



Grundmann, J. T. et al. (2019) Small Spacecraft Based Multiple Near-Earth Asteroid Rendezvous and Landing with Near-Term Solar Sails and ‘Now-Term’ Technologies. In: 69th International Astronautical Congress, Bremen, Germany, 1-5 Oct 2018, pp. 2071-2087. ISBN 9781510881655

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Deposited on: 22 September 2018

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IAC-18-A3.4B.6

Small Spacecraft Based Multiple Near-Earth Asteroid Rendezvous and Landing with Near-Term Solar Sails and ‘Now-Term’ Technologies

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Abstract

Physical interaction with small solar system bodies (SSSB) is the next step in planetary science, planetary in-situ resource utilization (ISRU), and planetary defense (PD). It requires a broader understanding of the surface properties of the target objects, with particular interest focused on those near Earth. Knowledge of composition, multi-scale surface structure, thermal response, and interior structure is required to design, validate and operate missions addressing these three fields. The current level of understanding is occasionally simplified into the phrase, "If you've seen one asteroid, you've seen one asteroid", meaning that the in-situ characterization of SSSBs has yet to cross the threshold towards a robust and stable scheme of classification. This would enable generic features in spacecraft design, particularly for ISRU and science missions. Currently, it is necessary to characterize any potential target object sufficiently by a dedicated pre-cursor mission to design the mission which then interacts with the object in a complex fashion. To open up strategic approaches, much broader in-depth characterization of potential target objects would be highly desirable. In SSSB science missions, MASCOT-like nano-landers and instrument carriers which integrate at the instrument level to their mothership have met interest. By its size, MASCOT is compatible with small interplanetary missions. The DLR-ESTEC Gossamer Roadmap Science Working Groups' studies identified Multiple Near-Earth asteroid (NEA) Rendezvous (MNR) as one of the space science missions only feasible with solar sail propulsion. The Solar Polar Orbiter (SPO) study showed the ability to access any inclination, the Displaced-L1 (DL1) mission operates close to Earth, where objects of interest to PD and for ISRU reside. Other studies outline the unique capability of solar sails to provide access to all SSSB, at least within the orbit of Jupiter, and significant progress has been made to explore the performance envelope of near-term solar sails for MNR. However, it is difficult for sailcraft to interact physically with a SSSB. We expand and extend the philosophy of the recently qualified DLR Gossamer solar sail deployment technology using efficient multiple sub-spacecraft integration to also include landers for one-way in-situ investigations and sample-return missions by synergetic integration and operation of sail and lander. The MASCOT design concept and its characteristic features have created an ideal counterpart for this and has already been adapted to the needs of the AIM spacecraft, former part of the NASA-ESA AIDA mission. Designing the

combined spacecraft for piggy-back launch accommodation enables low-cost massively parallel access to the NEA population..

Keywords: multiple NEA rendezvous, solar sail, GOSSAMER-1, MASCOT, small spacecraft, asteroid sample return

1. Introduction

Any effort which intends to physically interact with specific asteroids requires understanding at least of the composition and multi-scale structure of the surface layers, sometimes also of the interior. Mobile Asteroid Surface Scout (MASCOT)-like landing modules and instrument carriers can provide a first access [1][2][3][4]. They integrate at the instrument level to their mothership and are compatible with small interplanetary missions. [5][6] The DLR (German Aerospace Center) – ESTEC (European Space Research and Technology Centre) GOSSAMER Roadmap NEA Science Working Groups studied small spacecraft concepts. Multiple NEA Rendezvous (MNR) was identified as a science mission only feasible with solar sail propulsion [7], like a Solar Polar Orbiter (SPO) [8] and a Displaced L1 (DL1) spaceweather early warning mission [9]. These and many other studies outline the unique capability of solar sails to provide access to all SSSB, at least within the orbit of Jupiter. Since the original MNR study, significant progress has been made to improve multiple NEA rendezvous trajectories. [10]

