# Solar Sails for Planetary Defense & High-Energy Missions

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***Abstract*— 20 years after the successful ground deployment test of a (20 m)² solar sail at DLR Cologne, and in the light of the upcoming U.S. NEAscout mission, we provide an overview of the progress made since in our mission and hardware design studies as well as the hardware built in the course of our solar sail technology development. We outline the most likely and most efficient routes to develop solar sails for useful missions in science and applications, based on our developed 'now-term' and near-term hardware as well as the many practical and managerial lessons learned from the DLR-ESTEC GOSSAMER Roadmap. Mission types directly applicable to planetary defense include single and Multiple NEA Rendezvous ((M)NR) for precursor, monitoring and follow-up scenarios as well as sail-propelled head-on retrograde kinetic impactors (RKI) for mitigation. Other mission types such as the Displaced L1 (DL1) space weather advance warning and monitoring or Solar Polar Orbiter (SPO) types demonstrate the capability of near-term solar sails to achieve asteroid rendezvous in any kind of orbit, from Earth-coorbital to extremely inclined and even retrograde orbits. Some of these mission types such as SPO, (M)NR and RKI include separable payloads. For one-way access to the asteroid surface, nanolanders like MASCOT are an ideal match for solar sails in micro-spacecraft format, i.e. in launch configurations compatible with ESPA and ASAP secondary payload platforms. Larger landers similar to the JAXA-DLR study of a Jupiter Trojan asteroid lander for the OKEANOS mission can shuttle from the sail to the asteroids visited and enable multiple NEA sample-return missions. The high impact velocities and re-try capability achieved by the RKI mission type on a final orbit identical to the target asteroid's but retrograde to its motion enables small spacecraft size impactors to carry sufficient kinetic energy for deflection.**

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## 1. INTRODUCTION

Any effort which intends to physically interact with asteroids requires understanding of the composition and multi-scale surface structure, or even the interior. Mobile Asteroid Surface Scout (MASCOT) landing modules and instrument carriers can provide a first access [1-4]. They integrate at the instrument level to their mothership on 'small' as well as larger 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. Target-flexible Multiple NEA Rendezvous (MNR) [7], Solar Polar Orbiter (SPO) [8], and Displaced $L_1$ (DL1) spaceweather early warning [9] were identified as science missions uniquely feasible with solar sail propulsion. Many such studies outline the unique capability of solar sails to provide access to all small solar system bodies (SSSB), at least within the orbit of Jupiter. Since, significant progress has been made to improve MNR trajectory design. [10] [184][185] (cf.[238])

Although it is relatively easy for solar sails to rendezvous with Near-Earth and Potentially Hazardous Objects (NEO, PHO) in any inclination over the relevant range of semi-major axis and eccentricity, it remains notoriously difficult for sailcraft to land on or interact physically with a SSSB target. The German Aerospace Center, DLR, qualified solar sail deployment technologies in the GOSSAMER-1 project. [11][13] This technology development continues in the GOSOLAR large photovoltaic arrays project. [12]

*A Brief History of…*

The idea of an outward propulsive force of sunlight, and thus of sunlight as a practical source of energy, goes back to Kepler's observations on the directionality of comets' tails of 1619. [14] Its magnitude was predicted by Maxwell in 1873 [15] and Bartoli in 1876 [16]. That year, the foundations of semiconductor technology were laid by Adams's and Day's discovery of an electrical current driven by selenium exposed to light. [17][18] Kepler's hypothesis was experimentally demonstrated as pressure due to radiation by Lebedev in 1901 [19] and Nichols and Hull in 1903 [20]. Solar sailing for space propulsion was proposed first by Oberth [22] and Tsiolkovsky in 1923 and 1924, respectively [21]. Garwin introduced the term 'solar sailing' in 1958. [23] It was then considered a key option to go beyond Mars or Venus. Photovoltaics developed from a curiosity [24][175][176] to *the* power source in space, with very few exceptions [25-29]. The discovery of gravity-assists in 1961 made the solar system instantly accessible with available launchers [30]. This disruptive paradigm change from a mostly inaccessible solar system requiring huge nuclear-electric spaceships [31][32] to the Voyager missions firmly established the combination of chemical propulsion with gravity-assists in solar system exploration [33-38] from Earth [39-41]. Fitting space probes into existing fairings advanced electronics and miniaturization. [42-44] Nuclear power sources became small niche devices for the outer solar system [45] beyond the extending reach of developed photovoltaics. [177-179] Electric propulsion only made it into any mission in the 1990s, on photovoltaic power. [40][47-50][238] Among the solar sail demonstrators launched so far, [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 8$^{th}$, 2010, passing Venus at 80800 km distance and achieving about 20° deflection of theIKAROS' trajectory.

