Near-Earth Asteroid Retrieval Mission (ARM) Study

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The Asteroid Redirect Mission (ARM) concept brings together the capabilities of the science, technology, and the human exploration communities on a grand challenge combining robotic and human space exploration beyond low Earth orbit. This paper addresses the key aspects of this concept and the options studied to assess its technical feasibility. Included are evaluations of the expected number of potential targets, their expected discovery rate, the necessity to adequately characterize candidate mission targets, the process to capture a non-cooperative asteroid in deep space, and the power and propulsion technology required for transportation back to the Earth-Moon system. Viable options for spacecraft and mission designs are developed. Orbits for storing the retrieved asteroid that are stable for more than a hundred years, yet allow for human exploration and commercial utilization of a redirected asteroid, are identified. The study concludes that the key aspects of finding, capturing and redirecting an entire small, near-Earth asteroid to the Earth-Moon system by the first half of the next decade are technically feasible. The study was conducted from January 2013 through March 2013 by the Jet Propulsion Laboratory (JPL) in collaboration with Glenn Research Center (GRC), Johnson Space Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC).

I. Introduction

NASA has conducted studies on the exploitation of near-Earth asteroids (NEAs) since the 1970s,[1-5] but the propulsion required to transport large amounts of mass or entire small asteroids back to the Earth-Moon system had remained an unresolved challenge, and a wide variety of propulsion concepts were considered.[6-8] In 2010 NASA conducted a study that considered the feasibility of using of near-term, high-power (~40-kW) Solar Electric Propulsion (SEP) to rendezvous with a small NEA (with a mass of order 10 t), capture it, and return it to the International Space Station.[9,10] Based in part on this 2010 study the Keck Institute for Space Studies (KISS) at the California Institute of Technology, and NASA's Jet Propulsion Laboratory (JPL) jointly sponsored a study in 2011-2012 on the feasibility of capturing and returning a somewhat larger, but still very small NEA (with a mass of up to ~1000 t) to translunar space. The study included participants from six NASA centers, eight universities, commercial companies, and others. The results of that study are described in several conference papers[11-14] and the study's final report.[15]

It was based on this report that NASA chartered a three-month study in 2013 with the primary objective of looking at the asteroid retrieval mission concept in sufficient depth to determine if its feasibility would stand up to more detailed scrutiny. The study was conducted from January 2013 through March 2013 by the Jet Propulsion Laboratory (JPL) in collaboration with the Glenn Research Center (GRC) and supported by Johnson Space Center (JSC), the Langley Research Center (LaRC), and the Marshall Space Flight Center (MSFC). It is the results of the three-month study that are summarized in this paper.

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There are three key parts to the overall asteroid redirect mission:

1. An observation campaign to identify a sufficient number of potential targets around which a viable mission implementation plan can be developed and executed.
2. A robotic asteroid redirect vehicle with sufficient on-board propulsion capability to rendezvous with, capture, and redirect a near-Earth asteroid with a mass up to 1000 t to translunar space in a reasonable flight time.
3. A human spaceflight capability that can rendezvous with the returned asteroid in translunar space in order to inspect it, study and sample it, to determine its composition and internal structure, and assess its potential for resource utilization.

A. Relevance

This mission fits well into the overarching objectives of the nation's Human Space Program, which is to enable humans to step ever deeper into space and eventually to Mars. Exploration of a captured asteroid is consistent with the capability development framework philosophy and could be a first step to using new capabilities (SLS and Orion) already under development. Additionally, the high-power SEP and solar array technologies are essential for future human exploration missions beyond low-Earth orbit.[16-25]

To find suitable targets for this mission the current asteroid observational campaign will be enhanced. These enhancements will live on beyond the target selection for ARM and extend discovery and characterization of the current observational programs to include smaller asteroids. The capture, return, and close-up inspection of the asteroid would provide insight into the ability to control and deflect a large mass helping to inform future planetary defense measures. The methodologies and technologies developed to rendezvous with, capture and control a tumbling asteroid can be used in Earth orbit to rendezvous and capture large pieces of orbital debris.

While not a science mission, the delivery of an entire small near-Earth asteroid to an accessible lunar orbit would allow scientists to retrieve and examine, in detail, bulk composition of the captured target, furthering our understanding of the formation of the solar system.

The captured asteroid could also provide opportunities for the commercial sector, which has recently expressed interest in mining asteroids. Sampling techniques and potentially in situ resource utilization (ISRU) demonstrations would path-find future applications. The demonstration of high-power solar arrays and high-power electric propulsion systems would support U.S. competitiveness in the commercial satellite industry.

II. Mission Concept Overview and Mission Design

The asteroid redirect mission concept uses a robotic spacecraft equipped with a high power, solar electric propulsion (SEP) system to rendezvous with, capture, and redirect a small asteroid with a mass of up to 1000 t to a long-term stable lunar orbit. An overview of the mission concept is given in Figure 1. The electric propulsion subsystem, with a nominal input power of 40 kW, enables the asteroid redirect vehicle (ARV) to be launched using a single Atlas V-class launch vehicle or a heavy lift launch vehicle such as the Space Launch System (SLS) or Falcon Heavy. For the Atlas V-class launch, the SEP system is used to spiral out from an initial elliptical Earth orbit to a Lunar Gravity Assist (LGA) in approximately one to one and a half years. The LGA boosts the ARV to escape from the Earth-Moon system and starts it on its heliocentric transfer to the asteroid. The heliocentric transfer of two to three years (depending on the target) is then completed using the SEP system resulting in rendezvous with the asteroid. The more capable SLS and Falcon Heavy launch vehicles can launch the ARV on trajectories directly to the LGA eliminating the Earth-spiral phase, shortening the total mission flight time by one to one and a half years, and simplifying the flight system and mission design.

