Small Landers and Separable Sub-Spacecraft for Near-term Solar Sails

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Following the successful PHILAE landing with ESA's ROSETTA probe and the launch of the MINERVA rovers and the Mobile Asteroid Surface Scout, MASCOT, aboard the JAXA space probe, HAYABUSA2, to asteroid (162173) Ryugu, small landers have found increasing interest. Integrated at the instrument level in their mothership they support small solar system body studies. With efficient capabilities, resource-friendly design and inherent robustness they are an attractive exploration mission element. We discuss advantages and constraints of small sub-spacecraft, focusing on emerging areas of activity such as asteroid diversity studies, planetary defence, and asteroid mining, on the background of our projects PHILAE, MASCOT, MASCOT2, the JAXA-DLR Solar Power Sail Lander Design Study, and others. The GOSSAMER-1 solar sail deployment concept also involves independent separable sub-spacecraft operating synchronized to deploy the sail. Small spacecraft require big changes in the way we do things and occasionally a little more effort than would be anticipated based on a traditional large spacecraft approach. In a Constraints-Driven Engineering environment we apply Concurrent Design and Engineering (CD/CE), Concurrent Assembly, Integration and Verification (CAIV) and Model-Based Systems Engineering (MBSE). Near-term solar sails will likely be small spacecraft which we expect to harmonize well with nano-scale separable instrument payload packages.

Key Words: Small Solar System Body Lander, Small Spacecraft, PHILAE, MASCOT, Solar Power Sail

1. Introduction

One of the most persistent criticisms of solar sailing as a means of spaceflight propulsion concerns the class of missions where it is the most promising method to provide equal access to all targets: small solar system body (SSSB) applications. These currently include planetary science, exploration, planetary defence, and the emerging field of asteroid mining. All of these depend crucially on in-situ operations: landing is essential, and short of being beached for disposal like ROSETTA, it is generally considered that solar sails can't land. Thus, separable landers necessarily will be an indispensable part of any solar sail mission headed to SSSBs.

SSSB missions come in two basic categories. The division has so far been slight or at best gradual due to the constraints of established methods of spacecraft propulsion in most fields. For planetary defence, however, it is most pronounced:

First, prior to any particular interest, there are missions to investigate the properties of small solar system bodies in general; these are mainly scientific or of equivalent design.

Second, there are missions to interact in specific ways with one specific object that has become a recognized interest to such a degree and confidence that exclusively dedicated missions are warranted.

The main difference between these two categories is that for the first, careful deliberation in scientific committees picks the target and timing,[1] while for the second, nature alone does.

1.1. The impact of Chelyabinsk on SSSB missions

The widely reported airburst of the Chelyabinsk bolide on February 15th, 2013, returned the focus on planetary defence. This ~500 kiloton TNT-equivalent event caused by a ~20 m diameter chondritic body[2] was just barely non-lethal.[3-8] It clearly demonstrated the value of preparedness regarding natural disasters.[4] In its aftermath, the size-frequency distribution of natural impactors at Earth, their effects, and technical options for mitigation were extensively revisited.[9] The historic focus on km-sized near-Earth objects (NEO)[10-13] was extended to the much more frequent small impactors with regional or locally devastating effects.[14-15] These strike somewhat more frequently than previously expected [16-22] but are also within reach of current non-nuclear mitigation methods,[23-29] alleviating non-technical concerns.[23,28,29,102,103]

1.2. NEOs as a first goal for in-situ resource utilization

Significant commercial interest in the exploitation of SSSB resources in space has emerged. 'Asteroid mining' is currently in a process of analysis and concepts definitions, surveying and prospecting related fields of science and engineering. The legal framework is of particular importance to the commercial stakeholders.[104] Experience from similar activities in extreme environments on Earth is also reviewed.[105]

1.3. SSSB science heritage and perspective

Science missions do not fly frequently. Thus, science output and consequently launch mass is typically maximized to the limit of accessibility of *any* suitable target object for affordable launchers within the space agency mission class. As a corollary, among the SSSB missions they are least under pressure 'to separate "desirements" from "requirements" […] to prevent intolerable increases in cost and schedule.'[106]

For science missions, the target object *can* become a constraint on the scientific mission concept. Many interesting objects are difficult to reach without curtailing mission scope. Thus, in most cases, a more easily accessible similar object is selected. There may however be missions for which just one object of the vast number of solar system bodies discovered so far is of interest and accessible at the same time.[1]

Conceptually, there is a very wide overlap of interest and methods and technologies of these three small solar system body application fields. A prominent example of this synergy is the joint U.S.-European Asteroid Impact Deflection Assessment (AIDA) mission.[107]

2. Embracing constraints

Whether one specific object of interest or a wider choice of target objects is desirable – there are two basic fundamentals of spaceflight to address the challenge:

i) Reduction of spacecraft mass by designing the best mission possible into the envelope of constraints and capabilities of the present infrastructure; i.e., to accept significant constraints beyond those which would commonly apply to a specific mission and then to stick by them.

ii) Improving the Δv of the spacecraft after launch from Earth; that is, decide to add propulsion-related functions to the design and to accept advanced or new technologies into such key functions to mission success, under mission responsibility.

2.1. Constraints-driven design: small organic integrated

The first way is none less than a paradigm shift in spacecraft design from established agency and industry procedures and standards which in a linear fashion derive a design from a basic set of stakeholder requirements in processes that inherently work as one-way roads expanding into an open design space.

But many SSSB missions are developed in reaction to an interest which is in some way newly discovered, not unlike as in planetary defence scenarios.[14-16,29]. Exploration or science missions with stringent target selection constraints[1] are easily over-constrained into infeasibility by any other artificial burden beyond the constraints imposed by nature and the serendipity of discovery. In the broader sense, mission and spacecraft design acts in response to an objective that with the ongoing accumulation of knowledge on it poses fluid requirements, possibly until launch and thereafter.

Development can easily find itself between the hard natural constraint of timely accessibility of the physical target and the artificial constraints created by the phased and requirements-driven development method[30] that most in industry and government agencies are used to. Fundamental assumptions and normally frozen requirements may have to be questioned repeatedly to maintain feasibility, without the time to change hardware already produced due to lead time issues. The design also has to flow constantly into the – possibly also changing – constraits envelope related to a timely launch.

As soon as the spacecraft mass and size is constrained to limits below those of comparable mainstream science missions the design becomes fundamentally constraints-driven and requires overall optimization and organic integration to enable the maximum possible mission. This need for thorough optimization blurs interface boundaries of sub-units as well as the organizatorial structure and its work package divisions. Efficiency of thorough optimization can depend on minor detail; attention to detail can thus not be postponed until the appropriate project phase: The earlier hardware can be exercised and tested, the more design space within the envelope of constraints is liberated from margins allocations by detailed understanding of the design. Similarly, it is very unlikely that early resource allocations can be upheld because blanket application of a structured margins philosophy[30] may already overconstrain the design. Every subsystem needs to be optimized as far as possible within the system and the given timeframe, not just enough to pass under its allocation limits.

All this sounds very inconvenient to the user of established standard methods of spacecraft design, often to the point of 'you can't do that's. But it all is characteristic of small spacecraft and common practice in their design, particularly for all the many flown as secondary payloads in Earth orbit.

2.2. Propulsion: beyond hydrazine and fly-by

The second way, improvement of overall Δv, offers a growing choice of reasonably developed propulsion methods, from larger fuel fractions to 'alternatives' like solar-electrical propulsion (SEP) meanwhile proven in small missions, e.g. DEEP SPACE 1,[31-33] SMART-1,[34] HAYABUSA.[35,36] Once accepted for BEPICOLOMBO,[37] it reduced the fuel fraction from 56% for CASSINI-HUYGENS or MESSENGER to 34%.

