New Moon Explorer Robotic Precursor Mission Concept

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A low-cost reconnaissance mission concept has been devised of Earth's 'New Moon', the recently discovered Earth orbital companion asteroid 2016HO3. 2016HO3 provides a compelling destination to address science, economic, and asteroid protection objectives and could serve to influence the future direction of human exploration in cis-lunar space by offering an additional destination for human exploration and utilization. Key enabling technologies, solar sail propulsion, thin film power generation and telecommunications capabilities, and small spacecraft technology have reached a development milestone enabling an affordable reconnaissance mission. Leveraging the solar sail technology and mission expertise resident at the National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center (MSFC) resulting from the Human Exploration and Operations Mission Directorate (HEOMD) funded Near Earth Asteroid (NEA) Scout mission, and combining this with the science and instrument expertise at the Goddard Space Flight Center (GSFC), a 12U scale small spacecraft mission can characterize 2016HO3. Spin rate, pole position, shape, structure, mass, density, chemical composition, temperature, thermal inertia, regolith characteristics, and spectral type can be determined using a small, CubeSat form factor within a three year time of flight. This paper outlines the outcome of a concept study for the New Moon Explorer (NME), a solar sail propelled reconnaissance mission of 2016HO3.

I. Nomenclature

ΔV = delta velocity

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II. Introduction

NASA's renewed commitment to the human exploration and development of cis-lunar space, with the goal of returning astronauts to the Moon, comes with an opportunity expand our knowledge of the Earth's neighborhood and provide much-needed reconnaissance of our new orbital companion, the recently discovered asteroid 2016HO3. While 2016HO3 is not strictly a new moon of the Earth, in that it is not orbiting the Earth as a truly captured asteroid might, it is, for all practical purposes an orbital companion that will be around for the foreseeable future. A timely, low-cost reconnaissance of 2016HO3 might influence the future direction of human exploration in cis-lunar space and may provide an additional destination for human exploration and utilization. Coincident with these events, solar sail propulsion and small spacecraft technology have reached a development milestone that may allow an affordable reconnaissance mission. Leveraging the solar sail technology and mission expertise resident at NASA MSFC resulting from the HEOMD-funded Near Earth Asteroid (NEA) Scout mission, and combining this with the science and instrument expertise at GSFC, a 12U scale small spacecraft mission can be developed to characterize 2016HO3. This paper outlines the outcome of a concept study for the New Moon Explorer (NME) solar sail propelled reconnaissance mission of 2016HO3.

A. Science Objectives and Mission Concept

NME will explore a natural companion to the Earth and a possible human mission target, asteroid 2016HO3, and will determine its spin rate, pole position, shape, structure, mass, density, chemical composition, temperature, thermal inertia, regolith characteristics, and spectral type. By tracking the orbital changes of 2016HO3 and linking these to its physical characteristics, NME will measure the effects of non-gravitational forces (YORP and Yarkovsky) to refine estimates of potential perturbations induced in the orbits of 50 – 100 meter class asteroids. This size range is the most numerous class of potentially destructive asteroid impactors and their orbits are the most affected by non-gravitational forces. Measurement of the physical characteristics of 2016HO3 and refinement of its orbit will contribute to evaluation of this asteroid as a potential target for a human mission.

NME will also evolve the capability of solar sail propulsion to the next logical level as the area of the sail is increased to 200 m^2 with metallic Triangular Rollable and Collapsible (TRAC) booms replaced by ultra-lightweight composite booms, reducing spacecraft mass and inertia and increasing thermal stability making the system level propulsion performance significantly advanced over anything flown previously. NASA MSFC, having developed the NEA Scout solar sail flight system, is the only organization in the country with experience in deep space solar sail system design and test, and soon, flight operations with the launch of NEA Scout on the Space Launch System (SLS) Exploration Mission 1 (EM-1).

