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Flights are Ten a Sail – Re-use and Commonality in the Design and System Engineering of Small Spacecraft Solar Sail Missions with Modular Hardware for Responsive and Adaptive Exploration

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Abstract

The exploration of small solar system bodies started with fast fly-bys of opportunity on the sidelines of missions to the planets. The tiny new worlds seen turned out to be so intriguing and different from all else (and each other) that dedicated sample-return and in-situ analysis missions were developed and launched. Through these, highly efficient low-thrust propulsion expanded from commercial use into mainstream and flagship science missions, there in combination with gravity assists propulsion. In parallel, the growth of small spacecraft solutions accelerated in numbers as well as individual spacecraft capabilities. The on-going missions OSIRIS-REx (NASA) or HAYABUSA2 (JAXA) with its landers MINERVA-II and MASCOT, and the upcoming NEASCOUT mission are examples of this synergy of trends. The continuation of these and other related devlopments towards a propellant-less and highly efficient class of spacecraft for solar system exploration emerges in the form of small spacecraft solar sails designed for carefree handling and equipped with carried landers and application modules. These address the needs of all asteroid user communities – planetary science, planetary defence, and in-situ resource utilization – as well as other fields of solar system science and applications such as space weather warning and solar observations. Already the DLR-ESTEC GOSSAMER Roadmap for Solar Sailing initiated studies of missions uniquely feasible with solar sails such as Displaced L_1 (DL1) space weather advance warning and monitoring and Solar Polar Orbiter (SPO) delivery, which demonstrate the capabilities of near-term solar sails to reach any kind of orbit in the inner solar system. This enables Multiple Near-Earth Asteroid (NEA) rendezvous missions (MNR), from Earth-coorbital to extremely inclined and even retrograde target orbits. For these mission types using separable payloads, design concepts can be derived from the separable Boom Sail Deployment Units characteristic of DLR GOSSAMER solar sail technology, nanolanders like MASCOT, or microlanders like the JAXA-DLR Jupiter Trojan Asteroid Lander for the OKEANOS

mission which can shuttle from the sail to the targets visited and enable multiple NEA sample-return missions. These nanospacecraft scale components are an ideal match creating solar sails in micro-spacecraft format whose launch configurations are compatible with secondary payload platforms such as ESPA and ASAP. The DLR GOSSAMER solar sail technology builds on the experience gained in the development of deployable membrane structures leading up to the successful ground deployment test of a (20 m)² solar sail at DLR Cologne in 1999 and in the 20 years since.

Keywords: system engineering, small solar system body characterisation, small spacecraft solar sail, small spacecraft asteroid lander, responsive space, multiple NEA rendezvous

Nomenclature

a_c – characteristic acceleration of a solar sail.
(n m)² - square sail membrane size of n m · n m.

Acronyms/Abbreviations

Displaced Lagrage point 1 (L_1) mission/trajectory (DL1), Mobile Asteroid Surface Scout (MASCOT), multiple NEA rendezvous (MNR), near-Earth asteroid (NEA), solar polar orbiter (SPO).

1. Introduction

Solar sailing – understood as the concept of a propulsive force of sunlight – celebrates its 400th anniversary this year, by Kepler's observations and remarks published in 1619 on the directionality of comets' tails. A decade earlier already, Kepler in the practical manner of the renaissance man had written in a letter to Galileo, '*Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void*'. In the early 20th century, pressure due to radiation was experimentally demonstrated by Lebedev, and by Nichols and Hull. Oberth, Tsiolkovsky and Tsander first proposed it as propulsion method for space flight applications in the early 1920s.

The term 'solar sailing' was introduced by Garwin in 1958, at the beginning of the space age which was characterized by a rapid succesion of small scientific missions in Earth orbit and the first steps beyond. 'Let loose' by the successful launch of Sputnik on October 4th, 1957, space flight as we know it today was invented and developed virtually from scratch in practical terms, and at that in all defining functions of 3-axial stabilized science and applications spacecraft, within barely 2 years. Remarkably, this was done twice, in the open by the NASA/JPL Ranger lunar probe program (started December 21st, 1959; 1st orbital test launch on August 23rd, 1961) and covertly by the U.S. Corona reconnaissance satellite program (created immediately post-Sputnik on December 8th, 1957; 1st orbital test launch on April 13th, 1959).

