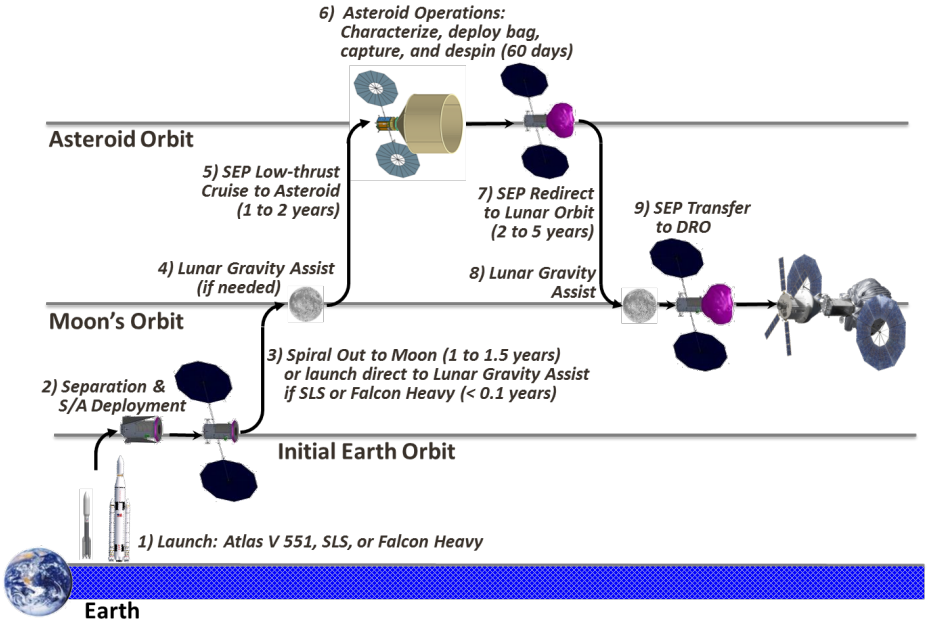
Objectives

Rendezvous with, capture, and redirect an entire near-Earth asteroid, with a mass of up to ~1,000 t, into a stable lunar orbit by the first half of the next decade.

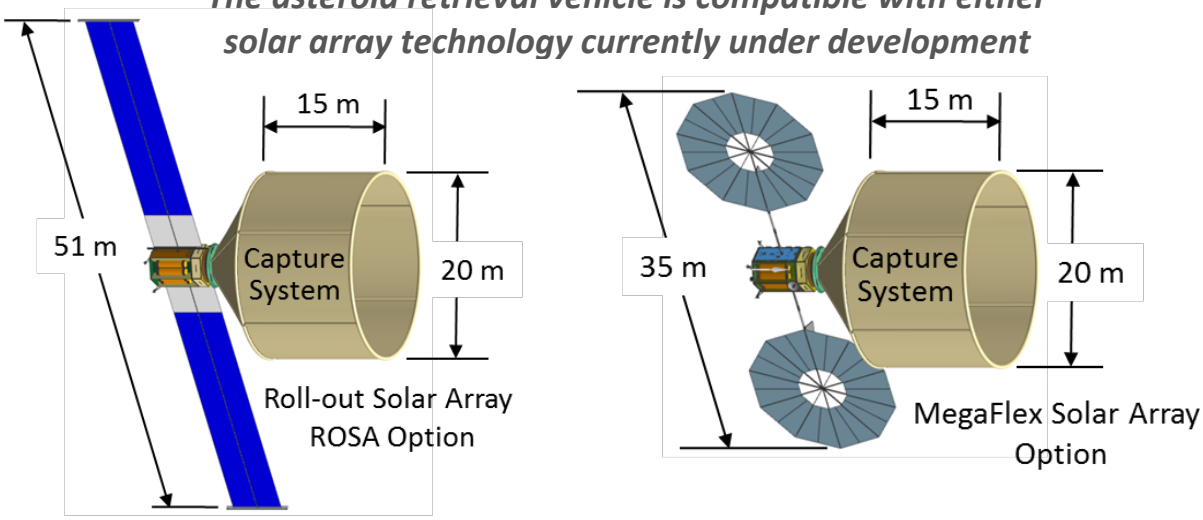
- Demonstrate high-power Solar Electric Propulsion (SEP).
- Demonstrate the ability to capture large non-cooperative objects in deep space.
- Stimulate the detection and characterization of small near-Earth asteroids.
- Use assets already under development (SLS and Orion) as a first step to using these new capabilities even deeper in space.

