Asteroid Retrieval Technology Development From the Asteroid Return Mission Study

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II. Executive Summary

- Goal of program

  The Keck Institute for Space Studies (KISS) workshops on the Asteroid Return Mission concept explored and established the feasibility of capturing and returning an entire near-Earth asteroid (NEA) to lunar orbit by the middle of the next decade, and identified the benefits that such an endeavor would provide to NASA, the nation, and the world. The goal of this technology development program was to start the process of working select technical issues identified in the study to significantly enhance the prospects of making the asteroid capture and return mission a reality.

- Key areas of accomplishment

    - Mission architecture definition

        1. Trajectory design
        2. SEP propulsion technology
        3. Mission/System Design
        4. Solar Thermal Power & Propulsion Technology Introduction
            a. Study beam-forming deployable reflector designs for solar concentrators.
            b. Monitor progress in solar-electric power production technologies.

    - Small Near Earth Asteroid (NEA) detection

        1. Modifications to the search/detection software employed in the Palomar Transient Factory (PTF).
        2. Demonstration of the upgraded PTF as a useful tool for detecting small NEAs.

    - In-Situ Resource Utilization (ISRU) for asteroids, specifically for power and propulsion

- Initial KISS study

    Two successful KISS workshops were convened on this subject (Sept 27-30, 2011 and Feb 7-8, 2012), and additional supporting work was performed outside the workshops. A study report was delivered to KISS in April 2012 (http://kiss.caltech.edu/programs.html#asteroid). This report documents the challenges and opportunities arising from capturing, characterizing, and mining a small (7-m diameter) NEA. The results of the initial study are also described in Appendix A of this report. The technical development effort selected four areas from among a number of technical challenges identified in the study. These are mentioned above.

- Technical Development Workshop (April 7-9 2014)

    Applications of Asteroid Redirection Technology. (35+ attendees)

    Workshop description:

    "Since the development of the asteroid retrieval mission concept a number of suggestions and ideas have been brought forward for applications to other missions (with interplanetary destinations), planetary defense, human space transportation, commercial exploitation and science investigations. We believe consideration of other applications is important, in part to increase understanding the multiple potential benefits of asteroid retrieval and in part to offset concerns that the technology is a "one-off," applicable to a single mission and not part of the NASA future. The asteroid retrieval mission concept is envisioned as a supporting step in the long-range human exploration program for missions beyond the Moon and eventually to Mars. Broader consideration of the technologies and opportunities inherent with asteroid retrieval would help put the first proposed asteroid retrieval mission in context as an essential step in expanding human presence beyond low Earth orbit."

III. Outcomes of the technical development program

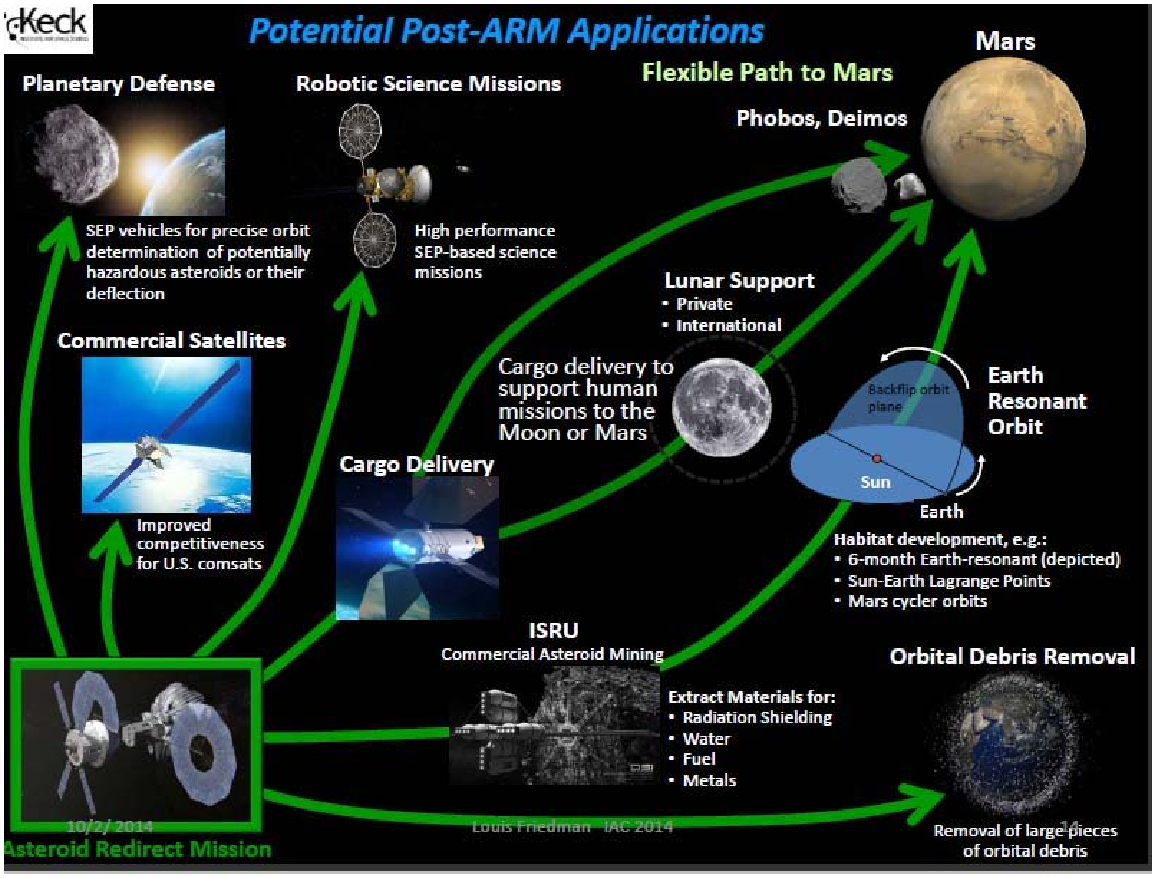
The ARM mission studies had very significant impact on NASA, resulting in a large amount of funding being allocated to develop and implement an ARM mission. However, with a change in US administration, the mission was cancelled in 2017 (*spacenews.com/nasa-closing-out-asteroid-redirect-mission/).*

There were numerous results from this technical development program. Here we report on the two areas which produced the most significant results: mission architecture and detection of small NEAs.