This was only possible through extensive re-use of existing artifacts (then, from the aeronautical industry), inspired design for re-use, and extremely agile project management methods (then only known to insiders under such illustrious names as Kelly's Rules or Battle's Law). Thus, in this year we may also celebrate 60 years of Responsive Space in practice, and 70 years in theory: like modern highly agile projects of complex spacecraft (e.g. the MASCOT nanolander), the projects of the early space age drew on a decade of studies preceding the turn towards flight hardware. [1][2][3]

2. Missions uniquely feasible by solar sailing

A solar sail never runs empty and will work until its non-expendable systems fail beyond the level of built-in redundancy and minimum required control authority. In theory unlimited, the attainable velocity gain (Δv) is a complex function of the sail's attitude, distance from the Sun, and its characteristic acceleration capability and ageing over its active lifetime. Parametrized for now available technologies, a mission Δv of serveral 10's km/s can be achieved within 10 years of active flight. The following three missions were identified and studied over a period of two years by the DLR-ESTEC GOSSAMER Roadmap Science Working Groups. Each was presented in a comprehensive peer-reviewed paper:

2.1 Displaced L1 advance spaceweather warning

The spaceweather early warning mission is stationkeeping with Earth ahead of the Sun-Earth Lagrange point L_1 towards the Sun, using the sail thust to augment Earth's gravity in the balance of orbital forces to generate an artificial Displaced L_1 point (DL1), and carrying a very lightweight suite of plasma instruments. The DL1 position was expected and required to at least double the warning time for oncoming solar storms which can disturb power grids, knock out spacecraft services, hinder radio communication, and increase high altitude radiation on Earth.

The Displaced L1 (DL1) mission is infeasible based on current launch capabilities for chemical L_1-displacement-sustaining propulsion. For 1 year at a DL1, position at twice the distance from Earth than L_1 an effective Δv of 9.5 km/s is required, leading to a mass ratio of 0.05 for chemical propulsion. Electrical propulsion becomes unfeasible at around 5 years at DL1, requiring nearly 50 km/s effective Δv (*sic!*) and a mass ratio of 0.2. The 10-year mission duration requirement set for the GOSSAMER Science Working Group missions – which was based on the highly successful ACE and SOHO spaceweather missions as lifetime and data continuity guidelines – requires an effective Δv of nearly 95 km/s. This is close to the ideal situation and the definition of the characteristic acceleration, a_c, as the sail is almost fully facing the Sun and stays close to it, at slightly less than 1 AU. Sail degradation would not lead to an abrupt mission end, the displacement distance ahead of L_1 would merely be reduced and the spacecraft recede in proportion back towards the purely ballistic L_1 region of halo orbits. This is a gradual corresponding to the reduction of sail quality by degradation. Conversely, a design margin in the sail would lead to an initially higher displacement ahead of L_1, towards more than the required doubling of the warning lead time. [4]

2.2 Solar Polar Orbiter

The Solar Polar Orbiter for which the solar sail is used to raise the inclination of its heliocentric orbit much further than possible by gravity-assist fly-bys, chemical or electrical propulsion combined. A heavier helioseismic imaging payload could be raised in inclination sufficiently to observe the polar regions of the Sun, and could progress under sail power to somewhat higher latitudes still within the set lifetime. A light-weight plasma instruments payload could reach exact polar orbit within the required mission duration where the sail would be jettisoned to remove its influence on the plasma environment to be studied. The sail itself does however not run out of fuel to continue in either case, and could in theory be used for any useful minimal-mass extended mission purpose progressing to retrograde inclinations.

The SPO mission with its regular polar passes at low solar polar zenith to observer angle is infeasible based on current launch capabilities for conventional chemical/gravity-assist and electrical/gravity-assist propulsion. Ulysses, the only remotely similar mission flown so far, had to rely on a Jupiter gravity-assist plane change for a lightweight particle and field measurements payload without any imagers. It also had a polar revisit cycle around 6 years, passing several AU over the poles. For comparison, the ESA Cosmic Vision proposed Solar Orbiter, at first a solar-electric propulsion (SEP) mission to carry a science payload of 180 kg to about 35° maximum solar latitude and 0.22 AU minimum distance, became a conventional mission for the same payload mass. It was limited to 180 W consumption and to the same inclination but at a minimum approach of 0.284 AU. In a typical scenario it requires two Earth and five Venus gravity-assists over 8 years (VEEVVVV), after which it sees five cycles between 0.284 and 0.74 AU and to approximately ±34° solar latitude in the last 1⅔ years of its design life. Historically, the SPO mission is one of the most intensely studied and earliest proposed solar sail missions, for its intractability to conventional and other propellant-based propulsion solutions. [5]

2.3 Multiple NEO Rendezvous

The multiple NEO rendezvous (MNR) and fly-by mission visits and rendezvouses with at least three significant NEAs out of a pre-selected population, for at least several rotation periods of the respective object, and to perform faster fly-bys at additional other NEOs within the set lifetime of a decade. It was noted at the time that further optimization of the trajectory of the triple NEA rendezvous mission could bring down the requirements on the sailcraft to about 0.2 mm/s² characteristic acceleration, or (39…48 m)² sail size, as a final design goal for a 10-year mission duration. [6]

2.3.1 Advances in MNR trajectory design

Within 3 years, this goal was achieved by the solar sail trajectory development community, and surpassed in the number of rendezvous (up to 5 within 10 years), stay duration (≥100 days, each), and mission options per launch date (10's to 100's). [9] A stay of at least 100 days is comparable to the mission scenario of AIM at the binary NEA (65803) Didymos [7] and the on-asteroid activities phase of its lander, MASCOT2, on the small moonlet, 'Didymoon' [8].

