New Moon Explorer Mission Concept

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Abstract

New Moon Explorer (NME) is a smallsat reconnaissance mission concept to explore Earth's 'New Moon', the recently discovered Earth orbital companion asteroid 469219 Kamoʻoalewa (formerly 2016HO3), using solar sail propulsion. NME would determine Kamoʻoalewa's spin rate, pole position, shape, structure, mass, density, chemical composition, temperature, thermal inertia, regolith characteristics, and spectral type using onboard instrumentation. If flown, NME would demonstrate multiple enabling technologies, including solar sail propulsion, large-area thin film power generation, and small spacecraft technology tailored for interplanetary space missions. Leveraging the solar sail technology and mission expertise developed by NASA for the Near Earth Asteroid (NEA) Scout mission, affordably learning more about our newest near neighbor is now a possibility. The mission is not yet planned for flight.

Keywords: Kamoʻoalewa, solar sail, moon, Apollo asteroid

1. Introduction

The emerging capabilities of extremely small spacecraft, coupled with solar sail propulsion, offers an opportunity for low-cost reconnaissance of the recently-discovered asteroid 469219 Kamoʻoalewa (formerly 2016HO3). While Kamoʻoalewa is not strictly a new moon, it is, for all practical purposes, an orbital companion of the Earth as the planet circles the sun. Kamoʻoalewa's orbit relative to the Earth can be seen in Figure 1.

Using the technologies developed for the NASA Near Earth Asteroid (NEA) Scout mission, a 6U CubeSat mission propelled by a solar sail that is set to launch in 2020 [1], a similarly low-cost reconnaissance of Kamoʻoalewa is possible in the near-term. Herein we describe a12U scale small spacecraft mission to characterize Kamoʻoalewa which we call, New Moon Explorer (NME).

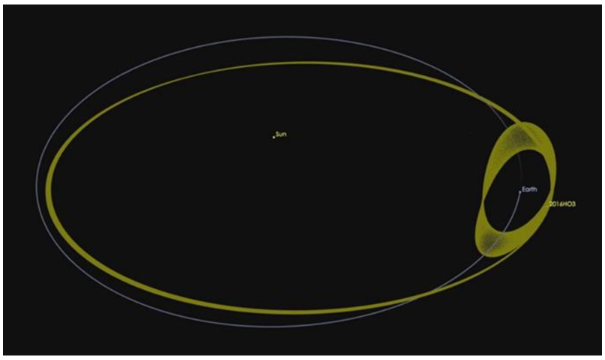

Fig. 1 The orbit of Earth's companion, Kamoʻoalewa as both it and the Earth orbit the Sun.

2. Mission Concept

NME will carry scientific instruments to determine the spin rate, pole position, shape, structure, mass, density, chemical composition, temperature, thermal inertia, regolith characteristics, and spectral type of Kamoʻoalewa. By tracking Kamoʻoalewa's orbital changes and correlating them to its physical characteristics, NME will measure the effects of non-gravitational forces (Yarkovsky-O'Keefe-Radzievskii-Paddack and Yarkovsky) to refine estimates of potential

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perturbations induced in the orbits of 50 – 100 meter class asteroids [2]. This size range is the most numerous class of potentially destructive asteroid impactors and their orbits are the most affected by non-gravitational forces. Measuring Kamoʻoalewa's physical characteristics and refining its orbit will contribute to evaluation of this asteroid as a potential target for a future human exploration mission.

By replacing the NEA Scout metallic Triangular Rollable and Collapsible (TRAC) booms with state-of-the-art by ultra-lightweight composite booms and increasing the sail size to 200 m^2, NME will evolve the capability of solar sail propulsion. The mission, if developed, would need to be launched by rocket to an earth-escape trajectory (for shortest flight time to the target).