Mission Architecture Studies

Mission Architecture:
The Mission Architecture task was completed and documented with the publication of Synergies of Robotic Asteroid Redirection Technologies and Human Space Exploration[1] at the 65th Conference of the International Astronautical Congress (2014). Whereas the first year of technical development for the Asteroid Retrieval study focused on the feasibility and mission design for capturing and moving a small asteroid from its natural orbit to cis-lunar space, the later technology development task examined how the various technologies required for such a mission can be used in other planetary exploration applications and might be incorporated in an architecture to extend human exploration to Mars. A workshop was held in April 2014 on Applications of Asteroid Redirection Technology, attended by 35+ participants.

[1] IAC-14.A5.3-B3.6.7, x26388: John R. Brophy, Jet Propulsion Laboratory, Caltech;_Louis Friedman, Executive Director Emeritus, The Planetary Society ;Nathan J. Strange, Jet Propulsion Laboratory, Caltech; Thomas A. Prince. Director, Keck Institute for Space Studies, Caltech; Damon Landau, Jet Propulsion Laboratory, Caltech; Thomas Jones, Florida Institute for Human and Machine Cognition; Russell Schweickart, B612 Foundation; Chris Lewicki, Planetary Resources, Inc.; Martin Elvis, Harvard-Smithsonian Center for Astrophysics; David Manzella ,NASA Glenn Research Center, USA



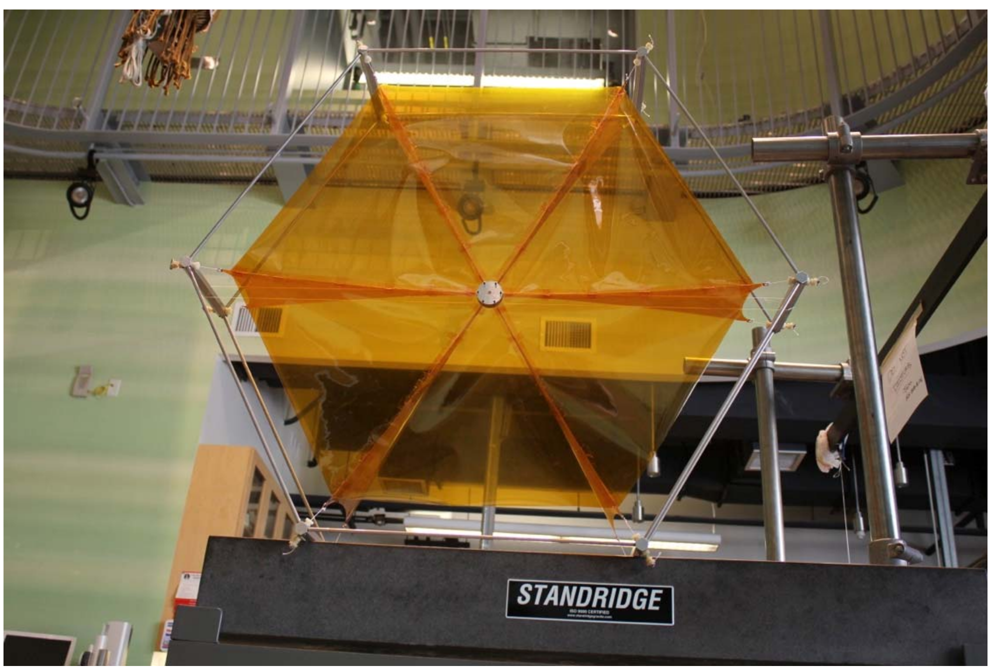
This workshop and the original study report formed the basis of the IAC publication mentioned above. The areas of research and technology included solar electric propulsion use on cargo missions to support human space flight, analysis of resonant heliocentric orbits that might enable intermediate flights between Earth and Mars, planetary defense applications of asteroid deflection, and applications to utilization of putative asteroid resources. A single architecture could, in principle, be derived from the options studied, but that would of course depend on program objectives outside the scope of a technology development study. Instead, various pathways for applications were identified, as well as areas for further study. A summary chart of all the considerations appears above.

The legacy of the ARM program is described in Appendix B.

Solar-thermal propulsion:
Part of the Mission Architecture effort was to develop solar-thermal power technology for multiple uses. One use is to take advantage of the anticipated availability of large quantities of water in cislunar space enabled by the return of one or more C-type asteroids. A 500-t, carbonaceous C-type asteroid may contain up to 100 t of water. This water, once extracted from the asteroid, could be used both for radiation shielding to protect astronaut crews from galactic

cosmic rays or in a solar-thermal propulsion system to provide transportation to a radiation-shielded habitat. Initial solar-thermal systems would likely use water directly as the propellant. Longer-term systems could use hydrogen (obtained by the electrolysis of water from the asteroid) to provide better performance. This has the potential to revolutionize human space transportation in a bootstrapping manner. Further, solar-thermal power could be used directly, i.e., without paying a Carnot-efficiency factor penalty, in the form of concentrated solar beams formed by suitable optics, with concentration factors in the range of 30-100, yielding fluences at 1 AU in the range of 65-130 kWsol/m2. This power could be used to facilitate water extraction, but also to enable mining operations. Solar electric propulsion is used to retrieve the first few asteroids, and then after the capability is established to extract large quantities of water from these objects, solar thermal propulsion – if it can be successfully developed – would take over and be used to transport astronaut crews in deep space.

As part of the solar-thermal effort, a 1 m diameter proof-of-concept physical model of a cylindrical gore solar concentrator was built. The model was made of 50 μm thick Kapton and it was supported by a rigid Aluminum edge frame. The surface gores were precision cut using templates made with a laser cutter. The rib panels were cut using paper templates. A lightweight design for the central hub was developed. The proof-of-concept model is shown in the following Figure.