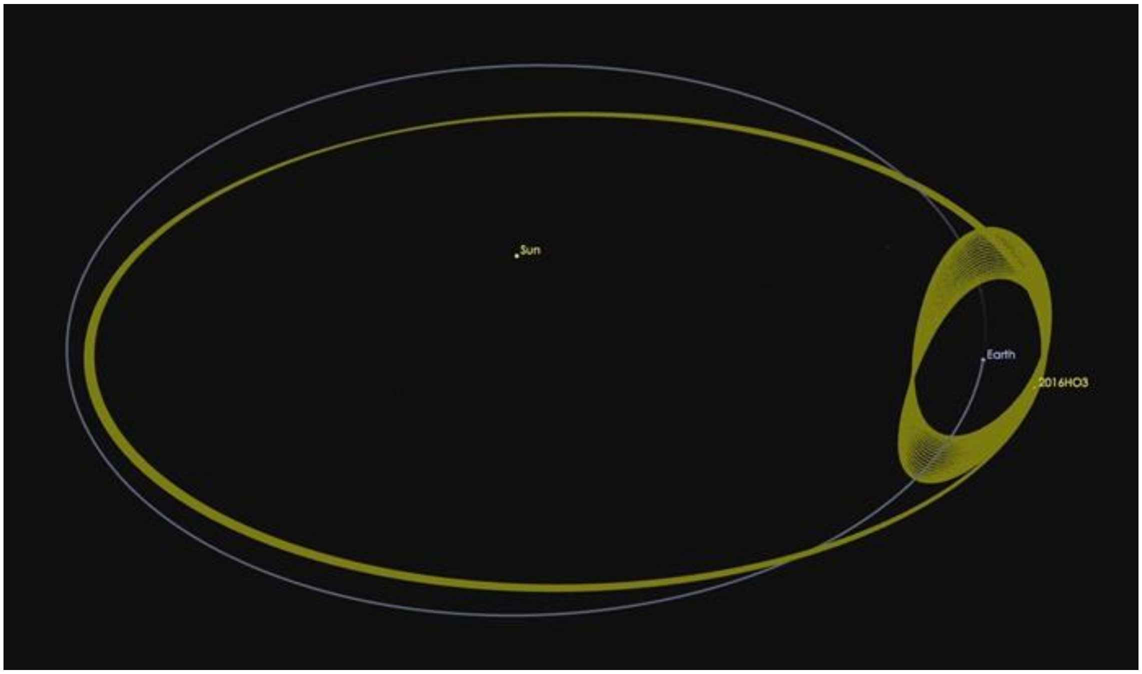


Fig. 1 Orbit of Earth Companion 2016HO3

B. Outcome and Benefits

NME will accomplish science objectives, performing reconnaissance of a scientifically compelling target with extensibility to future human missions, and continue to evolve small spacecraft exploration, reconnaissance, and science capabilities using the propellantless propulsion provided by solar sails. The case for human missions to asteroids are roughly segmented into four categories: better enable our understanding of asteroid formulation and our own origins; examine damage potential and possible mitigation techniques of Potentially Hazardous Asteroids (PHA); explore the economic viability of asteroid mining; evaluate near Earth asteroids as potential human mission destinations.

Continuing maturation of solar sail technology also enables more ambitious mission concepts. Solar sails use sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, highly reflective material. This continuous photon pressure provides propellantless thrust, allowing for very high ΔV maneuvers on long-duration, deep space exploration. Since reflected light produces thrust, solar sails require no onboard propellant. It is this propellantless propulsion capability that makes using it for 2016HO3 so compelling. With the sail, a spacecraft can accomplish multiple low-velocity fly-bys of the asteroid, enabling long-duration observations. With stepwise increases in solar sail capability, interstellar probes, solar polar imagers, and missions to the solar gravity lens for exoplanet observation can be better enabled.

III. New Moon Explorer Science Capture

A. Measurements

A series of moderate resolution visible images will be used to determine the spin rate, pole position, shape, structure (monolith vs. rubble pile), and regolith characteristics of 2016HO3. Images in bands across the 1 – 100 micrometer region will be used to map the chemical composition, temperature, thermal inertia, and regolith characteristics of 2016HO3 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 2016HO3 against the force generated by the solar sail.