Although it is comparatively easy for solar sails to reach and rendezvous with objects in any inclination and in the complete range of semi-major axis and eccentricity relevant to NEOs and PHOs (Potentially Hazardous Object), it remains notoriously difficult for sailcraft to land on or interact physically with a SSSB target. The German Aerospace Center, DLR, recently brought the GOSSAMER solar sail deployment technology to qualification status in the GOSSAMER-1 project [11]. Development of deployment technologies continues on the GoSOLAR large photovoltaic arrays. [12][13]

The idea of an outward propulsive force of sunlight, and thus the concept of sunlight as a practical source of energy, goes back to Kepler's observations and remarks published in 1619 on the directionality of comets' tails [14]. It was predicted to equal magnitude in 1873 by Maxwell on the basis of his electromagnetic theory [15] and in 1876 by Bartoli based on the Second Law of Thermodynamics [16]. The same year, the foundations for modern semiconductor-based electronics and photovoltaics were laid by Adams's and Day's discovery of an electrical current driven by selenium exposed to light. [17][18]

Kepler's propulsive force was finally experimentally demonstrated as pressure due to radiation by Lebedev in 1901 [19] and by Nichols and Hull in 1903 [20]. Solar sailing as a method of space propulsion was proposed repeatedly throughout the 20th century [21], beginning with Oberth and Tsiolkovsky in 1923 and 1924,

respectively [22][21]. The term 'solar sailing' as such was only introduced by Garwin in 1958 [23] when it was considered a key option to go beyond Mars or Venus. At the same time, photovoltaics developed from a curiosity [24][175][176] to the key power source in space, with very few recent exceptions such as [25][26][27][28][29], and the discovery of gravity-assist trajectories made the solar system accessible to immediately available launch vehicles [30]. The disruptive paradigm change from a mostly inaccessible solar system requiring nuclear-electric spaceships [31][32] to the Voyager missions within less than two decades firmly established the combination of chemical propulsion and gravity-assist as the foundation of solar system exploration [33][34][35][36][37][38] from Earth [39][40][41]. The need to fit space probes into the fairings of existing launch vehicles also advanced electronics design [42][43][44] and relegated nuclear power sources to small size and the outer solar system [45], beyond the extending reach of developed photovoltaics. [177][178][179] Electric propulsion took until the 1990s to make it into any mission, on photovoltaic power. [40][47][48][49][50][238] So far, solar sails only flew as simplified and/or sub-scale demonstrators in orbit. [51] The sole exception is the Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) [52][180], which accompanied JAXA's atmosphere observation orbiter, AKATSUKI, to Venus. The IKAROS first demonstrated solar sail effect in space, successfully and as predicted. It also performed the first gravity-assist of a solar sail on December 8th, 2010, passing Venus at 80800 km distance and achieving about 20° deflection of the trajectory.

The development of solar sail technology has been ongoing at DLR for many years at varying levels of intensity since the 1990s. A first phase culminated in a successful ground deployment test of a (20 m)² boom-supported sail on December 17th, 1999, in hope of near-term science missions such as ODISSEE and GEOSAIL which did not materialize. [53][54][55][56][57][58][59][60] Subsequently, the DLR-ESA (European Space Agency) GOSSAMER Solar Sail Technology Roadmap was initiated in 2009 to develop the technology independently from any mission to a TRL (Technology Readiness Level) acceptable for participation in science missions. [61][62] A three step approach from deployment demonstration (GOSSAMER-1) via control technology demonstration and selection (GOSSAMER-2) in safe orbits (cf. [63]) to a demo mission proving the principle in near-Earth space (GOSSAMER-3) was envisaged. GOSSAMER-1 was

brought to EQM (Engineering Qualification Model) status in an intense integration and verification campaign (cf. [64]) leading to TRL5 status [65] (according to [66], cf. also [66][67][68][69][70][71] for other commonly used TRL definitions) on which we report on it separately at this conference. [181][173] The further development of deployment technologies will focus on membrane-based solar arrays using thin-film photovoltaics. [12][72][73][182][240]. The research and testing of the materials used in solar sails as well as other membrane-based large-scale deployable structures is meanwhile continued [115][118][163][183] (for background information also cf. [232][112][113][114][116][117]).