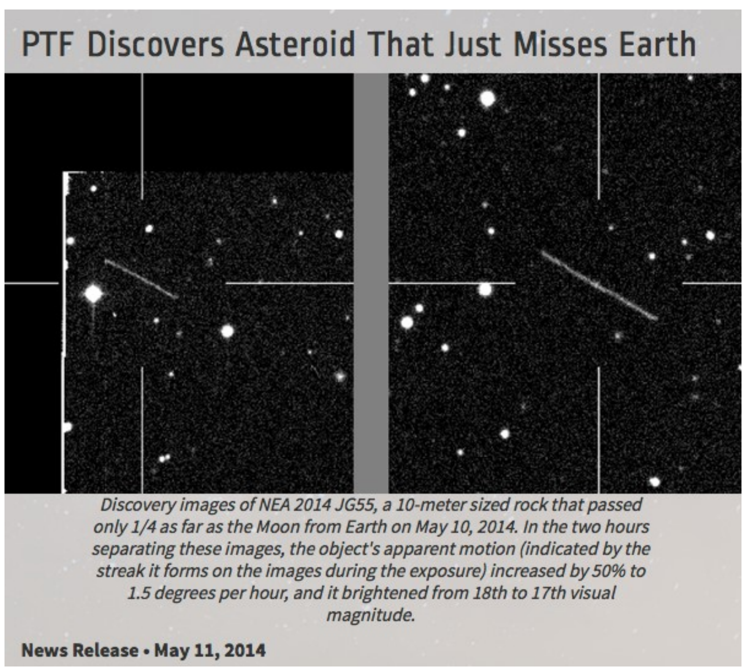


Front view of proof-of-concept model

Small NEA Detection - *Advances in Techniques to Search for Small Asteroids*

As part of the Keck program that initiated the NASA Asteroid Return Mission (ARM), technical development work was undertaken with KISS funds to develop new techniques for detecting small asteroids, down to 5-10 meters in size, appropriate as possible candidate targets for the ARM mission. Work was initiated using the Palomar Schmidt Telescope using a CCD camera with 7.25 square degree field of view and making 60-second exposures. Small asteroids can only be detected close to the Earth because of the small amount of light they reflect and therefore they have large angular velocities across the sky, somewhat analogous to earth satellites. They therefore appear as linear features (“streaks”) in the images from the Schmidt telescope.

A sophisticated software pipeline was developed to identify asteroid streaks employing machine-learning techniques (see Waszczak et al., reference below). The initial trials of the pipeline in 2014-2015 yielded immediate results: a 7.5 meter diameter asteroid, less than 1/3 the distance to the Moon. See figure below.



Discovery images of NEA 2014 JG55, a 10-meter sized rock that passed only 1/4 as far as the Moon from Earth on May 10, 2014. In the two hours separating these images, the object's apparent motion (indicated by the streak it forms on the images during the exposure) increased by 50% to 1.5 degrees per hour, and it brightened from 18th to 17th visual magnitude.

Caltech has built a new ½ Gigapixel CCD camera for the Palomar Schmidt Telescope, the Zwicky Transient Facility (ZTF), that has a 47 square degree field of view, more that 6 times that of the earlier camera. In addition, the camera is more sensitive allowing 30 second exposures. For small asteroids, the improvement in detection rate should increase by about x20. Instead of a rate of about one small asteroid detection per month, the rate should now be about one per day. Although the possibility of an ARM mission is now less probable, the scientific interest in characterizing the population of near earth asteroids is even higher. Surveys using the new Palomar Schmidt CCD camera are be a major step forward in detecting small asteroids. This program would not have been possible without the earlier KISS funding. The ZTF instrument will begin survey operations in May 2018.

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Papers, published work

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- Brophy, J. R., 2017. *Legacy of the Asteroid Redirect Mission (ARRM). 35th International Electric Propulsion Conferece.* [Included as an appendix.]

Presentations

There were numerous presentations on the ARM mission and technology. Two early presentations are given here:

- May 21, 2013, Testimony by Louis Friedman to the Subcommittee on Space - Next Steps in Human Exploration to Mars and Beyond (2pm at 2318 Rayburn House Office Building Washington, D.C. 20515)
- “Trending Topics in Space Technology”, Strathclyde Univ., Glasgow by Marco Tantardini
- March 28, 2013, Presentation by Paul Dimotakis and Louis Friedman on the KISS Study on Asteroid Return Mission to the National Research Council Technical Panel on Human Spaceflight, The Keck Center, Washington DC.

Media Coverage

Media coverage of the ARM mission was very extensive and the number of press articles is too numerous to list here, although a representative sample may be found here: http://kiss.caltech.edu/papers/asteroid/papers.html

External Funding

External funding proposed/received to continue work started with Keck Institute funding.

- A very significant amount of NASA funding went towards the development of the ARM concept, a direct result of the initial Keck Institute study program. In FY2014 alone, NASA budgeted over $100M for development of the mission.

- Caltech President’s and Director’s Fund for small NEA detection: $597,540

- NSF Growth Funding for small NEA detection: $390,000

IV. Future Work

The ARM technical work will continue as NASA funded development for space solar electric propulsion. See Appendix B for a detaled description of follow-on work.

The small NEA detection work will continue as part of the Zwicky Transient Facility (ZTF). Funding has been requested in the past from NASA to support ZTF asteroid work and a new proposal will be submitted in June 2018.