3. Science

3.1. Measurements

Spin rate, pole position, shape, structure (monolith vs. rubble pile), and regolith characteristics of Kamoʻoalewa will be determined by taking a series of moderate resolution visible images. Images in bands across the 1 – 100 micrometer region will be used to map the chemical composition, temperature, thermal inertia, and regolith characteristics of Kamoʻoalewa in addition to determining its spectral type. Long-term proximity of the spacecraft to the asteroid will allow calculation of the mass by balancing the gravitational attraction of Kamoʻoalewa against the force generated by the solar sail.

3.2. Kamoʻoalewa

With a distance from Earth that varies between 38–100 times that to the moon, and a thermal environment very similar to that experienced by an earth orbiting satellite, Kamoʻoalewa is a perfect target for NME. Communication with NME is relatively simple, enabling consistent communication during long-term science data acquisition. In addition, ground-based observing can complement spacecraft measurements to obtain high precision estimates of its long-term orbital evolution. Kamoʻoalewa is fairly small, 40–100 m in diameter, and is therefore in the range of a typical earth-impact asteroid threat. It is a low-mass object that is very susceptible to the YORP and Yarkovsky effects, yet it is still large enough, with well-defined orbital elements, to be a viable mission target.

3.3. Spacecraft Payload

To obtain the measurements proposed will require a visible imager and an infrared camera in addition to the measurements that can be made by tracking the motion of the spacecraft itself. The NEA Scout mission is outfitted with a visible imager inherited from Enhanced Engineering Cameras (EECAM) on the Mars 2020 rover and the Orbiting Carbon Observatory, OCO-3, programs (Figure 2) that was supplied by the Jet Propulsion Laboratory (JPL). NME can use this same system with the addition of a filter wheel assembly to allow measurement of the color variations across the asteroid's surface. Color images are not required for basic measurements that determine spin rate, pole position, shape, structure, and regolith characteristics.

Fig. 2 The JPL OCO-3 camera that will fly on the NEA Scout mission may be upgraded by adding a filter wheel to enhance science return for NME.

An infrared camera that leverages a micro-bolometer detector sensitive from 1 to 100 micrometers is also baselined. The detector flew on board Near Infrared Spectral Tomography (NIRST), one of the eight instruments on the Satellite for Scientific Applications D (SAC-D)/Aquarius earth-observing mission [3]. The camera is a modified, commercial, off the shelf (COTS) mid-wave infrared (MWIR) imaging radiometer with "stripe" band-pass filters mounted directly onto the focal plane array (FPA). The FPA and the band-pass filters are at TRL >6 and leverage development efforts from other flight instruments.

Using ground-based observations from one or more large telescopes, such as the Hawaiian Keck telescope to determine the spectral type of Kamoʻoalewa prior to the final design of the instrument payload is an option to be considered. If such information were available, the filter wheel assembly on the visible imager could be de-scoped and the infrared filter set optimized to match the expected composition of the target.

4. Spacecraft Concept

The NME spacecraft is designed to be a 12U CubeSat form factor and is derived from heritage systems developed for the NEA Scout and Lunar Ice Cube missions. [4] The spacecraft bus and its systems are designed to operate beyond LEO in deep space. All of the spacecraft subsystems will have flight heritage from prior to launch. An onboard context camera will provide an image of the deployed NME solar sail. The overall spacecraft configuration is shown in Figure 3 and key subsystems briefly described below.

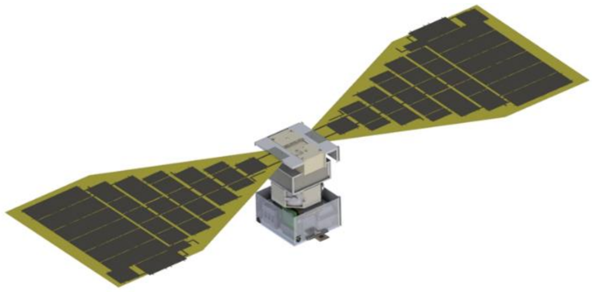

Fig. 3 The NME spacecraft concept with solar panels deployed. The solar sail propulsion system is not shown.