Mission Overview

- Utilizes a 40 kW solar electric propulsion system to rendezvous with a near-Earth asteroid and redirect it to translunar space in the 2021 timeframe.
- Utilizes 50-kW-class solar arrays current under development by the Space Technology Mission Directorate's Solar Array System program.
- Is capable of launching in 2017 or 2018 on an Atlas V 551, Falcon Heavy, or the Space Launch System (SLS).
- The storage orbit for the redirected asteroid is a stable distant retrograde orbit (DRO) in the Earth-Moon system with an orbit altitude of ~70,000 km above the lunar surface.
- The DRO is reachable by SLS/Orion with two crew members in a 22 to 25 day mission.



The asteroid retrieval vehicle is compatible with either solar array technology currently under development



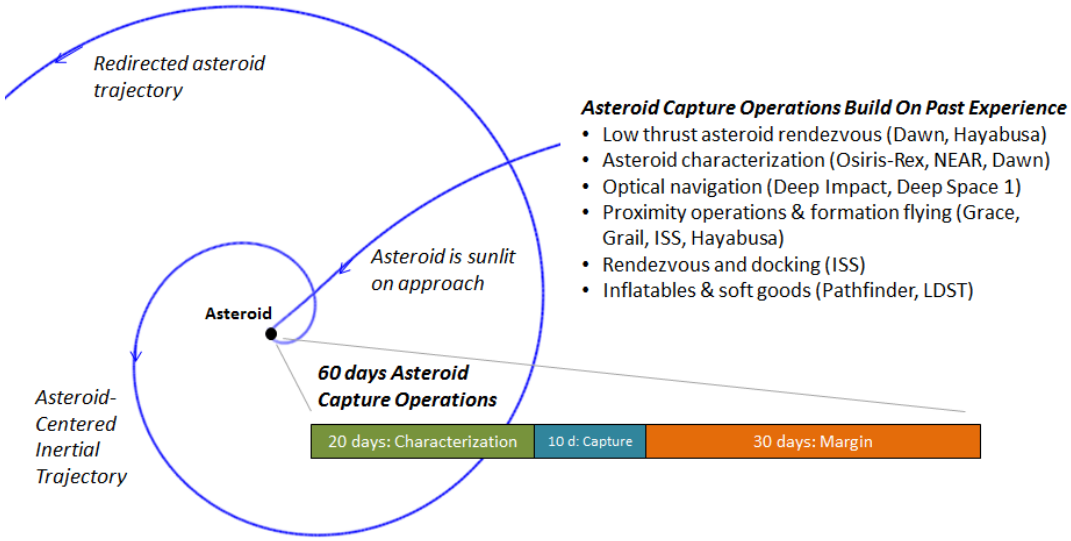
Three Key Program Phases

1) **Observation Campaign** to discover and **characterize** an adequate number of targets around which a robust asteroid redirect mission could be planned.
2) **Asteroid Redirect Mission (ARM)** to capture and return an entire NEA by the middle of the next decade.
3) **Asteroid Redirect Crewed Mission (ARCM)** to rendezvous with the asteroid in translunar space using SLS/Orion, and inspect it, sample it, and ultimately dismantle it to assess its internal structure and resource potential.