Appendix A: Documentation of Program Description

IAC-12,A5,4,11,x13356

PROJECT 5S: A SAFE STEPPING STONE INTO THE SOLAR SYSTEM

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Abstract

The human exploration program, at least in NASA, has been directed to move beyond the Moon and travel on a flexible path into the solar system. Reaching a Near-Earth Asteroid (NEA) is a major human space flight goal but such missions have tight times and life-support requirements that require huge steps from current capabilities. An objective between the Moon and a NEA is needed. Example interim objectives are the Lagrangian points in either the Sun-Earth or Earth-Moon (EM) system. The nearest of these pointsbeyond the Moon is E-M L2. The Lagrangian points are empty (as far as we know). As objectives for human flight,it has been argued that they suffer from a lack of public interest and of meaningful objectives for astronaut operations. To provide a physical target, a robotic spacecraft could retrieve a small NEA and bring it to a Lagrangian or other nearer-Earth point to be accessed and utilized for human-mission objectives. This paper reports on the results of a recently completed study of an asteroid retrieval mission sponsored by the Keck Institute for Space Studies (KISS) at the California Institute of Technology. The study included an evaluation of potential targets, mission objectives, mission and system design, and potential capture mechanisms. The study concluded that, while challenging, there are no fundamental show stoppers and that such a mission would be possible with technology expected to be available in this decade. The final destination selected (for safety and mission operations) was high lunar orbit. Two options for target selection are considered: (i) retrieving a small (7 meter) NEA with a mass of order 500,000 kg, and (ii) taking a similar size boulder of a large known carbonaceous NEA. Several areas of technology and program requirements were identified, but the most important conclusion was that this approach enables meeting a goal of humans going to a NEA by the mid-2020s. The advantages and benefits for human explorationare considerable as are the advances that would be made in space-resource utilization and science for further exploration and development of the solar system. The combination of the robotic mission to move the asteroid and the human mission to go to its new destination and conduct astronaut operations there would provide a boost and purpose to human space flight.

Background

The Keck Institute for Space Studies (KISS) at Caltech sponsored a study last year to investigate the feasibility of identifying, robotically capturing,and returning an entire Near-Earth Asteroid (NEA) to the vicinity of Earth by the middle of the next decade. Although the idea is at first startling, the study resulted in focusing on a feasible mission design achievable within current technological constraints. The rationale for considering such a proposal as moving a NEA *closer* to Earth is that it may provide the only affordable NEA target for a human-crewed mission that could reasonably be achieved by the mid-2020s, the target date set by the Obama Administration for the human space program.

The results of the study and an example mission and spacecraft design for the robotic asteroid capture and retrieval mission are given in References 1,2, and 3. The spacecraft concept is illustrated in figure 1. This paper presents recommendations from that earlier

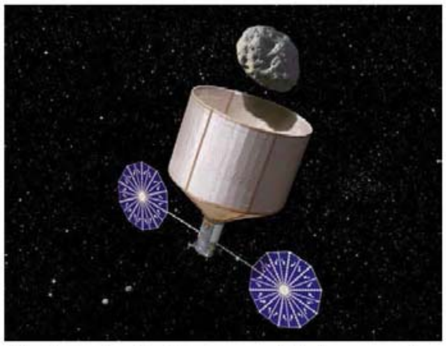

Fig. 1: An asteroid retrieval spacecraft in the process of capturing a 7-m, 500-ton NEA.(Credit: Rick Sternbach KISS)

study for follow-on work, necessary to further investigate the mission, spacecraft and program requirements; the synergy with the human space

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program and an international approach to the mission design.
The KISS study included two workshops with 30+ participants, all of whom contributed to the final report. They are acknowledged at the end of this paper.

A Safe Stepping Stone into the Solar System
The KISS study identified a belt & suspenders approach for safely moving an asteroid *toward* Earth. The following four levels of safety were identified:

1. The asteroid is small – only about 7 meters in diameter. Its total mass would be approximately the same as the International Space Station. (A 7 meter asteroid, such as we are considering, has a mass approximately between 350-700 metric tons; the ISS mass is 420 metric tons.
2. We will select a carbonaceous asteroid, the type that routinely and harmlessly breaks-up in Earth's atmosphere because of its small size and its loose internal structure.
3. The trajectory design for moving the asteroid toward the Earth keeps it on a non-impact trajectory at all times. Therefore, if the flight system fails, the resulting orbit is no more dangerous than that of thousands of natural and man-made objects in near-Earth space.
4. The target destination in the Earth-Moon system is chosen such that celestial mechanics perturbations will result in an impact on the Moon, not on Earth.

Safety is in the title of this mission concept for another reason: the very purpose of the mission is to ensure astronaut safety by providing a stepping stone in interplanetary space where human-crewed operations can be tested while the astronaut is still only a relatively short time away from return to Earth and before extensive long-duration, large life support missions must be mounted. The NEA target that we will create will enable a 3-4 week round-trip human mission rather than the currently known 4-7 month mission for when the target is in its natural orbit.

For this reason we call this *A SAFE STEPPING STONE INTO THE SOLAR SYSTEM: Project 5S.*

Rationale
An important non-intuitive conclusion from the study was that putting a target NEA in Earth-Moon space may well be the only way to enable a human-crewed NEA mission by the mid-2020s. This is because a mission to a natural NEA requires first identifying one and certifying its safety. Only a couple of known candidates exist, and they all involve missions of many months duration -- far beyond any planned or currently conceived human-mission capability. Discovering a new one is always a possibility, but any such discovery may need to be confirmed over at least two synodic periods of the asteroid's orbit. The synodic orbit of any mission candidate is almost certainly several years. Adding up these time requirements and the requirement for a robotic precursor mission for safety reasons, one concludes that a human mission to a natural NEA will require 10-15 years *after* candidate targets are found and it's worth noting that none have been as yet.

As described in Reference 3, an asteroid-retrieval mission with current systems could take 6-10 years, so a 2016 launch would enable the target to be in place by 2022-26. A round-trip first human mission could approach this asteroid in its new location and return home in less than one month.

Enabling human flight into the solar system, finally going beyond the Moon, is the principle rationale. But the robotic mission of moving the asteroid has large synergies with other important space-mission objectives. To wit: planetary defense – developing the technology to move a threatening asteroid away from Earth; asteroid resource utilization – conducting studies and technical developments to enable retrieval of mineral and volatile resources from a NEA; development of large low-thrust systems for future mission applications and enhancing the scientific program of discovery and characterization of NEAs – a necessary step for our proposed mission and a long-sought scientific goal in space studies.

Required Work
As earlier noted, a preliminary mission and spacecraft design and feasibility analysis has been conducted and described in the references. In this paper we describe our recommendations for next steps.