2.3. Large lightweight photovoltaics and solar sails

An obvious next step is the use of large-area structures, to generate more photovoltaic power for SEP or to create solar sails – or both: A solar power sail has been proposed by the Japan Aerospace Exploration Agency, JAXA, for a Trojan asteroid sample-return mission[38] on the basis of the successful solar sail demonstrator IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) launched with the Venus Climate Orbiter, AKATSUKI.[39-41] Although by unusual launch requirements not mass-limited but required to have a comparatively high minimum mass, IKAROS can be considered a small spacecraft in this context due to the way it was instituted as a mission, designed and built.[42]

3. Small landers and separable sub-spacecraft at DLR

This section provides an overview of recent projects and activities at DLR, either scientific missions or technology demonstrators involving SSSB aspects, also partly related to the NEOShield Project funded by a 7th Framework Programme (FP7) grant from the European Commission (EC).[43]

3.1. PHILAE – comet lander

ROSETTA was an ESA Horizon 2000 Cornerstone Mission. It was launched in 2004 and reached its target, comet 67P/Churyumov-Gerasimenko in 2014.[44,45] After remote investigation of the comet nucleus in mid-2014, the ROSETTA Lander, PHILAE, (Fig. 1) performed the first ever landing on the surface of a comet on November 12th, 2014.[46,47]

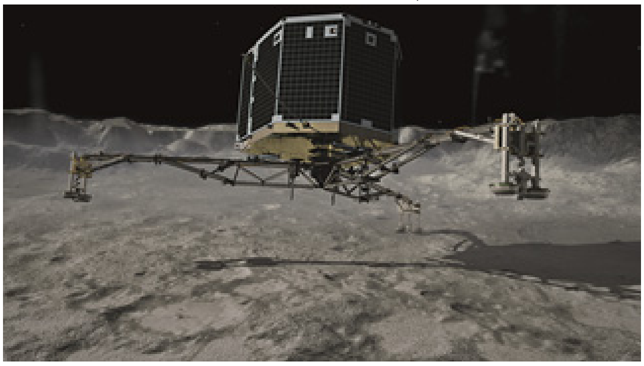

Fig. 1. PHILAE before a touch-down (artist's concept)

It has an overall mass of 98 kg, carrying 26.7 kg of science payload in a carbon fibre / aluminium honeycomb structure. The power subsystem includes solar generators, primary and secondary batteries. The central data management system communicates by S-band, using the ROSETTA as relay. During cruise the Lander has been attached to the Orbiter with the Mechanical Support System which also includes the push-off device separating PHILAE from the Orbiter.[48,108,109] Carried outside, PHILAE was able to support ROSETTA during the Mars fly-by and while the comet was out of view of the boresighted mothership instruments (Fig. 2). It also monitored the deployment status of the photovoltaic arrays for ROSETTA's aphelion hibernation. This welcome mission redundancy was only possible because PHILAE is a self-contained spacecraft.

After separation at an altitude of 20.5 km, the descent to the surface took just under 7 hours. At touch-down at Agilkia, a cold gas thruster, anchoring harpoons and ice screws should have prevented re-bouncing[49,50] but the lander immediately bounced off again. The cold gas system did not provide thrust and the harpoons did not fire. PHILAE finally came to rest at a heavily shadowed site, Abydos, where it successfully conducted scientific measurements until all energy was depleted on November 15th, 2014, 00:07 UTC.[51]

Fig. 2. Mars and 67P: worlds and spacecraft deployables as seen from a small spacecraft's perspective – © ÇIVA/PHILAE/ROSETTA/ESA

During this scientific sequence on the comet of 57 hours, PHILAE was powered mostly by its primary batteries helped by the initial charge of the secondary batteries and some photovoltaic input. Several instruments and subsystems were operated simultaneously, and each experiment at least once.

The long-term operations phase envisaged experiments working mainly in sequence scheduled according to energy availability and data relay capacity. Telemetry of June 13th, 2015, 20:28 UTC showed that it had been intermittently active already since May. Signals were received sporadically till July 9th, but operation could not be re-established.[52,110] PHILAE was located on close-in fly-by photography, wedged in between rocks, shortly before ROSETTA was beached on 67P.

PHILAE represents the first time that a lander, though in itself a complete spacecraft, was *not* the driving element of the main mission. It was not considered essential *before* the call for proposals for instruments to fly aboard ROSETTA. The concept of integrating a lander at the instrument level of the orbiter has been continued by BEAGLE 2 on MARSEXPRESS and the MINERVA series and MASCOT on the HAYABUSA missions.

3.2. MASCOT – asteroid lander

In the last few years, DLR has developed the Mobile Asteroid Surface Scout, MASCOT, a small asteroid lander which packs four full-scale science instruments (Fig. 3) and relocation capability into a shoebox-sized 10 kg spacecraft. It carries the near-IR soil microscope, MicrOmega, (MMEGA),[129] a high dynamic range black-and-white camera

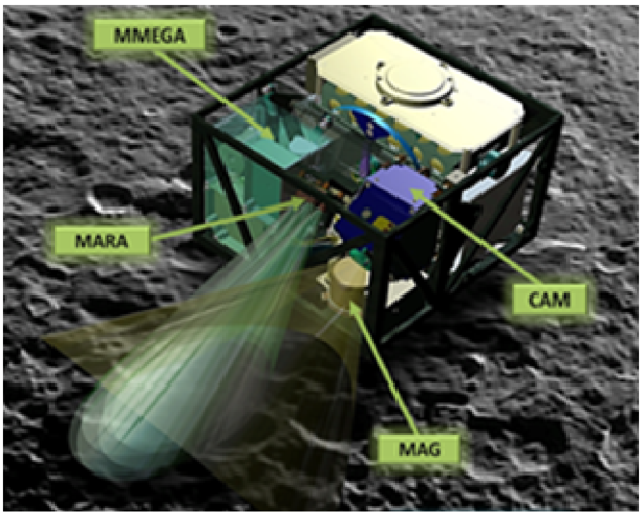

Fig. 3. MASCOT, its science instruments and field of view on the asteroid surface, outer insulation foil removed for clarity (artist's concept)

with night-time multicolour illumination (CAM),[126] a 6-channel thermal IR radiometer (MARA),[127] and a fluxgate magnetometer (MAG).[128]

After delivery in June 2014, MASCOT was launched aboard HAYABUSA2 (HY2) on December 3rd, 2014. In 2015, the first in-flight calibration session was completed, and the Preload Relief Mechanism (PRM) was successfully actuated, making MASCOT separation-ready. HAYABUSA2 is now in cruise to asteroid (162173) Ryugu[53] using SEP.

MASCOT, following constraints set in envelope by its mothership and in time by the target asteroid, is an organically integrated high-density design.[54-59] MASCOT's structure is a highly integrated and ultra-lightweight truss-frame of CFRP/ Rohacell® foam sandwich.[60,61] It has three mechanisms: i) the PRM to release a controlled kN-range preload across the separation interface which suppresses detrimental vibrations; ii) the Separation Mechanism to realize a gentle push-off of MASCOT at ~5 cm/s out of the Mechanical Support Structure (MESS) recessed in the HY2 envelope; and iii) the Mobility Mechanism for uprighting and hopping on the asteroid.[62] MASCOT uses semi-passive thermal control, with two heatpipes, a radiator, and Multi-Layer Insulation (MLI) for heat rejection in active phases, supported by a heater for thermal control in passive cruise phases.[63] During on-asteroid operation, it uses a primary battery as power supply; in cruise, it is supplied by HY2. The Power Conversion and Distribution Unit (PCDU) applies a mixed isolating/non-isolating conversion concept adapted to grounding in a nonconductive structure.[64] All data is sent to Earth via HY2 as relay using redundant UHF-Band transceivers and two patch antennae with omnidirectional coverage. The redundant On-Board Computer (OBC) provides data storage, instrument interfacing, command and data handling, as well as autonomous surface operation functions. The operational redundancy mode is configurable between two CPUs and two I/O & mass memory modules to optimize power consumption and robustness. Knowledge of the landers attitude and illumination key to science and mobility is determined by a set of sensors: optical distance sensors, photo electric cells, and thermal sensors.