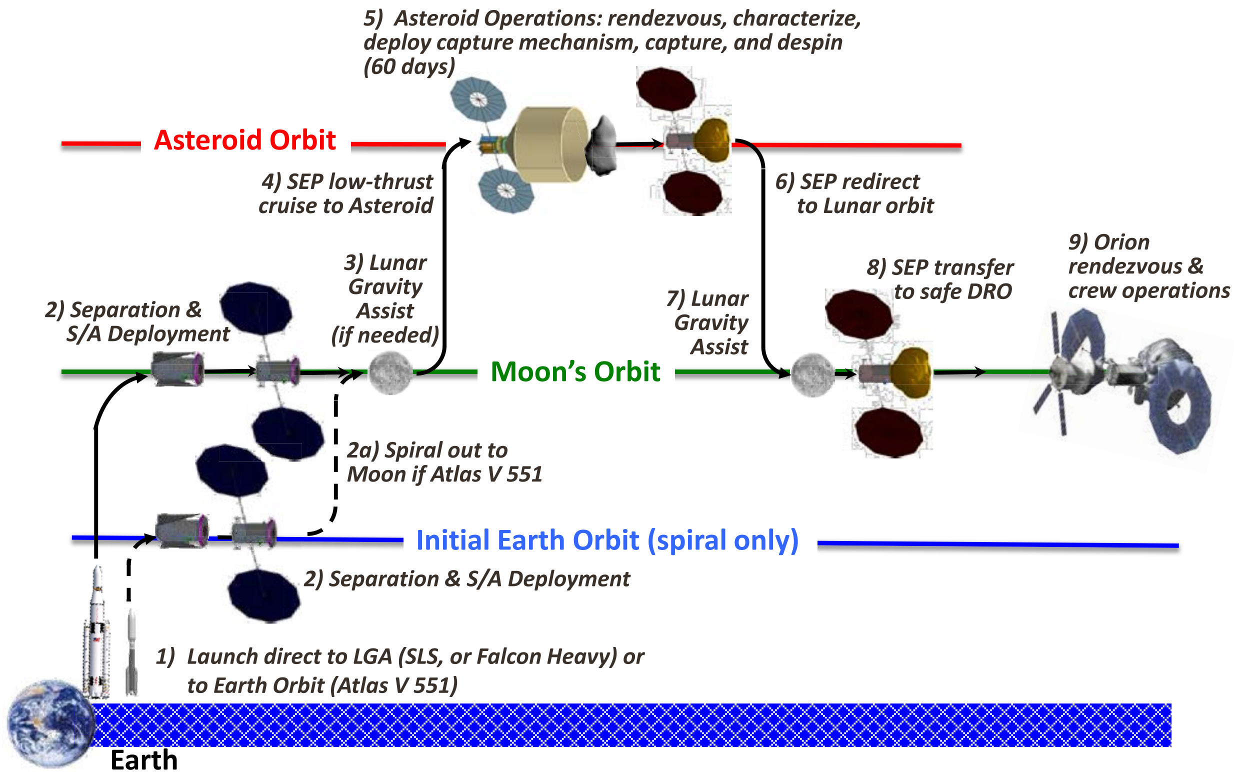

Figure 1. Asteroid redirect mission overview.

As the ARV approaches the target, optical navigation is used to enable the spacecraft to zero in on the asteroid and rendezvous with it. Once at the asteroid, the mission design allocates 60 days to complete the in situ characterization of the object necessary to produce a good shape model, accurately determine its spin state, and then execute the capture, de-tumbling and despin procedures. A detailed timeline for the concept of operations at the asteroid indicates that approximately 30 days are required to complete these functions resulting in a margin of 30 days.

The conceptual ARV spacecraft is designed to return an asteroid with a mass of up to 1000 t to the Earth-Moon system. At the time of asteroid capture, the wet mass of the ARV would be in the range 7 t to 10 t depending on how much propellant is expended getting to the asteroid. This means that the amount of propellant that would be needed for a given ΔV increases by a factor of 100 after the asteroid is captured. This scaling drives the mission design to minimize the post-capture ΔV. It is also why SEP is enabling for the ARM concept.

The design drivers that govern the trajectory performance include the asteroid parameters (mass, V_∞, and Earth encounter geometry), the SEP performance parameters (specific impulse [Isp], power, and efficiency), and the launch vehicle performance capabilities. Higher Isp from the SEP module system would require less propellant for the same maneuver than a lower Isp system at the cost of increased time. Increasing the power to the electric propulsion subsystem increases thrust and lowers the time to perform these maneuvers. A larger capability launch vehicle allows either more propellant mass to be sent (good for lower Isp systems) or a launch to a higher energy trajectory that reduces flight time (good for higher Isp and/or lower power systems). The key systems engineering task is to find system designs that appropriately balance the risk across major mission elements.

The nominal retrieval strategy is to find an asteroid with a natural Earth close approach so that it could be redirected to a lunar flyby.[26] The resulting lunar gravity assist would loosely capture it into the Earth-Moon system. From this point, solar perturbations and thrust from the spacecraft's SEP system would be used to target a second lunar flyby that would then be used to enter a long-term storage orbit accessible by crewed missions. It is highly desirable to place the asteroid in an orbit with a very long lifetime. Although the current mission concept would return an asteroid that is too small to survive Earth entry, it would be still important to preserve the asteroid in a stable orbit as a resource for future deep space human missions.

Table 1. 2009 BD example mission delta-V and phase durations.

Mission Leg	Delta V (m/s)	Duration (yr)
Spiral	4662	1.4
To Asteroid (Go to leg)	3868	1.8
Asteroid Ops	(hydrazine)	
Earth Return (Fetch leg)	152	3.0
To Storage Orbit	60	1.4
Total	**8742**	**7.6**

Using asteroid 2009 BD as an example mission target a sequence of events and the corresponding mission ΔVs are given in Table 1 assuming an Atlas V-class launch to an elliptical Earth orbit. This table indicates a total ΔV of about 8.7 km/s is required. Retrieval of 2009 BD with an Atlas V-class launch vehicle would require an early 2017 launch, which is programmatically problematic, in order to allow time for the low-thrust Earth-departure spiral. A heavy launch vehicle (Falcon Heavy or SLS) would allow a direct launch in mid- to late-2018 using this interplanetary trajectory. A 2018 launch with an Atlas V-class would require selection of a different target asteroid such as 2011 MD.

Medium fidelity trajectories were developed using the low-thrust tool Malto.[27] High fidelity interplanetary trajectories were developed using two independent tools (Mystic[28] and Copernicus[29]), which produced ΔVs that agreed to within 3 m/s. Mystic is the trajectory tool currently used on the Dawn mission. Earth-spiral trajectories were built independently at JPL and GRC using custom integrators and agreed within 1%. The endgame and DRO trajectories were built in Mystic. Integrations were done using gravitational perturbations from the Earth, Moon, Sun, Jupiter, and Venus. Earth oblateness effects were included for the spiral trajectories. An Isp of 3000 s with a 60% efficiency for the electric propulsion (EP) system was used with a maximum power input to the EP system of 40 kW (end of life at 1 AU) and a conservative $1/r^2$ power variation in available solar array power with solar range. A typical duty cycle of 90% for thrusting with the SEP system was assumed. This duty cycle is appropriate for early formulation studies. The Dawn mission has an actual duty cycle of approximately 95%. On the transfer to Vesta, Dawn would typically thrust for 160 hours per week then shut down the electric propulsion system and spend 8 hours communicating with Earth. The ARM flight system includes a gimbaled high-gain antenna and would not need to turn off the SEP system to communicate with Earth, making the 90% duty cycle even more conservative.

