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MULTIPLE NEO RENDEZVOUS USING SOLAR SAIL PROPULSION

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ABSTRACT

The NASA Marshall Space Flight Center (MSFC) Advanced Concepts Office performed an assessment of the feasibility of using a near-term solar sail propulsion system to enable a single spacecraft to perform serial rendezvous operations at multiple Near Earth Objects (NEOs) within six years of launch on a small-to-moderate launch vehicle. The study baselined the use of the sail technology demonstrated in the mid-2000's by the NASA In-Space Propulsion Technology Project and is scheduled to be demonstrated in space by 2014 as part of the NASA Technology Demonstration Mission Program. The study ground rules required that the solar sail be the only new technology on the flight; all other spacecraft systems and instruments must have had previous space test and qualification.

The resulting mission concept uses an 80-m X 80-m 3-axis stabilized solar sail launched by an Athena-II rocket in 2017 to rendezvous with 1999 AO10, Apophis and 2001 QJ142. In each rendezvous, the spacecraft will perform proximity operations for approximately 30 days.

The spacecraft science payload is simple and lightweight; it will consist of only the multispectral imager flown on the Near Earth Asteroid Rendezvous (NEAR) mission to 433 Eros and 253 Mathilde. Most non-sail spacecraft systems are based on the Messenger mission spacecraft.

This paper will describe the objectives of the proposed mission, the solar sail technology to be employed, the spacecraft system and subsystems, as well as the overall mission profile.

1. INTRODUCTION

NASA may send humans to a NEO sometime in the early part of the next decade. Before committing a crew to visit any particular NEO, an assessment of the object must be performed robotically so the crew systems appropriate for the NEO's unique environment can be developed for minimal risk to the crew and to the mission. For example, the surface systems and operations plans for a loosely gravitationally-bound "rubble pile" asteroid will vary considerably from those required to support operations on or near an asteroid composed of a single large piece of rock. Clearly, some sort of pre-human reconnaissance is required; hence the need for a robotic precursor exploration of multiple potential targets.

Various propulsion system options have been considered for this class of precursor mission, and none can match the ability of a solar sail to visit multiple targets sequentially; chemical and solar electric power (SEP) systems simply run out of fuel.

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, reflective material. The continuous photonic pressure provides propellantless thrust to hover indefinitely at points in space or to conduct orbital maneuvering and plane changes more efficiently than conventional chemical propulsion. Because the Sun supplies the necessary propulsive energy, solar sails require no onboard propellant, thus reducing payload mass.[1]

The NASA MSFC Advanced Concepts Office examined the feasibility of performing such a solar sail reconnaissance mission at low cost using a small launch vehicle.

2. MISSION IMPLEMENTATION SUMMARY

The mission concept described herein assumes an 80-m X 80-m 3-axis stabilized solar sail spacecraft launched by a small rocket (such as an Athena-II) to rendezvous with asteroids 1999 AO10, Apophis, and 2001 QJ142 – all of which are on the most recent listing of "Human Accessible NEAs." These were selected as candidates to enable a point system design to be formulated. In each rendezvous, the spacecraft would perform proximity operations for approximately 30 days. The notional spacecraft science payload was selected to be simple and lightweight, consisting of only the multispectral imager flown on the NEAR mission to 433 Eros and 253 Mathilde. Most non-sail spacecraft systems baselined were used in the Messenger and other flight-proven mission spacecraft.

2.1 Science Payload: The Near Earth Asteroid Rendezvous (NEAR) Multispectral Imager

The NEAR camera was selected as the notional mission payload based of its capabilities, which have been previously demonstrated with the NEAR mission's encounter and high-resolution imaging of two asteroids in the late 1990's.[2] The NEAR camera technical specifications are described in Table 1.

Table 1: NEAR Multispectral Imaging System.

Objective	Comment
Mass	Camera head 5 kg; Electronics 4.5 kg
Power	Camera head 2 W; Electronics ~11W
Field of View	2.25° X 2.9°, in 244 X 537 pixels = 3.9 X 5.1 km from 100-km distance
Resolution	9.5 X 16.1 m from 100-km distance
Wavelength Range	400-1100 nm

2.2 Solar Sail Propulsion System

In the early 2000's, NASA funded the development of two prototype solar sail systems for ground testing to validate design concepts for sail manufacturing, packaging, launch to space, deployment, attitude control subsystem function, and to characterize the structural mechanics and dynamics of the deployed sail in a simulated space environment.