Surveying SSSB-related missions for the next years, it is apparent that flight opportunities will arise for such a small versatile add-on landing package to complement and enhance the main mission's objectives at relatively low cost. DLR uses the experience[65] gained on MASCOT to build on its heritage by carrying forward the idea of further derivatives guided by interest from ongoing SSSB mission studies. MASCOT derivates differ in main features such as lifetime (long-lived vs. short-lived), landing velocity, or instrument suite (e.g. radar tomography vs. geology vs. geochemistry), but are all based on common platform elements.[66] The main goal is to advance the current design from the HY2-dedicated lander MASCOT to a generic instrument carrier construction set able to deliver a variety of payload combinations on different mother-missions to different target bodies. To minimize the effort of redevelopment and time for any new design, principles of Model Based Systems Engineering (MBSE)[67] and Concurrent Engineering (CE) methods[68-70] are used in follow-on studies of MASCOT- and PHILAE-like landers.

3.3. GOSSAMER-1 – 5-in-1 small spacecraft design

The GOSSAMER-1 large lightweight structures and solar sail deployment technology demonstrator[115] has recently completed qualification testing at DLR Bremen.[113-114,117] It is presented in 117). The DLR GOSSAMER technology is one of several recent approaches to harness the outward propulsive force of sunlight[71-75] for practical near-term spaceflight applications. It grew from the lessons learned of earlier DLR work culminating in the successful ground deployment of a (20 m)² boom-supported sail on December 17th, 1999.[76]

The GOSSAMER-1 low-Earth orbit deployment demonstrator (Fig. 4) was to be the first step in the DLR-ESTEC GOSSAMER roadmap,[77] however, the flight phase of the project was discontinued after design completion and qualification.

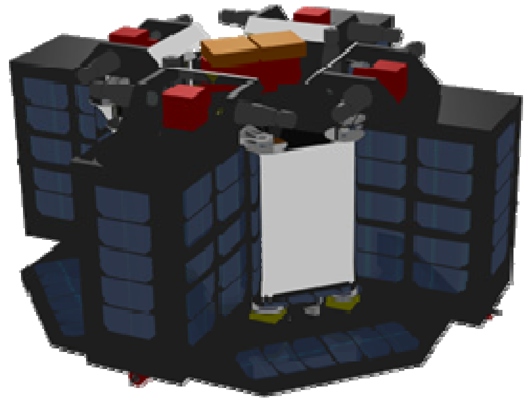

Fig. 4. GOSSAMER-1 solar sail deployment demonstrator configuration for low Earth orbit consisting of 4 BSDUs surrounding the CSCU[112-115,117]

The Roadmap intended to enable unique science missions not feasible using other post-launch propulsion methods. Studied in detail were: i) multiple NEO rendezvous (MNR);[78,111] ii) Displaced-L_1 (DL1) spaceweather buoy;[79] and iii) a Solar Polar Orbiter (SPO).[80] All are small spacecraft within the capabilities of currently available sail technology and sized as secondary payloads to proceed from GTO or other high Earth orbits by a small kickstage or sailing.[81,113-115]

Regarding SSSB missions, a major advantage of solar sailing is the ease of target object change during the mission shown in the analysis of the MNR reference mission.[78,111] The DL1 and SPO missions are similar to rendezvous with low-*i*/*e* NEOs and high-*i*/*e* SSSBs, respectively, indicating a robust and flexible principle of propulsion for all SSSB missions.

Landing modules like MASCOT were an option[83] for MNR missions and a separable payload orbiter was baselined for SPO.[80] Separable sub-spacecraft are also a key feature of the DLR GOSSAMER concept to jettison all items only required for the deployment of the sail membrane. A GOSSAMER solar sail consists of five independent spacecraft coupled at launch which separate once mechanical deployment is initiated and therafter only communicate in a wireless network to synchronize it. Bluetooth® is used between the GOSSAMER-1 Central Sailcraft Unit (CSCU) and the four Boom Sail Deployment Units (BSDU). The networking concept has already been carried on to the network of Remote Units and Lander of the lunar analog demonstration mission of the ROBEX Alliance[118] which successfully passed a first field test in September 2016 on the flanks of Mt Etna.[119]

3.4. GoSolAr – large lightweight photovoltaics

The capability to accelerate without propellant remains a mission enabler for high-Δv and hypervelocity missions unique to solar sailing.[82,83] However, some mission flexibility of the kind provided by solar sailing is, within the limits of fuel capacity and photovoltaic power, also possible for low dry mass SEP missions, cf. the trajectory adaptations of Deep Space 1 and Hayabusa or the double rendezvous of Dawn with (4) Vesta and (1) Ceres. High-power SEP plays a role in all SSSB applications. Large lightweight deployable structures for photovoltaics are also required for in-situ power,[26,27] and there are several use cases closer to Earth orbit.[38-41,81]

After the termination of the Gossamer-1 project at the end of 2015, the team and its experience seamlessly continued into the new GoSolAr project with focus on deployment systems for huge thin-film photovoltaic arrays.[112] A $(5\ \text{m})^2$ flexible photovoltaic membrane generator demonstrator is slated to fly on the 50 kg class S^{2}TEP bus system developed on-site in parallel.[116] It is envisaged to be scalable to $(20\ \text{m})^2$ and more.

3.5. AIDA = DART + AIM + MASCOT2

The Asteroid Impact & Deflection Assessment (AIDA) mission is a first experiment to demonstrate and characterize impact hazard mitigation by using a kinetic impactor to deflect an asteroid. It is a joint NASA-ESA mission which includes the NASA Double Asteroid Redirection Test (DART) mission and the ESA Asteroid Impact Monitor (AIM) rendezvous mission.[107] The target is the binary NEA (65803) Didymos, with the deflection experiment to occur in October, 2022. DART impacts on the secondary member of the binary at ~6 km/s to alter its orbital period. The AIM spacecraft will monitor results of the impact in-situ.[84] DLR is currently applying MASCOT heritage and lessons learned to design MASCOT2 for AIM's bistatic Low Frequency Radar (LFR) with Philae/Rosetta CONSERT[85] heritage to explore the inner structure of Didymoon and its impact response. The accelerometer DACC characterizes the surface by mechanical interactions of landing, relocation, bouncing and self-righting, and may monitor the seismic response to DART's impact. CAM, MARA, and MAG are also carried. The MASCOT2 baseline design (Fig. 5) envisages minimum modifications as necessary to adapt the short lifetime optimized design of MASCOT to a long-lived solar-powered mission with a partially changed suite of instruments. The Constraints-Driven Design, CE and Concurrent AIV approach of MASCOT is applied according to the resources envelope constraints and timeline requirements of the AIM mission.[86]

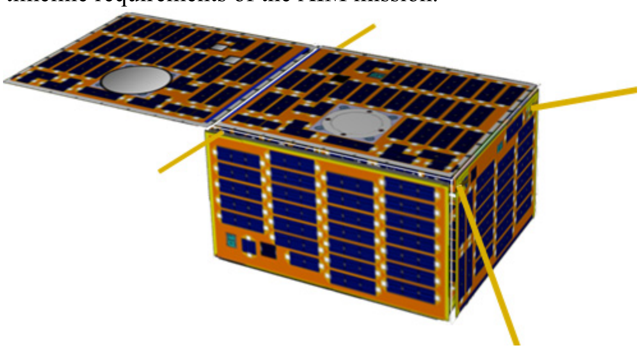

Fig. 5. DLR MASCOT2 lander design for the ESA AIM mission

3.6. Everyone's favourite MASCOT

A whole host of small SSSB lander studies at DLR followed Philae's landing(s) and MASCOT's launch in late 2014, ranging from brief email exchanges to 2-year efforts, from smaller and simpler spacecraft to Philae-sized ambitious robotic laboratory stations, and from 1:1 or 'tactical' re-use[83] to entirely new designs with more subtle re-use of MASCOT and Philae features at unit level. In all, the original MASCOT design appeared quite well prepared for strategic re-use.[47,87] One key feature is shared by all new MASCOToids: they are self-contained spacecraft integrated at the instrument level from the perspective of their respective mothership missions.