During the two months prior to the ARV asteroid arrival, the planned duty cycle is dropped to 50% to allow additional time for acquiring OpNav images. This is very similar to the methodology used by Dawn in its approach to Vesta. Additional xenon propellant is included to provide margin for unintentional missed thrust periods, and 6% xenon margin is applied on top of the xenon required for the trajectory (including missed thrust margin) to cover other typical uncertainties including flow rate errors, fill errors, and leakage. Furthermore, the propellant mass is calculated for the maximum launch capability (i.e., the fully margined spacecraft mass plus the launch vehicle margin) so that the launch vehicle margin is a true margin useable by the mission.

The Earth-Moon capture LGA places the asteroid in a loosely captured Earth orbit that would eventually escape the Earth-Moon system if left alone. The “Endgame” phase would use low-thrust arcs, solar perturbations, and lunar flybys to transition from this initial capture orbit to a long-term stable storage orbit. For the 2009 BD example, it would require about 42 m/s and 8 months, and end on Feb 15, 2024 with an LGA that would place the asteroid into the long-term storage orbit. Currently the baseline storage orbit is a Lunar Distant Retrograde Orbit (DRO).[30,31,32] This is a 70,000 km orbit of the Moon that revolves clockwise, in the opposite sense of the Moon’s orbit around the Earth. This orbit is actually a 3-body orbit and is dynamically in orbit around both the Earth and Moon simultaneously. DRO orbits are known to be very stable. In this application the asteroid would initially enter the DRO in an unstable region around the Earth-Moon L1 and L2 points in order to minimize ΔV, and 20 small additional maneuvers totaling 16 m/s over 8 months would be used to trim this initial DRO into one that is stable for over 100 years.

The final DRO period and inclination would be chosen to provide monthly access for Orion launches and to minimize the number of orbits when the Moon shadows the DRO (such orbits would be skipped for Orion missions). The Orion could access this orbit after it is stabilized in October 2024 (for 2009 BD).

III. Observation Campaign

The ARM Observation Campaign would comprise activities to identify NEAs that are roughly 5 m to 10 m in diameter that could be candidates for retrieval, and to characterize their key physical properties well enough to establish retrieval feasibility. The observation campaign would be enabled by the assets and techniques developed under NASA's Near-Earth Object Observation (NEOO) program. The study concluded that the NEA population contains enough candidates, with the right characteristics, to support an asteroid redirect mission, but there is a need to increase the rate of discovery of 10-m-class NEAs (now approximately two per year with the right orbital characteristics). The set of parameters that define a retrievable NEA are identified in Table 2. The values in Table 2 are guidelines, in some cases, asteroids with masses greater than 1000 t and/or with a V_∞ as large as 2.6 km/s could be retrieved. The study team generated recommendations for enhancements of the existing NEOO capabilities that could increase the discovery rate of candidate targets by a factor of two to ten. Such an increase would be sufficient to meet the needs of an asteroid redirect mission that would have approximately four years to find a primary target and an adequate number of backup targets, assuming a launch in late 2018.

Discovering new potential targets alone is not sufficient to identify good candidates for retrieval. Physical characterization is also required to reduce the uncertainty in the object's size, mass, and spin state to know if it is within the capability of the asteroid redirect vehicle to capture, despin, and transport to the lunar DRO. There are sufficient existing assets worldwide to perform the necessary characterization observations.

The key to the observation campaign is illustrated in Fig. 2 which indicates that there are on the order of a hundred million NEAs in the 5- to 10-m diameter size range (27-30 absolute magnitude range). Only about 370 NEAs in this size range have currently been discovered. To estimate the number of NEAs that could make good candidate targets for ARM, simulations of the discovery process, using the population model from Harris[33] and the latest NEO orbit distribution model[34] were performed.[35] The results from a detailed simulation of the Pan-STARRS1 (PS1) survey using realistic sky coverage, cadence and loss factors, revealed a deficiency in the NEO orbit distribution model for the Earth-like orbits of interest to ARM, necessitating a normalization of the population of objects in these orbits to match the known detection rate.[35] Once this normalization is made, the simulations indicate that of order 50,000 10-m class NEAs approach Earth with a small enough V_∞ to be retrievable. About one-third of these, ~15,000, have orbits that approach closely enough to the Earth's orbit for retrieval (within 0.03 AU) and also satisfy the requirement for a close-enough natural return to Earth (within 0.3 AU) in the early 2020s. The current list of potential targets is given in Table 3. At least 20 additional selectable targets are expected to be discovered and adequately characterized by 2018.

Table 2. Reference NEA Characteristics for Retrieval.

Characteristic	Reference Value
Orbit: V_∞ relative to Earth*	< 2 km/s
Orbit	Natural return to Earth early 2020's
Mass	< 1,000 metric tons
Spin rate	< 2 rpm
Size and Aspect Ratio	5 m < mean diameter < 10 m, Aspect ratio < 2/1
Spectral Class	Known Type (C-type with hydrated minerals desired)

* V_∞ is the velocity of an object would have if all of its energy with respect to a given body (e.g. the Earth or the Moon) were converted to kinetic energy.

