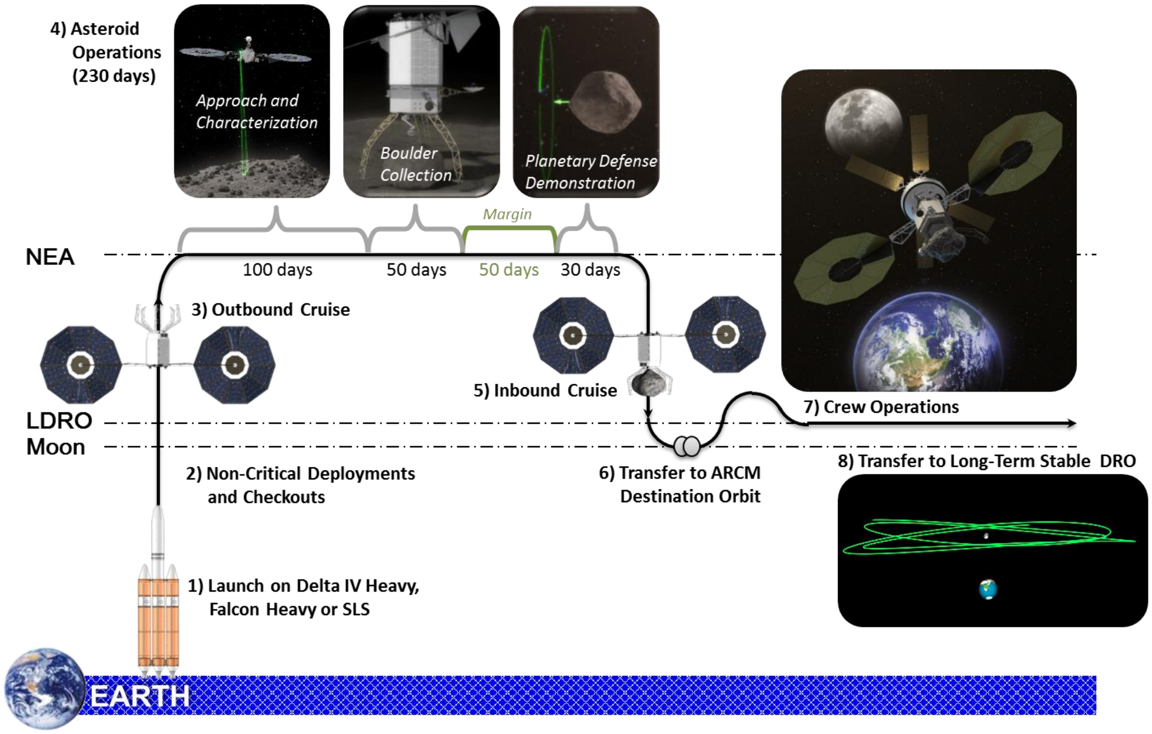


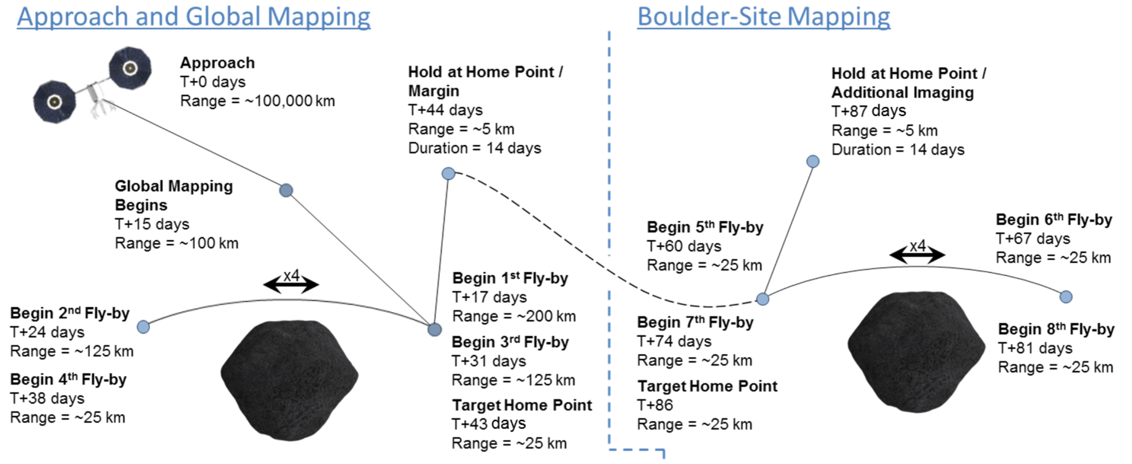
Figure 3. ARRM Operations Overview.

