SOLAR SAIL PROPULSION FOR INTERPLANETARY SMALL SPACECRAFT

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ABSTRACT:

NASA is developing solar sail propulsion for use by small robotic interplanetary spacecraft. Solar sails use sunlight to derive useful thrust by reflecting solar photons from a large, mirror-like sail made of a lightweight, highly reflective material. Using reflected sunlight to obtain thrust instead of relying on the use of reaction mass has many advantages for exploring the inner solar system, including extremely large total ΔV and significant launch window flexibility.

NASA's Near Earth Asteroid (NEA) Scout project will use an $86m^2$, thin-film solar sail to propel a small spacecraft (10cm x 20cm X 30cm; <14kg) on a two year voyage to image Asteroid 1991VG. NEA Scout will launch on NASA's Space Launch System (SLS) in late 2019. NEA Scout is being developed by the NASA Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL) with participation of multiple other NASA facilities. The technical challenges of developing a large, lightweight, compactly-stowed solar sail with a predictable deployed shape and thrust characteristics have been significant. To achieve a truly flyable sail has required many engineering innovations – most of which were of unforeseen difficulty when the project began. Examples include the development of a solar sail thrust model that takes into account the actual anticipated deployed shape of the sail at the micro-, meso- and macro-scales; Control of the spacecraft system Center of Mass versus its Center of (light) Pressure; and thermal deformation of the booms, causing an unacceptable change in the shape of the solar sail. Finally, packaging all of the subsystems required for long-term interplanetary flight into such a small form factor required many iterations to successfully achieve.

Solar sail propulsion has been considered for many years with several simple deployment-only demonstration missions conducted in Low Earth Orbit (LEO). Developing a solar sail that has to function as a propulsion system over many years was a significant technical challenge and much more complicated to achieve than anticipated. The NEA Scout mission, and successor missions being considered, are paving the way for the routine use of solar sails on affordable robotic explorers of small bodies throughout the inner solar system.

1. BRIEF HISTORY OF SOLAR SAILS:

Solar sails are a form of propellantless propulsion – they derive thrust by reflecting solar photons rather than expelling propellant. Though their acceleration is low, on the order of millimeters per square second, it is constant and since they can theoretically operate indefinitely in the presence of sunlight, their effective total ΔV can be very high. Solar sails are ideally suited for small, robotic space missions conducted within the inner solar system though they can have innovative application in different regions of space.

Solar sails are highly efficient, allowing spacecraft to hover indefinitely at points in space or conduct orbital plane changes more efficiently than is possible using conventional chemical propulsion. Solar sails can also propel a space vehicle to tremendous speeds – enabling rapid exploration of the outer solar system.

Several space missions have used solar photon pressure to provide thrust. The early NASA Echo Balloon program, for example, measured the effects of solar pressure on the motion of the balloon as its orbit decayed [1]. In 1974, when NASA's Mariner spacecraft was in danger of running out propellant for its attitude control system, mission controllers decided to use the solar pressure on the spacecraft's solar arrays to keep the spacecraft's attitude stable [2]. These are but a few examples where solar radiation pressure has either been used or measured by operational spacecraft.

The Russian Space Agency conducted the first in-space solar sail deployment from a Progress resupply vehicle after it undocked from the Mir Space Station in 1993. Called Znamya, the sail deployment was successful. In 1999, the second Znamya solar sail collided with a deployed spacecraft antenna and was shredded [3].

NASA began developing solar sails in the early 2000's. Two different 20 m x 20 m solar sail systems were developed and tested at the Glenn Research Center's (GRC's) Space Power Facility at Plum Brook Station, Ohio [4]. The sails tested at Plumbrook were the largest ever constructed by NASA, one of which can be seen in Fig. 1.

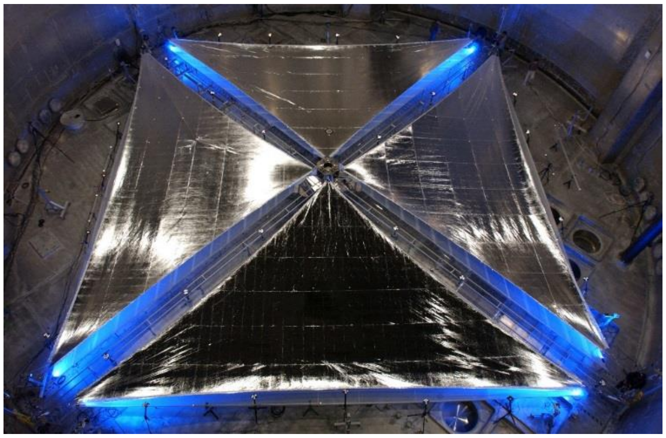

Figure 1. NASA tested this 400 m^2 solar sail which was deployed using rigid mechanical booms at NASA's Plumbrook Station.