Each team developed a square sail configuration consisting of a reflective sail membrane, a deployable sail support structure, an attitude control subsystem, and all hardware needed to stow the sail for launch were developed. In addition, each sail team was tasked to document a 100 x 100 meter square sail point design and demonstrate scalability and cost metrics for even larger (150 x 150 meters) sails.

ATK Space Systems' approach utilized their rigid coilable boom, sliding masses along the booms for an attitude control system (ACS) subsystem and a CP1 sail membrane. L'Garde, Inc. developed a sail incorporating their inflatable and sub-Tg rigidizable boom, a control vane based ACS, and Mylar for the sail membrane.[3]

In 2011, as a follow-on to the ground test program, NASA selected L'Garde, Inc. to develop Sunjammer, a 1200m^2 sail for demonstration in deep space as early as 2014. At the time this project might begin, the Sunjammer will have been space-validated, reducing the risk of mission infusion and satisfying an agency goal of transitioning NASA-demonstrated technology to planned human exploration mission implementation.

Outside of NASA, solar sailing has been tested in space. In the summer of 2010, the Japanese Aerospace Exploration Agency (JAXA) launched a solar sail spacecraft named IKAROS into deep space. The IKAROS (14 m by 14 m) is the first in-space demonstration of solar sailing.[4]

For this study, a 3-axis stabilized square solar sail based on the design developed by Able Engineering Company's (now ATK Space Systems). The ATK team design utilized their "CoilABLE" mast technology, with its high packing factor and high strength to weight ratio for their primary structural mast elements. The sails were fabricated by SRS Technologies (now Nexolve.) from 2.5 micron aluminum coated CP1, with a 3-point (mast tips and central structural) attachment configuration. The sails were tensioned to provide a nearly flat sail topography and included a negator spring system to insure constant tension in the sails during all operational modes. Attitude control was provided by two translating ballast masses internal to the mast and mast tip rotating spreader bars. The ballast masses can translate the entire length of the masts to offset the system center of mass from the center of pressure and provide pitch and yaw attitude control. The mast tip spreader bars can be rotated to provide a "pinwheel" effect roll control for the sail. Micro-pulsed plasma thrusters were also specified for secondary/ backup attitude control.

Based on the scale-up of 20 meter Ground System Demonstration, Table 2 summarizes the values that were assumed for the 10,000 m^2 sail point design.

Table 2: Values assumed for sail point design.

Summary of 10,000 m^2 sail design	
Operating Temperature	25°C at 1.0 au
First Natural Frequency	0.03 Hz
Stowed Package	1.9 m dia. by 0.54 m
Control Systems	Runners & Spreader Bars
System Mass	113 kg
Characteristic acceleration:	0.73 mm/s^2
with 130 kg SC:	0.35 mm/s^2

In flight, deployment operations would begin with deployment of the masts (refer to the right side of Figure 1). The stowed strain energy of the coiled longerons powers the deployment, controlled by paying out the lanyards. The action of unfolding the masts occurs at a rate of 2.5 cm/sec. Once the mast has fully deployed, it is ready to support the raising of the sails. At the end of mast deployment, the snap action of a longeron tip completing the last few degrees of rotation will have released the bridle block that joins the lanyard to the two halyards that run back down the mast to the quadrant corners of the still stowed sails. In the launch configuration the halyards are wrapped around the longeron so that during mast deployment they unwind and form a slack line from the mast tip to the stowed sail quadrants.

When the mast assessment is complete, the second stage of system deployment, raising the sails, is initiated. The motor is commanded to turn (now in reverse), and the lanyards are reeled in, which pulls the sails up as the halyards run over the pulleys and down the mast. All quadrants would follow this process simultaneously as they share the halyard drive mechanism housed in the stowage structure. Raising the sails will progress at a slow controlled pace, averaging less than 1 cm/sec. Figure 1 shows the fully deployed 20-m solar sail at Plum Brook Station.