2. Motivation

The recent achievements in solar sail trajectory design [10][184][185] (cf. [238]) and sailcraft hardware development [13] [52] [74] [75] [76] [77][78][79][80][81][186][187][188][189][190][191][192][193] made clear that a point has been reached where a review of the results and ongoing efforts should be made for a determination which road they should take. The development towards this point happened during more than a decade, on the background of a sustained resurgence of interest in small solar system bodies (SSSB), with the successful conclusion of the HAYABUSA and ROSETTA/PHILAE missions, the launch of HAYABUSA2 [39] with the small lander MASCOT aboard [1], the launch of OSIRIS-REx [41], the flight of the IKAROS [52] [74] [75] [76] [77], and the first steps towards a long-term Solar Power Sail (SPS) propelled sample-return mission to the Trojan asteroids of Jupiter [78][79][80].

Among small solar system bodies, the near-Earth asteroids (NEA) in many ways may hold keys to our future on Earth and in space and merit exploration for planetary science, planetary defense, and possibly asteroid mining.

2.1 Small Spacecraft

From around 1985 onwards, small spacecraft and affordable rideshare launch options emerged. [82] We define small space probes in analogy to small Earth satellite class definitions on which there is no consensus, yet. [83] [84] [85] [86] With the additional requirements for propulsion and communication of space probes, we rely on a practical combination of criteria based on launch accommodation [87][88], as well as key design concepts associated with the respective Earth-orbiting small spacecraft. [3] We use the SI (Système international d'unités, International System of Units) unit prefixes for spacecraft smaller than 'minisatellites'. Consequently, we classify MASCOT (9.8 kg) and its derivatives as 'nanolandings' and PHILAE (96 kg) as a 'microlander', [3] also for the

similarity in design with highly compact microsatellites such as BIRD (92 kg) [89], TET-1 (110 kg) [90], or AsteroidFinder (~127 kg) [91].

The design-driving constraints apply mainly to the launch configuration of the sailcraft. Thus, we define 'micro' sailcraft as those which fit launch opportunities using the U.S. ESPA (EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter) small spacecraft rideshare platform and/or the various Arianespace ASAP (Ariane Structure for Auxiliary Payload) and VESPA (Vega Secondary Payload Adapter) platforms' 'micro' positions, and 'mini' sailcraft as those which fit the respective platforms' 'mini' positions. [87] [88] 'Nano' sailcraft would be those small enough to ride in place of cubesats, such as NEAscout [81]. Together, we refer to all of these as 'small' sailcraft.

2.2 Multiple NEA Rendezvous (MNR)

A near-term mission scenario for solar sails is the multiple NEA rendezvous (MNR) [10] identified already by the DLR-ESTEC GOSSAMER Roadmap NEA Science Working Groups' studies as one of the space science missions presently only feasible with solar sail propulsion. [7] Solar Polar Orbiter (SPO) [8], Displaced L1 (DL1), spaceweather early warning mission [9], and retrograde kinetic impactor [97][98][99] studies showed the ability to access any inclination and a wide range of heliocentric distances. Current MNR trajectory studies visit 5 different NEAs in a rendezvous scenario for >100 days, each, with one near-term first-generation sailcraft within 10 years from Earth departure ($c_3 \geq 0$). [10] This rendezvous duration is comparable to the mission scenario of AIM (Asteroid Impact Mission) at the binary NEA (65803) Didymos. [92] The sequence of asteroids to be visited can be changed easily and on a daily basis for any given launch date and even after launch and between rendezvous. [10]

3. MNR Mission Scenario

Therefore, a sailcraft carrying a set of five MASCOT landers based on a common design but differently equipped with science instruments and landing or mobility related systems appears desirable. Which lander is used can be decided after arrival at the target asteroid. Many features of the MASCOT lander design can be shared with the core sailcraft and its four boom-sail deployment units (BSDU) Indeed, this sharing of design elements and heritage has been done already, for the GOSSAMER-1 EQM BSDU and the ROBEX lunar-analog demonstration mission scientific Remote Units (RU) design. [93][194] The economy of scale is obvious considering that one such mission would already consist of 10 independent sub-spacecraft physically connected at launch but to be separated step-by-step throughout the mission. The initial connection

also enables resource-sharing between all initially connected as well as those still connected throughout cruise.