3.7. Head on by solar sail and AsteroidSQUADS/*i*SSB

In an ad-hoc effort for the 2011 Planetary Defence Conference, a PHA massively-serial multiple flyby/impact mission concept was studied that combines a heavy launch vehicle test flight opportunity with a concerted practical exercise of the complete NEO observation and interplanetary spaceflight infrastructure. Adding a bipropellant propulsion module to a stripped-down derivate of the then-current AsteroidFinder/SSB[88-90] Earth-orbiting survey satellite designed for standard 'micro' secondary payload envelopes of $1 \cdot 0.8 \cdot 0.8\ \text{m}^3$; 180 kg, (unlike the final AsteroidFinder design[91-94]), AsteroidSQUADS/*i*SSB envisaged the same EMCCD sensor technology for imaging of the target NEA right down to impact at up to 1000 frames/s.[28] Akin to the Gossamer Roadmap SPO mission concept,[80] a sail-based active hypervelocity kinetic impact mission on a retrograde orbit emerges, putting within reach encounter velocities in excess of 75 km/s for kinetic impactors larger than 100 kg.[120-122] (Fig. 6) Terminal guidance at such closing speeds is a formidable challenge,[82] but possible[123-125] and enhanceable to cooperative NEA targets by pre-landed transponders.[78,83,111]

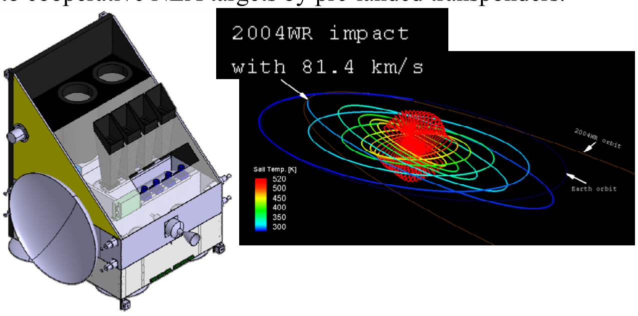

Fig. 6. AsteroidSQUADS/*i*SSB imaging kinetic impactor[28] – head-on retrograde solar sail intercept trajectory, sail temperature colour-coded[122]

3.8. Solar Power Sail Lander for a Trojan sample return

From a scientific point of view, there is an enormous reward in the most primitive samples containing information about the ancient solar system, as well as the origin of life in our solar system. Thus, JAXA studies a Trojan asteroid sample return mission based on the operation of a mother spacecraft (MSC), and a daughter spacecraft/lander (DSC). The MSC transfers the DSC to a Trojan asteroid for in-situ analysis. The extended mission is the return of collected samples back to Earth. The DSC performs the collection of soil samples from the target asteroid, in-situ analysis of the samples, sample-transfer from DSC to MSC, and DSC disposal before the MSC returns samples to Earth.

DLR and JAXA conducted a joint study of the DSC lander design. The stowed envelope of the DSC was fixed by the MSC design to Ø650 · 400 mm and 100 kg wet mass, (Fig. 7) again creating the Constraints-Driven Engineering situation that the MASCOT team was already well accustomed to.

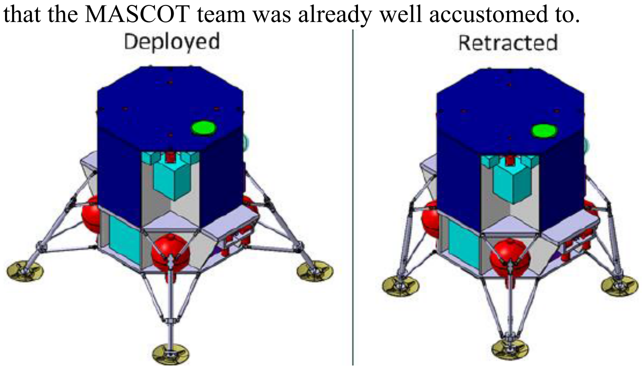

Fig. 7. Lander design for the Solar Power Sail Trojan mission

A strawman science payload was defined to address the key planetary science questions regarding most primitive SSSBs and Jupiter Trojans to understand their i) origin and constrain models of solar system evolution by analysis of isotopic ratios and volatile species; ii) chemical evolution of organics by mass and species identification; iii) dynamical evolution and thermal history by measuring physical properties of surface materials. Including margins, 20 kg and 600 Wh were allocated to the instruments. Proposed instruments included at least two different sample collection devices (e.g. bullet and pneumatic drill) feeding a distribution storage for 6 samples, a high-resolution mass spectrometer with M/ΔM >30000 at 2≤ MZ ≤1000 using overlapping MZ range mass spectroscopy methods, a hyperspectral grain-scale mineralogy microscope with 10…20 µm resolution in the visible and near-IR from 0.8 to 3.6 µm, a Raman spectrometer, a multispectral 360° panoramic imager covering the same near-IR range and ability to focus on the sample collection location with a combination of fixed wide-angle and pointing narrow-angle sensor heads, a bottom side close-up camera, a radiometer, a magnetometer and a thermogravimeter. The operation of this payload to achieve in-situ analysis of samples requires 2¼ asteroid days assumed at 10 h, each, and generates ~500 MByte net science data. It was expected that the actual suite of instruments with a best estimate mass <20 kg is optimized and if necessary downselected to fit the spacecraft constraints.

Communication between DSC and MSC during the on-Trojan phase requires ~1 GByte to be transmitted over up to 250 km while the asteroid rotates beneath the MSC with a period of 10…22 hrs. UHF, S- or X-band solutions are feasible, trading antenna directionality vs data rate.

At the large heliocentric distance, a purely primary battery powered system based on PHILAE and MASCOT was considered but the peak power during propulsion activity of ~360 W combined with the high impedance of proven long-term storable Li-$SOCl_2$ cells drove battery size several times beyond the required net energy capacity of ~1 kWh. Thus, a battery of small, low temperature capable, low-fade Li-ion cells in 18650 standard format was selected. It allows fine adaptation to available volume and mass and shows graceful degradation with regard to failure margins to be considered, resulting in a nameplate capacity of only 1.3 kWh.

Average power consumption varies between ~10 W and ~200 W including margins, with science mode close to the minimum. Thus, a photovoltaic generator utilizing only all otherwise unused surface areas of the lander even at Jupiter distance can provide ~2 W and a significant extension of the lifetime in low power modes and phases. With an ultra-low power survival mode, the battery average state of charge can be kept indefinitely at the same level to enable ground loop intervention in case of unexpected events, environmental conditions or discoveries.

Low dissipation in the very low temperature Trojan asteroid environment constitutes a significant challenge for thermal design. Furthermore, the lander configuration is mainly defined by equipment operational requirements such as surface sample transfer paths, optical fields of view, etc. Therefore, there is little freedom to change component locations to improve thermal performance. The baseline thermal control system design is a semi-passive concept using radiators, heaters and insulations. Generated heat from the E-box and instruments, the high power components during the Science phase, is directly transferred to the top plate and radiated to the space. The battery is thermally isolated from the other components by MLI and stand-offs, and temperature is controlled by heaters. DSC and MSC are thermally decoupled. During the passive cruise, battery temperature is maintained by heaters supplied by the MSC. Other component temperatures are indirectly maintained by heat transfer from the battery. After the brief high-power propulsive phase, the lander generally cools down and requires some heating or artificially increased instrument activity to maintain optimal battery temperatures.

