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-L_1 (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'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] 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 8^{th}, 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][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 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 '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 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] 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]).

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
		10 May 2025	26 Feb 2027	657
2000 SG_{344}	123			
		29 Jun 2027	06 Sep 2028	436
2015 JD_3	164			
		18 Feb 2029	24 Sep 2030	584
2012 KB_4	160			
		04 Mar 2031	29 Sep 2032	576
2008 EV_5	171			
		20 Mar 2033	30 Sep 2034	560
2014 MP	//			

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]).

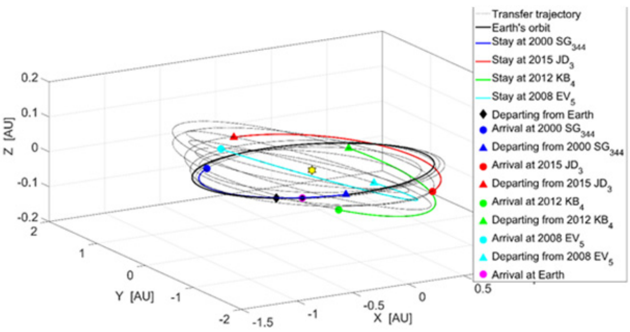

Fig. 1 – 3D view of the complete Earth-return trajectory

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 EV_5 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.

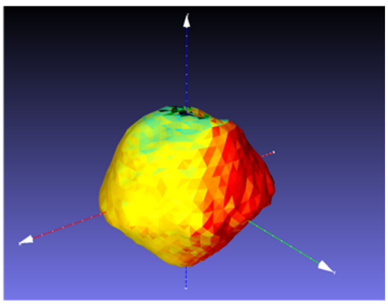

Fig. 2 - Surface thermal model of (341843) 2008 EV_5

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 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 detailled 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.

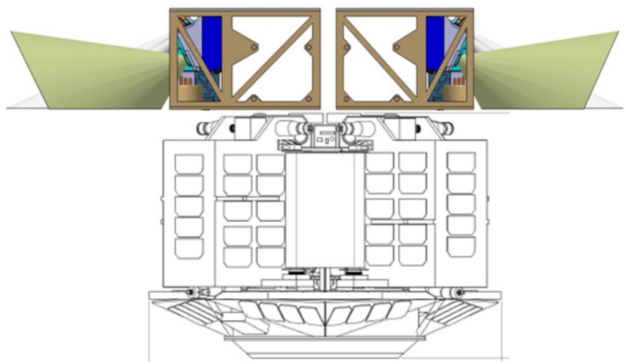

Fig. 3 - Notional accommodation of MASCOT-style nanolanders aboard a GOSSAMER-style microsailcraft

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 detailled 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.

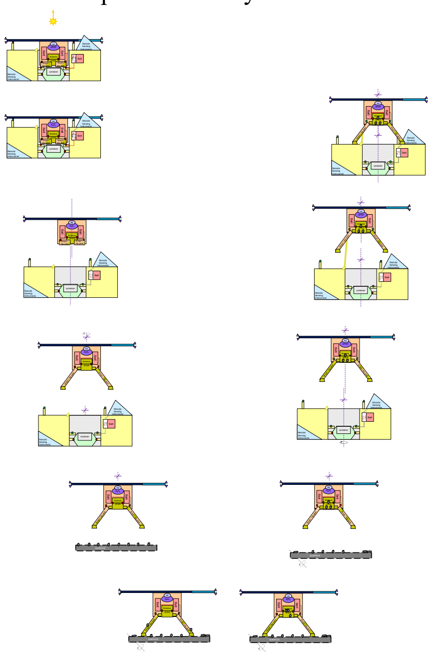

Fig. 4 – Concept of operation of a shuttling microlander aboard an advanced minisailcraft, first deployment and sample retrieval followed by berthing and transfer

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.

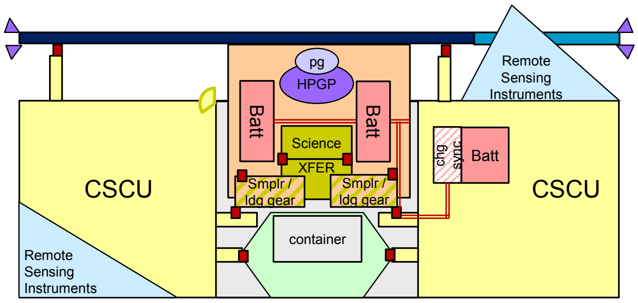

Fig. 5 – Notional accommodation of a multiple sample-return microlander aboard an advanced minisailcraft with shared use of CSCU pre-deployment photovoltaics, battery, and lander propulsion