*The development of solar sail technology at DLR*—A first phase culminated in a successful ground deployment test of a (20 m)² boom-supported sail on December $17^{th}$, 1999. Near-term science missions such as ODISSEE and GEOSAIL however did not materialize. [53-60] 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 an acceptable TRL (Technology Readiness Level). [61][62] It envisaged 3 steps: Deployment demonstration (GOSSAMER-1) and control technology evaluation (GOSSAMER-2) in safe orbits (cf. [63]), and a demo mission proving the principle in near-Earth space (GOSSAMER-3). GOSSAMER-1 was brought to EQM (Engineering Qualification Model) status in an intense integration and verification campaign (cf. [64][246]) leading to TRL5 status [65] (according to [66], cf. [67-71]). [181][173][240] Further development of deployment technologies at DLR focuses on membrane-based thin-film photovoltaics [12][72][73][182][240][242] and dedicated support functions for interplanetary applications [247]. The research and testing of the materials used in solar sails as well as other membrane-based large-scale deployable structures or for thermal isolation purposes is meanwhile continued, as well [115][118][163][183] (also cf. [112][113] [114][116][117][232]). Fidelity to the intended as well as knowledge of the actually deployed shape of the membrane is as critical for solar sail thrust vectoring as it is for power generation using thin membrane based photovoltaics. [248]

## 2. MOTIVATION

The recent achievements in solar sail trajectory design [10][184][185] (cf.[238]) and sailcraft hardware development [13][52][74-81][186-193] 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 background is a decade of sustained interest in SSSB with HAYABUSA, ROSETTA/PHILAE, HAYABUSA2 [39], OSIRIS-REx [41], IKAROS [52][74-77], and first steps towards a long-term Solar Power Sail (SPS) sample-return mission to a Jupiter Trojan asteroid, the Outsized Kite-craft for Exploration and Astronautics in the Outer Solar System (OKEANOS) [78-80]. NEAs 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.

*Small Spacecraft*—Affordable rideshare launch options exist for several small Earth satellite classes. [82-86] With additional requirements for propulsion and communication in mind, we apply practical criteria based on launch accommodation [87][88] and basic spacecraft design concepts. [3] MASCOT (9.64 kg) and its derivatives are 'nanolanders'. PHILAE (96 kg) is a 'microlander' [3] by similarity in design with highly compact microsatellites such as BIRD (92 kg) [89], TET-1 (110 kg) [90], or AsteroidFinder (~127 kg) [91]. Design-driving constraints apply mainly to the launch configuration. Thus, 'micro' sailcraft are those which fit the U.S. ESPA or the various Arianespace ASAP and VESPA platforms' 'micro' positions. 'Mini' sailcraft fit the respective larger slots. [87][88] 'Nano' sailcraft are those small enough to ride in place of cubesats dispensers, such as NEAscout [81]. Together, all these are 'small' sailcraft.

## 3. MNR MISSION SCENARIO

Target-flexible multiple NEA rendezvous (MNR) [10] is a space science mission presently uniquely feasible with solar sail propulsion, as already identified in a GOSSAMER Roadmap study. [7] The parallel SPO [8], DL1 [9], and earlier retrograde kinetic impactor (RKI) [97-99][244] studies showed the ability to access any inclination and a wide range of heliocentric distances – each mission type requiring a $\Delta V$ infeasible with chemical propulsion and well beyond the limits of present electrical propulsion. At one extreme, hardly departing from the Earth, the sail of a DL1 mission constantly lifts the sailcraft against the gravity of the Sun to follow the Earth well inside its orbit but at the same rate. At the other extreme, the RKI completely reverses its initial obital path in the solar system: Retrograde orbits can be used to significantly increase the impact speed of projectiles for kinetic energy deflection strategies. Typical prograde orbit impact speeds of 10-15 km/s can be raised to 60 km/s for a head-on retrograde impact near Earth, thus significantly reducing the mass of projectile required to deflect an asteroid of a given size [244]. Even higher encounter velocities are possible in intercepts at lower heliocentric distances. [97-99] In order to deliver a projectile to a retrograde orbit, a solar sail can be used to 'crank' the orbit inclination by pitching the sail such that a component of thrust is alternately directed above/below the orbit plane every half-orbit. Clearly, the targeting of the impact of the projectile onto an asteroid from a retrograde orbit would be challenging at such speeds. However, the leverage delivered is substantial and, again, can significantly reduce the mass of projectile required to deflect an asteroid of a given size.