Table 1. Possible Return Candidates

Asteroid	Asteroid Diameter	Asteroid V_∞	Current Best Return Mass	Return Date	Notes
2007 UN12	4–12 m	1.2 km/s	490 t	Sep-20	
2008 EA9	7–20 m	1.9 km/s	130 t	Nov-20	
2013 EC20	3–6 m	2.6 km/s	120 t	Mar-21	Earth flybys 2013
2010 UE51	5–15 m	1.2 km/s	130 t	Oct-22	Spitzer flyby 2013
2009 BD	4–11 m	1.2 km/s	590 t	Jun-23	A/M; Spitzer flyby 2013
2011 MD	6–17 m	1.0 km/s	690 t	Jul-24	rot. rate; Spitzer fb 2014
2008 HU4	6–16 m	0.5 km/s	1600 t	Apr-26	Earth flyby 2016
2012 TF79	8–23 m	0.3 km/s	170 t	Mar-27	Spitzer flyby 2016
2006 RH120	3–9 m	1.0 km/s	490 t	Oct-28	A/M; rot. rate
2012 LA	8–21 m	1.5 km/s	230 t	May-29	Spitzer flyby 2018
2011 BL45	9–26 m	1.4 km/s	1400 t	Aug-29	Spitzer flyby 2015
2008 UA202	3–9 m	1.9 km/s	310 t	Oct-29	

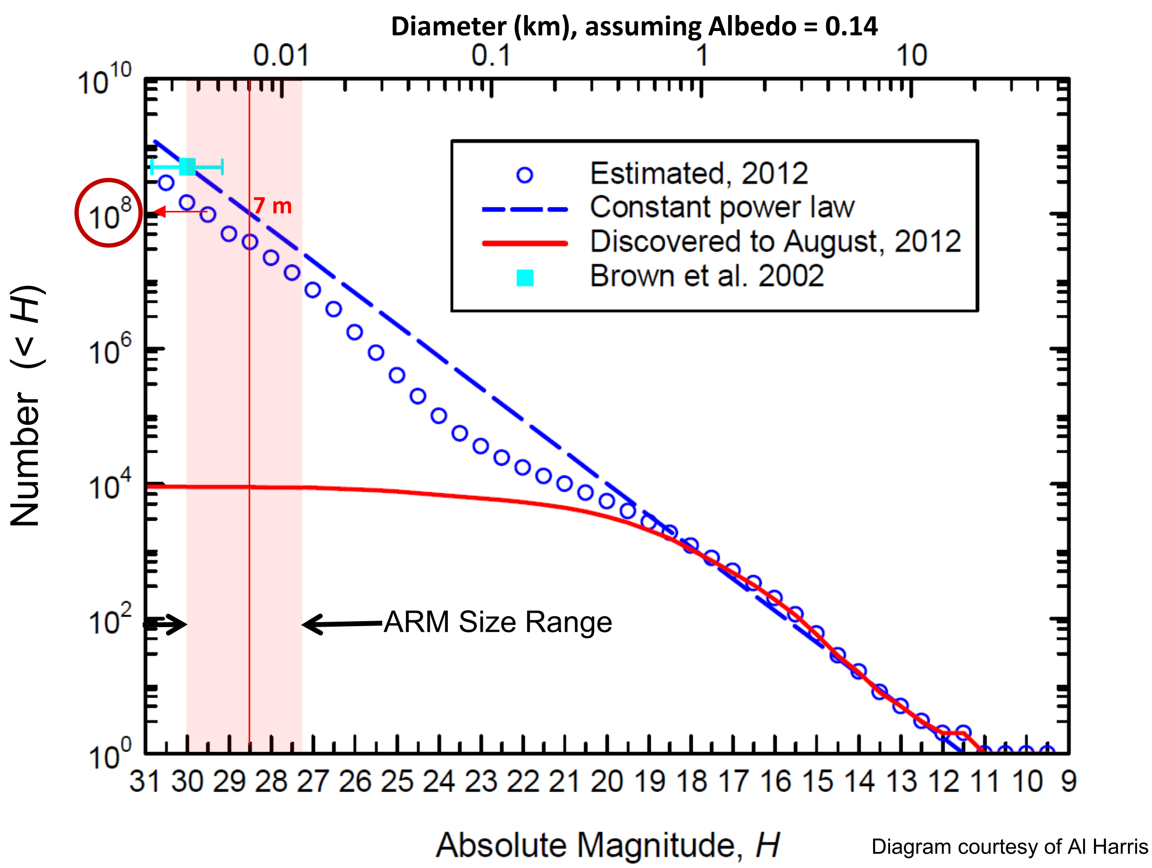

Figure 2. NEA population model suggest that there are approximately a hundred million asteroids in the size range of interest for the asteroid redirect mission.

IV. Solar Electric Propulsion (SEP) Technology

The technical trade space considered in this study is show in Fig. 3. The three highlighted options were selected for detailed study to assess how well they balanced complexity, total cost, cost risk, technology return (extensibility, infusion), and technical risk across mission elements. Feasibility at this early stage of concept definition requires the establishment of appropriate technical margins throughout the flight system (especially mass and power). These margins are shown in Table 4 for Option 2 from Fig. 3.