Observation Campaign

An asteroid return project cannot progress very far without a robust set of attractive target asteroids around which primary and backup opportunities can be planned. We propose an observing campaign targeted to find small accessible NEAs. This is the most critical near-term activity, because of lead-time requirements and implications on mission design.

Detailed Trajectory Design and Orbit Stability Analysis

The mission analysis described in the final report from the KISS workshops demonstrates the energetic and technological feasibility of capturing an asteroid and returning it to Earth. However, follow-on mission analysis is necessary to assess the next level of detail and to focus on operational detailssuch as how to keep the return trip on a non-impacting trajectory with Earth, and the determination of the long-term stability of the asteroid parking orbit.

Propulsion Technology:

This task focuses on two key transportation-related issues. First, the asteroid return mission is enabled by the use of solar electric propulsion (SEP). The propulsion system assumes near-term advances to the SEP technology currently flying. Traditionally, the most expensive, difficult-to-develop component in an electric propulsion subsystem is the Power Processor Unit (PPU). The PPU converts the solar array current and voltage into the currents and voltages necessary to operate the electric thruster. For the Hall thrusters required by the asteroid retrieval mission, the PPU must provide 10-kW of electric power to the thruster at 800 V. The goal of this proposed task is to prototype a new PPU architecture that eliminates the transformer isolation used in traditional PPUs to enable the development of a simple, low-mass, low-cost PPU. The elimination of transformer isolation is made possible by direct-drive technology work underway at JPL. The proposed PPU is not a direct-drive design, but uses the non-isolation feature of direct-drive technology.

The second task will to develop solar-thermal power technology for multiple uses. One use is to take advantage of the anticipated availability of large quantities of water in cislunar space enabled by the return of one or more C-type asteroids. A 500-t, carbonaceous C-type asteroid may contain up to 100 t of water. This water, once extracted from the asteroid, could be used both for radiation shielding to protect astronaut crews from galactic cosmic rays or in a solar-thermal propulsion system to provide transportation to a radiation-shielded habitat. Initial solar-thermal systems would likely use water directly as the propellant. Longer-term systems could use hydrogen (obtained bythe electrolysis of water from the asteroid) to provide better performance. This has the potential to revolutionize human space transportation in a bootstrapping manner. Further, solar-thermal power could be used directly, i.e., without paying a Carnot-efficiency factor penalty, in the form of concentrated solar beams formed by suitable optics, with concentration factors in the range of 30-100, yielding fluences at 1 AU in the range of 65-130 kW_{sol}/m^2. This power could be used to facilitate water extraction, but also to enable mining operations. Solar electric propulsion is used to retrieve the first few asteroids, and then after the capability is established to extract large quantities of water from these objects, solar thermal propulsion – if it can be successfully developed – would take over and be used to transport astronaut crews in deep space.

Capture Technology

The primary goal of this task is to design a robust and reliable capture approach enabling safe transport of the asteroid to it target destination. We are studying two cases, depending on target identification – one to capture a whole asteroid of approximately 7 meters diameter – one that will have to be discovered in our proposed observation campaign. The other is to capture a boulder of approximately the same size on a larger, already discovered asteroid dislodging and then capturing it. Potential designs and interfaces with the spacecraft for both of these are described in Ref. 2. We now need to investigate several design approaches both for capturing the asteroid, including handing its de-spin and tumble, and for containing it while being transported and tradeoff the resulting system design requirements .

Mission/System Design

The primary goal of this task will be to follow up on issues raised during the KISS Phase 1 study and the supporting "Fetch" study conducted by Glenn Research Center's (GRC) COMPASS team. The initial study used a point design to establish feasibility with only brief treatment of system tradeoffs and optimization. In this follow-up phase, trades will be analyzed in more depth and to seek optimal solutions. This activity will also be used to maintain contact with and coordinate inputs from the KISS Phase 1 study participants, to engage international organizations to participate, and to analyze architectural approaches to develop an international roadmap for the resulting proposed program.

In particular, mission and system design should be studied to incorporate participation of potential international players– both in the robotic and human missions. International planning and cooperation are widely viewed as necessary in the human program – building on the International Space Station and the follow-on considerations of the Global Exploration Strategy Framework (Ref. 4). It is also a principle for flagship mission planning, as evidenced in the two most recent flagship proposals (Mars Sample Return and Jupiter System Mission). The European Space Agency, Russia, and Japan all have interest in asteroid missions, with Japan conducting sample-return missions and Europe on their way for a comet rendezvous after visiting several asteroids. The estimated scope and cost of the Asteroid Retrieval Mission permit international options for sharing to be defined. These include the various elements of the power system: thrusters, power conditioning, solar arrays, structure; the capture mechanism including possible tethers, net, sealing container, grappling, de-spin and collection of the asteroid material; observation campaign contributions on Earth and from space missions; supporting technology test and precursor missions including missions to different asteroids; and then of course all the elements and devices of human life support and crew operations on or near the asteroid not too dissimilar from the many tasks of the crew on the International Space Station.

Another important mission design task will be to more closely coordinate with the human space flight program plans for asteroid exploration. This goes along both with international cooperation goals and with the need for robotic precursors. Astronaut Tom Jones has elaborated on this required development. (Ref. 5). The investigation of human-crew operations at the NEA is particularly important – whether it be astronauts in space suits operating on the surface of the asteroid or in a crew module tele-robotically interacting with the asteroid. How this is done will define future directions and roles for human space exploration.

The human mission development will be pursued in parallel with the conduct of the asteroid retrieval mission and we imagine extensive virtual participation of the human crew in the robotic asteroid capture mission. The next phase of work to create the 5S will integrate human mission planning into the proposed robotic mission plan and tele-robotic technologies into the human mission plan. A preliminary approach to this shown in figure 2was developed in the earlier study.