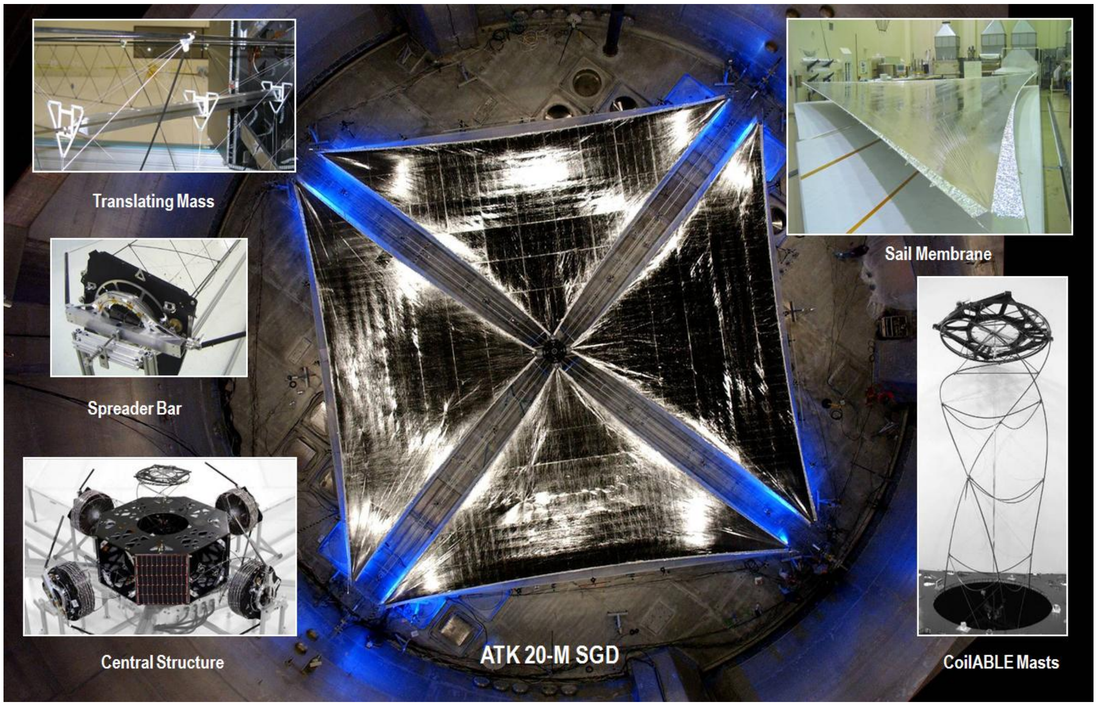

Fig. 1: Technology Area Breakdown Structure for In-Space Propulsion Technologies.

2.3 Mission Trajectory

The trajectories developed for this study were developed with a tool called Solar Sail Spacecraft Simulation Software (S5). The S5 software incorporates high fidelity solar radiation pressure models, planetary ephemeris, and an optimization suite to facilitate detailed trajectory and guidance navigation and control design for a solar sail spacecraft.

The mission design goal was to seek out a set of optimal trajectories such that three consecutive NEO rendezvous could be achieved in less than six years. The set of viable NEOs were selected from a NASA human exploration study that ranked NEO targets in terms of feasibility and scientific interest.

The trajectory design assumed a departure from the Earth-Moon system on January 1, 2018 with a C3 curve (which identifies payload as a function of characteristic energy) of zero. The rational for using a C3 of zero was to best demonstrate the solar sail propulsion system capability without using a launch vehicle as a crutch for the trajectory design. Initially, a small subset of NEOs was selected and minimum time optimal trajectories were generated using S5. The results are presented in Figure 2.

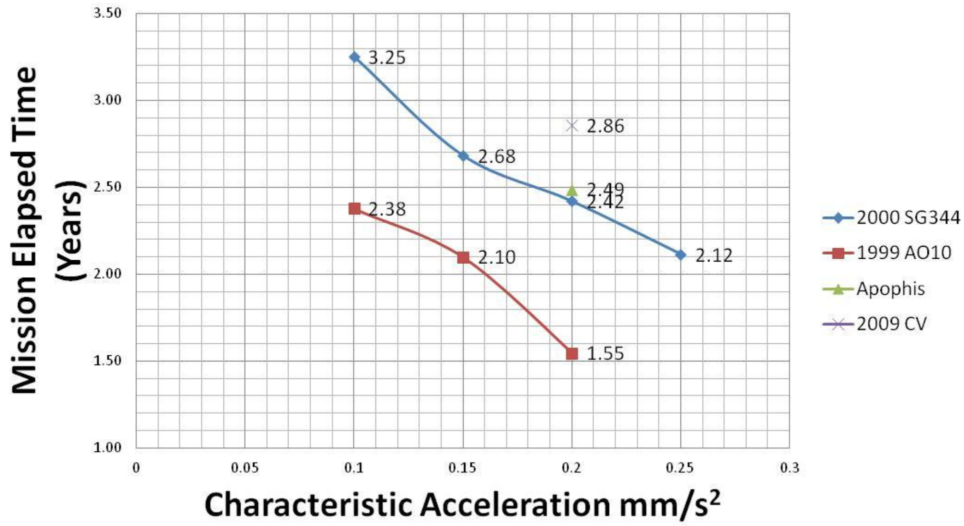

Fig. 2: Sail Performance vs. NEO.