Key Spacecraft Characteristics

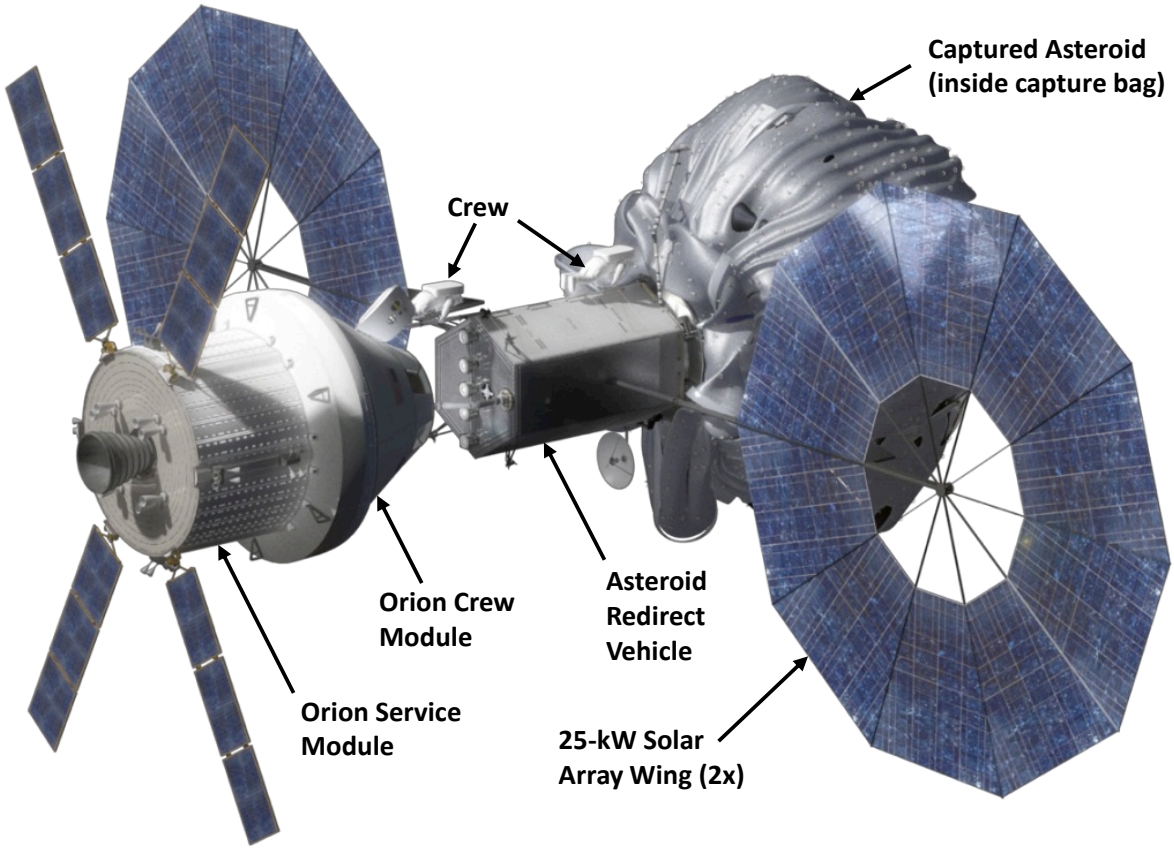
Dry Mass: 3950 kg dry (maximum expected value)
Propulsion: 40-kW, 3000-s Hall thruster-based SEP with four 10-kW thrusters plus one spare
Propellant: up to 12 t of xenon
Power: 50-kW ROSA or MegaFlex solar arrays (beginning of life at 1 AU)
Telecom: X-band, two 100-W TWTAs; 1.0-m HGA; 3 LGAs, S-band
Capture Mechanism: Inflatable, non-rigidizable structure deploys a ~15-m diameter capture bag. Cinch lines close the bag to capture the asteroid.
Example Sensors: Wide-field camera for optical navigation, medium-field camera for close range mapping, visible and IR spectrometer for chemical characterization, and a laser altimeter for mapping and final autonomous control of the capture event

Asteroid rendezvous, capture, and redirect operations build on past mission experience



EXECUTIVE SUMMARY

The Asteroid Redirect Mission (ARM) described in this report brings together the capabilities of the science, technology, and the human exploration communities on a grand and exciting challenge, propelling U.S. leadership in robotic and human space exploration beyond low Earth orbit. This report 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, how to significantly improve their discovery rate, how to adequately characterize candidate mission targets, the process to capture a non-cooperative asteroid in deep space, and the power and propulsion technology required. Viable options for spacecraft and mission designs were 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, were 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 the Glenn Research Center (GRC) and supported by Johnson Space Center (JSC), the Langley Research Center (LaRC), and the Marshall Space Flight Center (MSFC).



History

NASA has conducted studies on the exploitation of asteroids since the 1960s, but in-space relocation of large asteroid masses had remained an unresolved challenge. In 2007, Dr. John Brophy (JPL), who had led the development of the ion-propulsion system for the Dawn mission, recognized that near-term advancements in high-power Solar Electric Propulsion (SEP) could potentially overcome the transportation limitations. Brophy formed a team in 2010 with members from JPL, JSC, GRC, and UCSC to respond to a NASA internal call for proposals "supporting early formulation of revolutionary concepts to benefit NASA missions and meet other national and global challenges." The team proposed to evaluate the feasibility of rendezvousing with a small NEA, capturing it, and returning it to the International Space Station using high-power SEP. Based in part on this study, in 2011–2012, Brophy, Louis Friedman (The Planetary Society), and Fred Culick (Caltech) led a study jointly sponsored by the Keck Institute for Space Studies (KISS) at the California Institute of Technology, and JPL on the feasibility of capturing and returning a small NEA to translunar space. The study included participants from six NASA centers, eight universities, commercial companies, and others. It was based on this report that NASA chartered the 2013 feasibility study that is being reported here.