The landing on the Trojan surface has to be performed autonomously due to the Earth-response time of 60…100 min at a duration of the whole landing manoeuvre of 1 hr or less. Autonomous operation requires a comprehensive set of attitude sensors including an inertial measurement unit (IMU), a laser-based altitude and slope sensor (LASS), and an on-board navigation camera (ONC) similar to the one used on HAYABUSA2 for ground control point (GCP) and crater navigation. The lander is guided by GCP until the LASS can provide measurements from about 100 m altitude down. The GCP catalogue of features is generated during the remote sensing phase of the MSC prior to DSC separation after arrival at the Trojan and also during descent reheasals.

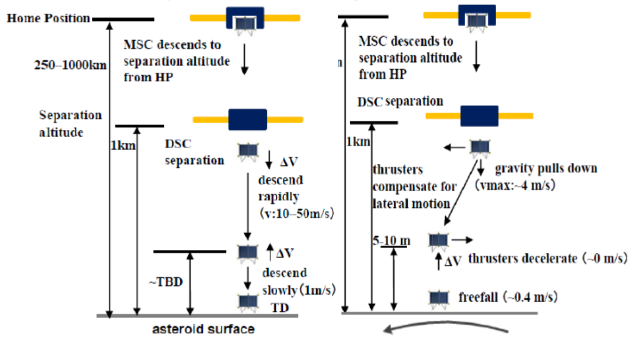

Fig. 8. Baseline and alternative DSC descent profiles

The descent begins from the MSC home position ~250 km out. The DSC is separated at ~1 km altitude and enters a rapid descent at >10 m/s controlled by thruster action. It decelerates to ~1 m/s at low altitude and lands at this velocity from a stop at the corresponding freefall altitude. Alternatively, a freefall descent with first a vertical deceleration and then a horizontal velocity matching burn ending at ~5…10 m altitude is possible, concluded by a freefall touchdown at ~0.4 m/s from this altitude. (Fig.8) The decmposition of vertical and horizontal burn and the final freefall are to avoid contamination or disturbance of the landing site by directly impacting thruster plumes. The total Δv for descent and landing is <20 m/s, requiring in <1 kg propellant based on a design target asteroid of 15 km radius, 0.5…4 g/cm³ density and a 10 h rotation period.

The landing system is the classical core body with 4 cantilever landing legs with a footpad radius of 0.6 m, using Al honeycomb damping elements. It is required to absorb <1 m/s impact velocity and cope with residual rotation rates ≤0°.1/s of all axes on a local slope and terrain roughness of ≤30°. The legs are moderately folded in the launch configuration and deployed by a pre-loaded spring and wire cutters. Accelerometers on the legs sense touch-down.

A cold-gas propulsion system has been selected for simplicity and system-level performance, fed from a tank at the lander's center of gravity. A redundant 12 thruster configuration with varied cant angles was selected as a robust and efficient solution. The cold gas system also feeds the pneumatic drill and its counter-thrust device. It requires special attention to leakage due to the 16-year cruise and remote sensing phase and the small propellant mass required. Non-contaminating fuels include He, N_2, and Ar in conventional high-pressure systems and CO_2 in a system based on the IKAROS RCS[39]. A N_2 blow-down system appears to have the best system-level performance in this lander application.

The lander structure is an octagonal body with an intersecting mid plate which also provides interface points to the MSC and divides the lander into two levels. The upper level is inside the MSC. The lower level will protrude from the MSC into the apogee engine cavity of the launch vehicle and is less restricted in diameter. The lander is closed at the top and bottom by two octagonal plates. A hash configuration for the inner shear walls ensures sufficient stiffness of the lander and load transmission during launch and landing. The continuous shear walls additionally are used for the mounting of the majority of the components, with a preferred location at the intersection points of two walls. Since most components are mounted to the inner hash, the lander does not need to be closed by outer panels completely. The structure consists of CFRP-Al honeycomb sandwich plates.

4. Practical aspects of 'small' interplanetary spacecraft

Small spacecraft pose their own unique challenges, some resulting from the opportunities that uniquely present themselves to them, others from the common misunderstanding that size matters in terms of the effort required or total cost of ownership.

4.1. Earth-escape launch capabilities and opportunities

Due to the advances in spacecraft miniaturization, launch vehicles have substantial margins on smaller interplanetary missions. IKAROS was added to achieve the minimum lauch mass for the JAXA Venus probe AKATSUKI, and therefore not mass-optimized.[42] Also carried were one interplanetary and three Earth-orbiting cubesats. The launch of HAYABUSA2 also carried PROCYON, SHIN'EN 2 and ARTSAT2: DESPATCH (FO-81).[95] Future launches may follow and offer affordable launch opportunities, likely under similar conditions as for secondary passengers to Earth orbit. These face significant schedule and physical size constraints, and AIV challenges which are highly unusual to the interplanetary community, but have been mastered in the course of PHILAE and MASCOT.

4.2. Integration and verification challenges

Assembly, Integration and Test/Verification (AIT/AIV) is the final stage in producing a spacecraft and readying it for launch. Choosing the right philosophy or approach of the verification and validation process is crucial and driven by risk tolerance. Less verification implies but does not necessarily create more risk. More verification implies but does not guarantee less risk.[96]

The classical Prototype Approach evolves in a mostly sequential and also successive fashion and gives the highest confidence that the final product performs well in all aspects.[97] However, if the schedule is heavily constrained, this extensive and time consuming method cannot be applied. The Protoflight Approach, where a single flight model is tested with replacing critical subsystems during the integration process, is also not applicable, since it is very likely that the chosen payloads and the system itself have very heterogeneous maturity levels. Hence, the test philosophy will lead to a Hybrid Approach with a mixture of conventional and tailored model strategies. This approach is common practice in scientific robotic missions[96] but it can be maximized for effectivity and time even further. Like 'Concurrent Engineering', a methodology based on the parallelization of engineering tasks to optimize and shorten design cycles in early phases, the term 'Concurrent AIV' (CAIV) has recently been introduced to express many simultaneous running test and verification activities.[98] In effect, the development, test and verification tracks of Software Development, Functional Testing, Mechanical AIV and Thermal AIV can get their own independent routes sharing their verification processes. Almost all environmental and functional tests with subsystems can be performed on EM and STM level before the QM and FM are fully assembled which effectively reduces potential delays, e.g. seven models of MASCOT were used in parallel this way. The development of onboard software can be performed completely independent with first simulated payloads and later with real hardware-in-the-loop electronic as and when they become available.

The challenges in creating parallel development lines will be found in team and facility resources if these are not readily and on-demand available. The key is to identify test dependencies, test sequences and which tests could be performed in parallel. This philosophy is also more complex as it requires overview of the development process of the mother spacecraft, the ongoing progress on system level as well as the insight in all payloads and subsystems.

Preceded by on-site CEF studies since 2008, MASCOT passed a dynamically adapted test programme using CAIV. It kept project risk within acceptable bounds and shortened the system-level AIV phase from typically 4-5 years to 2½ years within a project timeline of 3 years focused on the HY2 launch. Approx. 30 MASCOT system level tests were successfully completed, including Shock, Vibration, Thermal Vacuum, Full System Functional, EMC and Integration campaigns. Aboard HAYABUSA2 approx. 10 further test campaigns were passed for Sinusoidal Vibration and Mass Balance, Acoustic Vibration, Thermal Vacuum and System End-to-End tests. More than 50 additional System Unit tests were performed, excluding any test performed by the payloads or subsystems at the collaborating partners. Almost 100 different test campaigns were performed in roughly half the time usually allocated for such a prototype project which would follow a standardized way. Some subsystem test campaigns necessary for optimized operations planning are ongoing or planned. All these activities expand the experience base for future MASCOT activities leading up to the asteroid surface science mission.[58,99)]

5. Conclusions

In this paper we presented an overview of the characteristics and peculiarities of small spacecraft, in the form of landers and solar sailcraft studied, designed or built in DLR. Our experience has shown that the transition to 'small' mission environments demands a considerable change of culture, customs and habits in spacecraft design work from those used to working on 'large' scentific interplanetary missions.[100,101)] It also shows that with focused work, determination, and an open mind, this challenge can be mastered – and enjoyed.