4.1. Electrical Power and Communications

Power and communications will be provided by the Lightweight Integrated Solar Array and anTenna (LISA-T). LISA-T is a low-volume, low-mass, flexible deployable on which both power generation and communication are embedded. [5] LISA-T stows compactly for launch and deploys into a large surface are on orbit. The technology has reached TRL-6 and is currently progressing toward a LEO flight demonstration in the early 2020's.

LISA-T significantly reduces both mass and stowed volume when compared to other solar array options. The LISA-T power panels can be packaged as high as $462kW/m^3$ stowage efficiency and 379W/kg specific power. The embedded LISA-T antennas can be stowed at thicknesses as low as 0.7mm to provide transmit / receive communications at up to 12dBi each. The LISA-T will use high efficiency inverted metamorphic multi-junction (IMM) solar cell as well as an array of x-band helical antennas, resulting in a significant reduction in overall mass and solar array and antenna stowage volume. The array is coupled with a gimbal which will provide 180° articulation in 1-axis. This will allow both the solar array panels and antennas to be pointed at their respective targets without slewing and changing the thrust axis of the solar sail, a feature lacking on NEA Scout.

The mission will require the use of a quasi-directive antenna coupled with a robust interplanetary smallsat transponder. Initial trajectory models show that a favorable alignment of the Earth, spacecraft, and Kamo'oalewa during the science mission phase eliminates the need for a steerable antenna through careful placement of the antenna structure on the spacecraft. In addition, the use of LISA-T allows the antenna to be pointed with the existing gimbal. The JPL Iris transponder [6], with established flight heritage on several missions, including Mars Cube One (MarCO), NEA Scout, and Lunar IceCube, will provide sufficient gain and data rates at a distance of 0.25 AU using the DSN 34 m ground stations and the Morehead State University 21 m DSN affiliate station. These data rates will meet the requirement of getting the required volume of science data generated to the ground in a timely manner.

4.2. Thermal Design

Thermal management is a significant challenge for interplanetary smallsat missions. The lack of sufficient radiant surface areas on the small spacecraft, combined with very different thermal environments experienced during deployment and deep space, creates a design challenge. Experiences from the NEA Scout and Lunar IceCube missions will be leveraged to design an effective thermal management system that will employ deployable thermal radiators, heat pipes, optically reflective surfaces, and strategically placed resistive heaters.

4.3. Radiation Environment

The anticipated radiation environment will be dominated by galactic cosmic rays with the long term effects of high total ionizing dose, displacement damage, and transient single particle effects. Single event effects will be caused by these energetic particles (heavy ions and protons) as they pass through a semiconductor material. Given the mission duration, cumulative ionizing damage due to solar wind and trapped protons and electrons are also expected. Radiation requirements will be met through targeted shielding, the use of radiation hardened electronics, and implementation of flight software fault detection and recovery techniques.

4.4. Momentum Management

Actively managing the sail's momentum will be accomplished by an Active Mass Translator (AMT) leveraging heritage from the NEA Scout mission. The AMT's planar movement permits changing the positioning of the spacecraft Center of Mass (CM) relative to the Center of Pressure (CP) [7]. The attitude control system (ACS) uses the AMT to modify the large solar disturbance torque of the deployed sail in order to provide momentum management for the reaction wheels. This capability to adjust the AMT greatly reduces, but does not eliminate, reliance on propellant because it can only manage two of the three axes. Alternative concepts currently being developed by MSFC, such as variable reflectance control devices [9], will be evaluated to further reduce or eliminate the dependency on propellant and increase the overall momentum management capability of the spacecraft.