Approach and Characterization Phase

The primary goal of the Approach and Characterization Phase is to obtain the knowledge about the asteroid environment needed to support execution of the subsequent proximity operations phases. This information includes: a global image collection and topography model to support selection of candidate boulder sites; a set of high-resolution images and topography models that cover the immediate vicinity of five candidate boulders to support selection of a primary and back-up boulder target; and a body rotation model, gravitation potential model, and global set of optical navigation landmarks that are sufficiently accurate to support autonomous and ground navigation throughout all three proximity operations phases.

Current Baseline Strategy

Figure 4 graphically presents the current baseline strategy for the Approach and Characterization Phase. The phase is divided into three sub-phases: Approach, Global Mapping, and Boulder-Site Mapping.



Approach (15 days)	**Global Mapping (43 days)**	**Boulder Site Mapping (43 days)**
• Begins at ~100,000 km range • ARV approaches asteroid at 75-95 deg phase angle • NFOV camera used to locate asteroid and update shape and spin models • 70% SEP duty-cycle used during approach • Ends at ~100 km range	• 4 fly-bys at ~1 km range with 7 days between close approaches • Image majority of the surface at < 25 cm resolution • Finalize detailed shape and gravity model candidate boulder site identification • 14-day hold at home point or holding orbit • Selection of up to 5 candidate boulder sites for further reconnaissance • Update Boulder-Site Mapping trajectory/imaging plan	• 4 fly-bys at ~1 km range and 0.1 m/s velocity with 7 days between close approaches • Flyby phasing and geometry is designed to allow 1-cm resolution imagery of 5 candidate boulder sites • Develop detailed maps of the boulders and surrounding area • 14 day hold at home point or holding orbit • Final selection and prioritization of boulder targets

Figure 4. Overview of the Approach and Characterization Phase.

The Approach sub-phase begins when the spacecraft reaches 100,000 km from the body. At this point, the SEP system is throttled-down to a 70% duty cycle to slow the approach and the target asteroid is located using the NFOV camera. It is expected that the uncertainty in the asteroid ephemeris will be on the order of several thousand km or better based on the preceding observations from Earth. Using a combination of radiometric and optical point-source navigation observables, a refined ephemeris for the asteroid and an updated thrust profile for the spacecraft will be developed to facilitate rendezvous.

After 15 days of approach, the Global Mapping sub-phase begins at a range of 100 km. During the Global Mapping sub-phase, the coarse models for the shape, mass distribution, and rotation state of the target asteroid that are developed on the ground for planning purposes will be significantly refined to the level needed to support subsequent close-proximity navigation activities. The other major objective of this sub-phase is to develop a global catalog of images and a derived topography model with an accuracy of 25-cm to support selection of five candidate boulders for closer inspection. Both goals are achieved through a sequence of four flyby trajectories. The flyby trajectories allow ARRM to incrementally refine knowledge of the asteroid environment while maintaining a high degree of robustness to the remaining uncertainty in that environment. These flybys also provide ample opportunity to achieve the range and resolution of images needed to support development of the global topography model using the method of stereophotoclinometry (SPC)[10]. The Global Mapping sub-phase ends with a 14-day holding period during which five candidate boulders are selected for closer inspection and the location-specific operations plans associated with those targets are made.

In the Boulder-Site Mapping sub-phase, four additional flybys are planned to obtain high-resolution images of the five candidate boulder sites at 1.5 cm resolution or better. Based on these images, topographic maps of the immediate vicinity of each boulder are to be developed to a resolution of 3 cm. Similar to the Global Mapping sub-phase, a 14-day hold period is planned at the end of the Boulder-Site Mapping sub-phase for selection of a prime and up to two back-up boulder targets and the necessary operations plan updates.