References

1) A. Zimmer, E. Messerschmid, Target Selection and Mission Analysis of Human Exploration Missions to Near-Earth Asteroids, Planetary Defence Con. 2011, IAA-WPP-323, S05_0930_2150884.
2) Olga P. Popova, Peter Jenniskens, et al., (The Chelyabinsk Airburst Consortium), Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery and Characterization.Science 342 (2013).
3) Число пострадавших при падении метеорита приблизилось к 1500, РосБизнесКонсалтинг (RBC), 18 February 2013, 00:00, http://top.rbc.ru/incidents/18/02/2013/845595.shtml (accessed 22JAN2015 14:05)
4) Andrew E. Kramer, After Assault From the Heavens, Russians Search for Clues and Count Blessings, New York Times, 17 Feb. 2013, http://www.nytimes.com/2013/02/17/world/europe/russiaru-seek-clues-and-count-blessings-after-meteor-blast.html?_r=0 & Benjamin Bidder, Meteoriten-Hagel in Russland: "Ein Knall, Splittern von Glas", http://www.spiegel.de/wissenschaft/weltall/meteoriten-hagel-in-russland-a-883565.html (acc. 22JAN2015)
5) Meteorite hits Russian Urals: Fireball explosion wreaks havoc, up to 1,200 injured (photos, videos), February 16, 2013, 23:58, http://rt.com/news/meteorite-crash-urals-chelyabinsk-283/
6) Meteorite-caused emergency situation regime over in Chelyabinsk region, Russia Beyond The Headlines (Rossiyskaya Gazeta), Interfax, 5 March 2013, http://rbth.co.uk/news/2013/03/05/meteorite-caused_emergency_situation_regime_over_in_chelyabinsk_region_23513.html (accessed 22JAN2015)
7) Svend Buhl, Karl Wimmer, S. Pethukhov, P. Murmorov, et al., Trajectory Projection of the Chelyabinsk Superbolide and Location of Recorded Meteorite Finds, status of 18 July 2013, www.meteorite-recon.com via http://en.wikipedia.org/wiki/Chelyabinsk_meteor#mediaviewer/File:Strewnfield_map_of_Chelyabinsk_meteorites.jpg (accessed 22JAN2015)
8) M. Boslough, D. Crawford, D. Spalding, N. Singer, R. Montoya, Sandia supercomputers offer new explanation of Tunguska disaster – Smaller asteroids may pose greater danger than previously believed, December 17, 2007, https://share.sandia.gov/news/resources/releases/2007/asteaste.html (acc. 24OCT2015).
9) 4th IAA Planetary Defense Conference 2015 – Conference abstracts, papers, presentations, report, http://pdc.iaaweb.org/?q=content/2015-frascati (acc. 21OCT2016)
10) L.W. Alvarez, W. Alvarez, et al., Extraterrestrial cause for the Cretaceous–Tertiary extinction". Science 208 (4448): 1095–1108.
11) D.A. Kring, Guidebook to the Geology of Barringer Meteorite Crater, Arizona (a.k.a. Meteor Crater), 2007, Lunar and Planetary Institute, LPI Contribution No. 1355, http://www.lpi.usra.edu/publications/books/barringer_crater_guidebook/ (24OCT2015).
12) University of Bologna (Italy) – Department of Physics – Tunguska Home Page – Tunguska Scientific Publications, 2010, http://www-th.bo.infn.it/tunguska/tu99public.htm (24OCT2015).
13) J.S. Lewis, Rain of Iron and Ice: The Very Real Threat Of Comet And Asteroid Bombardment, 1997 amended paperback edition.
14) A.B. Chamberlin, NEO Discovery Statistics, http://neo.jpl.nasa.gov/stats/ (accessed 21OCT2014)
15) A. Harris (U.S.), The Value of Enhanced NEO Surveys, 3rd IAA Planetary Defence Conf. 2013, Flagstaff, IAA-PDC13-05-09
16) A. Harris (U.S.), The Population of Near-Earth Asteroids and Current Survey Completion, IAA-PDC13-02-09P
17) P. G. Brown, J. D. Assink, L. Astiz, R. Blaauw, M. B. Boslough, et al., A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors, Nature 503 (2013), 238-241.
18) P. Brown, R. E. Spalding, et al., The flux of small near-Earth objects colliding with the Earth, Nature 420 (2002), 294-296.
19) M.B.E. Boslough, D.A. Crawford, Low-altitude airbursts and the impact threat, Int. J. of Impact Engineering 35 (2008) 1441-1448
20) M. Boslough, Airburst Warning and Response, Planetary Defence Conference 2011, IAA-WPP-323, S4_1610_2166721
21) G. Gisler, Low-Altitude Atmospheric and Water-Surface Effects of Small Impacts, IAA-PDC13-05-05
22) Linda Billings, NASA/JPL Near-Earth Object Program Office, Newly Released Map Data Shows Frequency of Small Asteroid Impacts, Provides Clues on Larger Asteroid Population, Nov.14, 2014, http://neo.jpl.nasa.gov/news/news186.html (22JAN2015)
23) J.T. Grundmann, Small Solar System Body Mitigation: A Realist's Approach, IAA-WPP-301, P206 (full paper on request)
24) L.A. Kleiman, Project Icarus: an MIT Student Project in Systems Engineering, Cambridge, Mass., MIT Press, 1968, Report № 13
25) R. Kahle, Modelle und Methoden zur Abwendung von Kollisionen von Asteroiden und Kometen mit der Erde, D 83, TU Berlin, August 2005.
26) J. Bellerose, C. Foster, D. Morrison, B. Jaroux, D. Maruro, Performance and Derived Requirements of a Gravity Tractor serving as a precursor to a Kinetic Impactor within the NEOShield Study Framework, IAA-PDC13-04-18.
27) A. Gibbings, M. Vasile, J.-M. Hopkins, D. Burns, I. Watson, Experimental Characterization of the Thrust Induced by Laser Ablation onto an Asteroid, IAA-PDC13-04-21.
28) J.T. Grundmann, S. Mottola, et al., ASTEROIDSQUADS/*i*SSB – a Synergetic NEO Deflection Campaign and Mitigation Effects Test Mission Scenario, IAA-WPP-323 S5_0910_2162714.
29) M. Boslough, Impact Decision Support Diagrams, Planetary Defence Conference 2011, IAA-WPP-323, P68_2167459
30) ESTEC/ESA, Margin philosophy for science assessment studies, SRE-PA/2011.097/ issue 1, revision 3, 15/06/2012
31) M.D. Rayman, P.A. Chadbourne, J.S. Culwell, S.N. Williams,