The time of flight is a strong function of relative orbit phase angle and orbit plane wedge angle between the solar sail spacecraft's starting orbit and the target NEO's orbit. A simple NEO selection process was then put in place to speed up the NEO tour options. The three selections are detailed in Figures 3 through 5.

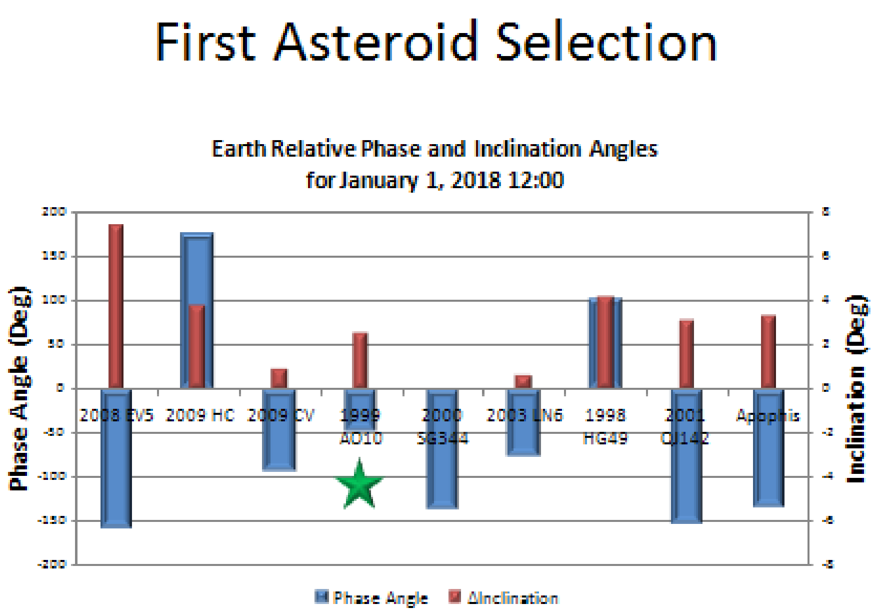

Fig. 3: First NEO Selection.

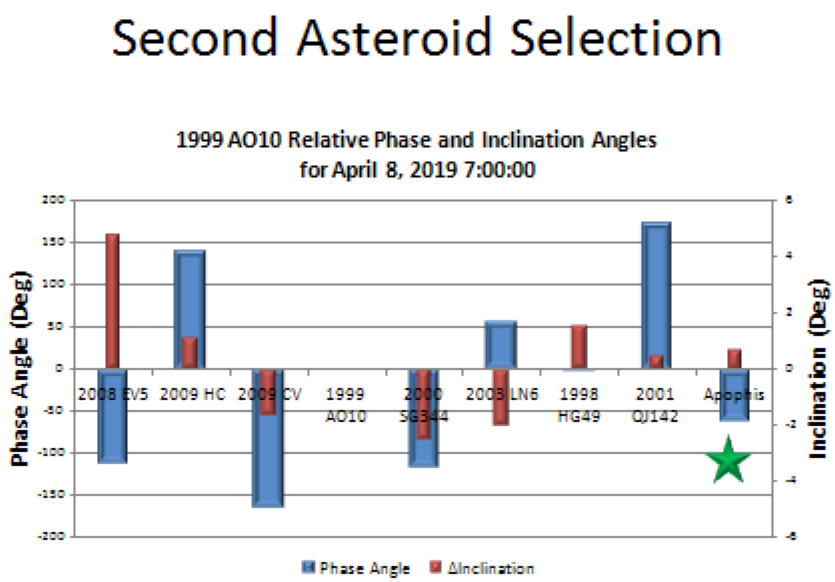

Fig. 4: Second NEO Selection.