Status and Planning

Trade studies and analysis of the current baseline strategy for the Approach and Characterization Phase are currently underway. Current work is focused on ensuring that trajectory design allows ample probability of achieving the necessary images and on analyzing other trajectory options that may allow for reduction in the duration of this phase, an improved variety of images to support topographic mapping, or a reduction in the complexity associated with the ground navigation operations. In the near-future, covariance analysis and schedule development are planned to further scope the expected navigation performance in this phase.

Boulder Capture Phase

At the conclusion of the Approach and Characterization Phase, the ARRM project team will have characterized the target asteroid, selected a prime boulder target, and identified up to two backup boulders. The Boulder Capture Phase, depicted in Figure 5, follows the Approach and Characterization Phase and includes all the operations to capture the target boulder and prepare it for the return back to cis-lunar space. Unlike the previous phases, the Boulder Capture Phase requires significant onboard autonomy given the large one way light time communication delays (up to 13 minutes for 2008 EV_5) coupled with the sub-second decisions required to land and operate on the surface of a rotating asteroid. The phase is divided into five sub-phases – Rehearsal, Descent, Surface Operations, Ascent, and Restraint – and includes up to three separate landing attempts. The Rehearsal and Descent operations follow a similar Operations Concept to that of the OSIRIS-REx mission[11] with the additional autonomy required to achieve a half meter landing error.

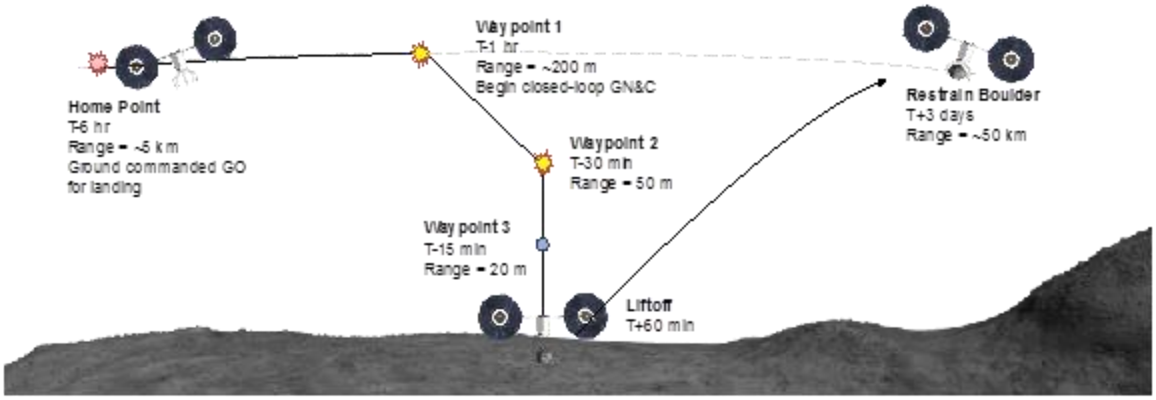


Figure 5. Boulder Capture Operations Concept for Descent, Ascent, and Restraint.

The Rehearsal sub-phase begins with the ARV holding at a Home Point approximately 5 km from the surface of the asteroid. At this point the ground evaluates the health of the ARV, and uploads the final landing site parameters, including the 3 cm model of the boulder and surrounding terrain for use in onboard TRN. Once the health of the vehicle has been established, the team sends a GO command for the spacecraft to execute the first landing rehearsal “dry run” which will take the ARV to Waypoint 1, 200 m above the surface of the asteroid, before autonomously aborting to a safe drift away trajectory. Waypoint 1 was chosen to be at a range that allowed for the ARV to acquire a direct relative navigation solution from the onboard RPO sensors, while at the same time not requiring that solution for safe operations. After confirming the success of the first dry run, the operations team develops a maneuver to return the ARV to the Home Point, and gives the GO for the ARV to autonomously descend to Waypoint 2 at a range of 50 m from the surface of the asteroid. From Waypoint 1 to Waypoint 2 the onboard Guidance Navigation and Control (GN&C) Subsystem uses the relative navigation solution to target the surface of the asteroid, and then match rates with the surface such that by the time the ARV reaches Waypoint 2 the spacecraft has achieved a position directly above the target boulder where it will perform a short hold prior to autonomously aborting to a safe drift away trajectory. The operations team will then verify the ability of the ARV to use the onboard navigation solution to perform full onboard closed-loop control at the accuracy required for the final landing attempt. After confirming success of the second dry-run, the operations team again returns the ARV to the Home Point.