Table 1 shows the mission parameters for the sequence shown in the reference paper Pelsoni et al. [10] at a characteristic acceleration of 0.2 mm/s² which is within the capability of current and near-term sailcraft technology by Seefeldt et al. [11]. Only NHATS (Near-Earth Object Human Space Flight Accessible Targets Study) and PHA asteroids were considered with parameters obtained from [95][96]. It is worthwhile to note that the arrival at 2014 MP after 3431 days or nearly 9.4 years is not necessarily the end of the mission, nor is it the 222-day stay there still within the 10-year trajectory design goal. The visit at 2014 MP may well be followed by another departure and more journeys to and stays at other NEAs, as long as the sailcraft remains flightworthy.

Table 1. Mission parameters for the considered sequence. (For parameters passed from sequence-search algorithm to optimizer see [10]).

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
2000 SG ₃₄₄	123	10 May 2025	26 Feb 2027	657
2015 JD ₃	164	29 Jun 2027	06 Sep 2028	436
2012 KB ₄	160	18 Feb 2029	24 Sep 2030	584
2008 EV ₅	171	04 Mar 2031	29 Sep 2032	576
2014 MP	//	20 Mar 2033	30 Sep 2034	560

A return leg to the Earth instead of 2014 MP extends the total mission duration slightly to 4131 days (11.3 years,— Figure 1). The duration of the mission does not depend on a finite amount of fuel aboard. It only depends on the quality of the spacecraft and the interest in its continued operation (cf. [94]).

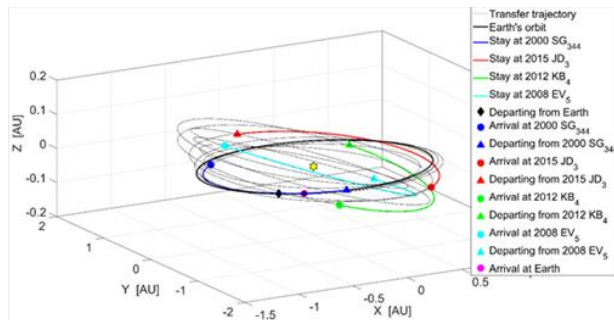


Fig. 1. 3D view of the complete Earth-return trajectory

3.1 The Unknown Unknowns

It is worth noting how little is known about all the asteroids mentioned above that would be of use to a highly optimized spacecraft design. Presently, 2008 EV₅ is the only one for which a shape model is available

[100] which can be used together with the other few known parameters [101][102] to calculate a likely asteroid thermal environment, see Figure 2 below. [195]

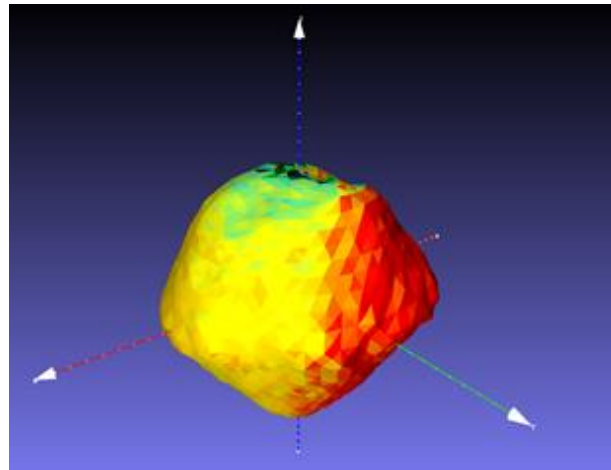


Fig. 2. Surface thermal model of (341843) 2008 EV₅

Thus, the design of the spacecraft, and in particular the landers, needs to be very robust and anticipate a very wide variation of the conditions on the ground, cf. [145][146][147][148][196][197][198]. MASCOT can already cope with the rather strong seasonal variations on Ryugu. [199][128][200]

4. GOSSAMER-style Integrated Landers

A key design feature of GOSSAMER solar sails is the Boom Sail Deployment Unit (BSDU) which is moving away from the Central Sailcraft Unit (CSCU) to uncoil the booms and unroll and unfold the sail segments. During deployment, four BSDUs synchronously move away from the central bus unit, each with two spools on which one half of either adjacent sail is stowed. The BSDUs communicate and exchange power through a wired interface while attached to the CSCU. After the connections are separated, the 5 sub-spacecraft communicate in a wireless network. (For a detailed discussion see [11][13][103][104][105][106][107][108][109][110][111][173][174][181] and references therein.)