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-deploment 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 fictious impact was found from another sequence to 2005 TG_{50}, 2015 JF_{11}, 2012 BB_4 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 AG_5 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 AG_5, 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 AG_5 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 $c_3 > 0$ 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 km^2/s^2, 60 km^2/s^2, and 64 km^2/s^2. 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 technolgy, 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 technolgy, 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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Biography

Jan Thimo Grundmann *is a research engineer at DLR for 10½ years. He received a Diploma in Mechanical Engineering – Aerospace Engineering from the RWTH Technical University of Aachen, Germany, in 2006. He works in the projects MASCOT, MASCOT2, Gossamer-1, GoSolar, and ROBEX. He supports system engineering in these projects, related studies, and at the DLR Bremen CEF on electrical topics. He is also pursuing system studies in planetary defence, spacecraft reliability and space project responsiveness.*

Waldemar Bauer *is research engineer at DLR Bremen since 9 years. In 2015, he obtained his PhD in space debris research at the Technical University Braunschweig and the diploma in mechanical engineering – Aerospace Engineering – at the Hochschule Bremen in 2007. He invented a new method, SOLID, for in-situ detection of space debris and micrometeoroids. SOLID is currently undergoing on orbit testing. It is envisaged to implement the sensor on a large number of satellites in different orbits in the future. In 2016 he took over the system engineering task of the DLR project ReFEx. He participated in a large number of feasibility studies using the Concurrent Engineering approach and is involved into the educational activities at the University Bremen.*

Jens Biele *works as a senior staff scientist at DLR (German Aerospace Center) in Cologne, Germany. He is involved in the Rosetta Lander and Hayabusa2 MASCOT lander projects as payload manager and scientist and has also been involved in a number of solar system exploration studies. Before his current position, he spent one year as a Postdoc with the Max-Planck-Institute for Chemistry in Mainz. He obtained his Ph.D. in 1998 in geosciences at the Free University Berlin while doing atmospheric research with the Alfred-Wegener-Institute for Polar and Marine Research. He studied experimental physics at the University of Kaiserslautern and at Imperial College, London. His field of special expertise is cometary science, regolith mechanical properties as well as probes, payloads and small systems, in particular landers, for missions to small bodies in the solar system.*

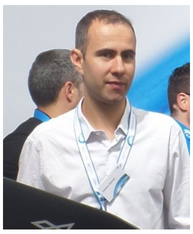
Ralf Boden *received his Dipl.-Ing. from the Technical University Munich, where he has been studying mission architectures and spacecraft design for small body exploration. During his Diploma thesis, Ralf has been working on the development and testing of GNC sensors and other thermal hardware as thermal engineer on DLR's MASCOT asteroid lander team. He joined JAXA's Solar Power Sail study group in 2014, where he worked on the design and development of a robotic lander for the exploration of the Jupiter Trojan asteroids. He received his Dr.Eng. from the University of Tokyo in 2017, on the topic of cold gas propulsion systems for small spacecraft. He is currently working as a lunar lander systems and integration engineer at ispace-inc in Tokyo.*

Kai Borchers *holds a B.Sc. in Computer Science and a M.Sc. in Systems Engineering. Since 2011 he works as a research assistant for the department of Avionics Systems at the Institute of Space Systems of the German Aerospace Center (DLR). His main tasks are the description of FPGA designs and their functional testing with focus on random constraint and assertion-based verification.*

Matteo Ceriotti *received his M.Sc. summa cum laude from Politecnico di Milano (Italy) in 2006 with a thesis on planning and scheduling for planetary exploration. In 2010, he received his Ph.D. on "Global Optimisation of Multiple Gravity Assist Trajectories" from the Department of Aerospace Engineering of the University of Glasgow (United Kingdom). During 2009-2012, Matteo was a Research Fellow at the Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, leading the research theme "Orbital Dynamics of Large Gossamer Spacecraft". In 2012, he returned to the University of Glasgow as a Lecturer in Space Systems Engineering, within the School of Engineering. His main research interests are space mission analysis and trajectory design, orbital dynamics, trajectory optimisation, particularly focusing on high area-to-mass ratio structures.*

Federico Cordero *is a spacecraft system engineer with +25 years' experience in space avionic systems and satellite flight operations. He graduated at the Turin Polytechnic in Computer Science and is working in Telespazio-Vega (Darmstadt)* *since 2000 for supporting ESA in the flight operations for Integral, METOP-B, Gaia, Lisa Path Finder and Euclid missions and in a number of in-house projects related to on-board computer software/hardware development and procurement, among which the DLR MASCOT on-board computer. He previously worked for Thales Alenia (Turin) and Fiat Avio (Turin) as member of the system engineering teams in charge of the avionics for Beppo SAX satellite, SOHO Ultraviolet Spectrometer, Tethered satellite, TCS and ECLSS Columbus manned module, Integral satellite, Cyclone-4 launcher.*