4.5. Solar Sail Propulsion System

The solar sail area will be 200 m^2 in a quadrant configuration. Using the same 2.5 micron CP-1 fabric used on both NanoSail-D and NEA Scout, the design leverages advancement in solar sail propulsion technology from NEA Scout (TRL-7) and hard-won lessons learned regarding its development. An artist concept of the NME imaging Kamo‘oalewa is shown in Figure 4. NME has some key differences from NEA Scout, notably use of composite booms and a quadrant sail configuration compared to NEA Scout’s metallic booms and single-sail membrane configuration. NME’s solar sail was sized using in-house analysis tools developed by Roccor. The Roccor Solar Sail Tool, or SST, is a closed form analysis tool capable of comparing performance outputs of TRAC and slit-tube boom architectures with a variety of solar sail system and mission requirements. Nonlinear buckling analysis results are developed to supplement the closed form solutions for critical structural performance parameters of TRAC and slit-tube architectures. These nonlinear results are inputted to the SST and compared against system parameters and mission requirements, such as sail tension, deployed frequency, stowage volume, and spacecraft maneuvers.

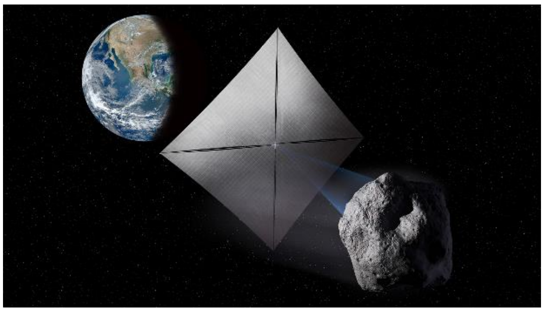

Fig. 4 Artist concept of NME imaging Kamo‘oalewa during flyby.

5. Concept of Operations

After deployment from the launch vehicle, NME will complete a small propulsive Trajectory Correction Maneuver (TCM) with a cold gas Reaction Control System (RCS) to begin targeting Kamo‘oalewa prior to sail deployment. The sail will be deployed approximately 7 days into the mission and used to help target a series of Lunar Gravity Assists (LGAs) over a period of 1-2 months to build up an escape energy of as much as 2 km^2/s^2 for the transfer from the Earth-Moon system to Kamo‘oalewa.

After escaping from the Earth-Moon system, two Earth Gravity Assists (EGAs) are used to reduce the overall time of flight. The first EGA flyby occurs six months after Earth escape and the second EGA flyby occurs a year after that. The final phase of the interplanetary transfer is done entirely with the sail and takes an additional 480 days. The total time of flight for the Design Reference Mission (DRM) is 1082 days.

This timeline leverages both an increased solar sail area and lower relative mass from NEA Scout to achieve a significant increase in characteristic acceleration, defined as the acceleration achieved at 1 AU and zero sun incidence angle. The mission trajectory appears in Figure 5.

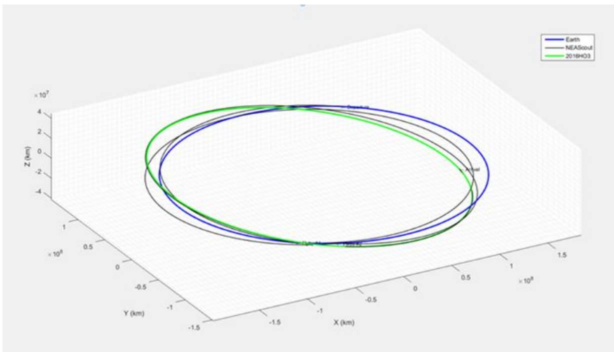

Fig. 5 The NME spacecraft trajectory is shown in a sun-centered coordinate system.

6. Conclusions

With the completion of the NEA Scout spacecraft and it’s soon flight, solar sail propulsion is now a viable option for small, interplanetary spacecraft. The discovery of Kamo‘oalewa provides an opportunity to use this low-mass and relatively inexpensive capability to characterize Earth’s newly discovered neighbor and increase our understanding of near-Earth space.

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