The Descent sub-phase begins at the Home Point with the same sequence of actions that were previously exercised in the Rehearsal sub-phase – an update of the onboard state given the latest landing site map, and a GO from the ground to begin the landing attempt. From this point forward all operations will be autonomously executed onboard the spacecraft until departure from the surface of the asteroid. After the final GO, the ARV executes the same series of actions that were rehearsed previously to reach Waypoint 2 and then begins the final vertical descent to the boulder site. At a range of 20 m the ARV reaches the final waypoint prior to landing, where in order to limit debris generated by the landing attempt the onboard GN&C inhibits firing any thrusters with a plume directed towards the surface of the asteroid. From 20 m to touchdown, the micro-gravity of the target asteroid accelerates the ARV to the final touchdown velocity of approximately 10 cm/s. The sub-phase ends with the CRS "legs" actively absorbing the landing velocity for a soft touchdown on the surface of the asteroid.

Figure 6. Robot Arm and Microspine Gripper Tool Prototypes.

Once safely on the surface of the asteroid, the Surface Operations sub-phase begins. During this sub-phase, the ARV autonomously actuates the two seven degree-of-freedom robot arms to place the Microspine Gripper tools on the surface of the target boulder. The grippers capture the boulder through a two-stage process. In the first stage, hundreds of Microspine hooks opportunistically grip features in the natural rock surface to create a stable drilling platform. In the second phase, an integrated rotary percussive drill places an anchor into the boulder.

Finally, during the Ascent and Restraint sub-phases, the CRS legs push the ARV off the surface of the asteroid while simultaneously extracting the boulder from the surface regolith. In a single motion, the CRS legs break any cohesive forces between the boulder and the regolith and accelerate the entire ARV and boulder stack to a departure velocity sufficient to reach an altitude of 20 m at which point the onboard GN&C system executes a maneuver to place the ARV on a safe drift away trajectory. Once on the drift away trajectory the autonomous phase of the capture operations conclude, and the ground operations team will then command the CRS to provide final restraint of the boulder in preparation for return to cis-lunar space.

A key challenge for the ARRM is designing a system that will be robust to the uncertainties in the asteroid surface and boulder properties. The FAST provided key data to the Project team to help identify and, where possible, bound those uncertainties; for example, in the cohesive force of the asteroid regolith. The Project will continue to add robustness to the design throughout the development phase to mitigate risks associated with these uncertainties.

Planetary Defense Phase

ARRM has a top-level objective to perform a demonstration of a slow-push planetary defense asteroid deflection technique. The baseline ARRM will satisfy this objective by using the EGT[2] to impart a small but measureable deflection of the target asteroid. The EGT is similar to the standard gravity tractor[12] where the spacecraft uses a high-efficiency, low-thrust propulsion system to counteract the gravitational attraction between the spacecraft and the asteroid. Providing a thrust equal to the gravitational force, the distance between the spacecraft and the asteroid will remain constant, effectively "pulling" the asteroid toward that spacecraft. The EGT uses this same concept, however the mass of the spacecraft is now augmented by the mass of the boulder, thus increasing the force on the asteroid and reducing the time required to achieve the same deflection. While the ARRM will demonstrate this method with a ~20 t boulder, an actual planetary defense mission would not have the limiting requirement of returning the collected material and could thus collect a much larger boulder, further increasing the effectiveness of this technique.