B. Target

Asteroid 2016HO3 is a perfect target for NME, with a distance from Earth that varies between 38–100 times lunar and a thermal environment very similar to that experienced by an earth orbiting satellite. Because of the target's unique orbit, communications to NME are simplified enabling more consistent communication of long-term spacecraft measurements. In addition, ground-based observing can complement spacecraft measurements to obtain high precision measurements of long-term orbital evolution. Asteroid 2016HO3 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.

C. Payload

The measurements proposed 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 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 surface. Such filters will allow tracking albedo variations across the asteroid surface that can be tied to the compositional variations determined using the infrared camera and will be useful for determination of the spectral type of the target. Color images are not required for basic measurements that determine spin rate, pole position, shape, structure, and regolith characteristics.

An infrared camera will be utilized that leverages a micro-bolometer detector sensitive from 1 to 100 micrometers and thus allowing the system to be optimized for the proposed observations. 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 in Low-Earth orbit launched June 10, 2011. 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 is a space qualified VOx microbolometer array with a read out integrated circuit (ROIC) [1], manufactured by Institut National d'Optique (INO), Canada. The FPA and the band-pass filters are at TRL >6 and leverage development efforts from other flight instruments [2]. The imaging radiometer operates in a push broom mode to build up images as the focal plane is scanned across the target.

A possible alternative to be examined is the use of ground-based observations from one or more large telescopes, such as the Keck telescope in Hawaii where NASA has guaranteed observing time, in order to determine the spectral type of 2016HO3 prior to the final design of the instrument payload. 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. As an example, if the target were a carbonaceous asteroid we would place a filter across the 3.4-micrometer C-H stretch vibration to quantify the organic content of 2016HO3: this filter is not required if an ordinary chondrite or stony target is expected.

Fig. 2 Jet Propulsion Laboratory OCO-3 Camera

IV.   New Moon Explorer Spacecraft Concept

A. Spacecraft Summary

The 12U NME bus is derived from heritage systems and leverages subsystems development from the NEA Scout and Lunar IceCube SLS EM-1 missions. The spacecraft bus and its systems are designed to operate in the harsh beyond-lower Earth orbit (LEO) radiation and thermal environments and to withstand vibration, shock, and thermal effects during launch, using the Exploration Upper Stage (EUS) enabled SLS configuration as a point design for environmental conditions. A permutation of all bus subsystems will have flight heritage from the EM-1 and/or previous missions and therefore essentially all will have achieved TRL-7 prior to launch. A solar sail context camera will provide an image of the deployed NME solar sail. The overall bus configuration is shown in Fig. 3 and key subsystems briefly described below.