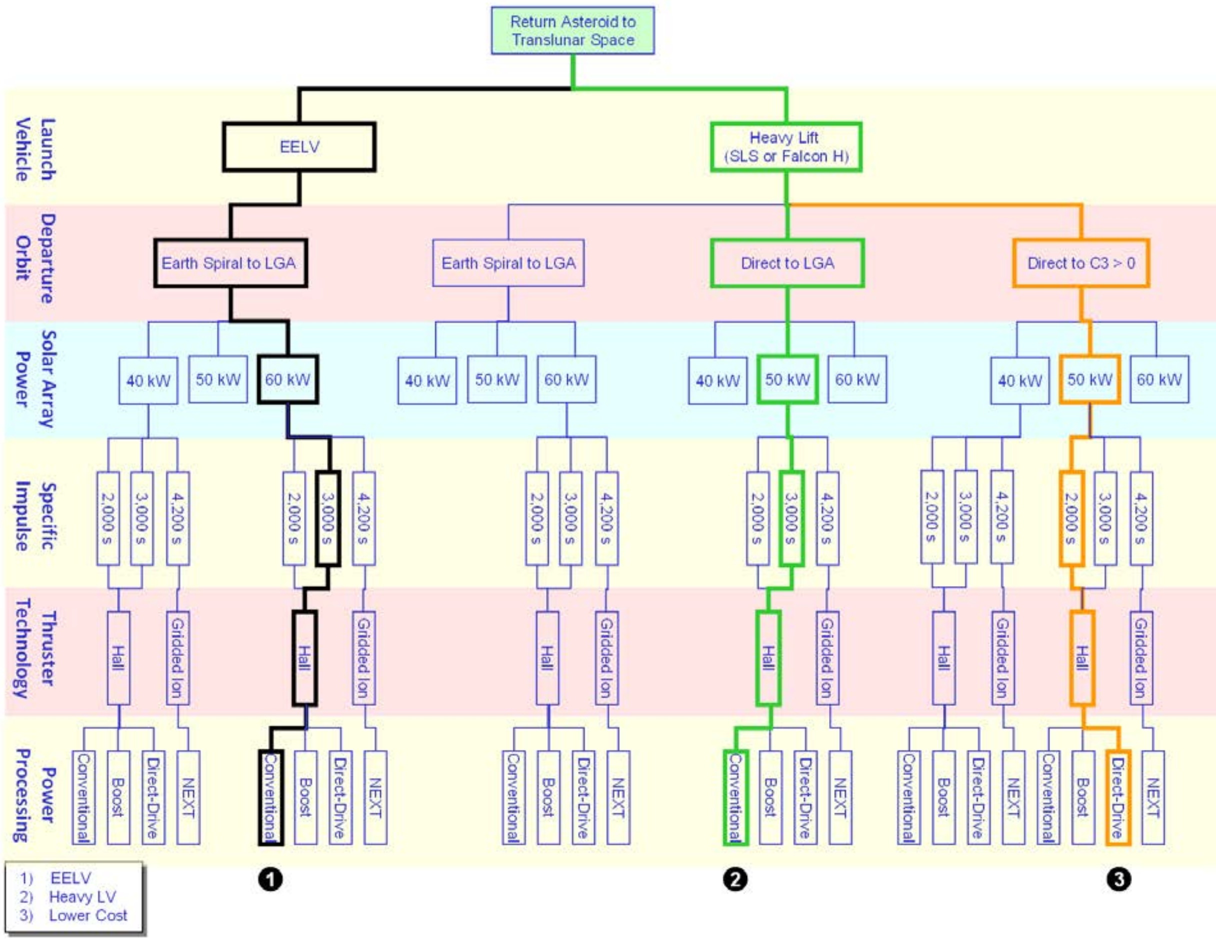

Figure 3. Architecture trade-space with three options selected for detailed evaluation.

Table 4. Key Flight System Margins for Option 2 from Fig. 3.

Resource	CBE	Growth Contingency	Maximum Exepcted Value (CBE + Growth)	System Margin	Growth Contingency + Margin	Growth Contingency + Margin (%)
Flight System Dry Mass (kg)	3,615	1,100	4,715	450	1,550	43%
Battery DOD - Launch (Wh)	3,210	792	4,002	606	1,398	44%
IPS Power (W)	40,000	2,000	42,000	4,000	6,000	15%
Non-IPS Power (W)	1,307	271	1,578	922	1,193	91%
Xe Propellant Capacity (kg)	8,000	0	8,000	2,000	2,000	25%
Hydrazine Propellant Capacity (kg)	200	0	200	200	200	100%

B. Asteroid Redirect Vehicle (ARV)

The ARV would be composed of two modules, as indicated in Fig. 4, to enable parallel development, assembly, and testing: a Solar Electric Propulsion (SEP) Module, and a Mission Module. The Mission Module would be comprised of an Avionics Module, sensor suite, and the capture mechanism. The SEP Module would include all of the power and propulsion for the ARV, and the Avionics Module would include all other spacecraft bus functions.

1. The SEP Module

The asteroid redirect mission concept would be enabled by high-power solar electric propulsion. Solar electric propulsion missions always show better performance at higher power levels and this mission is no different. Mission design trade studies indicate that the best combination of asteroid mass and flight times are obtained at the highest power levels. The study, therefore, selected the highest solar array power level that could reasonably be available for launch in this decade. That corresponds to about 50 kW, which is the upper end of the 30-kW to 50-kW range of power levels currently under development in the two Solar Array System (SAS) development activities sponsored by NASA's Space Technology Mission Directorate (STMD). A 50-kW solar array beginning-of-life at 1 AU would enable operation of a 40-kW electric propulsion system and the spacecraft at end-of-life with appropriate margins. The 40-kW input power would be processed by multiple, magnetically shielded Hall thrusters operating in parallel with a specific impulse of 3,000 s. Because the asteroid redirect mission is enabled by these technologies it is an ideal platform to meet the needs of STMD's SEP Technology Demonstration Mission. The asteroid redirect mission would demonstrate deployment and operation of a new class of large lightweight, high-specific-power, flexible-blanket solar arrays in space along with the operation of a high-power, high-performance electric propulsion system. The flight configurations of the ARV are shown in Figs. 5 and 6 for the two SAS solar array technologies, ROSA and MegaFlex. The asteroid redirect mission is compatible with either solar array technology.

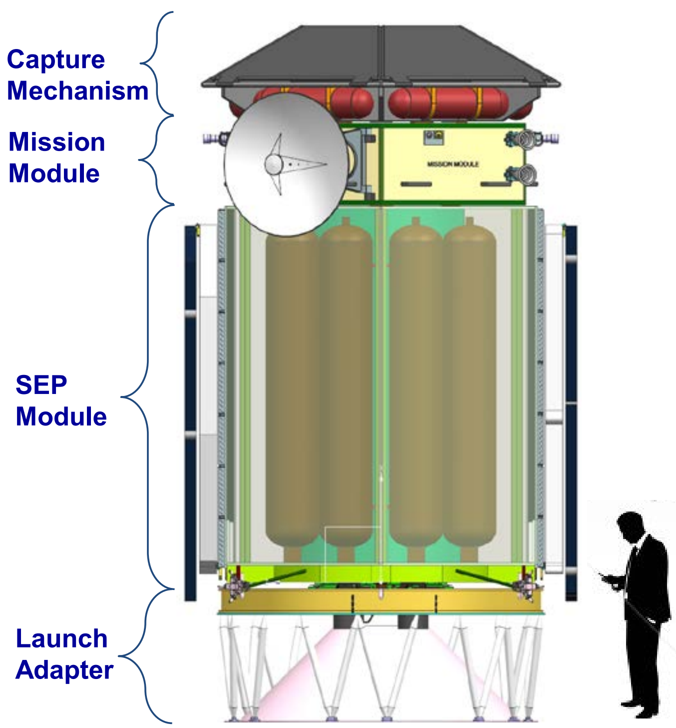

Figure 4. Asteroid Retrieval Vehicle capable of storing up to 10 t of xenon is shown with a 50-kW ROSA solar array in the stowed configuration on top of a custom launch adapter.