For example, the sequence Earth – 2003 WT_{153} – (65679) 1989 UQ – (401954) 2002 RW_{25} discussed in [10] contains two large, almost km-sized PHAs most likely well suitable for MASCOT-like landers, after a very small first target which could be of interest to ARRM-like missions [11]. The total Δv for this sequence of only 3 targets is 52.1 km/s which is considered not feasible with current or near-termn high-performing electric-propulsion technology [10]. Low-thrust missions requiring a consumable propellant are restricted to the thin end of the low-Δv tail of the total ΔV distribution of sequences and consequently require optimization for this parameter which in turn sacrifices the target change and launch date flexibility of the solar sail based solution which was optmized without any limit on the level of ΔV. For example, Maiwald and Marchand [a] found a 5-NEA sequence Earth – 2001 QJ_{142} – 2000 SG_{344} – 2009 OS_5 – 2007 YF – 1999 AO_{10} for Earth departure on March 21st, 2023 which only requires 16.6 km/s total Δv. However, all targets are very small (H≈24), thus likely unsuitable for passive landers like MASCOT and MASCOT2, and some have poorly defined orbits.

2.3.2 Proposed MNR mission desgns

An early example of a set of proposals for a flight mission with solar sail development efforts included based on a NEA rendezvous mission profile, with one or three target NEAs and a sample-return option for each rendezvoused object had already been proposed as a small spacecraft mission within the space sciences program of DLR in the 2000's on the conventional science missions track under the designation ENEAS (Exploration of a Near-Earth Asteroid with a Solar

Sail). [12][13][14][6] Except for the triple NEA sample return profile the envisaged spacecraft were generally within the expected capabilities for a first science mission sailcraft as assumed for the GOSSAMER Roadmap Science Working Groups' spacecraft, and the single-target missions were close to the properties expected for GOSSAMER-3 (see section 3 below).

Also the other mission types generated mission proposals such as ODISSEE [15][16] or GEOSAIL. [17][18][19].

2.4 …and in-between as well: in-flight re-targeting

Due to the open-ended nature of solar sail propulsion, there is scope for responsive and adaptive mission profiles. For example, long duration missions to solar system targets (planetary, asteroids and short period comets) could in principle be re-directed to new targets of opportunity en route. These could include new long period comets passing through the inner solar system for the first time. For a solar sail of sufficiently high performance, the sail could target the crossing of a new comet at the ecliptic plane, either at the descending or ascending node [26]. Solar sails also offer opportunities for responsive and adaptive mission profiles for asteroid science. In such a scenario, the new science data acquired at the first target could inform the selection of later targets in a tour of multiple near Earth asteroids.

This, in a way, establishes the fourth uniquely feasible mission profile of solar sailing, in-flight re-targeting.

However, the changes from one peculiar flight regime to another may also require changes in the trajectory optimization tool chain as much as it requires a mission-flexible sailcraft design, able to cope with calmly Earth-tracking DL1 operations, hot near-Sun inclination cranking, and agile station-keeping in the vicinity of a (comparateively) tiny rock in deep space.

3. DLR GOSSAMER solar sail concept & technology

The GOSSAMER Roadmap as originally envisaged [20][21] consisted of three steps of flight testing to create the fundamental technologies required for successful solar sail science missions:

- GOSSAMER-1: low cost technology demonstrator, exclusively for membrane deployment technology, with a (5 m)² sail in very low Earth orbit (LEO).
- GOSSAMER-2: validation of solar sail attitude control technologies on a (20 m)² sail at altitudes where photonic pressure becomes dominant.
- GOSSAMER-3: fully functional (50 m)² solar sail to validate the design approach and prove sufficient guidance, navigation and attitude control to conduct planetary science and space weather missions.

Note that the size and all other parameters of GOSSAMER-2 and -3 are approximate since detailed designs of these spacecraft remain to be completed.

The fundamental technological advancement in the GOSSAMER Roadmap era was the complete reversal of the entire sail and boom stowage and deployment concept. Both of these key deployables were moved from stowage volumes within the Central SailCraft Unit (CSCU), the centerbody of the deployed sail, to the boom tips, and all mechanisms and other hardware needed only once for their deployment necessarily went with them, introducing a new modular spacecraft concept: the Boom Sail Deployment Unit (BSDU).