***Dr. Bernd Dachwald** is professor for astronautical engineering at FH Aachen University of Applied Sciences, Germany. He is project director for FH Aachen's IceMole project and lead of the Enceladus Explorer consortium. He is also adjunct lecturer for space systems engineering at RWTH Aachen University. Before his current position, he was mission operations director for SAR-Lupe at the DLR German Space Operations Center at Oberpfaffenhofen and postdoc mission analyst at DLR Cologne. In 2003, he obtained his PhD in aerospace engineering from the University of the Armed Forces Munich for low-thrust trajectory optimization with a novel method that involves neural networks and evolutionary algorithms. He has studied aerospace engineering at the University of the Armed Forces Munich and postgraduate business administration at the University of Hagen. His current fields of scientific research are space mission analysis, design, and optimization, intelligent methods for spacecraft trajectory optimization and attitude control, innovative space technologies (especially solar sails and subsurface sampling), solar system exploration (especially icy moons and small bodies), astrobiology, and planetary defense.*



***Etienne Dumont** studied at ISAE-Supaéro, Toulouse, France and KTH, Stockholm, Sweden from which he obtained in 2009 two degrees both equivalent to Master of Science. After a Master thesis written at ESA ESTEC on LEO constellations for gravity field measurement, he joined in summer 2009 the DLR (German Aerospace Center) Institute of Space Systems in Bremen. As a member of the division for Launch Vehicle System Analysis, he works on the preliminary design of space transportation systems, especially rockets such as Ariane 5 ME, Ariane 6 but also in-space transportation such as Moon landers. Recently he joined the development effort towards a European reusable launch vehicle with the lead of Callisto demonstrator at DLR.*

***Christian D. Grimm** is a research engineer at the German Aerospace Center (DLR), Institute of Space Systems in Bremen, Germany, since 2010. He received his Master degrees in Astronautics and Space Engineering from Cranfield University, UK, as well as in Space Technology from Luleå University of Technology, Sweden. Within the MASCOT Project he functioned as Integration Lead as well as AIV/AIT Manager which he continues to assist the ongoing preparations of the landing Mission in 2018. He currently supports the GoSolAr Project in Systems Engineering as well as in AIV/AIT related matters and within the department of Landing and Exploration Technologies he takes part in multiple design and flight studies as a test engineer, for example the SpaceIL Moon lander for the Google Lunar X-Price or the upcoming JAXA MMX Mission. In addition, he is pursuing now a doctorate degree concentrating on new technologies of advanced small body landers and their supporting mechanisms.*

***David Herčík** is a researcher at the Technical University in Braunschweig, Germany, working at the Institute for Geophysics and extraterrestrial Physics since 2012. He is a project manager for the MASCOT magnetometer, a scientific instrument developed at the institute. He was also involved in other projects as a researcher: Proba 2, SOSMAG, JUICE. He finished his Ph.D. in 2014 at the Technical University in Prague and Czech Academy of Sciences, while working on data analysis from numerical simulations of Solar wind interaction with Mercury. His field of research covers space plasma physics, magnetometry, scientific instrumentation testing, data analysis, and software development.*

***Tra-Mi Ho** received her Ph.D. in Physics from the University of Bern, Switzerland, in 2004. Her research interests are the development of satellite and landing systems, solar system science and exploration She is project manager of the asteroid nano-lander MASCOT currently aboard the JAXA probe HAYABUSA2 to (162173) Ryugu and related follow-on 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. She is head of department of the System Engineering and Project Office at the DLR Institute of Space Systems in Bremen, Germany.*

Rico Jahnke received his diploma in mechanical engineering and aerospace engineering from the University of Applied Sciences of Aachen in 2010 and joined DLR. Currently, he is deputy head of the Mechanical Dynamical Test Laboratory at the DLR Institute of Space Systems, Bremen, Germany. He works on the technological development of membrane-based deployment systems in the GOSSAMER-1 and GOSOLAR projects at the DLR Institute of Space Systems in Bremen, Germany.

Aaron D. Koch received a Master's degree in Mechatronics from the Technical University of Ilmenau in 2006. He has been with DLR for 7 years and is currently a member of the department for Space Launcher Systems Analysis. He has been project leader of the ESA project ATILA. His career started as a trainee in the Thermal and Structures division at ESA/ESTEC.

