Small Spacecraft Solar Sailing for Small Solar System Body Multiple Rendezvous and Landing


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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 and a wide range of heliocentric distances, with a separable payload module delivered by sail to the proper orbit. The Displaced-L₁ (DL₁) spaceweather early warning mission study sailcraft operates close to Earth, where all objects of interest to PD must pass and low delta-v objects 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. For example, the MASCOT Mobility hopping mechanism and its power supply concept have already been adapted to the specific needs of MASCOT2 which was to be carried on the AIM spacecraft of ESA as part of the NASA-ESA AIDA mission to binary NEA Didymos. The methods used or developed in the realization of MASCOT such as Concurrent Engineering, Constraints-Driven Engineering and Concurrent Assembly Integration and Verification enable responsive missions based on now available as well as near-term technologies. Designing the combined spacecraft for piggy-back launch accommodation enables low-cost massively parallel access to the NEA population.

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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’ 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 Tsioflovsky 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] 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] Electric propulsion took until the 1990s to make it into any mission, on photovoltaic power. [40][47][48][49][50] 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], 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 demonstraion 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][66][67][68][69][70] on which we report on it separately at this conference. [173] The further development of deployment technologies will focus on membrane-based solar arrays using thin-film photovoltaics. [12][71][72][73]
2. MOTIVATION

The recent achievements in solar sail trajectory design [10] and sailcraft hardware development [13] [52] [74] [75] [76] [77][78][79][80][81] 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 ROSSETTA/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 analog 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 'nanolanders' and PHILAE (96 kg) as a 'microlander', 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 Ariane-space 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 (cₚ ≥ 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] 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 Peloni 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]).

<table>
<thead>
<tr>
<th>Object</th>
<th>Stay time [days]</th>
<th>Start</th>
<th>End</th>
<th>Time of flight [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td></td>
<td>10 May 2025</td>
<td>26 Feb 2027</td>
<td>657</td>
</tr>
<tr>
<td>2000 SG344</td>
<td>123</td>
<td>29 Jun 2027</td>
<td>06 Sep 2028</td>
<td>436</td>
</tr>
<tr>
<td>2015 JD3</td>
<td>164</td>
<td>18 Feb 2029</td>
<td>24 Sep 2030</td>
<td>584</td>
</tr>
<tr>
<td>2012 KB4</td>
<td>160</td>
<td>04 Mar 2031</td>
<td>29 Sep 2032</td>
<td>576</td>
</tr>
<tr>
<td>2008 EV5</td>
<td>171</td>
<td>20 Mar 2033</td>
<td>30 Sep 2034</td>
<td>560</td>
</tr>
</tbody>
</table>

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] to calculate a likely asteroid thermal environment, see Figure 2 below.

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]. MASCOT can already cope with the rather strong seasonal variations on Ryugu.

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 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][112][113][114][116][117][118][173][174] 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 ensures 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), [124] 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. (For a detailed discussion see [129][130][131][132][133][134][135][136][137][138]) MASCOT2 is a long-life derivate 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 replace MMEGA to study the interior of the impact target (65803) S1 ‘Didymoon’ before and after impact.

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. 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] Figure 4 shows the first sample retrieval cycle of such a lander.

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](image-url)

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 subspacecraft 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 TG₉₀, 2015 JF₉₁, 2012 BB₄, and 2014 YN, diverting 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] 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]

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 c₃ > 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 c₃ 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 c₃ 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 c₃ of up to approximately 56 km/s², 60 km/s², and 64 km/s². Still higher velocities can be achieved by adding upper stages similar to the launch configuration of NEW HORIZONS. [174]

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.

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Domnik Quantius completed his diploma in mechanical engineering, majoring in aerospace, at the Technical University of Aachen (RWTH). Since 2007 he is scientific employee in the System Analysis Space Segment department of the German Aerospace Center Institute of Space Systems with concentration on Concurrent Engineering (CE), mission analysis and life support systems. Being part of the core team of the CE facility at DLR Bremen, he was involved in more than 30 CE studies as mission analyst, systems engineer or team leader and is trained in project management and systems engineering. Since 2011 he is giving lectures for spaceflight dynamics at the University of Bremen. Since 2013 he is heading the group Concept Development for Satellites & Human Spaceflight and was technical manager of the DLR POST-ISS project - an architectural study for the continuation of astronomical research in Low Earth Orbit.