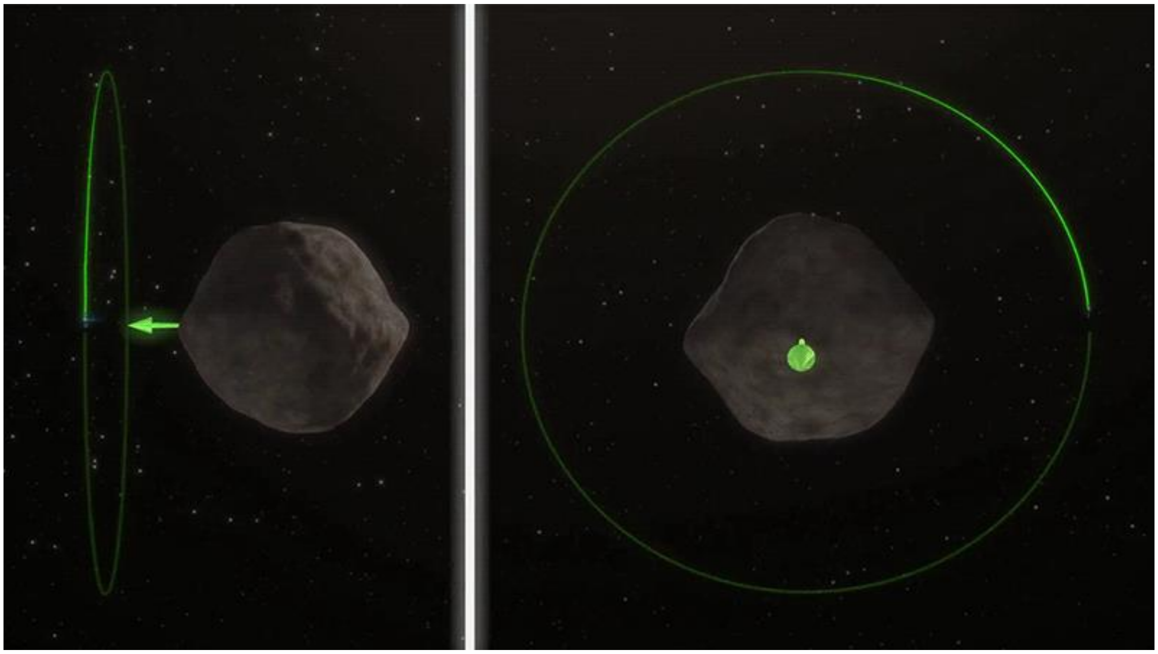


Figure 7. Notional EGT Halo Orbit for 2008 EV$_5$.

During the Planetary Defense Phase of the ARRM, rather than maintaining a constant range at a stationary point on the asteroid's velocity vector, the ARV will insert into a "halo orbit" around the velocity vector[13] as shown in Figure 7. In the straight-line stand-off approach, the thrusters must be canted at extreme angles or the spacecraft must increase the stand-off range in order to prevent the plume of the SEP from impinging on the asteroid, both of which reduce the efficiency of the technique. In order to address these issues, the halo orbit size and range is set by plume divergence of thrusters and the period is set such that the centripetal acceleration negates the non-axial gravitational component. This allows the thrusters to nominally point along the spacecraft axis with no cant angle.

Actual orbital operations will need to account for the asteroid's non-uniform gravitational field, and the potential offset center-of-mass due to the irregular shape and density distribution of the boulder, which will require some thruster canting in order to maintain the orbit. The gravity field will be well known following the characterization phase and the center-of-mass of the boulder-ARV system will be known following restraint, which will allow for the calculation of the nominal attitude, thrust magnitude, and thruster cant profile over an orbit. Since the nominal timeline allows for up to 30 days in this EGT orbit, full ground-in-the-loop navigation would be operationally intensive, so the ARV will again utilize onboard TRN with the MFOV camera imaging landmarks as well as the asteroid limb while on the illuminated side of the asteroid. Ongoing analysis is looking at placing this camera and gimbal assembly on a boom which would allow continuous limb viewing over the entire orbit. However, preliminary linear covariance analysis, displayed in Figure 8, has shown that even with just two imaging arcs, approximately 10 minutes each, would be sufficient to provide the relative navigation information required to maintain the orbit. The baseline case has these arcs occurring immediately after the ARV crosses the terminator to the sunlit side and just prior to crossing back towards the eclipsed side.

