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

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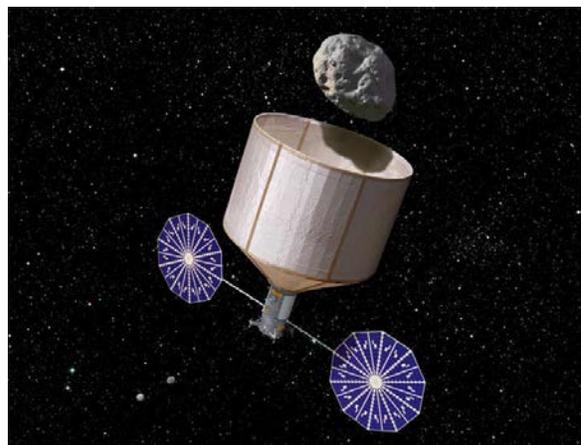
### Abstract

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 points beyond 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 exploration are 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

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 details such 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 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 kW<sub>sol</sub>/m<sup>2</sup>. 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 its 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 handling 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, grapple, 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 2 was developed in the earlier study.

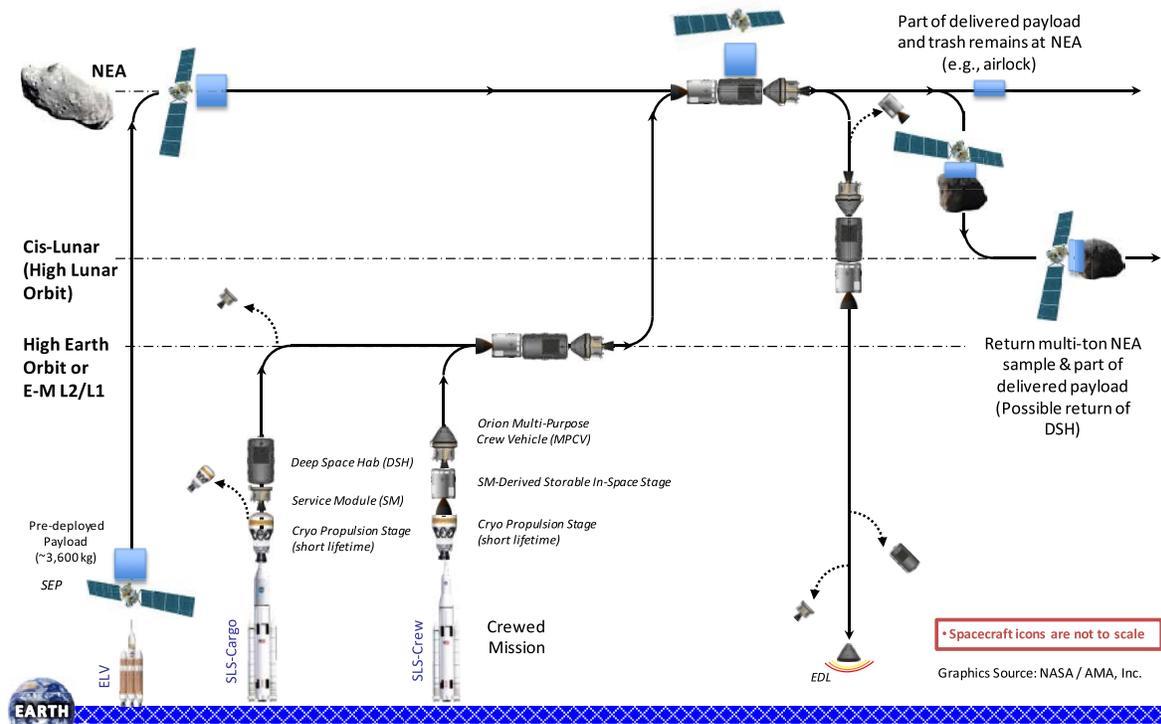


Fig. 2: Human Mission Operation Concept

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