Current MNR trajectory studies visit within 10 years from Earth departure ($c_3 \geq 0$) 5 different NEAs for >100 days rendezvous, each, with one near-term first-generation sailcraft. [10] Rendezvous duration is comparable to the Asteroid Impact Mission (AIM) at binary NEA (65803) Didymos. [92] The sequence of NEAs is not driven or constrained by a-priori trajectory design or launch window requirements. It can be changed easily on a daily basis, even after launch and between rendezvous. [10] A sailcraft carrying a set of 5 MASCOT landers with different science instruments and landing or mobility related systems appears desirable. Which lander is used can be decided after arrival at target asteroids. Much of the MASCOT lander design can be shared with the core sailcraft and its four boom-sail deployment units (BSDU). Design elements of the GOSSAMER-1 EQM BSDU were shared in the ROBEX lunar-analog demonstration mission's Remote Units (RU). [93][194] MNR missions consisting of 10 independent sub-spacecraft physically connected at launch and separated step-by-step throughout the mission enable resource-sharing as well as economies of scale. Table 1 shows the mission parameters of the reference paper. [10] The required characteristic acceleration, $a_c$ = 0.2 mm/s², is within the capability of current sailcraft technology. [11] Only NHATS (NEO Human Space Flight Accessible Targets Study) and PHA were considered with parameters obtained from [95][96]. Note that neither arrival at 2014 MP after ~9.4 years nor the 222-day stay there still within the 10-year trajectory design goal is necessarily the end of the mission. 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 – Reference MNR mission sequence. [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 Earth instead of 2014 MP extends the total mission duration slightly to 11.3 years (Fig. 1). Mission duration only depends on spacecraft quality and interest in its continued operation (cf. [94]), not on consumables aboard.

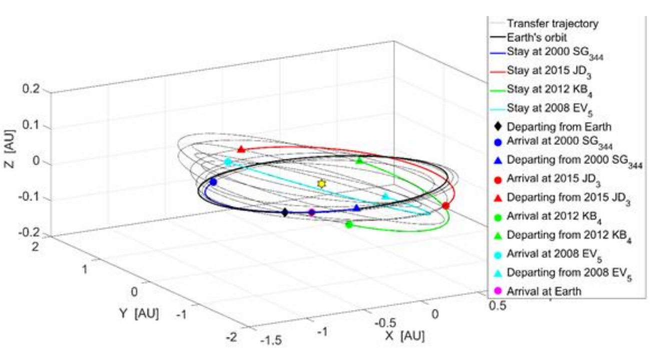


**Fig. 1 – 3D view of the complete Earth-return trajectory**

MNR trajectory searches turn up 100's of possible sequences per launch date. The sequence Earth – 2003 $WT_{153}$, (65679) 1989 UQ – (401954) 2002 $RW_{25}$ [184] contains two almost km-sized PHAs after a very small first target possibly of interest to ARRM-like missions [102]. Its total ΔV for only 3 targets is 52.1 km/s, considered not feasible with near-term high-performing electric-propulsion technology [184]. Low-thrust missions requiring a consumable propellant are restricted to the thin end of the low-ΔV tail of the total ΔV distribution of sequences. They require optimization for this parameter which sacrifices the target change and launch date flexibility of the solar sail based solution. For example, Maiwald and Marchand [238] found a 5-NEA sequence Earth – 2001 $QJ_{142}$ – 2000 $SG_{344}$ – 2009 $OS_5$ – 2007 YF – 1999 $AO_{10}$ for Earth departure on March 21st, 2023 which only requires 16.6 km/s total ΔV. However, all targets are very small (H≈24) and likely not suitable for passive landers. Also, this solar-electric propulsion (SEP) MNR mission is no longer 'small' [238].