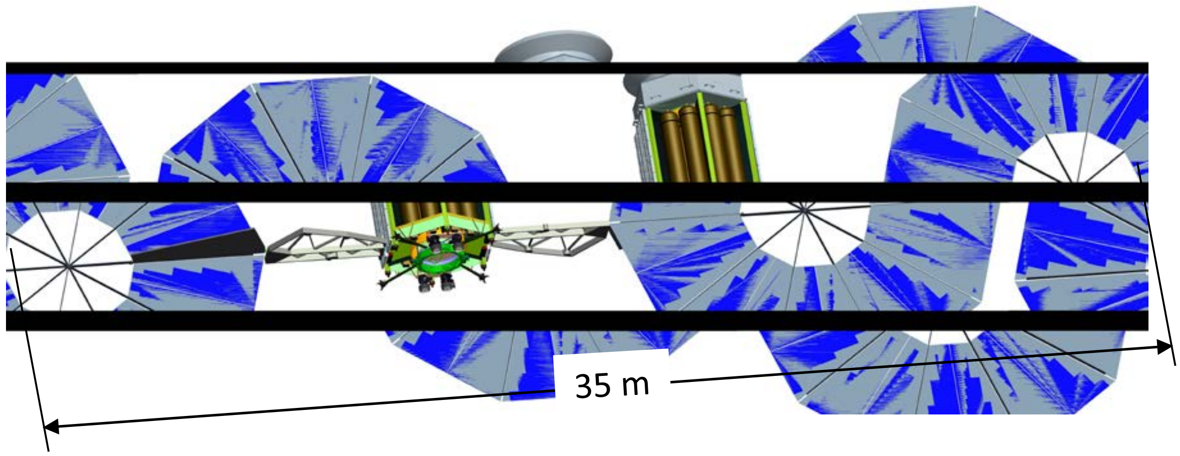

Figure 5. ARV flight configuration pictured with the MegaFlex solar arrays.

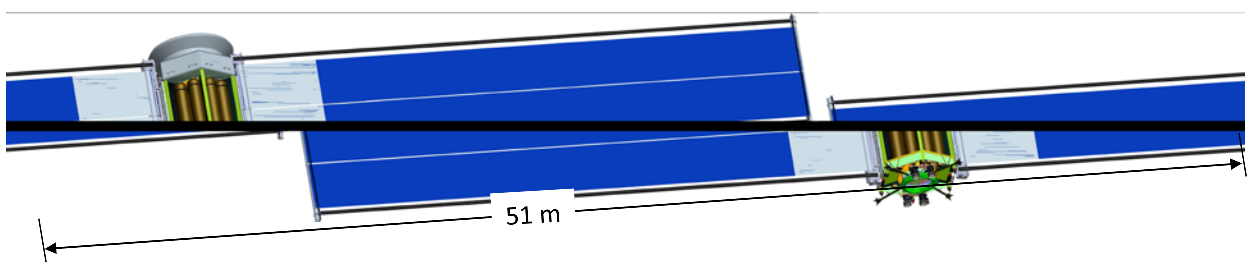

Figure 6. ARV flight configuration pictured with ROSA solar arrays.

The conceptual ARV configuration is dominated by the need to be able to store up to 12 metric tons of xenon. This is significantly greater than the 0.43 t of xenon launched on the Dawn mission, which is the largest xenon propellant load launched to date. Commercial communication satellite manufacturers typically launch only a few hundred kilograms of xenon used for orbit raising and station keeping maneuvers. Consequently, there are no existing tanks that meet the needs of the asteroid redirect mission, so a new tank development is required. The study team identified a solution that minimizes the development risk and cost and provides the lightest tank mass. This approach uses a composite overwrapped pressure vessel with a seamless aluminum liner design made using existing industry manufacturing techniques.

2. Hall thruster stuff

The electric thruster is an enabling element of the ion propulsion subsystem. The feasibility study evaluated a number of candidate thrusters, some currently under development and some that have already flown, for their applicability to ARM. Three key features dictate the thruster evaluation: specific impulse, maximum input power, and propellant throughput capability. If the power level per thruster is too low or if the xenon throughput capability per thruster is too low, then the number of thrusters required becomes excessive. If we consider a 40-kW electric propulsion system with 10 t of xenon, consisting of three thrusters plus one spare, then each thruster/PPU string must operate at 13.3 kW and have a propellant throughput capability of 3400 kg. There are no existing thrusters that have this combination of characteristics along with the ability to operate a specific impulse of 3000 s. Two laboratory model Hall thrusters bracket this capability, the magnetically shielded version of the H6 with the designation H6MS[36] and the NASA 300M thruster.[37] The feasibility study assumed the development of a new 12.5-kW Hall thruster that incorporated the best design features of the H6MS and 300M thrusters. The thruster development would be done jointly with an industrial partner who would then design and fabricate the flight thrusters.

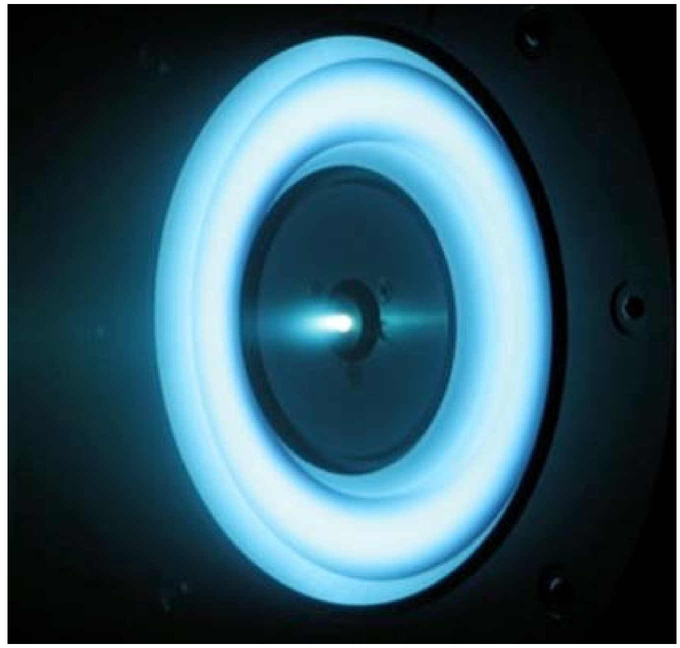

Figure 7. NASA's H6MS magnetically-shielded Hall thruster operating at 9 kW with a specific impulse of 3,000 s.