JAXA (the Japanese Aerospace Exploration Agency) in 2010 launched the Interplanetary Kite-craft Accelerated by Radiation Of the Sun, (IKAROS) mission into deep space, becoming the first to demonstrate controlled solar sail propulsion [5]. That same year, NASA launched the NanoSail-D2, which deployed a 10 m^2 sail in Earth orbit. Made from spare parts left over from the sail NASA tested (and shown in Fig. 1), NanoSail-D2 successfully demonstrated drag propulsion as a viable method for end-of-life spacecraft deorbit [6].

The Planetary Society in 2015 successfully flew their privately-funded 32m^2 LightSail-A in low Earth orbit and plan to fly their LightSail-2 in 2018 [7]. The University of Surrey demonstrated a drag sail similar in design to the NASA NanoSail-D2 with the InflateSail in 2017 [8].

2. SOLAR SAIL MISSION APPLICATIONS:

The GeoSail mission concept is potentially the simplest application of solar sailing due to its low required sail acceleration. A small solar sail with a characteristic acceleration of order 0.1 mm/s^2 can be used to precess a long elliptical Earth-centered orbit to keep a science payload permanently within the Earth's geomagnetic tail. The sail forces the orbit major axis to precess at close to 1^o per day so that the major axis of the ellipse always point along the Sun-Earth line, with the orbit apogee directed away from the Sun. Since a low mass field and particle instrument suite is typically required for geomagnetic tail missions, GeoSail would be an ideal and early science mission to take full advantage of the capabilities afforded by a solar sail [9].

Solar physicists and those responsible for monitoring space weather would benefit from the Heliostorm. Heliostorm would use a solar sail to station a space weather monitoring payload sunwards of the classical L1 Lagrange point close to the Sun-Earth line. The sail would be canted so that the artificial equilibrium position is displaced both sunwards, and slight off the Sun-Earth line to ensure that the sail is away from the solar radio disk when viewed from the Earth. Being displaced sunwards of the classical L1 region, the space weather payload will detect solar coronal mass ejections earlier than is currently possible and potentially double the warning time of impending terrestrial space weather events [10].

Solar sails can also create artificial equilibria high above the ecliptic plane. For a sail with a characteristic acceleration of order 0.2 mm/s^2 the sail can be stationed directly over the polar axis of the Earth at the summer solstice. An imager located at such an artificial equilibrium position, hovering so that its acceleration counters the Earth's gravity, would provide a real-time, hemispherical view of high latitude regions and the poles for climate science, albeit with a low spatial resolution due to the large Earth-spacecraft distance of order 3 million km. Conventional spacecraft in polar orbit can provide high spatial resolution, but the temporal resolution of high latitude regions is typically poor since images from many polar passes need to be assembled to provide full coverage of the Arctic and Antarctic [11].

Solar sails can place spacecraft into high-inclination solar orbits, regions mostly in accessible to conventionally-propelled spacecraft due to their extremely high ΔV requirements. The sail-propelled spacecraft would spiral inwards to a close, circular heliocentric orbit, the radius of which is limited by the thermal tolerance of the sail film (typically limited to 0.25 AU). Then, the orbit inclination of the solar sail is changed by turning the sail and alternately directing a component of the light pressure force above and below the orbit plane every half orbit. For example, a solar sail with a high characteristic acceleration of 1 mm/s^2 can deliver a payload to a solar polar orbit at 0.5 AU [12].

Sailing on light is the only technology we now have that may be extensible to practical interstellar flight. Sunlight diminishes with distance, but a powerful laser could focus light over interstellar distances and the resulting beamed light sail can continue to accelerate a spacecraft to achieve velocities required for interstellar precursor missions if not, eventually, true interstellar missions. To achieve this goal will require a large space-based laser, presumably solar powered. Such a capability is many decades into the future [13].

3. NEXT STEPS

3.1 Near Earth Asteroid Scout

The NASA Near-Earth Asteroid (NEA) Scout mission will demonstrate the capability of an extremely small spacecraft, propelled by an 86 m^2 solar sail, to perform reconnaissance of an asteroid as shown in Fig. 2. The solar sail will be based on the technology developed and flown by the NASA NanoSail-D2 and the Planetary Society's LightSails. Funded by NASA's Human Exploration and Operations Mission Directorate and managed by NASA MSFC, the NEA Scout mission will be launched on the first flight of the SLS in 2019.