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Kaname Sasaki received his Master degree in Aerospace Engineering from Tokyo University, Japan. Since 2013 he works at the department of Mechanics and Thermal Systems of the DLR Institute of Space Systems in Bremen, Germany. He has been involved in the development and testing activities for the asteroid lander MASCOT, the DLR payload HP³ as part of the NASA/JPL Mission INSIGHT and the membrane-based deployment systems in the GOSSAMER-1. Currently, he works as a system engineer of the MASCOT project, as well as a thermal engineer in the GoSOLAR project.

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Peter Spietz is working on the technological development and adaptation of the membrane-based photovoltaics of GOSSAMER-1 for the project GoSOLAR at the DLR Institute of Space Systems in Bremen, Germany. He was project manager and system engineer of GOSSAMER-1 and the first DLR Research & Development ‘Kompaktsatellit’ project, ASTEROIDFINDER/SSB for which he also led the Phase 0 competitive studies of the payloads CHARM and LIVESAT. Previously, he worked at the Institute of Environmental Physics (IUP) of the University of Bremen on the GOME ozone monitoring instrument series.
Tom Sproewitz is head of the department Mechanics and Thermal Systems of the DLR Institute of Space Systems since 2012. In 2001, he graduated from the Technical University Chemnitz, Germany with a Diploma in Applied Mechanics as part of Mechanical Engineering. After graduation he worked at the DLR Institute of Composite Structures and Adaptive Systems as mechanical engineer until 2009. He was involved in the development, manufacturing and mechanical testing of the ROSETTA-Lander PHILAE as Mechanical Analysis Engineer. Since 2009, he works at the Institute of Space Systems in Bremen with focus on structures, mechanisms, deployment systems as well as environmental testing. He worked as structural engineer on the DLR payload HP³ as part of the NASA/JPL Mission to Mars, IN-SIGHT.

Maciej Sznajder is a scientific co-worker at the department Mechanics and Thermal Systems of the DLR Institute of Space Systems. In 2010 he graduated computational astrophysics at the University of Zielona Góra, Poland. In 2013 he defended Ph.D. in theoretical physics at the University of Zielona Góra and in 2016 a Ph.D. in materials engineering at the Bremen University, Germany. Since 2010, he works in a field of materials degradation mechanisms which take place under space conditions. Currently, he is involved in the technological development of membrane-based deployment systems in the GOSSAMER-I and GOSolar projects at the DLR Bremen.

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Norbert Tóth has studied electrical engineering at the Óbuda University in Hungary. He is working since 2010 at DLR Bremen in the department Avionics Systems. His main interests are embedded system design, HW&SW development and wireless communication for Space Systems. He was the work packet leader (Command and Data Handling, CDH) for GOSSAMER-I and for ROBEX Lander and Remote Unit. Currently he is working on the GOSolar CDH and on the MASCOT checkout, operations.

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Christian Ziach received his Master in aerospace engineering from the University of the German Armed Forces in Munich in 2005 and his Master in Business and Economic Studies from the University of Hagen, in 2011. He served as a military officer tasked as team lead, missile system analyst, and deputy project manager for high altitude long endurance reconnaissance UAV payload introduction. In 2012 he joined DLR to work as system engineer and deputy project manager for the MASCOT asteroid nano-lander currently flying aboard the JAXA probe HAYABUSA2, including related studies such as MASCOT2 on ESA’s AIM orbiter in the joint NASA-ESA AIDA mission and the Jupiter Trojan micro-lander aboard JAXA’s planned Solar Power Sail mission. He also worked as system engineer for the S2TEP small satellite project. Since 2017 he works as an investment manager on high-technology enterprises for High-Tech Gründerfonds, Bonn, Germany.