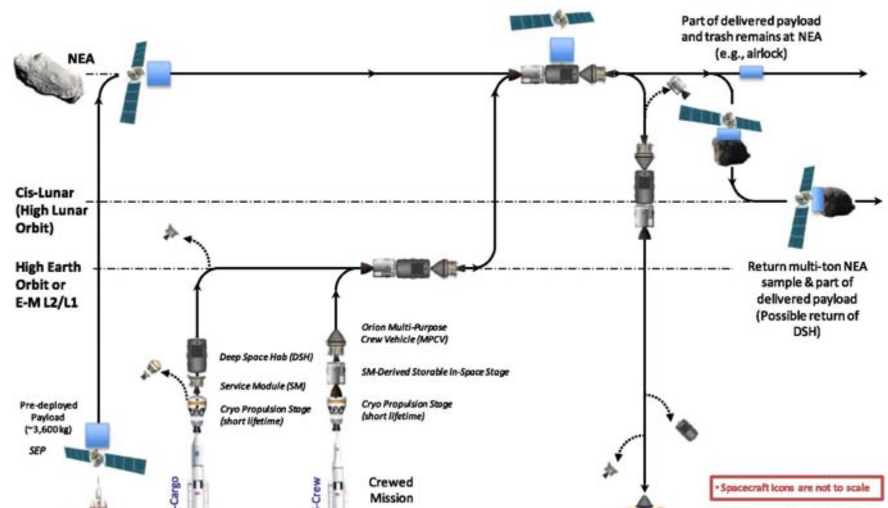

Fig. 2: Human Mission Operation Concept

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Acknowledgement

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Appendix B: Documentation of Legacy of ARM

Legacy of the Asteroid Redirect Robotic Mission (ARRM)

IEPC-2017-031

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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NASA's proposed Asteroid Redirect Robotic Mission (ARRM) began with the recognition in a 2010 NASA study that emerging high-power solar electric propulsion technology could be used to rendezvous with, capture, and return an entire, very small (~10,000 kg), near Earth asteroid to the International Space Station. A 2011 workshop by the Keck Institute for Space Studies (KISS) extended this NASA study to asteroid masses of order 500,000 kg by returning them to cislunar space. Subsequent detailed NASA studies in 2013-2014 confirmed the feasibility of this concept. This led to the establishment of the Asteroid Redirect Mission program that consisted of a robotic mission to return multiple tons of asteroid material to cislunar space and a crewed mission to rendezvous with the robotic vehicle, perform two extra vehicular activities (EVAs), collect samples of the asteroid material, and return this material to Earth. Implementation of ARRM proceeded midway through Phase B before being cancelled in April 2017. Although ARRM was cancelled, it left a near-term legacy of positive impacts to the human spaceflight community, the planetary defense community, the deep space science community, and asteroid mining interests.

I. Introduction

THE idea to exploit the natural resources of asteroids is older than the space program [1]. Numerous studies have identified and evaluated the benefits and challenges of exploiting the natural resources of near-Earth asteroids (see for example [2-13]). These studies and others identify three generic approaches for mining asteroids: 1) Mine and process the material at the asteroid and return only the processed material; 2) Mine the asteroid and return the raw material for processing; 3) Return an entire small asteroid to a more convenient location for processing. For all of these approaches, transportation is a major challenge, both to rendezvous with the target asteroid, as well as to return the asteroid material (processed or unprocessed) to the desired point of use. To address the transportation problem, most conceptual studies of asteroid mining assumed the use of reaction mass that, in one form or another, is obtained from the asteroid itself.

This situation changed significantly beginning with a 2010 NASA study [14]. This study recognized that near-term advances in high-power solar electric propulsion (SEP) could make it feasible to capture and return an entire small near-Earth asteroid (NEA), with a diameter of about 2 m and a mass of roughly 10,000 kg, to the International Space Station, without using reaction mass obtained from the asteroid itself. This approach promised to greatly reduce the cost and complexity of returning large amounts (10's to 100's of tons) of asteroid material to cislunar space. The 2010 NASA study was followed by a feasibility study conducted at the Keck Institute for Space Studies (KISS) which investigated two options for asteroid retrieval [15]. The first option considered the capture and return to cislunar space of an entire small near-Earth asteroid with a diameter of approximately 8 m and a mass of order 500,000 kg. The other option examined the feasibility of extracting a boulder several meters in diameter from the surface of a larger NEA and returning this boulder to cislunar space. A key feature of both options was to create a high-value target in cislunar space for a human mission beyond low Earth orbit for the first time since 1972. NASA considered the KISS concept sufficiently interesting that it sponsored follow-on studies to investigate the feasibility in more detail. These studies,

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which focused primarily on the concept to capture and return an entire ~8-m diameter asteroid, confirmed the feasibility of this mission concept [16-24]. In the course of subsequent formulation studies, NASA ultimately decided that picking a multi-meter diameter boulder off a larger NEA would develop a broader range of technologies extensible to future human exploration of Mars and its moons [25]. This mission concept became known as the Asteroid Redirect Robotic Mission (ARRM). In parallel with this selection, NASA established the Asteroid Redirect Mission (ARM) Program consisting of two missions, ARRM and a joint human/robotic mission called the Asteroid Redirect Crewed Mission (ARCM). ARRM would use a robotic spacecraft with a high-power SEP system to rendezvous with a near-Earth asteroid, land on the surface, extract a 2-6 m diameter boulder from the surface, and return that boulder to cislunar space. ARCM would have an astronaut crew in the Orion vehicle rendezvous with and dock to the ARRM vehicle, conduct two extra vehicular activities (EVAs) to obtain samples of the boulder, and return those samples to Earth.

Implementation of ARRM was led by the Jet Propulsion Laboratory (JPL) from 2014 through mid. 2017 with major participation by Glenn Research Center, Goddard Space Flight Center, Langley Research Center, Johnson Space Center, and Kennedy Space Center. The ARRM Pre-Phase A/Phase A study was conducted from June 2014 through July 2016. Following a successful Key Decision Point-B review ARRM entered Phase B in August 2016. Approximately mid-way through Phase B, the ARRM activity was terminated by NASA in April 2017. Even though the mission will not be implemented, its existence impacted a significant range of NASA's interests. While its long-term legacy remains uncertain, the short-term legacy of the Asteroid Redirect Mission is highlighted briefly below.