*The Unknown Unknowns*—Hardly anything of use to a highly optimized spacecraft design is known on these NEAs. 2008 $EV_5$ is the only one in [10] with a shape model [100] and a few other known parameters beyond its orbit [101][102]. Fig.2 shows a likely asteroid thermal environment. [195][243].

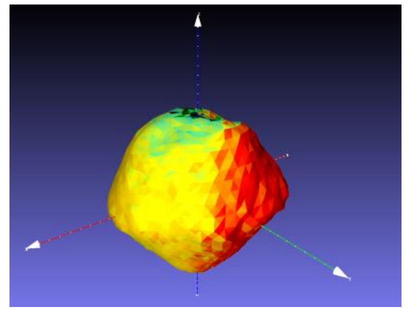

**Fig. 2 – Surface temperatures of 121 K to 364 K (blue to red) on (341843) 2008 $EV_5$ for March 4th, 2031, 0h and 3.725 h rotation, TI = 450, PM = 0-[100][101][195][243]**

Thus, spacecraft and lander designs need to be very robust and anticipate very wide variation of the surface conditions, cf. [145-148][196-198]. MASCOT was already designed to cope with the rather strong seasonal variations that were expected on Ryugu [128][199][200] and it can be adapted to other variables of the environment, as well. [3][241]

## 4. GOSSAMER-STYLE INTEGRATED LANDERS

A key design feature of GOSSAMER solar sails are 4 Boom Sail Deployment Units (BSDU) which synchronously move away from the Central Sailcraft Unit (CSCU) to uncoil the booms and unfold the sail segments. They connect through wired interfaces while attached. After separation, the 5 sub-spacecraft communicate in a wireless network [11][13][103-111][173][174][181]. This communication and a Charging Network (CN) which enables the exchange of energy across sub-spacecraft boundaries can be extended to more than 5 nodes, to support landers still attached to the CSCU after sail deployment. GOSSAMER-1 already supports non-separable high data rate devices, the deployment monitoring cameras. [140-142]

*Lander Options*—When landers are separated from the carrying sailcraft like MASCOT from HAYABUSA2, by a pre-set spring force, the sail trajectory has to ensure that the separated lander arrives at its target, similar to AIM for MASCOT2. [2] The sail may be in very slow fly-by, or in a stable solar-radiation-pressure displaced orbit or station-keeping. [120-122] Proximity operations of solar sails likely pose significant challenges and depend critically on sail attitude control methods yet to be proven in flight.

Alternatively, a self-propelled lander can be used. At the asteroid, the sail would be parked at a safe distance and detach the lander for proximity operations. OKEANOS, the spin-deployed JAXA Solar Power Sail follows this concept.

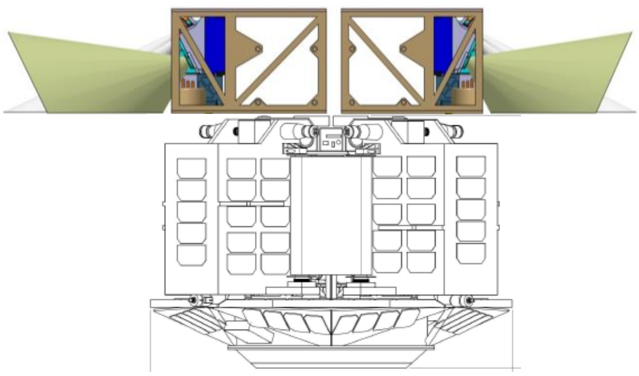

**Fig. 3 – Notional accommodation of MASCOT-style nanolanders aboard a GOSSAMER-style microsailcraft**

*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 hyperspectral near-IR soil microscope, MicrOmega, (MMEGA), [124][201][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 more detail, [129-138][25][203-205][239]).

*MASCOT2*—A long-life MASCOT derivate was developed for ESA's AIM orbiter [165] of the joint NASA-ESA Asteroid Impact & Deflection Assessment (AIDA) mission [166][167] including the DART kinetic impactor test spacecraft [168]. A Low Frequency Radar [139][169-171] and an accelerometer (cf. [206][207][233-236]) replace MMEGA to study the interior of DART impact target (65803) S1 'Didymoon' before and after impact. MASCOT2 was developed using the DLR Bremen Concurrent Engineering Facility (CEF). [208-210] It has turned out to be very flexible baseline for several further studies pursuing different small body science goals, and appears as a good reference for the MNR mission.