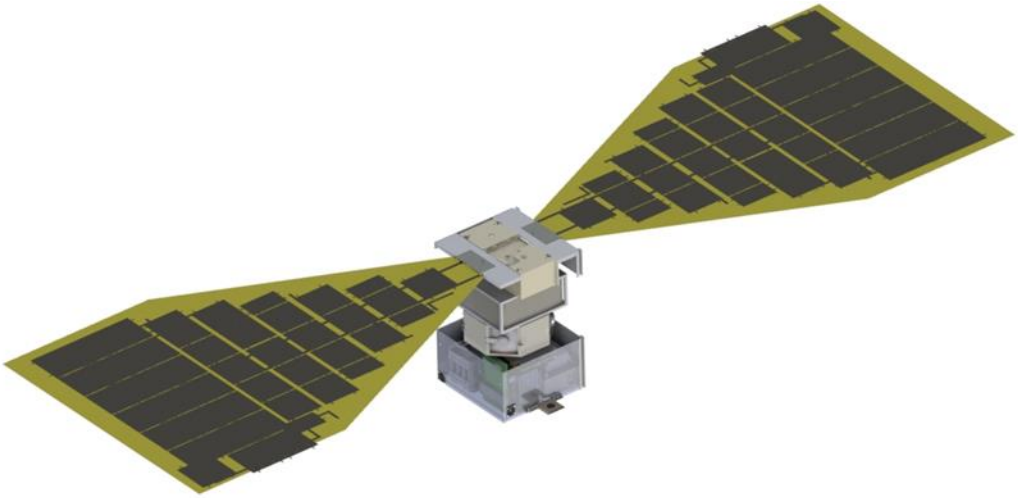


Fig. 3 Conceptual Model of New Moon Explorer in Flight Configuration (Deployed Solar Sail Membrane not Shown)

B. Electrical Power and Telecommunications System

Power will be generated with a planar configuration of the Lightweight Integrated Solar Array and anTenna (LISA-T), which will also provide a communications array. LISA-T is a low-volume, low-mass, flexible deployable on which both power generation and communication are embedded. LISA-T stows compactly for launch and deploys into a large surface are on orbit. The technology has reached TRL6 and is currently progressing towards TRL7.

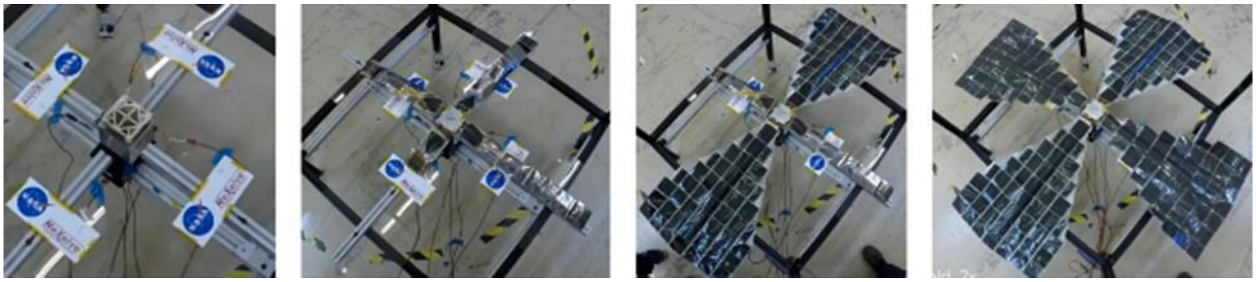


Fig. 4 LISA-T Power Generation Deployment Sequence in Planar Configuration

For NME, a planar LISA-T significantly reduces both mass and stowed volume when compared to state of the art (SOA) technology options. The LISA-T power panels can be packaged as high as 462kW/m3 stowage efficiency and 379W/kg specific power while supplying 100's of watts beginning of life power. Simultaneously, the embedded LISA-T antennas can be stowed at thicknesses as low as 0.7mm and masses around 1.1g to provide transmit / receive communications at up to 12dBi each. The planar LISA-T for NME will utilize high efficiency inverted metamorphic multi-junction (IMM) solar cell as well as an array of x-band helical antennas. When compared to SOA option this results in 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 power panels and antennas to be pointed at their respective targets without slewing and changing the thrust axis of the solar sail.

The NME mission requires 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 2016HO3 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 incorporated antenna array of LISA-T allows the antenna to be pointed with the existing gimbal if necessary. The JPL Iris transponder, 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 are sufficient to meet the requirement of getting the required volume of science data generated to the ground with margin.