The four BSDUs of a GOSSAMER-type sailcraft are identical self-contained autonomous spacecraft operating synchronously as a self-coordinating deployment flotilla, coupled mechanically only by their temporary attachment to the booms rolled up inside them. Each BSDU unrolls one CFRP boom end. For the GOSSAMER-1 QM, the booms were already scaled for the (20 m)² class sail of GOSSAMER-2. The four boom ends are part of only two continuous booms crossing at the centre of the CSCU to form the square sail's diagonals. In the centre, they expand to their full cross-section first, at the location of the highest bending loads in the linear regime (i.e., before it comes to buckling). In addition to half a boom, each BSDU also holds a sail spool on either side carrying one half, each, of the two adjacent sail quadrants.

The deployment process is driven by the boom spool motor pushing the boom out; the sails are gradually released from their slightly brake-retarded sail spools. This gradual and mildly restrained sail release process ensures a minimum amount of circumferential tension already in the deploying sail, to keep it from wrapping around any other moving parts in a weightless environment as it could if it were released as one package from its container like a parachute commonly is.

The design of GOSSAMER-1 was carried forward to the point where hardware integration of a qualification model (QM) had been completed. The AIV process was carried out by a very small residual project team, in parts using an adaptation to a model strategy containing only one comprehensive model of the concurrent AIV approach pioneered in parallel by MASCOT [mc]. The GOSSAMER-1 EQM consists of one fully functional train of the deployment relevant units and two adjacent membrane quadrants. It subsequently completed qualification-level testing, including a ground deployment test in TVAC space qualification environment only restricted by the size of available facilities. The GOSSAMER-1 EQM is applicable for all possible GOSSAMER-1 launched system configurations, from upper stage attached payload to independent free-flyer. [22][23][24][25]

4. The Sail to Soil problem and the missing link

The MASCOT nanolander which successfully completed its mission on PHA (162173) Ryugu on October 3rd, 2018, was developed in parallel to the work on GOSSAMER-1, often sharing expertise and resources. Already during its cruise 2014-2018 with JAXA's sample-return probe HAYABUSA2 to Ryugu and ever since, MASCOT evoked interest from every small solar system body mission under consideration or in preparation that we are aware of.

We describe the development and mission of MASCOT aboard HAYABUSA2 in our related contributions to the IAC 2019, and references therein. [27][28]

Solar sails are large, extremely lightweight and mechanically 'soft' structures. Even under the best circumstances and most optimistic assumptions, it is hard to imagine to ever operate them within touching distance of an asteroid, other than for a definitely mission-concluding beaching on the rock.

However, solar sails of the GOSSAMER kind already consist of 5 independent small spacecraft connected at launch to act as one. It is easy to expand the related set of interfaces to include one or more independent nanolanders like MASCOT2. For a 5-target MNR cruise, this results in the 10 flight(model)s per sail mission.

Alternatively, for slightly larger missions, a shuttling lander can be carried which may also return samples to the sail destined or Earth return – note that Earth from the point of view of heliocentric trajectory design is just another near-Earth object. Such a lander design, though PHILAE-sized carrying many MASCOT elements and philosophies, was already studied by JAXA and DLR for the OKEANOS Solar Power Sail mission to a Jupiter Trojan asteroid.

5. Discussion

Solar sail missions based on the GOSSAMER design principle, and in particular such MNR missions carrying several landers, create a system of systems which includes trajectory design and scientific objectives which can change after launch. Changing objectives will necessarily induce changing levels of maturity in the elements of mission design and mission control because already established decisions, optimizations or command sequences are invalidated and have to be recreated in a new form. This poses new challenges to system engineering. Based on the experience with a large number of MASCOT follow-on studies, and the development of MASCOT itself which involved the convergence of subsystems with vastly different maturity levels at project kick-off, it appears possible that these challenges can be tackled by modern system engineering (SE) methods such as concurrent engineering (CE) and model-based system engineering (MBSE). In studying and creating flexible and responsive solar sail missions for MNR and other tasks, these methods need to be adapted and extended to include aspects of spaceflight not yet covered by SE methods develped for hardware and software design. [29][30][3]

6. Conclusions

Building on our studies of solar sail based and nanolander supported multimple NEO rendezvous missions we outline ways to realize further steps in system engineering methods development towards fully eveloved and optimized mission designs integrating hardware, software and trajectory design. Near-term sails, with the perspective of flying sails as soon as possible to create a base of practical experience in time for full-scale planetary science missions, are seen as a necessary path to substantiate these concepts by practice. It appears essential for success in these endeavours to maintain an active small spacecraft oriented programme to continue development of all relevant methods and technologies with frequent flights to prove the principles. To really move ahead without losing the experience and knowledge accumulated in the project teams, missions need to be flown in a development cycle many times shorter than the average career lifetime in the space business. When the asteroid comes – whether it is headed for Earth impac or just very interesting scientifically –, there may not be enough time for a new generation to learn it all yet over again.

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