*Sample-Return Lander*—Samples of the NEAs visited can be returned by a larger lander shuttling between the NEAs and the sailcraft. Landing gear development can build on the lessons learned from PHILAE [207][211][212]. Technologies to pick up and transfer asteroid samples are demonstrated by the HAYABUSAS and OSIRIS-REX. The lander design for the JAXA Solar Power Sail mission, OKEANOS, to pick up samples from a Jupiter Trojan asteroid emphasizes in-situ analysis of samples due to the very long duration return journey. [149][150] For MNR, the in-situ analysis suite of instruments can be reduced due to shorter mission duration facilitating sample return to Earth. [174][213-215] Figure 4 shows the first sample retrieval cycle of such a lander.

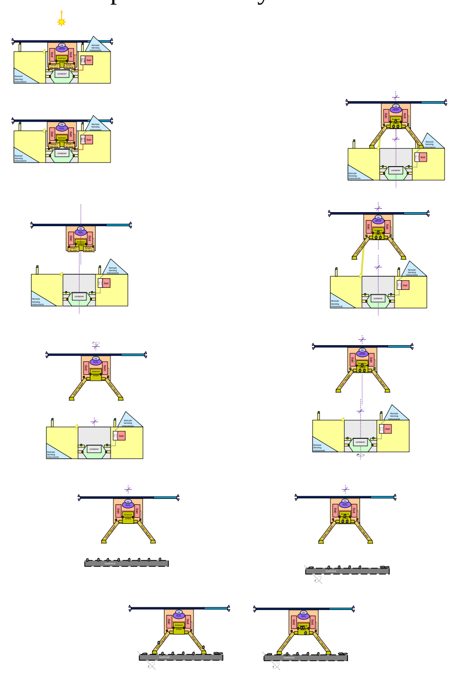

**Fig. 4 – Concept of operation of a shuttling microlander.**

*Resource Sharing of Lander(s) and Sailcraft*—As in the GOSSAMER-1 concept, many resources are shared with the CSCU in cruise and the CSCU-BSDUs before sail deployment. Landers which have to expect rough terrain (cf. MASCOT) and unexpected shadowed areas (cf. PHILAE) require a relatively large battery while a deployed sailcraft in deep space only needs a relatively small battery. Batteries of still-attached lander(s) can support the CSCU during deployment of the sail when the BSDUs have already separated from it. The deployed sailcraft can generate power using ultra-lightweight membrane-mounted photovoltaics similar to GOSOLAR technology. [12] The landers' photovoltaics generators exposed to the outside in launch configuration and after BSDU separation can generate the pre-/in-deployment power for the CSCU.

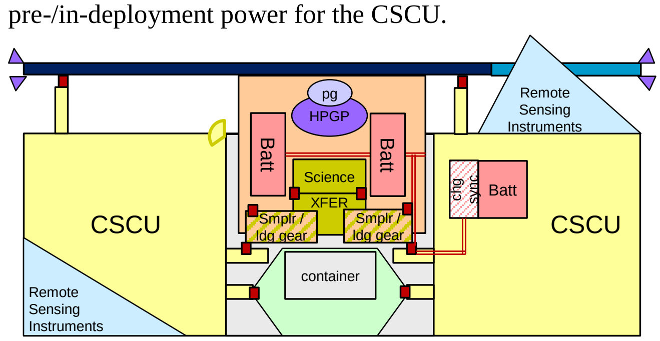


**Fig. 5 – Notional accommodation of a minisail with shared use of photovoltaics, battery, and propulsion**

Science instruments of the landers, in particular panoramic cameras and thermal infrared sensors, can monitor sail deployment and membrane ageing, cf. [13][151][164]. The fields of view (FoV) of the MASCOT instruments CAM (light green) and MARA (light grey) are indicated in Fig. 3, clearly showing their potential for various main spacecraft oriented monitoring tasks. 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. Note the upper limit of the CAM FoV in Fig. 3 which enables views of target asteroids akin to the view of 67P from PHILAE still aboard ROSETTA. These and more opportunities for resource sharing can be used to adapt landers similar to MASCOT, PHILAE, or the OKEANOS lander into GOSSAMER-style integrated sub-spacecraft performing a common mission. Figure 5 shows an example.