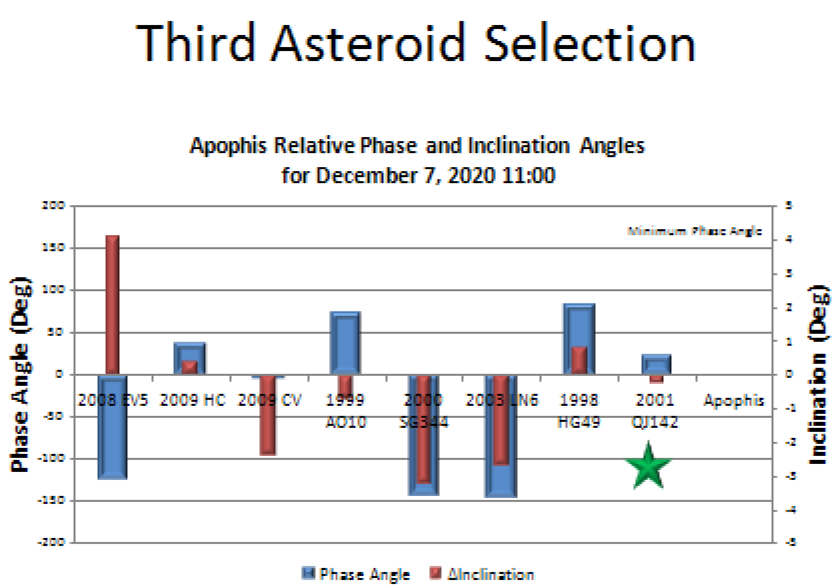

Fig. 5: Third NEO Selection.

Using the simple selection criterion, the selected NEO tour resulted in a 6 year mission. The sequence of NEOs for rendezvous was 1999 AO10, Apophis, then 2001 QJ142. The resulting mission timeline is detailed in Table 3. The convergence criteria for all mission designs were 100 km in position and 0.1 km/sec in velocity.

Table 3: NEO Tour Timeline.

Event	**Time**
Transfer to 1999 AO10	1.54 years
Science	35. days
Transfer to Apophis	2.50 years
Science	30. days
Transfer to 2001 QJ142	1.70 years
Science	30. days

2.4 Spacecraft Configuration

To minimize mass, the spacecraft was partitioned into two stages. The central stage is designed to house the sails, payload etc. The secondary stage, which is designated as the jettison bus, is designed to house any structures or components that are used to perform temporary functions during launch and the early phases of the mission. Figure 6 depicts an expanded view of the spacecraft and jettison bus.

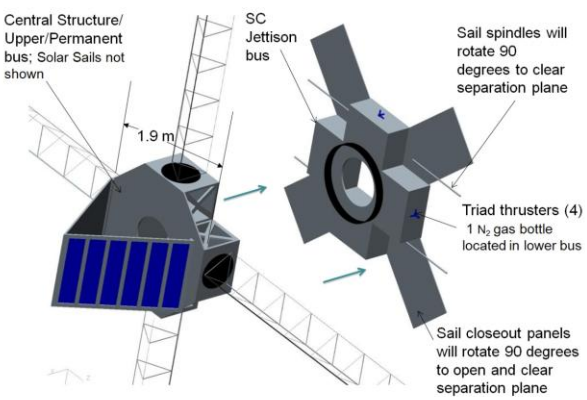

Fig. 6: The jettison bus is discarded after use to reduce the overall spacecraft system mass.

To maintain heritage, the spacecraft has an octagonal outer mold line that is approximately 2-m wide by almost 1-m high. The spacecraft consists of a triangular solar panel subassembly mounted to the spacecraft forward face. Cold gas thrusters positioned on the jettison bus are used to de-spin the spacecraft after launch vehicle separation. A light-band, mounted to the aft face and forward face of the central structure and jettison bus respectively, is utilized for separation. A total of 4 spools and 4 close-out panels attached to the jettison bus are used to stow the solar-sails (not pictured) prior to sail deployment. The close-out panels and spools are designed to rotate 90° to mitigate interface impact during separation. Figure 6 shows the main spacecraft with deployed 60-m coilable booms. The NEAR camera (not pictured) is located in the main spacecraft payload compartment integrally mounted to the outer surface, facing the jettison bus. The payload compartment is the interior of the main spacecraft along the longitudinal axis providing sufficient structural surface area for mounting hardware that must remain with the main spacecraft.

2.5 Spacecraft Structures

The spacecraft bus will be aluminum where required for passive heat rejection, primarily on panels facing deep space. But most of the structure will be Carbon-Carbon (C-C) composite to minimize weight. Spacecraft system components, the NEAR camera payload, the sail system mass and appropriately distributed or non-structural mass for thermal control, lines, and cables were added to the structural model. Twenty percent of the total non-structural mass, including sail system and payload, was the conservative estimate of the primary structural mass. An additional 25% of the primary structural mass was also added for secondary structure.