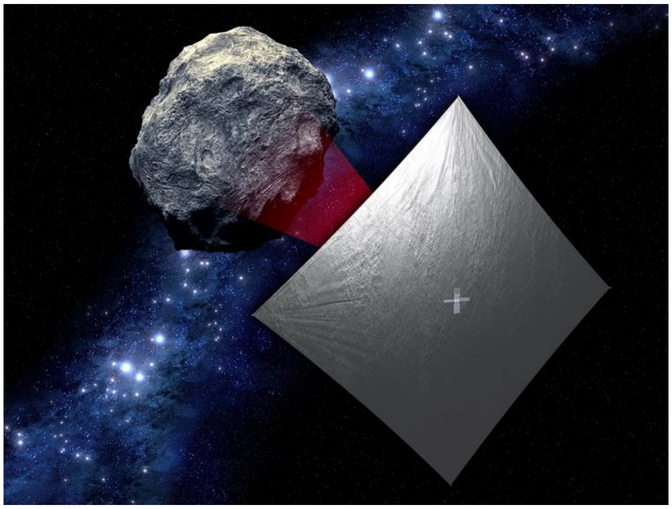

Figure 2. Artist concept of the NASA Near-Earth Asteroid Scout performing reconnaissance of Asteroid 1991VG.

The NEA Scout uses a 6U CubeSat form factor, which is being primarily developed by NASA's Jet Propulsion Laboratory, to house a fully functional, though miniaturized, interplanetary spacecraft. The complete NEA Scout spacecraft bus measures 10 cm X 20 cm X 30 cm and weighs less than 14 kilograms. The sail has been tested and deployed several times using the facilities at NASA MSFC. One such test can be seen in Fig. 3.

Figure 3. The NEA Scout's 86 m^2 solar sail was successfully deployed in a recent test near NASA's George C. Marshall Space Flight Center.

The spacecraft will be placed on an Earth escape trajectory by the upper stage of NASA's SLS during its maiden flight in 2019. The primary mission for the flight is a test of the Orion crew capsule, which will be sent into a lunar flyby before it returns to Earth. Within the Orion Stage Adapter (OSA) are 13 individual CubeSat deployers, each containing a separate 6U spacecraft with their own unique mission requirements. After the Orion is deployed, the 13 CubeSat secondary payloads carried on the rocket will be deployed, one by one, from the OSA.

The NEA Scout will remain in the lunar vicinity until the low-thrust trajectory to the destination asteroid, 1991VG, can be attained. The spacecraft will then begin its 2.0 – 2.5 year journey to the asteroid. About one month before the asteroid flyby, NEA Scout will pause to search for the target and start its Approach Phase using a combination of radio tracking and optical navigation. The solar sail will provide continuous low thrust to enable a relatively slow flyby (10-20 m/s) of the target asteroid under lighting conditions favorable to geological imaging (<50 degree phase angle). Once the flyby is complete, and if the system is still fully functioning, an extended mission will be contemplated, perhaps leading to the reconnaissance of another asteroid or a re-flyby of 1991VG several months later.

3.2 New Moon Explorer (NME)

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 [14]. 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 (Fig. 4.). 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.

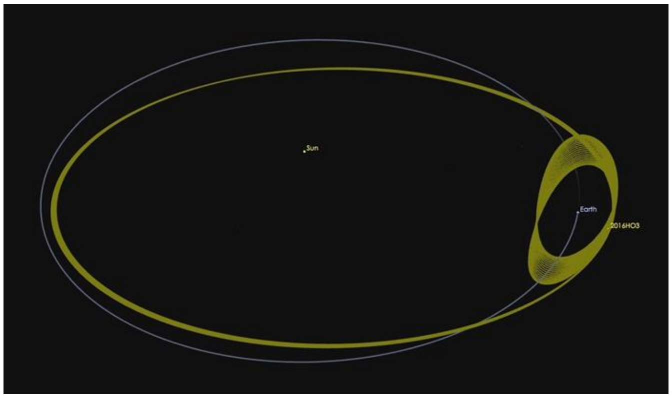

Figure 4. 2016HO3 is a constant companion of the Earth, co-orbiting the Sun with the Earth – making it essentially Earth's 2nd moon. Shown are calculations of its trajectory, relative to the Earth and Sun, over the next few years.

While it is not an approved mission, a notional mission concept has been created that would extend the technology of the NEA Scout to create a larger sail, ~200 m^2, providing more propulsive capability, to send a 12U cubesat to explore 2016HO3 in detail.

The mission to 2016 HO3 would begin with deployment from a future launch of NASA's SLS. About 12 hours after deployment, NME will complete a small propulsive Trajectory Correction Maneuver (TCM) with the reaction control system to begin targeting 2016 HO3 prior to deploying the solar sail. 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 2016 HO3.

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 2016 HO3. 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.

CONCLUSIONS:

After decades of concept studies, ground testing, and recent successful spaceflights, solar sail propulsion is now ready from mission implementation. The development has been, and will continue to be, incremental, with larger spacecraft deploying larger sails, increasing the capability and reach of the technology to more and more missions of interest.

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