Mission Design for Deep Space 1: a Low-Thrust Technology Validation Mission, Acta astronautica 45 (4-9): 381–388 (1999)
32) M.D. Rayman, P. Varghese, D.H. Lehman, L.L. Livesay, Results from the Deep Space 1 technology validation mission, Acta Astronautica 47 (2-9): 475–487 (2000)
33) M.D. Rayman, The successful conclusion of the Deep Space 1 Mission: important results without a flashy title, Space Technology 23 (2): 185–196 (2003).
34) D.M. Di Cara, D. Estublier, Smart-1: An analysis of flight data, Acta Astronautica 57 (2–8): 250–256 (2005).
35) H. Yano, et al., Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa, Science Vol. 312 (2006), 1350-1353.
36) J. Kawaguchi, A. Fujiwara, T. Uesugi, Hayabusa – Its technology and science accomplishment summary and Hayabusa-2, Acta Astronautica, Vol. 62, 639–647, 2008.
37) http://isa.ifsi-roma.inaf.it/BepiColombo/BC1/BC1.html (21OCT2014)
38) J. Kawaguchi, O. Mori, Y. Shirasawa, M. Yoshikawa, On the Trojan asteroid sample and return mission via solar-power sail – an innovative engineering demonstration, ACM2014.
39) O. Mori, H. Sawada, R. Funase, T. Endo, et al., Development of First Solar Power Sail Demonstrator – IKAROS, International Symposium on Space Flight Dynamics, Toulouse, Oct. 2009.
40) H. Yano, O. Mori, S. Matsuura, R. Funase, et al., IKAROS Team, JAXA Solar Power Sail Working Group, The Solar Power Sail Mission to Jupiter Trojans, 10th IAA LCPM 2013, S5
41) O. Mori, et al., IKAROS Extended Mission and Advanced Solar Power Sail Mission, 63rd IAC 2012, IAC-12,D1,1,3,x15786.
42) M. Umesato, T. Okahashi, Sailing Into Space, Two Men in a Race Against Time, http://www.nec.com/en/global/ad/cosmos/ikaros/.
43) A. Harris (DLR), et al., NEOShield – Progress Towards an International NEO Mitigation Program, IAA-PDC13-01-06.
44) G. Schwehm, ROSETTA – The comet rendezvous mission, ESA-SP-1179
45) K.-H. Glassmeier, H. Boehnhardt, D. Koschny, et al., The Rosetta Mission: Flying Towards the Origin of the Solar System, Space Science Reviews (2006), DOI: 10.1007/s11214-006-9140-8
46) S. Ulamec et al., RoLand, a Lander System for an active comet, IAA-95-IAA.11.1.06 (1995).
47) S. Ulamec, J. Biele, et al., Relevance of PHILAE and MASCOT in-situ Investigations for Planetary Defense, IAA-PDC15-04-08, 2015 IAA Planetary Defense Conference.
48) J. Biele, R. Willnecker, J.P. Bibring, H. Rosenbauer, et al., Philae (Rosetta Lander): Experiment status after commissioning, Advances in Space Research 38 (2006) 2025–2030.
49) M. Thiel, J. Stöcker, C. Robe, N.I. Kömle, G. Kargl, O. Hillenmaier P. Lell, The Rosetta Lander Anchoring System, 2003.
50) M. Hilchenbach, Simulation of the Landing of Rosetta Philae on Comet 67P/Churyumov-Gerasimenko, SIMPACK, 2004, p. 25.
51) J. Biele, S. Ulamec, M. Maibaum, R. Roll, et al., The landing(s) of Philae and inferences about comet surface mechanical properties, Science, Vol.349, issue 6247, aaa9816-1 (2015).
52) E. Hand, Comet lander's scientific harvest may be its last – Philae has fallen silent after fragmentary messages, Science, Vol.349, issue 6247, 459-460 (2015); also cf. M. Braun, K. Geurts, S. Ulamec, New command for Philae, http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-16365/#/gallery/21643
53) JAXA press release, Name Selection of Asteroid 1999 JU3 Target of the Asteroid Explorer "Hayabusa2", http://global.jaxa.jp/press/2015/10/20151005_ryugu.html , also http://www.minorplanetcenter.net/iau/lists/NumberedMPs160001.html , http://scully.cfa.harvard.edu/cgi-bin/showcitation.cgi?num=162173 (09OCT2015)
54) T.-M. Ho, V. Baturkin, R. Findlay, C. Grimm, et al., MASCOT - The Mobile Asteroid Surface Scout onboard the HAYABUSA2 Mission, 2016, SSR, DOI 10.1007/s11214-016-0251-6.
55) C. Ziach, V. Baturkin, T.M. Ho et al., MASCOT, the Small Mobile Asteroid Landing Package on its Piggyback Journey to 1999JU3: Pre-Launch and Post-Launch Activities, IAC-15-A3.4.6
56) C. Lange, et al., "How to build a 10 kg autonomous Asteroid landing package with 3 kg of instruments in 6 years?" – Systems Engineering challenges of a high-density deep space system in the DLR MASCOT project, 2624640 (1325), SECESA 2012
57) R. Findlay, T.-M. Ho, C. Lange, S. Wagenbach, L. Witte, C. Ziach, et al., A Small Asteroid Lander Mission to Accompany HAYABUSA-II, Proceedings of the 63rd International Aeronautical Congress, Naples, Italy, 2012, IAC-12-A3.4.7.
58) J.T. Grundmann, V. Baturkin, J. Biele, A. Bellion, et al., "You've got 2 Years, 6 Months, 1 Week and 48 Hours!" – the Ongoing Engineering Adventure of MASCOT and its Implications for Planetary Defence Missions, IAA-PDC13-04-06P.
59) C. Ziach, T.-M. Ho, et al., The Final Stages of MASCOT, a Small Asteroid Lander to Accompany HAYABUSA-II, IAC-13-A.3.4.6
60) M. Lange, O. Mierheim, C. Hühne. MASCOT - Structures Design and Qualification of an "Organic" Mobile Lander Platform for Low Gravity Bodies. Proc. of '13th European Conference on Space Structures, Materials & Environmental Testing', Braunschweig, Germany, ESA SP-727 (June 2014)
61) M. Lange, et al. MASCOT - A Lightweight Multi-Purpose Lander Platform. Proc. of '12th European Conference on Space Structures, Materials & Environmental Testing', Noordwijk, The Netherlands, ESA SP-691 (July 2012)
62) E. Canalias, M. Deleuze, S. Tardivel, C. Lange, C. Ziach, ANALYSIS OF THE DESCENT AND BOUNCING TRAJECTORY OF MASCOT ON 1999JU3, IPPW2015-6105, International Planetary Probe Workshop, 2015, Cologne
63) L. Celotti , M. Sołyga , R. Nadalini, V. Kravets, S. Khairnasov, V. Baturkin, et al., MASCOT thermal subsystem design challenges and solution for contrasting requirements, 45th International Conference on Environmental Systems, ICES-2015-83
64) J.T. Grundmann, J. Biele, R. Findlay, S. Fredon, T.-M. Ho, et al., One Shot to an Asteroid – MASCOT and the Design of an Exclusively Primary Battery Powered Small Spacecraft in Hardware Design Examples and Operational Considerations, № 3051, European Space Power Conference 2014.
65) C. Grimm, J. Hendrikse, C. Lange, J.T. Grundmann, et al., DLR MASCOT on HAYABUSA-II, A Mission That May Change Your Idea of Life! – AIV Challenges in a Fast Paced and High Performance Deep Space Project, sr104H00604H, ISTS 2013.
66) C. Krause, T.-M. Ho, et al., MAGIC - Mobile Autonomous Generic Insstrument Carrier for the in-situ Investigation of NEO Surfaces and Interior, IAA-WPP-323, P51_2161981
67) C. Lange, Using MBSE Methods to Design Generic System Platforms and Derivatives: A Methodology Applied to the Mobile Asteroid Surface Scout, Systems Engineering and Concurrent Engineering for Space Applications, SECESA 2014.
68) H. Schumann, A. Braukhane, A. Gerndt, et al., Overview of the New Concurrent Engineering Facility at DLR, SECESA 2008.
69) R. Findlay, A. Braukhane, D. Schubert, J.F. Pedersen, et al., Implementation of Concurrent Engineering to Phase B Space System Design, DLRK 2011 and CEAS Space Journal 2011.
70) Ross Findlay, Peter Spietz, et al., Concurrent engineering through the stages: AsteroidFinder (Phase B), SECESA 2010, 2072559.
71) J. Kepler, De Cometis Libelli Tres, 1619.
72) J.C. Maxwell, A Treatise on Electricity and Magnetism (1st ed.), 2, 391, Oxford, 1873.
73) A. Bartoli, Sopra I movementi prodotti della luce et dal calorie, Florence, Le Monnier, 1876; also Nuovo Cimento, 15, 193, 1884.
74) P. Lebedev, Untersuchungen über die Druckkräfte des Lichtes, Annalen der Physik, 1901
75) E.F. Nichols, G.F. Hull, The Pressure due to Radiation, Phys. Rev. (Series I) 17, 91-104, 1903
76) W. Seboldt, M. Leipold, M. Rezazad, et al., Ground-based demonstration of solar sail technology. Rio de Janeiro, 2000. 51st International Astronautical Congress. IAF-00-S.6.11.
77) U. Geppert, et al., The 3-Step DLR–ESA GOSSAMER road to solar sailing, Advances in Space Research 48 (2011) 1695-1701.
78) B. Dachwald, et al., Gossamer Roadmap Technology Reference Study for a Multiple NEO Rendezvous Mission, in: M. Macdonald (ed.), Advances in Solar Sailing, 2014 (3rd ISSS).
79) C.R. McInnes, et al., Gossamer Roadmap Technology Reference Study for a Sub-L_1 Space Weather Mission, in: M. Macdonald (ed.), Advances in Solar Sailing, 2014 (3rd ISSS)