## 5. PLANETARY DEFENSE EXERCISES

At the 2017 Planetary Defence Conference, a diversion from an ongoing MNR mission towards a fictitious newly discovered impactor, "2017 PDC", was studied (see [174] for details). Pre-impact rendezvous was not achieved from the reference scenario [10] but 2 potentially useful trajectories were found. A rendezvous with 2017 PDC, 3 years after the fictious impact was found from the sequence 2005 $TG_{50}$ – 2015 $JF_{11}$ – 2012 $BB_4$ – 2014 YN, diverting after the second target e.g. to determine the precise post-deflection trajectory of the asteroid, but also requiring a characteristic acceleration beyond near-term capabilities. A fast fly-by of 2017 PDC, 3 months before the fictitious impact was also found, to assess the state of the asteroid after deflection or to look for undetected partial disruption objects. PDC'13 exercise target 2011 $AG_5$ [152] more easily matches the reference 5-NEA-sequence. [10] Again, the last leg (Table 1) is replaced by a leg to PHA 2011 $AG_5$, for which a fictitious impact was expected for February 3rd, 2040. A methodology similar to [153-156][226] has been used. Total mission duration is ~12 years; arrival at 2011 $AG_5$ on May 25th, 2037, about 3 years before impact. [174] It would be possible to combine MNR solar sail technologies, tuned and optimized for deflection trajectories [97-99] with parallel advances in kinetic impactor guidance technology [227-230] using small spacecraft concepts [123].

*High velocity launch*—Due to the mass and deployment requirements of solar sailing, launch configurations can be very compact. A typical MNR design would fit 'micro' secondary passenger slots to GTO, with a small kick prpoulsion module to escape ($c_3$>0) included. A dedicated launch would be an option for missions requiring an extremely high $c_3$ or reduced flight time to target. Ariane 5 ECA [119] maximum velocity escape trajectory performance was calculated for $i$=6° (Kourou). When all unnecessary standard equipment units are removed, payloads of 500 kg, 250 kg, and 50 kg, can respectively be injected on escape trajectories of $c_3 \approx 56$ km²/s², 60 km²/s², and 64 km²/s². Still higher velocities can be achieved by adding upper stages similar to the launch configurations 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 enables a 100-day NEA rendezvous every 2 years per spacecraft. [10] Small spacecraft technology enables shoebox-sized one-way landers [1] and fridge-sized sailcraft [11] able to perform these trajectories. By a modest increase in size, samples can be returned to Earth. [5] Current large launch vehicles can carry several such sailcraft at a time [87][88] or accelerate one to solar escape, although due to gravity-assist trajectories [33], most won't require this. [30] So far, these bricks stand largely independent of each other. But gravity-assist sequencing begins to include low-thrust propulsion, and vice-versa, e.g. [39][41][158-161]. Tools for such complex trades are developed by Model-Based System Engineering. [3][162] It appears that easier access to the solar system, less constrained by launch windows or payload limitations, can be achieved by connecting all these bricks. Small MNR missions are affordable entry level practice systems. 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 are 5 NEA rendezvous of at least 100 days, each, in 10 years by one spacecraft. The small spacecraft approach enables the use of surplus launcher payload capability in the market with a potential of 10's of launches per year. If the spacecraft concept here presented were serialized, the number of NEAs studied could be increased by orders of magnitude within a few decades. The small mass of small spacecraft solar sails also enables very high launch energy missions based on available geostationary market launch vehicles to the most challenging targets of the solar system, including planetary defence scenarios.