This communication and Charging Network (CN) can be extended to more than 5 nodes, to support landers attached to the CSCU after sail deployment. GOSSAMER-1 already supports non-separable attached high data rate devices, the deployment monitoring cameras. [140][141][142]

4.1 Landers

It is assumed that landers are separated from the carrying sailcraft like MASCOT from HAYABUSA2, by a pre-set spring force. The solar sail trajectory is to ensure that the separated lander arrives at its target similar to MASCOT2 on AIM. [2] The sail may be in

very slow fly-by, or in a stable solar-radiation-pressure displaced orbit or station-keeping. [120][121][122] Genuine proximity operations of a solar sail likely pose significant challenges and depend critically on sail attitude control methods yet to be proven in flight. Alternatively, a self-propelled lander needs to be used. At the asteroid, the sail would be parked at a safe distance and detach the self-propelled spacecraft for all proximity operations. The spin-deployed JAXA Solar Power Sail follows this concept.

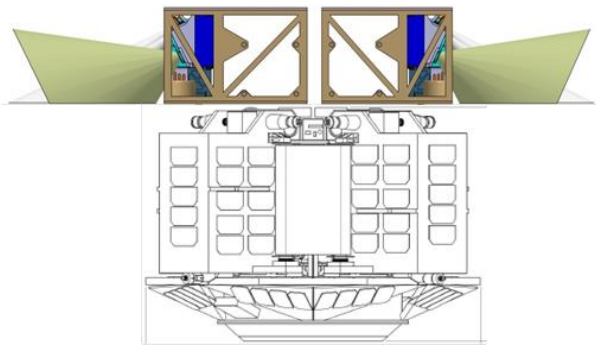


Fig. 3. Notional accommodation of MASCOT-style nanolanders aboard a GOSSAMER-style microsailcraft

MASCOT – DLR in collaboration with the French space agency, CNES, has developed the Mobile Asteroid Surface Scout, MASCOT, a small one-way asteroid lander which packs four full-scale science instruments and relocation capability into a shoebox-sized 10 kg spacecraft. [1] It carries the near-IR soil microscope, MicrOmega, (MMEGA), [201][124][202] a high dynamic range black-and-white camera with night-time multicolour illumination (MasCAM), [125] a 6-channel thermal IR radiometer (MARA), [126][143] and a fluxgate magnetometer (MasMAG). [127] MASCOT is an organically integrated high-density constraints-driven design built in a short time using concurrent engineering methods. (For a detailed discussion see [129][130][131][132][133][134][135][136][137][138][203][204][205][239]) MASCOT2 is a long-life derivative for ESA's AIM orbiter [165] of the joint NASA-ESA AIDA (Asteroid Impact & Deflection Assessment) mission [166][167] including the DART kinetic impactor test spacecraft [168]. A Low Frequency Radar [139][169][170][171] and an accelerometer (cf. [206][207][233][234][235][236]) replace MMEGA to study the interior of the impact target (65803) S1 'Didymoon' before and after impact. MASCOT2 was developed using the DLR Bremen Concurrent Engineering Facility (CEF). [208][209][210]

A Shuttling Sample-Retrieval Lander – NEA samples of the asteroids visited can be returned by one larger lander shuttling between the NEAs and the

sailcraft. Technologies to pick up and transfer asteroid samples already exist, and landing gear development can build on the lessons learned from Philae [211][212][207]. It was demonstrated by the HAYABUSA mission, and has been further developed for HAYABUSA2 and OSIRIS-REx. We evolve our design from the lander design for the JAXA Solar Power Sail mission to pick up samples from a Jupiter Trojan asteroid which emphasizes in-situ analysis of samples due to the very long duration return journey. [149][150] For the MNR scenario, a reduced in-situ suite of instruments can be considered due to shorter mission duration facilitating sample return to Earth. [174][213][214][215] Figure 4 shows the first sample retrieval cycle of such a lander.