This Study

The current study builds on the results from the KISS study with the primary objective of looking at the asteroid redirect mission concept in sufficient depth to determine if its feasibility would stand up to more detailed scrutiny. The conclusion of this study is that an asteroid redirect mission is indeed feasible and could be launched as early as 2017 given a sufficient funding profile. Such a mission could return a near-Earth asteroid (NEA) with a mass of up to approximately 1000 metric tons to a stable lunar orbit by 2021–2025 depending on the target. The study identified a class of lunar orbits called Distant Retrograde Orbits (DROs) that have attractive characteristics for an asteroid redirect mission. These orbits are stable on a time scale of greater than a hundred years and are reachable by both a robotic asteroid redirect vehicle with a 1000-t asteroid and by the Orion vehicle with two crewmembers onboard launched by the Space Launch System (SLS), enabling human missions to interact directly with an asteroid for the first time.

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 return a near-Earth asteroid with a mass up to 1000 t 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.

This report describes the detailed investigation of the first two parts conducted under this study and provides a high-level description of the third part. The third part was the

subject of a parallel study conducted by JSC provided on separately in the Asteroid Crewed Mission Reference Concept of Operations.

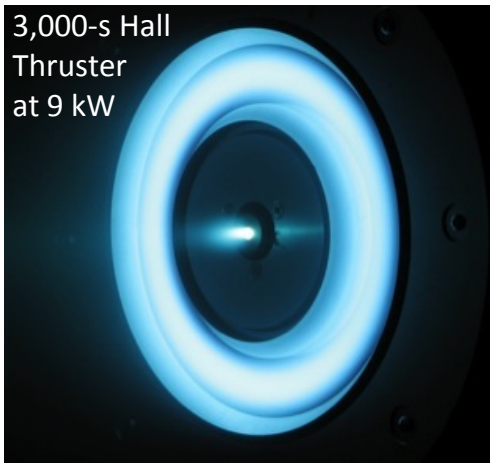
Observation Campaign

The observation campaign is 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). Therefore, 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 has approximately four years to find a primary target and an adequate number of backup targets, assuming a launch in late 2017. 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 Observation Campaign section of this report includes a set of specific recommendations for establishing additional characterization asset arrangements and agreements that would be needed to meet the ARM needs.

Asteroid Redirect Vehicle (ARV)

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

The SEP Module



The asteroid redirect mission is 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 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 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 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.

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. Other concepts were received from industry that may also be feasible, but these have not yet been examined in detail.

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 used to de-tumble and then despin the spacecraft/asteroid combination.

Avionics Module

To reduce the cost 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 sensor suite supports optical navigation, asteroid characterization, and asteroid capture. The following sensors are currently in the ARM reference design:

- Wide-field camera – used for long range optical navigation
- Medium-field camera – used for close range mapping of the asteroid

- Visible and IR Spectrometer – used for chemical characterization of the asteroid
- Laser Altimeter – used for asteroid characterization and mapping and for final autonomous control of the capture event

Launch System

The study assessed the feasibility and mission performance of three different launch vehicles: Atlas V 551, Falcon Heavy, and the Space Launch System (SLS). The mission is feasible with all three launch vehicles. The lower performance of the flight-proven Atlas V can be compensated for with the SEP system by spiraling out from an Earth elliptical orbit and using a Lunar Gravity Assist (LGA) to escape from Earth. The spiral out adds a year to a year and a half to the flight time required to get to the target NEA. The higher performance capabilities of the Falcon Heavy or SLS launch vehicles enable elimination of the Earth-spiral phase and would launch the ARV directly to the LGA. This simplifies the flight system design, shortens the overall mission duration, and enables later launch dates.

Safe Lunar Storage Orbit

Retrieval of the asteroid is accomplished by using the SEP system to make small adjustments to the asteroid's orbit in order to target a lunar gravity assist maneuver enabling capture into the Earth-Moon system. The 40-kW SEP system provides a few hundred meters per second velocity change to the 1000-t asteroid over the three to five year return trip. This redirection is only possible for asteroids that naturally return close to the Earth-Moon system in the timeframe of interest. The lunar gravity assist provides a velocity change of ~1,600 m/s, which is sufficient to capture the asteroid into the Earth-Moon system. An additional ~60 m/s is provided by the SEP system to transfer the asteroid to the long-term-stable, lunar distant retrograde storage orbit. The asteroid size and composition would be selected such that it could not survive an Earth atmospheric entry. The long-term stable orbit is targeted to make the asteroid available as a destination for multiple future missions.