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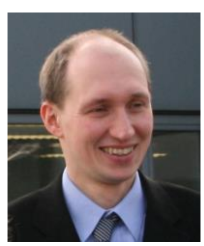
## BIOGRAPHY



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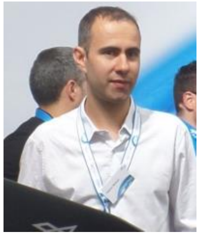

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***Ivanka Pelivan*** *received her PhD degree in 2013 at the University of Bremen while involved in spacecraft simulation software development at ZARM and at DLR. As a Marie-Curie fellow at Stanford University she applied the software library to the relativity mission GRAVITY PROBE B. Next to thermophysical modeling for the targets of the ROSETTA, HAYABUSA2 and AIM missions, she has been actively involved in preparation of data analysis for the ROSETTA instrument MUPUS. 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. She is Co-I of PHILAE lander instruments MUPUS, ROLIS and the MASCOT radiometer MARA.*

***Alessandro Peloni*** *holds a PhD in Aerospace Engineering from 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.*

***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.*

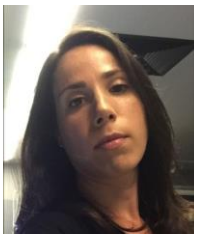
***Siebo Reershemius*** *received his Master Degree in Mechanical Engineering in 2010 and joined the DLR Institute of Space Systems in Bremen, Germany, as a research engineer. His main interests are deployable structures and mechanisms. He was engineer for structural analysis and mechanism development 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.*

***Thomas Renger*** *is the head of the Complex Irradiation Facility (CIF) at DLR Bremen. He is working in the design, commissioning, and operation of the facility and the execution of material degradation experiments. He has studied electrical engineering at the University of Rostock and joined the DLR since 2017.*

***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.



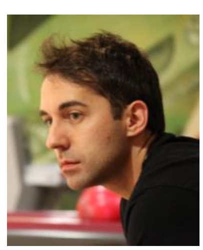
**Nicole Schmitz** has been working as aerospace engineer and staff scientist at DLR (German Aerospace Center)'s Institute of Planetary Research in Berlin, Germany, since 2007. She received a Diploma in Mechanical Engineering – Aerospace Engineering from the RWTH Technical University of Aachen, Germany, 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. 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 (i.a. 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. solar sails and advanced propulsion).

**Patric Seefeldt** is pursuing a Ph.D. at DLR and the University of Bremen on Development and Qualification Strategies for Deployable Membrane Spacecraft Systems. He works in the projects GOSSAMER-1 and GOSOLAR at the DLR Institute of Space Systems in Bremen, Germany. He studied mechanical engineering at the RWTH Technical University of Aachen, Germany, where he worked as a research associate at the Institute of Structural Mechanics and Lightweight Design.

**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. 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 Satellite AISAT and the DLR payload HP³ as part of the NASA/JPL Mission to Mars, INSIGHT.



**Maciej Sznajder** is a scientific co-worker at the department Mechanics and Thermal Systems of the DLR Institute of Space Systems. He has PhD degrees in physics and materials engineering. Since 2010, he works in the 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-1 and GOSOLAR projects at the DLR Bremen.*

***Simon Tardivel** received his M.S. in Aerospace Engineering from Supaero (Toulouse, France) in 2010. Under supervision of Dr. Scheeres, he received a Ph.D. in Aerospace Engineering Sciences from the University of Colorado Boulder in 2014, on the topic of the deployment of landers to asteroid surfaces. Since June 2017 he has been working at CNES (Centre National d'Etudes Spatiales) in Toulouse in mission design and analysis, notably on the MMX rover concept.*

***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-1 and for ROBEX Lander and Remote Unit. Currently he is working on the GOSOLAR CDH and on the MASCOT checkout, operations.*

***Elisabet Wejmo** is a research engineer at the German Aerospace Center (DLR), Institute of Space Systems in Bremen, Germany, since 2014. She is currently responsible for the power systems on the S2TEP and Eu:CROPIS satellites, but has also worked with the MASCOT project; doing mostly power system tests. In 2014 she received a Master's of Science and Space Engineering from Luleå University of Technology (LTU), Sweden.*

***Friederike Wolff** received her BSc in Aerospace Engineering (honors) from the Technical University of Delft (the Netherlands) in 2013. During the completion of her MSc in Space Science and Technology at the Luleå Technical University in Kiruna (Sweden), she participated in the REXUS/BEXUS program. Since 2015, she is working at the German Space Agency (DLR) at the Institute of System Dynamics and Control. Her current responsibilities include mission support for MASCOT (Mobile Asteroid Surface Scout) as well as the simulation, verification and optimization of the MASCOT Mobility Unit.*

***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.*

*For more comprehensive biographies please see [245].*