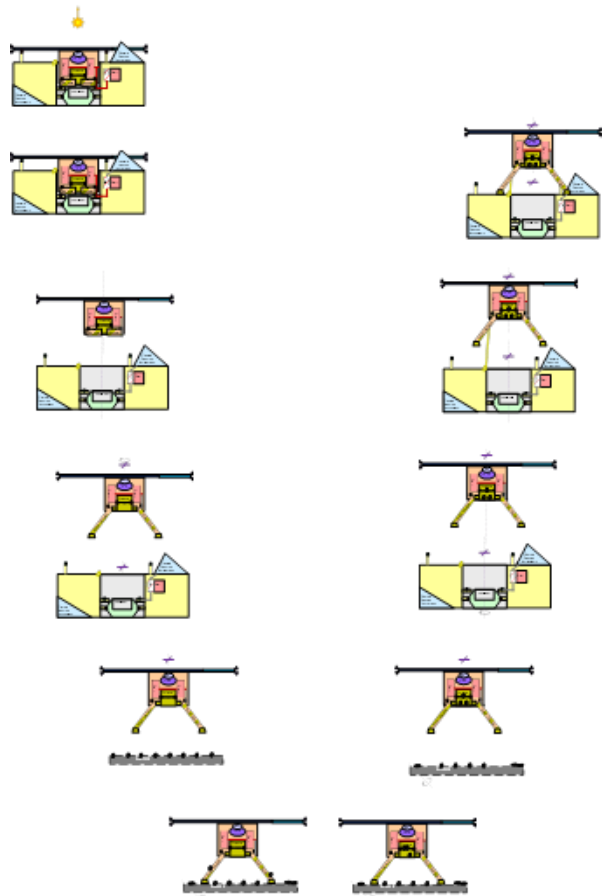


Fig. 4. Concept of operation of a shuttling microlander aboard an advanced minisailcraft, first deployment and sample retrieval followed by berthing and transfer

Once a propelled lander package is available which can return to its mothership, the same technology can be used to extend the amount of knowledge returned by asteroid fly-bys, particularly from dedicated and multiple fly-by missions, [216][217][218] by viewing the fly-by target(s) from more than one perspective. Where the resources are not available, e.g. for fly-bys of

opportunity [219][220][221][222][223][224] or at large distances, [225][237] a more MASCOT-like one-way package could be used.

4.2 Resource Sharing of Lander(s) and Sailcraft

Following the BSDU-CSCU concept of GOSSAMER-1, many resources can be shared with the CSCU in cruise and the CSCU-BSDUs before sail deployment. Landers which have to expect rough terrain and unexpected shadowed areas (cf. PHILAE) require a relatively large battery while a deployed sailcraft operating in deep space in almost all cases of nominal operation only needs a relatively small battery. Thus, the batteries of the still-attached lander(s) can support the CSCU during deployment of the sail membrane and booms when the BSDUs have already separated from it.

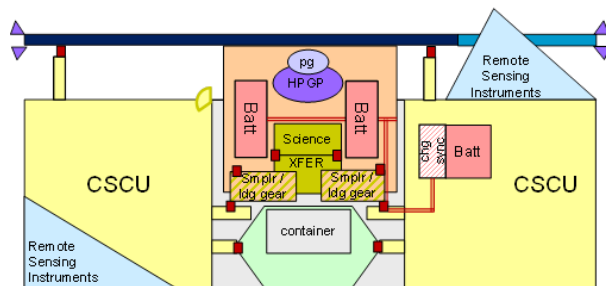


Fig. 5. Notional accommodation of a multiple sample-return microlander aboard an advanced minisailcraft with shared use of CSCU pre-deployment photovoltaics, battery, and lander propulsion

Similarly, the sailcraft can generate its power after deployment from ultra-lightweight membrane-mounted photovoltaics similar to the GOSOLAR technology currently under development. [12] The landers' photovoltaics generators exposed to the outside in launch configuration and after BSDU separation can therefore be used as a significant part of the pre-deployment and in-deployment power supply of the CSCU.