II.ARRM Impacts

The ARM Project impacted a number of NASA interests including high-power solar electric propulsion, human spacecflight, deep space robotic missions, in situ resource utilization, and planetary defense.

A. High-Power Solar Electric Propulsion Technology

One of the most important aspects of ARRM would have been the development and demonstration of a high-power solar electric propulsion system in deep space that would serve as a risk-reduction stepping-stone toward the development of mulit-hundred kilowatt systems needed to support human missions to Mars. Numerous Mars mission concept studies spanning decades have identified the need for very high-power SEP systems (100's of kilowatts or greater). However, the highest power electric propulsion (EP) system flown in deep space to date is the 2.5-kW ion propulsion system on NASA's Dawn spacecraft. Building a multi-hundred kilowatt SEP system based on the Dawn experience would likely expose such a project to unacceptably high risk. Flight implementation of an intermediate step up in power would significantly mitigate this risk. Demonstration by ARRM of an electric propulsion system at a power level of 40 kW would by sixteen times the state of the art for deep space EP systems. Implementation of a hypothetical 200 kW EP system, such as might be needed for human Mars missions, would then only be a more manageable factor of five increase relative to the ARRM system. Thus, a 40-kW electric propulsion system for ARRM appeared to be a reasonable stepping-stone forward to higher power systems.

Throughout all of the early feasibility and formulation studies of the asteroid retrieval concept conducted by NASA, one thing remained constant, the robotic mission concept would use a 40-kW, Hall-thruster based SEP system. The fine details of this system changed over time. For example, the output voltage range for the solar array was the subject of significant trade studies and debate. The maximum thruster input power, the maximum thruster specific impulse, and the details of the throttle table all changed over time. But, the basic architecture which used a small number of high-power, high-specific impulse, magnetically-shielded Hall thrusters, with a total electric propulsion system imput power of ~40 kW, remained constant. This was driven primarily by the assertion in the 2010 study [14] that a solar array with an output power of about 50 kW at 1 AU represented the best balance between implementation risk and pushing light-weight, deployable, solar array technology to higher power levels.

NASA's initial feasibility study in 2013 [22] considered launch readiness dates as early as 2017. Budget realities would result in the launch readiness date slipping approximately one year per year. At the time ARRM was terminated in 2017, the project was targeting a launch readiness date at the end of 2021. For launch dates in 2021 or later, a case could be made that 50 kW no longer represented the best stepping stone to multi-hundred kilowatt solar arrays projected to be needed to support human missions to Mars and that the ARRM spacecraft, or whatever replaces ARRM should target a higher power solar array.

To support a launch readiness date at the end of 2021, NASA initiated the development of the required Hall thrusters along with their power processing units (PPUs) and xenon flow control assemblies (XCAs). A competitive procurement activity managed by GRC selected Aerojet Rocketdyne for this development with significant risk reduction activities performed in parallel at GRC and JPL. The high-power Hall thruster for ARRM was given the name HERMeS (Hall Effect Rocket with Magnetic Shielding). Development of the thruster, PPU, and XCA are documented in numerous technical papers, see for example [26-63].

B. Human Spaceflight

Prior to ARRM, NASA intended to send astronauts to a near-Earth asteroid in the mid 2020s. In studying this concept it became clear to NASA that there were numerous difficulties that had the potential to significantly increase the cost of such a mission. These difficulties included lack of abort modes, vulnerability to solar flares, long flight times, and lack of resupply opportunities [64]. The ability to bring NEA's to cislunar space suggested that with respect to cost, complexity, risk, duration and resupply it may be better to bring these objects to the astronauts rather than to send astronauts to a NEA, at least initially [64]. Such a mission would likely be significantly easier and less expensive than a mission to a NEA in its native orbit, but would still draw astronauts away from low-Earth orbit for the first time in more than 50 years. It would have transit times measured in days not months, abort-to-Earth times also measured in days not months, and it would put astronauts in contact with only the second extraterrestrial object in history (the Moon being the first).

A key feature of such a mission would be the experience NASA would gain from working out the requirements and procedures for a human crew to interact with a robotic spacecraft in deep space. Such experience would be valuable for potential future human missions to Mars, which almost certainly will involve a mix of interacting human and robotic vehicles.

A significant part of ARRM's near-term legacy on human spaceflight is the expanded recognition and understanding by the human spaceflight community of the benefits that high-power solar electric propulsion can provide for human missions to the Martian system [71-81]. Prior to ARRM the benefits of high-power SEP for such missions was widely recognized within the electric propulsion community, but not as widely recognized outside of that community. ARRM and the mission studies that supported it and its extensibility to potential human missions to Mars changed this. A notable example of this is the so-called SEP/Chem hybrid architecture that combines the best features of high-power SEP with high-thrust chemical propulsion to reduce the overall flight times to those comparable to all-chemical propulsion architectures, while significantly reducing the initial mass in low-Earth orbit [74]. Significantly, this approach also reduces the overall mission risk, since the SEP/Chem hybrid vehicle could take all of the supplies and propellant necessary for the complete round-trip mission eliminating the need for a rendezvous with pre-positioned assets in Mars orbit in order to return to Earth.

Further impacts of ARM on low-thrust trajectory design are discussed in references [82-89].

C. Deep Space Robotic Missions

It has long been recognized that solar electric propulsion has the effect of making every launch vehicle better. That is, SEP can enable missions from smaller launch vehicles that would be impossible otherwise. Strange and Landau [83] have carried this concept to an extreme level, combining a 150-kW ARRM-derived robotic vehicle with a Block 1a Space Launch System (SLS). The resulting performance is impressive as an example of what might be possible. Such a system is projected to be capable of delivering 12,200 kg to orbit around Jupiter in a flight time of just 3 years; 8,500 kg to orbit around Saturn in 5 years; 4,400 kg to orbit around Uranus in 9 years; or 4,500 kg to orbit around Neptune in 13 years.

The version of ARRM selected by NASA for implementation would have required autonomous precision landing on an airless body, grasping a non-cooperative object, i.e., a 2-6 m boulder, extracting this boulder from the surface, securing it to the spacecraft, departing from the asteroid surface, and returning the multi-ton boulder to cislunar space. Successful execution of this concept would have significantly advanced NASA's capabilities for autonomous operations in close proximity to airless bodies as indicated by the body of work described in Refs [90-115].

