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II. Asteroid Surrounding Environment

ABSTRACT

Small Spacecraft Solar Sail Missions for Multiple Near-Earth Object Prospection: Remote Sensing, In-Situ Characterization and Sample Return

Jan Thimo Grundmann, Tom Spröwitz, Patric Seefeldt, Peter Spietz

DLR German Aerospace Center – Institute of Space Systems, Robert-Hooke-Strasse 7, D-28359 Bremen, Germany; jan.grundmann@dlr.de, Tom.Sproewitz@dlr.de, Patric.Seefeldt@dlr.de, Peter.Spietz@dlr.de

Bernd Dachwald

Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany; dachwald@fh-aachen.de

Solar sail technology has been developed by the German Aerospace Center (DLR) since the 1990s, culminating in a successful (20 m)² sail ground demonstrator deployment test in 1999 at DLR Cologne. [1] In the last years a further development of the technology for controlled deployment of gossamer spacecraft was made in the DLR GOSSAMER-1 Project [2].

The DLR-ESTEC GOSSAMER roadmap originally envisaged the extremely fast-paced development of solar sailing technology by a series of successively leapfrogging low-cost demonstrator flights leading towards the technological basis for first science missions [3]. In this framework, the GOSSAMER-1 deployment demonstrator for a (5 m)² sail structure in a low Earth orbit dominated by drag was to be followed by the (20 m)² sail effect and attitude control demonstrator GOSSAMER-2 for higher Earth orbits dominated by solar radiation pressure, and the (50 m)² GOSSAMER-3 sailcraft proving the principle within the Earth-Moon system. It was to demonstrate sufficient trajectory and attitude control for science missions using a simple lightweight camera for timed pointing and localization reference imaging and a magnetometer to study the space environment around a sail. Since the first Roadmap studies, the expected payload capability for this purpose increased from a few to several kg.

Three scientific mission types which are exclusively feasible with the unique capabilities of solar sail propulsion were identified and studied in detail by science working groups as candidates for a first science mission. These studies were based on the expected performance of solar sail technology developed in the Roadmap. Each mission was to be completed within 10 years:

- Multiple Near-Earth Asteroids (NEA) Rendezvous (MNR) & station-keeping, with optional Near-Earth Object (NEO) fly-bys of opportunity [4],
- Displaced Lagrange point 1 (DL_1) station-keeping solar storm early warning at twice L_1 distance from Earth [5],
- Solar Polar Orbiters (SPO) for solar wind and coronal research and/or spectroscopic imaging of the Sun [6].

For MNR, trajectories for several triple-rendezvous missions were calculated assuming near-term 1st-generation sailcraft performance. Notably, a solar sail based mission can change target NEAs *in flight* whenever new knowledge triggers a change of interest. The science payload of 12 kg included a multispectral imager, a vis-NIR point spectrometer, an IR radiometer, and three 1U-CubeSat-sized drop probes. [4] The spacecraft was expected to fit a standard ESPA or ASAP 'micro' piggy-back payload launch envelope. The 'mini'-class ENEAS missions with launch masses from 150 to 750 kg studied a decade earlier based on similar sail performance estimates include single- and triple-sample-return mission profiles. [7] Sailcraft with a performance between MNR and ENEAS could carry a single MASCOT-type [8] or several CubeSat-like landers to each rendezvous target. Sharing of the science payload between lander and sailcraft may be feasible for missions focusing more on a single target [9].

With the technology available already now, it would be possible to develop a lightweight solar sail that fulfills the mission requirements of a 10-year multiple NEO rendezvous mission, thereby providing the means to study, prospect, or even deflect such potentially mineable or dangerous objects. In recent years, DLR has gained significant experience in realizing small spacecraft based projects on very short timelines [10] with a high degree of strategic re-use [11] of proven components between projects such as MASCOT [8] and its successors [12], GOSSAMER-1 [2], ROBEX [13], the ADEO dragsail [14], the GOSSAMER successor project GOSOLAR for very large scale photovoltaics [15], and others. Also, the infrastructure has been expanded to include facilities for functional [16] and qualification testing [17], and the study and testing of critical effects of the space environment on new types of structures such as sail foils and thin-film photovoltaics [18].

Concurrently, much progress was made in the field of trajectory optimization. Even when the population is restricted from 12840 NEAs to the 1801 objects in the Near-Earth Object Human Space Flight Accessible Target Study (NHATS) set including 1597 Potentially Hazardous Asteroids (PHA), and heliocentric inclination limited to 5°, missions with a stay-time of ≥100 days at 5 NEA within <10 years appear feasible with *less* sail performance than assumed for MNR. To rendezvous with 5 NHATS objects including at least 1 PHA in <10 years, 4800 encounter sequences were found. The . [19]

Complementing the ability to rendezvous, there is the ability to reach very high impact velocities in the Planetary Defence context by turning inclination of the sailcraft heliocentric orbit retrograde. Near-term technology small spacecraft solar sail based deflection missions to (99942) Apophis have been studied achieving ~75 km/s at impact; a head-on impact on 2004 WR trajectory achieves 81.4 km/s. [20-22] Depending on the target object's size, it may be possible to access fresh subsurface material by artificial crater excavation. High-speed solar sails appear as a cost-effective approach due to their high impact energy to launch mass ratio, considering that sufficiently precise guidance (cf. e.g. [23]) has been achieved by Deep Impact at comet Tempel 1 [24-26], though at somewhat lower speed on a target somewhat larger than most NEAs. It is likely that before impact an agile impactor payload will have to be detached from the sail. The lightened sailcraft can then act as an observing fly-by spacecraft which may also continue on an extended mission beginning (cf. e.g. [24-27]).

The retrograde orbits used in the deflection and/or cratering or disruption applications as well as the MNR, DL_1 and SPO missions studied demonstrate by their Δv requirements that *any* asteroid is accessible by solar sail propulsion.

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