Science instruments of the landers, in particular panoramic cameras and thermal infrared sensors, can provide services on an operational spacecraft which are normally only designed into demonstrator spacecraft to monitor sail deployment and membrane ageing, cf. [13][151][164] and Fig. 3. Suitably designed and/or oriented instruments of the landers still attached can also double as 'orbiter' instruments, e.g., to monitor the asteroid in the vicinity of the sailcraft without the need to turn it for the pointing of a boresighted sailcraft camera. These and more opportunities for resource sharing can be used to adapt lander designs similar to MASCOT, PHILAE, or the Solar Power Sail Trojan lander into GOSSAMER-style-integrated sub-spacecraft performing a common mission. Figure 5 shows an example of this concept of sailcraft-lander integration,

including representations of the functional units mentioned above.

5. Planetary Defense Exercises

In the context of the 2017 Planetary Defence Conference, the scenario of a diversion from an ongoing MNR mission towards a newly discovered impactor was studied, based on the in-flight target change flexibility unique to solar sailing. Due to its early impact in 2027, this PDC's fictitious impactor 2017PDC requires more extensive modifications of the MNR sequence presented above, which we for now have to relegate to future work.

However, two potentially useful trajectories were found while at the PDC. A rendezvous with 2017PDC, 3 years after the fictitious impact was found from another sequence to 2005 TG₅₀, 2015 JF₁₁, 2012 BB₄ and 2014 YN, diverting after the second target and requiring a much higher characteristic acceleration. This could be used to determine the precise post-deflection trajectory of the asteroid. A fast fly-by of 2017PDC, 3 months before the fictitious impact was also found. This could be used to assess the state of the asteroid after deflection and to look for undetected objects from a partial disruption.

The asteroid 2011 AG₅ used for the PDC'13 exercise [152] more easily matches the existing 5-NEA-sequence. [10] The last leg to 2014 MP shown in Table 1 has again been removed to add a leg to the potentially hazardous asteroid 2011 AG₅, which was one of the two case studies considered during the Planetary Defense Conference 2013 for which the fictitious impact was expected to occur on February 3rd, 2040. A methodology similar to the one described in Sullo et al. [153][154][155][156][226] has been used for this study. The total mission duration is now 4398 days, about 12 years, and the sailcraft arrives 2011 AG₅ on May 25th, 2037, about 3 years before the fictitious impact. [174]

The deflection scenarios considered in this exercise were of a conventional propulsion type. However, it would be possible to combine the solar sail technologies discussed here for MNR, tuned and optimized for deflection trajectories [97][98][99] with parallel advances in kinetic impactor guidance technology [227][228][229][230] also using small spacecraft concepts [123].

High velocity launch – Due to the mass and deployment requirements of solar sailing, the resulting spacecraft launch configuration can be very compact. A typical MNR design would fit 'micro' secondary passenger slots of launch vehicles flying to GTO. Escape from GTO to $c_3 > 0$ offers the advantage of less

time spent in the radiation belts. Dedicated launches would be an option in the case of missions requiring an extremely high c_3 and/or reduced flight time to target. Based on the current performance of Ariane 5 ECA [119], the performance for a maximum velocity escape trajectory has been calculated. For a dedicated launch, all unnecessary standard equipment units were removed. The performance for different c_3 values and an inclination of 6° (Kourou) were calculated for payloads of 500 kg, 250 kg, and 50 kg, which respectively can be injected on escape trajectories with a c_3 of up to approximately $56 \text{ km}^2/\text{s}^2$, $60 \text{ km}^2/\text{s}^2$, and $64 \text{ km}^2/\text{s}^2$. Still higher velocities can be achieved by adding upper stages similar to the launch configuration of NEW HORIZONS [174] or LISA Pathfinder. [231]

6. Future Work

We have here collected the building bricks required to begin a wider exploration of our neighborhood by surveying the members of the solar system nearest to Earth for planetary science, planetary defense and planetary resources.