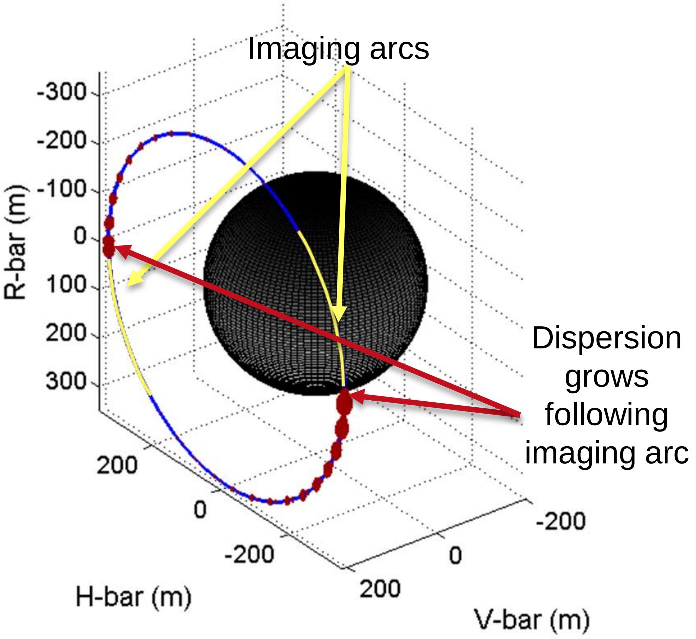


Figure 8. Linear Covariance Analysis of the EGT orbit assuming two 10-minute imaging arcs per orbit.

The short duration EGT demonstration will impart a small change in velocity on the asteroid that will be on the order of 10^{-5} m/s depending on the target asteroid and exact boulder mass. This small deflection is likely not going to be measurable immediately following the demonstration. However, depending on the orbital geometry, and given time to propagate, this deflection could be measured either through differential ranging from the ARV if the spacecraft remains in the asteroid vicinity (6 to 9 months for the current set of candidate targets), or via direct ground radar ranging to the asteroid during a future Earth close approach. For 2008 EV_5, it has been determined that close approaches in December of 2023, July of 2024, and April of 2025 will likely have strong enough signal-to-noise ratios to definitively verify the deflection. By not requiring the ARV to stay in the vicinity of the asteroid following the EGT demonstration, the ARRM can stay within the 230 day timeline described above. For other targets that do not have good radar opportunities following the demonstration, the timeline would need to be extended in order to verify the deflection. This could have an impact on the return mass capability of the ARV, requiring a shorter inbound cruise duration in order to return in time for the ARCM.

SUMMARY

NASA's Asteroid Redirect Mission (ARM) will be the first mission to return a multi-ton sample from the surface of an asteroid and allow for human exploration of the material after it is returned to cis-lunar space. The ARM is comprised of the Asteroid Redirect Robotic Mission (ARRM) and the Asteroid Redirect Crewed Mission (ARCM). In addition to collecting a 2-3 m boulder from an asteroid, along with accompanying regolith samples, the ARRM will also demonstrate the Enhanced Gravity Tractor (EGT) planetary defense technique. The ARCM will send two crew members in an Orion spacecraft to visit the Asteroid Redirect Vehicle and the returned boulder and collect samples over two EVAs.

Detailed operations concepts have been developed for the ARRM using the current reference asteroid target 2008 EV_5. This paper has provided an overview of the operations in the vicinity of the asteroid divided into three main phases: Approach and Characterization, Boulder Capture, and Planetary Defense. These operations have been designed with robustness and risk mitigation in mind. The Approach and Characterization Phase will provide the necessary imaging required to identify target boulders and develop topography maps required to perform TRN. This data directly feeds the Boulder Capture Phase which will progressively step through the descent trajectory in a series a dry-runs in order to verify the onboard GN&C systems prior to executing the fully autonomous capture attempt. This strategy, combined with a mission timeline allowing for up to three capture attempts, increases confidence in mission success. Beyond capturing a boulder and surface regolith samples, the demonstration of the EGT technique will be the first time that a measurable deflection will be imparted on an asteroid.

The ARM is a complex mission, combining human and robotic elements that will demonstrate new technologies and capabilities, provide the first-ever multi-ton sample return, and increase our ability to protect our home planet. This mission will not only advance human spaceflight toward the eventual goal of the exploration of Mars, but also provide valuable knowledge of asteroids, including how we may be able to utilize them as a future resource. The proximity operations presented in this paper provide the ability to capture and return a boulder from the surface of an asteroid and conduct a planetary defense demonstration, which are critical for the success of this challenging mission.

ACKNOWLEDGMENTS

The authors will like to thank the entire ARRM team for their dedicated effort in developing this mission from a concept to its current state in Phase A. The team, comprised of members spread across the country at the Jet Propulsion Laboratory, NASA Johnson Space Center, NASA Glenn Research Center, NASA Goddard Space Flight Center, NASA Langley Research Center, and NASA Kennedy Space Center, has spent many hours developing these spacecraft systems and operations. Without the work of this cross-agency team, this paper would not be possible. Part of the work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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