Alexander Koncz is Project and Systems Engineer at the German Aerospace Centre in Berlin, Germany. He obtained his Dipl.-Ing. in 2006 and his Dr.-Ing in 2012 in Aerospace Engineering from the University of Stuttgart on the subject of design and development of a humidity sensing instrument for the ESA ExoMars mission. He continued his studies as a Project and Systems Engineer for the AsteroidFinder FPA, MASCOT-CAM on Hayabusa 2, ExoMARS PanCAM HRC, JUICE Janus FPM and PLATO F-FEE.

Christian Krause works at the DLR (German Aerospace Center) MUSC (Microgravity User Support Center) in Cologne, Germany. He is involved in the Philae (Rosetta Lander) and HAYABUSA2 MASCOT lander projects, and MASCOT operations at the MASCOT Control Center (MCC).

Caroline Lange is a research engineer in space systems engineering at the German Aerospace Center, Institute of Space Systems in Bremen, Germany, where she started working at the Department of Exploration Systems in 2008. Currently she is a system engineer in the MASCOT project as well as workpackage manager and system engineer for the ROBEX (Robotic Exploration of Extreme Environments) Helmholtz Alliance, where she is responsible for the design of a small generic instrument package for lunar applications. Caroline has an engineer's degree in Aerospace Engineering from the University of Stuttgart and is currently also pursuing her doctorate in space systems engineering.

Roy Lichtenheldt is a research engineer at the German Aerospace Center (DLR), Institute of System Dynamics and Control in Oberpfaffenhofen, Germany. He received his Master degree in Mechatronics from Ilmenau University of Technology. During his work on several planetary exploration missions he obtained his Ph.D. from Ilmenau University of Technology in the field of dynamic simulations. In the institute he is responsible for high fidelity simulations in planetary exploration, terramechanics and the development of DEM software. He is in charge of the dynamical simulations of the INSIGHT HP^3-Mole and contributes to MASCOT and the ROBEX (Robotic Exploration of Extreme Environments) Helmholtz Alliance.

Volker Maiwald has graduated from RWTH Aachen in 2009 and became part of DLR's Institute of Space Systems in early 2010. As a system engineer his main fields of work are system analysis of future spacecraft and mission concepts as well as leading Concurrent Engineering studies in DLR's respective facility, the CEF. In addition he has been a lecturer for spaceflight dynamics at the University of Bremen since 2012 and recently submitted his doctoral thesis focusing on low-thrust trajectory and gravity assist optimization.

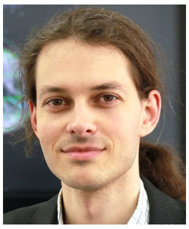
Tobias Mikschl is pursuing a Ph.D. at the University of Wuerzburg in the field of aerospace information technology. His current research concentrates on novel approaches for distributed spacecraft data-systems. He is currently working on the DLR funded innovation project SKITH (Wireless Satellite). Previously he worked on YETE (distributed spacecraft control) and did low level operating system implementations for the Biros satellite.

Eugen Mikulz is the main responsible person for the environmental testing at the DLR Institute of Space Systems in Bremen, Germany. He studied production engineering with the specialization in aerospace at the University of Bremen and reached his Master of Science degree. He was involved in the thermal vacuum or ambient testing in projects like Gossamer, ADEO, MASCOT, INSIGHT and ENMAP.

Sergio Montenegro *is professor and chair of aerospace information technology at the University Würzburg. He received his PhD degree in 1989 from the TU Berlin. In parallel he worked for the Fraunhofer Gesellschaft from 1985 - 2007. After that he changed its position for leading the department "Avionics Systems" of the Institute of Space Systems inside the German Aerospace Center (DLR) until 2010. His research topics are dependable real time distributed control systems with focus on aerospace applications already successful applied in satellites. These developed concepts and systems are currently adapted to UAVs like drones and networks of underwater UAVs.*

Ivanka Pelivan *received her PhD degree in 2013 at the University of Bremen with a thesis about a specialized satellite dynamics and environment simulator for a scientific class of Earth-bound satellites. As a Marie-Curie fellow at Stanford University she applied the developed software library to the relativity mission Gravity Probe B for data post-processing. She currently holds a HGF-Postdoc position that aims at further development of the satellite software library for solar system missions with focus on missions like ROSETTA, HAYABUSA2 and AIM. In 2012 she joined the DLR Institute of Planetary Research and has been actively involved in preparation of data analysis for the Rosetta instrument MUPUS in performing environment thermal modelling. As ROLIS (down-facing camera on ROSETTA's lander PHILAE) operations engineer she was responsible for test and generation of the camera command sequences and camera operation in flight. Currently she also coordinates a work package in the EU Horizon2020 project MiARD.*