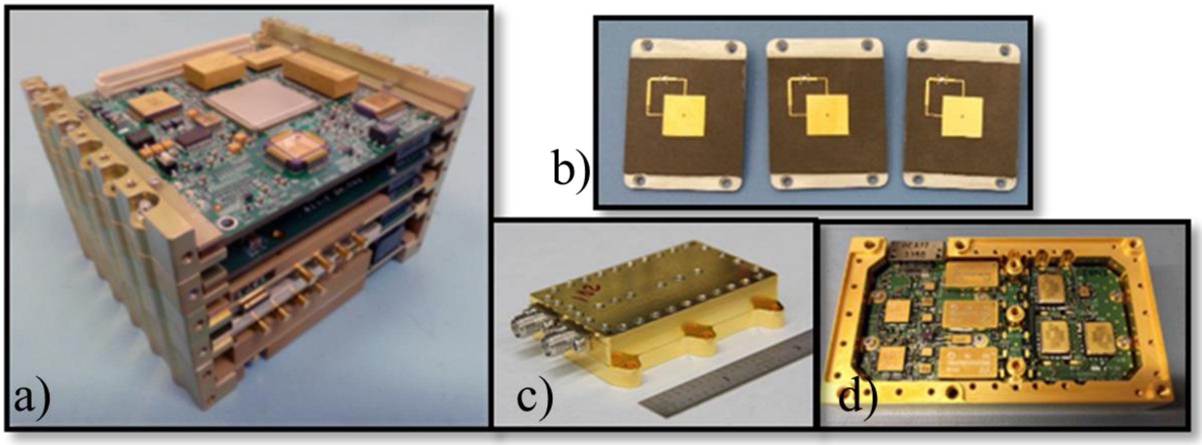


Fig. 5 a) JPL Iris Transponder, b) Patch Antennas, c) Low Noise Amplifier, and d) Solid State Power Amplifier

C. Ground Systems

The NME telecommunications strategy utilizes the high gain Morehead State 21 meter ground station for long stare times (up to 6 hour passes) and the Deep Space Network (DSN) 34 meter Beam Wave Guide (BWG) stations as back-up. The proposed mission operations strategy will support a data throughput more than sufficient to meet the science objectives.

The Morehead State University 21 meter antenna system, shown in Fig. 6, has been upgraded for integration into the DSN as an auxiliary station to support smallsat missions with the support of NASA's Advanced Exploration Systems (AES). The 21 meter class antenna system was developed by Morehead State University in 2006 as a multi-purpose instrument, serving as a university-based ground station as a radio telescope for astronomical research and as an experimental station for communications systems development. From its inception, it was anticipated that the antenna would provide telemetry, command and tracking services for small, low power satellites performing research in the lunar vicinity, at Earth-Sun Lagrange points, and at Near Earth Asteroids (NEAs) and potentially out to Mars at low data rates.

In 2016 AES and Morehead State University began to upgrade the Ground Station to DSN compatibility, which will result in operational capability targeted for Fall 2018. It has been given the designation Deep Space Network Station- 17 (DSS-17). The DSS-17 system consists of a simplified, single channel (Deep Space X-band) version of the DSN Block V Receiver and DSN Block VI Exciter. These systems include re-engineered versions of the uplink tracking and command system (UPL), the downlink tracking and telemetry system (DTT), the data capture and delivery system (DCD) and a "lite" version of the network monitor and control (NMC) system. A system of servers and network systems provide a secure link to the NASA IONet to process schedule requests for DSN services, to send spacecraft commands from the spacecraft operators, and to transfer telemetry and tracking data as well as network monitor data. Upgrades also included development of an improved, high power X-band feed with cryogenically cooled low noise amplifiers. A Hydrogen maser frequency standard was added to support tracking and ranging at the precision levels required by the DSN. The antenna will have the capability to provide all services associated with a DSN station, albeit at a reduced performance level compared with the standard DSN BWG station. DSS-17's performance, however, is ideally suited to "near Earth" deep space missions like NME.

Fig. 6 Morehead State University 21 m Ground Station (DSN DSS-17)

D. 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 an engineering challenge to accommodate these extreme thermal conditions. Experiences from the NEA Scout and Lunar IceCube missions will be leveraged along with extensive thermal modeling to design an effective thermal management system that will likely employ deployable thermal radiators, heat pipes, optically reflective surfaces, and strategically placed resistive heaters.

E. Radiation Environment

The NME radiation environment during the trajectory to 2016HO3 and during its encounters will be dominated by Galactic (Heavy Ion) radiation being outside the protective magnetic field of the Earth, long term effects (total ionizing dose, TID) and 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 (for TID), the use of radiation hardened electronics, and implementation of flight software fault detection and recovery techniques.