The development of MNR trajectories has reached a point where it enables rendezvous with NEAs for 100-day in-situ investigations every 2 years per spacecraft, using solar sail propulsion alone from the rim of Earth's gravity well. [10] Small spacecraft technology enables shoebox-sized one-way landers [1] and fridge-sized sailcraft [11] able to perform these MNR trajectories. By a modest increase in size, samples can be returned to Earth using the same basic technologies. [5] Current large launch vehicles can carry half a dozen or more of these lander-equipped sailcraft at once in their performance margins to geostationary transfer orbit where only a small push is required to escape Earth, on a mass-available basis. [88][87] By adding just one stage, the same class of launch vehicles can accelerate one such small spacecraft directly to a solar escape trajectory in the ecliptic plane. However, due to gravity-assist trajectories [33], most exploration missions don't require this kind of kickstart. [30]

So far, these bricks stand largely independent of each other. In most cases, the reason is simply that any one of these tasks alone is already difficult enough. But some bricks are getting connected, gravity-assist sequencing begins to ask for low-thrust propulsion, and vice-versa, to widen the tight and sometimes rare launch windows or to give a boost to calmly spiraling trajectories, e.g. [158][159][160][161]. The resulting system-level trade works favorably for the missions which enter such negotiations. [39][41] The tools for much more complex trades connecting many domain models are created by the development of Model-Based System Engineering. [3][162]

It appears that a much easier access to the solar system as well as near-Earth space, much less

constrained by launch windows or payload to target or thrust limitations, can be achieved by connecting all these bricks – small spacecraft technology, solar sail propulsion, solar-electric propulsion, high-energy escape launch systems – by comprehensive modelling, simulation, optimization, and most importantly practice in flight. The MNR mission based on small spacecraft solar sails and landers it is a most affordable entry level to practice their connection into one system.

This future work can start now.

7. Conclusions

We outlined a synergetic development path of small spacecraft solar sails and nano-scale asteroid landers enabling a substantial increase in the number of NEAs studied by planetary science in a dynamic manner which allows in-flight adjustment of the choice of rendezvous targets. The capability to change targets in flight also allows a mission already in flight to respond to extreme events such as a probable Earth impactor being discovered. It may also follow changing commercial interest in this manner. Within the capabilities of near-term first-generation sailcraft technology, the small spacecraft design concepts of GOSSAMER-1 and MASCOT enable a sailcraft performance sufficient to achieve 5 NEA rendezvous of at least 100 days, each, in 10 years by one spacecraft. Each rendezvous includes a target-adapted one-way nano-lander delivery or a sample pick-up at each target by a larger shuttling lander.

The small spacecraft approach enables the use of surplus launcher payload capability in the geostationary and high Earth orbit market with a potential of 10's of launches per year. If the spacecraft concept here presented were serialized in a manner akin to similar-sized communication satellite constellation spacecraft, the number of NEAs visited and studied in-situ could be increased by orders of magnitude within a few decades.

On the other hand, the small mass of small spacecraft solar sails also enables very high launch energy missions based on available geostationary market launch vehicles which can combine into fast, responsive and affordable missions to the most challenging targets of the solar system, including planetary defence scenarios.

Many of the technologies required for currently considered large space infrastructure and flagship science mission scenarios can be developed, brought to maturity (i.e., TRL9) and first fielded at low cost by continuing their development in entry-level applications in small spacecraft. Small solar sails in combination with small lander modules share many of these critical technologies and challenges.

Acknowledgements

The authors acknowledge the inspiring effort of the flights of HAYABUSA and IKAROS, the JAXA Solar Power Sail mission study to the Jupiter Trojan asteroids, and the ‘extra mile’ walked by all the participants of the solar sail studies of the past two decades at DLR and partners.

The corresponding author would like to thank Christian Gritzner, Ralph Kahle and Stefano Mottola for continuous support in learning more about small solar system bodies for the benefit and safe keeping of our not quite so small solar system body home.

The GOSSAMER/GOSOLAR team would like to thank Antonio Martelo Gomez for the GOSOLAR CEF & logo design of the 60th CEF campaign at DLR Bremen, and its derivatives generously provided.

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