Alessandro Peloni *is currently a PhD candidate in Aerospace Engineering at the University of Glasgow, UK. He works on the optimisation of deep-space solar-sail trajectories, with a focus on solar-sailing multiple-asteroid rendezvous mission design. He studied both astrophysics and astronautical engineering at the University of Rome Sapienza, Italy. Recently, he worked as a research assistant at the University of Glasgow, UK, where he developed an analytical mapping between highly non-Keplerian orbits and classical orbital elements.*



Dominik 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 astronautical research in Low Earth Orbit.*

Siebo Reershemius *received his Master Degree in Mechanical Engineering in 2010 and joined the DLR Institute of Space Systems in Bremen, Germany, as a research engineer. His main interests are deployable structures and mechanisms. He was engineer for structural analysis and mechanism development of the institute's first satellite, AISAT-1, launched in 2013, and is lead of the HP³ Support System, which is part of the DLR instrument HP aboard the NASA mission INSIGHT to be launched in 2018. Currently, he works on the technological development of membrane-based deployment systems in the GOSSAMER-1 and GOSOLAR projects.*

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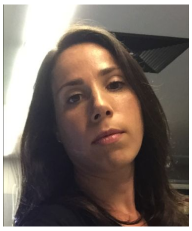
Johannes Riemann *is pursuing a Bachelor in Mechanical Engineering at University of Kassel. He completed an internship at the DLR (German Aerospace Center) in 2017 in which he studied high velocity launches for small payloads in respect of Planetary Defense scenarios. He went on to support the DLR in a study of power and thermal systems on a future Moon Transportation System as part of his Bachelor thesis.*

***Michael Ruffer** is a research assistant at the University Wuerzburg, Chair of Aerospace Information Technology since 2011. He graduated with a degree in electrical engineering from the University of Applied Sciences of Jena in 2005. After starting his career at X-SPEX GmbH, a small company developing professional video and audio systems, he now works on different third-party projects at the University Wuerzburg. His work includes project planning, system engineering, embedded software and electronics development. In Gossamer-1 he was responsible for the embedded software of the boom units.*

***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.*



***Nicole Schmitz** has been working as aerospace engineer and staff scientist at DLR (German Aerospace Center)'s Institute of Planetary Research in Berlin, Germany, since 2007. She received a Diploma in Mechanical Engineering – Aerospace Engineering from the RWTH Technical University of Aachen, Germany, in 2006. She is involved in the Hayabusa2 MASCOT lander project as project manager and Co-I of the MASCOT camera. Other technical and/or scientific contributions to missions include the ExoMars Rover's PanCam, Wisdom and ISEM instruments, the JANUS camera on JUICE, the MastCam-Z on the Mars-2020 rover, and the PROSPECT package on the Luna-27 mission. She has also been involved in a number of solar system exploration studies. Her main scientific interests are composition and geology of planetary surfaces, and terrestrial analog studies. During her time at DLR, she participated in numerous ESA and NASA analogue campaigns, where instruments for future Mars robotic mars missions were tested and further developed through scientific research in terrestrial analog environments, to meet the technical and scientific challenge of remote planetary surface exploration. One example is the Arctic Mars Analogue Svalbard Expedition (field years 2008-2014). She also spent three months in Antarctica as member of the GANOVEX (German Antarctic North Victoria Land Expedition) XI field crew (2015/2016).*

***Wolfgang Seboldt** retired from German Aerospace Center (DLR) in 2011 but is still consultant to DLR and lecturer at FH Aachen Univ. of Applied Sciences, Germany. He studied mathematics (Dipl.-Math.) and (astro)physics (Dr. rer. nat.) at Univ. of Bonn and Bochum. Since 1985 he was working at DLR Cologne for several divisions and institutes as head of "Mission Architecture and Advanced Technologies" section. He is (co-) author of more than 100 publications in the fields of plasma-astrophysics, planetary research/exploration and innovative space technologies (e.g., space solar power, Insitu-Space-Resources-Utilization (ISRU), solar sails and advanced propulsion). He also supervised many Master- and PhD-students, was the study-lead for national and ESA studies and consultant to ESA and the "Air and Space Academy (France)" on strategic/exploration issues, as well as member of the 'International Astronautical Academy' Study Group 3.10 on "Interstellar Precursor Missions"..*

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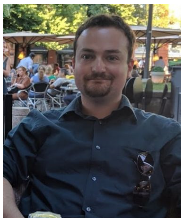

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