F. Momentum Management

Momentum management for the two sail in-plane axes (pitch and yaw) will be provided by an Adjustable 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). 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 for momentum management because it can only manage two of the three axes. Alternative concepts currently being developed by MSFC will be evaluated against the AMT and may further reduce or eliminate the dependency on propellant and increase the overall momentum management capability of the spacecraft.

G. Solar Sail

The NME solar sail will be 200 m^2 in a quadrant configuration. The design leverages advancement in solar sail propulsion technology from NEA Scout (TRL7) and hard-won lessons learned regarding the design, control, and development. The design for NME has some key differences from that of NEA Scout, notably use of composite booms and a quadrant sail configuration compared to NEA Scout’s metallic booms and single-sail membrane configuration. The 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 generated using ABAQUS explicit solution techniques 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. The capabilities of this tool culminate in the generation of maximum allowable solar sail areas for a particular mission that can be supported by a particular boom architecture.

The team performed an extensive boom trade, focusing on numerous boom geometry and laminate architectures. Thermal stability of composite booms minimizes distortion during flight enabling a quadrant configuration without significant deflection, enables a more predictable thrust magnitude and direction as a function of spacecraft attitude, reduces the spacecraft mass properties including overall mass and deployed inertia, and consequently reduces overall flight time.

H. Alternative Propulsion System Trade Study

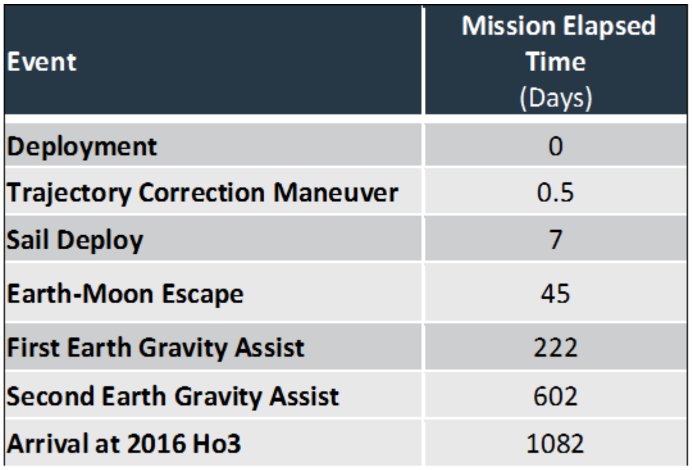
The NME team looked at various CubeSat-compatible propulsion systems to determine which might be feasible for a mission of this class. The ΔV required to reach 2016HO3 is very high due primarily to it being at a 7.8-degree inclination: 4.8 - 5.5 km/sec is required. Using state-of-the-art chemical propulsion systems would require >20 kg of propellant which is not viable for a 12U CubeSat. Various small solar electric propulsion systems were also assessed and most we not viable due to the mass and volume constraints imposed by the 12U CubeSat form factor. A possible exception is an ion thruster but the resulting power requirements may be too constricting for the proposed CubeSat form factor

V. Mission Design

The mission to 2016HO3 begins with deployment from the SLS EUS after the EUS completes a disposal maneuver targeted to heliocentric space. At about 12 hours after deployment, NME will complete a small propulsive Trajectory Correction Maneuver (TCM) with a cold gas Reaction Control System (RCS) to begin targeting 2016HO3 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/sec^2 for the transfer from the Earth-Moon system to 2016HO3.

After escaping from the Earth-Moon system, two Earth Gravity Assists (EGAs) are used to reduce achieve a significant reduction in the time of flight to 2016HO3. 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 or just short of 3 years.