A long-life, 12.5-kW, 3000-s Hall thruster represents the cutting-edge of Hall thruster technology. Computer modeling of the erosion processes in a magnetically shielded Hall thruster operating at 3000 s suggested that even at the 800 V required for this specific impulse level magnetic shielding should be effective at suppressing the key wear-out failure mechanism, i.e., erosion of the insulator rings that line the annular discharge chamber region where the ions are produced and accelerated.[38] To increase confidence that the computer modeling was correct, the STMD technology program performed a 115-hour test at JPL with the H6MS thruster operating at 9 kW and 3000 s (see Figure 7). The results from the 115-hr test suggests that a 12.5-kW magnetically shielded Hall thruster with a specific impulse of 3000 s could be development with propellant throughput capability well in excess of that required for the ARM.[36]

3. Capture Mechanism

Multiple options for the capture mechanism were considered and evaluated. A non-rigidized, inflatable capture bag approach was selected for this study to assess feasibility. The capture bag approach effectively deals with the range of asteroid mechanical property uncertainties and would work equally well if the asteroid was a rubble pile or solid rock. Importantly, this concept is testable in a 1-g environment enabling verification and validation of the system before launch.

The capture process itself is dominated by the spin state of the target. At relatively slow spin-rates of < 0.2 rpm (periods > 5 minutes) about one or more axes, the problem is relatively straightforward and small forces, < 0.1 g, are transmitted back to the spacecraft. At spin rates an order of magnitude higher, up to about 2 rpm (spin period of 30 seconds), the problem is more challenging. For this case, the study team identified a feasible approach in which the capture bag is closed tightly around the asteroid over a few minute period. Residual cross-axis spin is managed by force-controlled winches to keep accelerations reflected back to the spacecraft to less than 0.1 g while the RCS thrusters are subsequently used to de-tumble and then despin the spacecraft/asteroid combination.

4. Avionics Module

To reduce the cost, risk, and schedule for the flight system implementation, flight-qualified, deep-space avionics and sensors were identified that would work well for the asteroid redirect mission. This includes avionics and core flight software from the Soil Moisture Active/Passive (SMAP) project, the Mars Science Laboratory, and a sensor suite that could include instruments derived from the OSIRIS-REx mission.

Sensor Suite. The notional sensor suite supports optical navigation, asteroid characterization, and asteroid capture. The following sensors are currently in the ARM reference design:

- Narrow Angle Camera (NAC) – used for long range optical navigation and mapping of the asteroid

- Engineering Cameras – used for observation of the solar array and capture mechanism deployments
- Visible and IR Spectrometer – used for surface characterization of the asteroid
- Scanning LIDAR – used for asteroid relative navigation

V. Crewed Mission

The Asteroid Redirect Mission would be a natural stepping-stone supporting the Capability Driven Framework for extending Human Space Exploration beyond low-Earth orbit. The crewed mission concept would utilize the Orion Multi-Purpose Crew Vehicle launched on a Space Launch System (SLS) rocket with two crewmembers. The mission concept would develop capabilities useful for exploration far beyond this individual mission. A preliminary concept of operations for the crewed missions has been developed by the study team. The total mission duration would be approximately twenty-two days and includes two planned Extra-Vehicular Activities (EVAs) to explore the captured asteroid in distant retrograde orbit (DRO) about the moon (Fig. 8).

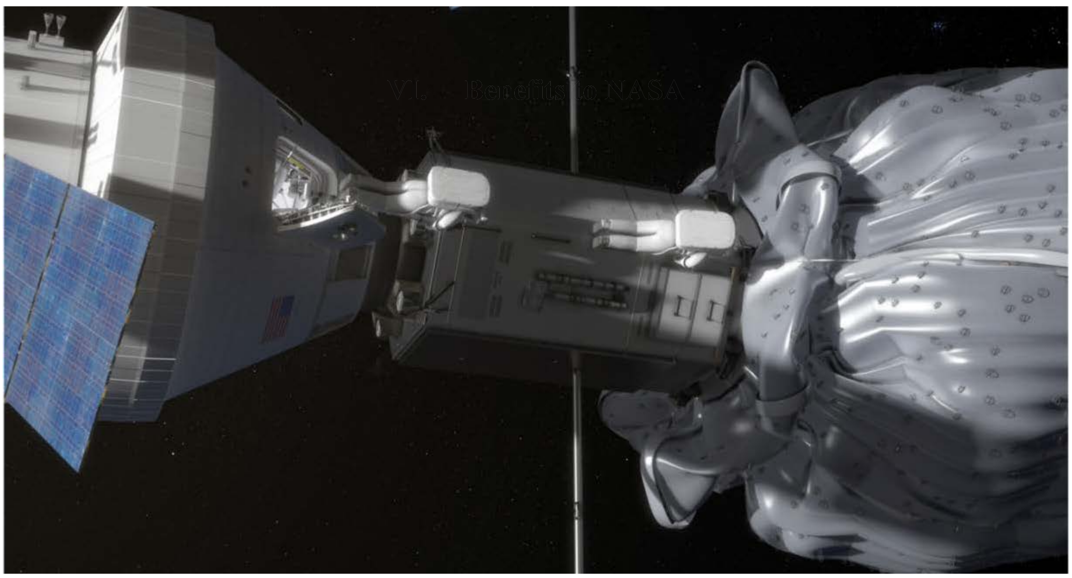

Figure 8. Illustration of the first crewed mission to the asteroid delivered to a Lunar Distant Retrograde Orbit (DRO). The asteroid is in the capture bag to the right of the picture and the astronauts are shown traversing the body of the ARV.

VII. Summary

ARM would be a key part of the nation's Human Space Program. It would provide an important step in human exploration deeper into space and eventually to Mars. This step would use assets already under development (SLS and Orion) and provide key demonstrations of these new capabilities well beyond low Earth orbit. It would provide an affordable path to sending humans to a near-Earth asteroid in the first half of next decade, and would result in a significant enhancement of NASA's exploration capabilities in deep space. Specifically it would:

- Demonstrate high-power solar electric propulsion enabling high-capability deep space transportation architectures for future human missions, including lower cost delivery of heavy cargo (such as landers and habitats) to Mars.
- Enable significantly faster deep space robotic missions to hard-to-reach destinations; and improve U.S. competitiveness in the commercial satellite industry.
- Demonstrate the ability to capture large non-cooperative objects in deep space.
- Demonstrate the ability to transport very massive objects with solar electric propulsion.

- Feed-forward to potential future human operations at other asteroids or Mars moons (Phobos and Deimos) by providing information on maneuvering, sampling, anchoring, and dust management at a small body.
- Stimulate the discovery and characterization of small NEAs, significantly improving what is known about this population that represents the vast majority of near-Earth objects.
- Through the enhanced discovery campaign needed for ARM, increase the discovery rate of potentially hazardous asteroids.
- Potentially jump-start an in situ resource utilization (ISRU) industry by providing a near-term target for fledgling asteroid mining companies.