The mass estimate for primary structure was based on a combination of a historical aluminum spacecraft structural mass fraction of 25-30% and C-C composite bus structural mass fraction range as low as 7-10% of total spacecraft mass. For example, the NEAR spacecraft, which was largely composite and carried the same camera payload, had a 12.7% structural mass fraction. Similarly, the Messenger spacecraft structure that was mostly C-C with Ti, steel, Al joints, and fasteners had a structural mass fraction of ~10% for a spacecraft that included >60% wet mass for propulsion. The sail system mass of the proposed sailcraft is only 30% of the total mass, but when deployed, it will require a strong, stiff central bus to support the four masts and the large sail acreage in the solar wind.

ATK provided a factor that gave an effective sail area from a known sail side length. Knowing the sail side length and the mass of the sailcraft allowed the calculation of characteristic acceleration.

The spacecraft must fit within a 92” diameter shroud envelope and withstand launch loads on the Taurus 3113 or Athena II launch platforms. A fixed solar array and sun sensor suite are mounted on the sun side of the central structure. When launched, the spacecraft will include 110 kg additional mass over the deployed sailcraft mass. The spacecraft central structure will have two parts. A portion of the bus providing cold nitrogen gas propulsion necessary to stabilize the spacecraft prior to and during sail deployment and part of the sail storage structure will be jettisoned after sail deployment to minimize the mass of the sailcraft. The camera payload and two star trackers, exposed after the departure of the jettison bus, are mounted on the deep space side of the sailcraft. Four sail spindles or drums and compartment closures will be connected to the jettison bus and will rotate away from the separation plane prior to bus separation via a 23” lightband separation system. The jettison bus will utilize the remaining cold gas to steer away from the sailcraft after bus separation.

2.6 Spacecraft Power

Figure 7 shows the placement of the solar panels with respect to the sail and the spacecraft bus. There are two identical panels at right angles to each other, each 45° from the center-line of the spacecraft. This arrangement assures that the sun will always be incident on at least one of the panels at an incidence angle of 45° or less. The solar array panels are sized based on this configuration. The other components of the power system are taken directly from the Messenger spacecraft.[5]

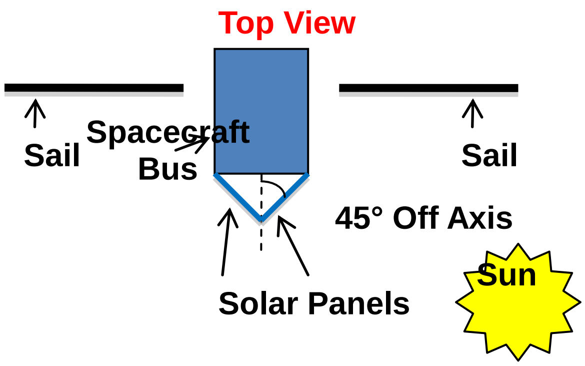

Fig. 7: The solar panels are attached to the front top of the spacecraft to avoid sail shadowing.

3. CONCLUSION

Solar Sail propulsion has been successfully demonstrated in space by JAXA. NASA, the European Space Agency, and others are developing large solar sail demonstration missions that will complete the transition of this important technology to the point where it can be infused into future science and exploration missions with minimal risk.

Sails of the size needed for a multiple NEO rendezvous mission are viable within the next 3-5 years and can provide significant benefit to the exploration of NEOs by reducing mission costs and enabling a single spacecraft to visit multiple NEOs within six years of launch.

REFERENCES

[1] McInnes, C.R., *Solar Sailing: Orbital Mechanics and Mission Applications*, Advanced is Space Research, Volume 31, Issue 8, April 2003, Pages 1971-1980.

[2] Cheng, A.F., *Near Earth Asteroid Rendezvous: Mission Overview*, Space Science Reviews, Volume 82, Issue 1, October 1997, Pages 3-29.

[3] Johnson, L., Young, Roy M., and Montgomery, Edward E., *Recent Advances in Solar Sail Propulsion Systems at NASA*, Acta Astronautica, Vol. 61 (2007), 376-382.

[4] Tsuda, Y., Mori, O., Funase, R., Sawada, H., Yamamoto, T., Saiki, T., Endo, T., and Kawaguchi, J., *Flight Status of IKAROS Deep Space Solar Sail Demonstrator*, Acta Astronautica, Volume 69, Issues 9-10, November-December, 2011, Pages 833-840.

[5] Santo, A. G., et al, *The Messenger Mission to Mercury: Spacecraft and Mission Design*, Planetary and Space Science, Volume 49, Issues 14-15, December 2001, Pages 1481-1500.