Table 1 NME Mission Timeline



Event	Mission Elapsed Time (Days)
Deployment	0
Trajectory Correction Maneuver	0.5
Sail Deploy	7
Earth-Moon Escape	45
First Earth Gravity Assist	222
Second Earth Gravity Assist	602
Arrival at 2016 Ho3	1082

The DRM leverages both an increased solar sail area and lower relative mass from NEA Scout resulting in a significant increase in characteristic acceleration, defined as the acceleration achieved at 1 AU and zero sun incidence angle. The mission trajectory appears in Fig. 7. Note that the spacecraft stays within relatively close range of Earth for the duration of the trip, commensurately alleviating some of the driving needs of the telecommunication subsystem.

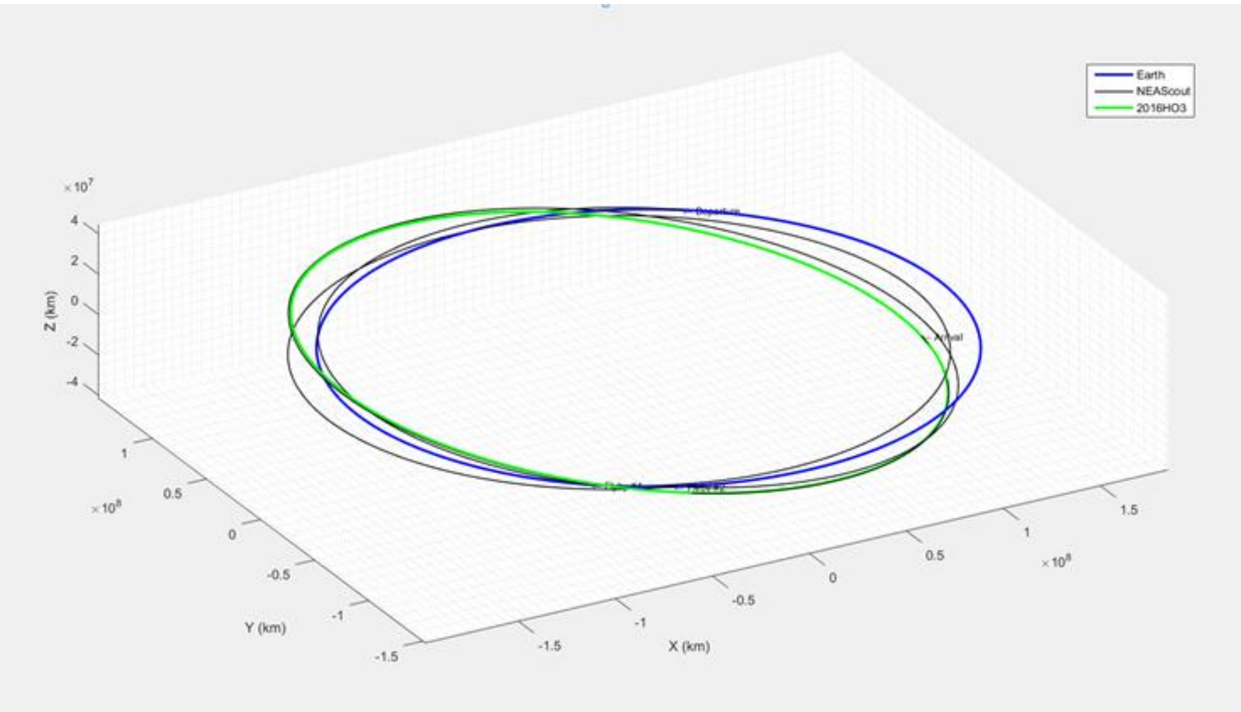


Fig. 7 Sun-Centered NME Design Reference Mission Management and Cost

VI. Conclusion

The NME science concept was devised, spacecraft concept matured, and mission analyses performed indicating the suitability of a closed-form mission solution that is compelling from scientific, technology maturation, and human exploration vantage points. Performance of the mission will aid in addressing a number of immediate scientific questions but also demonstrate extensibility to future missions. Building on the key lessons learned and technology development from both the NEA Scout and Lunar IceCube missions, a strong case can be made for investment in the NME mission concept as a robotic precursor.

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