Relevance to the Human Space Program

The delivery of up to 1,000-t asteroid to a stable high-lunar orbit would provide a unique, meaningful, and affordable destination for astronaut crews in the next decade. It would provide a destination that could support multiple subsequent missions, and ultimately could be the anchor for the development of a deep-space infrastructure at this location. Such an infrastructure could be devoted, in, part to initially determining how to extract useful materials from the returned asteroid, and ultimately to extracting these materials on a large scale to support human exploration farther out into the solar system. The development of in situ resource utilization (ISRU) techniques at a retrieved asteroid would demonstrate the feasibility of ISRU in general, potentially making it more likely to be adopted for use on the lunar surface and at Mars.

Sending astronauts to the retrieved asteroid in lunar orbit would provide an affordable path to meeting the nation’s goal of sending astronauts to a near-Earth object by 2025. This would mark only the second celestial object that humans will have ever come into contact with, and the first human mission beyond low-Earth orbit in 50 years.

Relevance to Science

Space science is not the objective of an asteroid redirect mission. However, it is extremely likely that ground-breaking science would result from the up-close examination of an entire small asteroid. Having access to the entire body, even a small one, could provide information on the effect of space weathering of the surface layers compared to the bulk material. Such information would be synergistic with the surface samples to be returned by OSIRIS-REx. Having access to the entire body should also provide information regarding the internal structure of the body and its homogeneity.

An observation campaign designed to discover a large number of 10-m-class near-Earth objects and characterize a fraction of them would significantly improve the current state of knowledge of this little-studied, poorly understood population. Such a campaign with its enhancements would also naturally discover an increased number of bigger, potentially hazardous, near-Earth objects.

The development of the SEP system for an asteroid redirect mission would lead directly to significantly improved SEP systems for deep-space robotic science missions. With larger, lighter, less expensive solar arrays and 3000-s Hall thrusters that have effectively unlimited life, more affordable SEP science missions could be developed. These systems would provide capabilities well beyond the Dawn system, significantly reducing flight times, launch costs, and reducing flight system development costs by easing mass and power constraints.

Relevance to the Commercial Sector

The asteroid redirect mission has the potential to impact the commercial interests of the United States. Near-term impacts would result from the development of the advanced, higher power solar arrays and electric propulsion technologies required for ARM that would also benefit U.S. commercial communication satellites. This will facilitate the development of higher power commercial satellites or the use of higher power on medium-sized satellites launched with smaller, less expensive launch vehicles.

By doing something bold, but achievable, NASA could stimulate interest in space science and technology, as it did in the 1960s, to the benefit of the U.S. economy. In the far-term, the ability to exploit near-Earth asteroid resources could usher in a new economic frontier based on people living and working in space.

Relevance to Planetary Defense and Orbital Debris Removal

Many of the ARM technologies, operational approaches, and systems would be applicable to planetary defense efforts. The ability to efficiently travel to, interact with, and maneuver an asteroid would directly inform efforts for diverting a potentially hazardous near-Earth object (NEO). These include the operational approaches and systems associated with the approach, rendezvous, and station-keeping mission phases of ARM utilizing a low-thrust, high-power SEP spacecraft, as well as interacting with, capturing, maneuvering, and processing the massive amounts of asteroid material. The use of a SEP spacecraft to deliberately alter the orbit of an asteroid is a direct demonstration of a rudimentary planetary defense capability at a small, safe, and affordable scale. However, since a 5-m to 10-m diameter asteroid is much less massive than an Earth-threatening NEO (diameter of 20 m or larger), the systems and techniques developed for ARM will have limited direct application to the deflection of such objects.

The technology developed for and demonstrated by ARM would be directly applicable to removing large pieces of orbital debris. There are many concepts in the literature that would make use of this capability in one fashion or another.

Relevance to International Participation and Cooperation

The asteroid redirect mission and utilization of the asteroid after its delivery to translunar space affords multiple opportunities for international participation and cooperation. International participation in the discovery and characterization of potential ARM targets would be highly beneficial and perhaps essential. There are multiple possibilities for international participation in the implementation of the asteroid redirect vehicle including contributed sensors and components of the flight system. Post-asteroid return, sampling, sample analysis, and material extraction experiments, both on the ground and in space, would also provide opportunities for international cooperation.

Observation Campaign

Analysis of the near-Earth asteroid population along with actual discovery rates of candidate ARM targets suggests that there is reasonable confidence a sufficient number of good targets exist and that the discovery rate of these targets (currently ~2 per year) could be increased by a factor of two to ten. For an ARM launched in 2018, there would be approximately four years in which to find appropriate primary and backup targets. At a discovery rate of 5 good targets per year, the asteroid redirect mission could have roughly 20 good targets by 2018.

Mission Design

High fidelity end-to-end, low-thrust trajectory designs were developed, based on asteroid 2009 BD that provide confidence that there will be no show-stoppers for the development of the very high–fidelity trajectories necessary for an actual mission. Lower-fidelity trajectories for twelve other known NEAs were used to estimate the maximum asteroid mass that could be retrieved based on the known orbital characteristics of these NEAs and the assumed capabilities of the ARV configured in this study. Mission design work also established at least one class of stable orbits in the Earth-Moon system. These orbits, known as distant retrograde orbits (DRO), have an orbit altitude relative to the Moon of about 70,000 km, are stable for more than a hundred years, and are accessible by both the ARV with a 1000-t asteroid and by crewed missions using SLS and Orion.

Solar Electric Propulsion

Solar electric propulsion is enabling for the ARM. The required capability represents a significant, but achievable advancement to the state-of-the-art. The ARM SEP system represents an important increase in power level relative to the highest power electric propulsion systems currently flying on commercial communication satellites and the highest power deep-space electric propulsion represented by the Dawn spacecraft. The ARM study team identified an approach that minimizes the development risk of the electric propulsion components. This approach heavily leverages the ongoing investments by NASA's Space Technology Mission Directorate in high-power, light-weight solar array development and advanced Hall thruster technology development. A proof-of-concept test for 115 hours of a 3000-s Hall thruster operating at 9 kW was performed during the study period. This test helped to establish confidence that the recently-developed magnetic shielding technology for Hall thrusters could be extended to 3000-s needed for ARM enabling the development of very long-life thrusters at this specific impulse.

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