D. Systems Engineering

ARRM also attempted to streamline the way flight projects are implemented at NASA. Two of the key features of this approach were the use of model based systems engineering [116-118], and the development of a capability driven system [119]. In the model-based systems engineering approach, the objective was to make the model be the one source of truth for the system that was accessible to all parties engaged in the flight system development regardless of their physical location. The capability-driven approach was intended to control costs by implementing a system whose performance largely driven the by capabilities of key subsystems.

E. Asteroid Mining

ARRM had a significant impact on multiple aspects of potential future asteroid mining activities, see for example [120-126]. Multiple asteroid retrieval studies by NASA from 2010 through 2014 confirmed the feasibility of a high-power SEP-based robotic vehicle to retrieve entire small asteroids with masses that are > 50X the mass of the SEP propellant. Return of hundreds of tons of asteroid mass to cislunar space enables asteroid mining equipment to stay relatively close to Earth. It also makes products derived from asteroidal materials available for relatively near-term space development in cislunar space [64]. While it is debatable what the most valuable near-term use of asteroid material will be, its use as radiation shielding to protect astronauts from galactic cosmic rays seems like a good candidate. Such an application would require lots of material, 100's to 1000's of tons, but would require little processing of this material.

Ultimately, asteroid mining will have to rely on asteroid-drived propellants to avoid the high cost of lifting propellants from Earth. Most concepts assume the use of water extracted from the asteroid as the source of this propellant for use either in solar thermal rockets or in LOX/H2 systems. ARRM's legacy with high-power, magnetically-shielded Hall thrusters suggests another possible approach. Asteroids are extremely poor sources of the inert gases typically used with Hall thrusters. However, asteroids are believed to have a significant amount of magnesium (~10 to 15%) and sulfur (~2 to 5%). Hall thrusters have been successfully operated on magnesium in the laboratory [126]. While no one has yet operated a Hall thruster on sulfur, it has a lower melting temperature than magnesium and a significantly lower temperature for the same vapor pressure. These features suggest that Hall thruster operation on sulfur may be easier than on magnesium. The low atomic mass of sulfur would enable high Isp operation in direct-drive systems with moderate solar array voltages [125].

F. Planetary Defense

Prior to ARRM, SEP was recognized as enabling or enhancing for most planetary defense techniques including kinetic impactors and gravity tractors [127]. A variation on the gravity tractor [128] is the so-called "enhanced" gravity tractor (EGT) in which the gravitational coupling between the asteroid and the spacecraft is enhanced by the spacecraft acquiring mass from the asteroid prior to the initiation of tractoring [129-130]. The resulting higher coupling force in an enhanced gravity tractor system requires high-power SEP in order to provide the necessary thrust levels. ARRM, with its 40-kW SEP system would have been the first demonstration of a gravity tractor, and specifically would demonstrated the EGT technique on a 100-m class NEA.

During the ARRM development, however, it was recognized that a planetary defense technique sometimes referred to as ion beam deflection (IBD) would benefit significantly from the development of high-power SEP systems. This technique is under appreciated by the planetary defense community. Ion beam deflection works by directing a beam of high-energy ions into the surface of the threat object and transferring the momentum of the ions to the object through inelastic collisions [131-136]. This is conceptually similar to a kinetic impactor with the impinging ions taking the place of the impacting spacecraft, but with two important differences. First, an ion beam deflection system can be designed so that the ions impact the asteroid surface at speeds much greater than is practical for kinetic impactors. Second, the ions can impact in the direction most effective for deflection. Ion impact speeds of 70 km/s are readily achievable, which would be roughly four to five times the impact speed of a kinetic impactor spacecraft. The finite power levels for the IBD vehicle means the transfer of momentum is necessarily spread out over time, typically over a timescale of months to years.

NASA is mandated by Congress to discover and track all NEOs greater than 140 meters in diameter. At the completion of this survey, if nothing is found on a collision course with Earth, then the impact risk will be dominated by Tunguska-scale objects, i.e., objects that are tens of meters in diameter [137]. IBD is particularly well suited to the deflection of objects in the size range of 50 m to 100 m diameter. A high-power IBD vehicle (of order 100 kW) could likely deflect such objects in matter of months. For example, if asteroid hypothetical asteroid 2017 PDC (used in the 2017 Planetary Defense Conference exercise) was 100 m diameter with a density of 2 g/cm³, it would take only two months of IBD operations for a 160-kW IBD vehicle to deflect it by one Earth radius, assuming that deflection operations began 3.6 years before impact [136].

III. Conclusion

NASA's ARM program, which consisted of a robotic mission (ARRM) and a crewed mission (ARCM) would have impacted a wide variety of NASA's interests including: the demonstration of high-power solar electric propulsion at 16x the power level of the current state-of-the art for deep space electric propulsion systems; demonstration of precision landing on an airless body; demonstration of the ability to grasp, extract, and control a large non-cooperative object on the surface of an asteroid; demonstration of a planetary defense technique known as an enhanced gravity tractor; demonstration of the ability to transport a multi-ton payload through deep space; demonstration of joint operations with crewed and robotic vehicles in deep space; the return to Earth of large quantities of C-type asteroid material; human exploration beyond low-Earth orbit for the first time in more than 50 years; and human exploration of only the second extraterrestrial body in history.

Work related to ARM created a near-term legacy that includes: appreciation by the human spaceflight community of the benefits of high-power solar electric propulsion for human missions beyond low-Earth orbit; development of the SEP/Chem hybrid approach for human missions concepts to Mars that provide the mass savings of EP missions with trip times comparable to all chemical propulsion missions; verification by multiple in depth studies of the feasibility of capturing and returning to cislunar space entire small near Earth asteroids; and emerging recognition by the planetary defense community of the potential benefits of high-power SEP for ion beam deflection of potentially hazardous asteroids in the size range of 50 to 100 m diameter.

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