80) M. Macdonald, C. McGrath, et al., Gossamer Roadmap Technology Reference Study for a Solar Polar Mission, in: M. Macdonald (ed.), Advances in Solar Sailing, 2014 (3rd ISSS)
81) P. Seefeldt, et al., Large Lightweight Deployable Structures for Planetary Defence: Solar Sail Propulsion, Solar Concentrator Payloads, Large-scale Photovoltaic Power, IAA-PDC15-P-20.
82) J.T. Grundmann, B. Dachwald, C.D. Grimm, R. Kahle, et al., Spacecraft for Hypervelocity Impact Research – an Overview of Capabilities, Constraints, and the Challenges of getting there, 13th Hypervelocity Impact Symposium 2015, session 11, #20.
83) J.T. Grundmann, W. Bauer, J. Biele, F. Cordero, B. Dachwald, et al., From Sail to Soil – Getting Sailcraft Out of the Harbour on a Visit to One of Earth's Nearest Neighbours, IAA-PDC15-04-17.
84) http://esamultimedia.esa.int/docs/gsp/completed/AIDA_MissionRationale_InterimRelease.pdf , http://esamultimedia.esa.int/docs/gsp/AIDAProjectOptions_v1a.pdf (accessed 22JAN2015)
85) W. Kofman, A. Herique, Y. Barbin, et al., Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar, Science, Vol.349, issue 6247, aab0639-1 (2015).
86) AIM's asteroid lander, http://www.esa.int/spaceinimages/Images/2015/04/AIM_s_asteroid_lander , http://www.esa.int/Our_Activities/Space_Engineering_Technology/Asteroid_Impact_Mission (accessed 24OCT2015).
87) C. Lange, J.T. Grundmann, et al., Technology and knowledge reuse concepts to enable responsive NEO characterization missions based on the MASCOT lander, IAA-PDC15-P-65.
88) S. Mottola, A. Börner, et al., AsteroidFinder: Unveiling the Population of Inner Earth Objects, 2008, IAC-08-A3.5.6
89) S. Mottola, et al., AsteroidFinder/SSB: A German Mission for the Search of IEOs, 2009, IAA-WPP-301, 01_10.
90) J.T. Grundmann, et al., Small satellites for big science: the challenges of high-density design in the DLR Kompaktsatellit ASTEROIDFINDER/SSB, COSPAR 2010, B-04-0043-10.
91) R. Findlay, et al., A Space-Based Mission to Characterize the IEO Population, 2011, IAA-WPP-323, P02_2149803.
92) J.F. Pedersen, O. Eßmann, et al., AsteroidFinder: A Small Satellite to Characterize the IEO Population, SSC11-IV-3.
93) J.F. Pedersen, R. Findlay, H. Müller, O. Eßmann, DLR-Kompaktsatellit: A Small German Spacecraft Developed by DLR for Substantial Scientific Return, DLRK 2011.
94) R. Findlay, O. Eßmann, et al., AsteroidFinder: Implementing a Small Satellite Mission to Detect IEOs, IAC-11-B4.2.8
95) wikipedia: 2014 in spaceflight, http://en.wikipedia.org/wiki/2014_in_spaceflight , http://en.wikipedia.org/wiki/PROCYON , http://www.pe0sat.vgnet.nl/satellite/commercial-scientific/shinen-2/ , http://www.pe0sat.vgnet.nl/satellite/commercial-scientific/artsat2/ , accessed 12JAN2015.
96) Larson, J.W., et al.: Applied Space Systems Engineering, Space Technology Series, McGraw-Hill Companies, Inc., 2009.
97) Ley, W., Wittmann, K., Hallmann, W.: Handbook of Space Technology, John Wiley & Sons, Ltd., 2009.
98) Grimm, C., et al.: Concurrent AIV and Dynamic Model Strategy in Response to the New Normal of so called Death March Projects, Aerospace Testing Seminar 2014.
99) C.D. Grimm, et al., On Time, On Target – How the Small Asteroid Lander MASCOT Caught a Ride Aboard HAYABUSA-2 in 3 Years, 1 Week and 48 Hours, IAA-PDC15-P-66.
100) J.T. Grundmann, J. Biele, M. Drobczyk, C. Lange, S. Montenegro et al., The Ends of Small – Practical Engineering Constraints in the Design of Planetary Defence Missions, IAA-PDC13-04-05P.
101) C.D. Grimm, J.T. Grundmann, J. Hendrikse, et al., Going Beyond the Possible, Going Beyond the "Standard" of Spacecraft Integration and Testing! – A Summary of the DLR Mascot AIV Activities within the Hayabusa2 Project from the First Unit Hardware Test to Final Check-out before Launch, 30th ISTS 2015.
102) F. Mellor, Colliding Worlds: Asteroid Research and the Legitimization of War in Space, Social Studies of Science 37/4 (August 2007), pp. 499-531.
103) C. Sagan, S.J. Ostro, Dangers of asteroid deflection, Nature 368, 501 (07 April 1994); doi:10.1038/368501a0
104) Legal Perspectives on Space Resources and Off-Earth Mining, Session E7.2, 59th IISL Colloquium on the Law of Outer Space, IAC 2016, Guadalajara, Mexico, http://iac2016.org/pdf/IAC2016_FP_FULL.pdf (accessed 21OCT2016), p. 173
105) AsteroidScience Intersections with In-Space Mine Engineering, ASIME 2016, Neimënster, Luxembourg, 21-22 September 2016, http://europlanet-scinet.fi/index.php?id=asime16 (21OCT2016)
106) D.M. Tobin, G.S. Haag, A. da Silva Curiel, et al., Off-The-Shelf Micro-Satellites for Science and Technology Missions, 11th AIA/USU Conference on Small Satellites, SSC97-V-4
107) A.F. Cheng, et al., Asteroid impact & deflection Assessment mission, Acta Astronautica, Vol. 115, pp. 262-269, 2015
108) J. Biele, S. Ulamec, Capabilities of Philae, the Rosetta Lander, Space Science Rev., 138, pp. 275-289; 2008
109) S. Ulamec, J. Biele, C. Fantinati, J.-F. Fronton, P. Gaudon, et al., Rosetta Lander - after seven years of cruise, prepared for hibernation, Acta Astron., Vol. 81, pp. 151-159, 2012
110) S. Ulamec, C. Fantinati, M. Maibaum, et al., Rosetta Lander – Landing and operations on comet 67P/Churyumov–Gerasimenko, Acta Astron., Vol. 125, pp. 80-91, 2016
111) A. Peloni, et al., Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission, Journal of Guidance, Control, and Dynamics, 2016, DOI: 10.2514/1.G000470
112) J.T. Grundmann, P. Spietz, P. Seefeldt, T. Spröwitz, GOSSAMER Deployment Systems for Flexible Photovoltaics, 67th IAC 2016, Guadalajara, Mexico, IAC-16-C3.3.6.
113) P. Seefeldt T. Spröwitz, J.T. Grundmann Verification Testing of the GOSSAMER-1 Deployment Demonstrator, 67th IAC 2016, Guadalajara, Mexico, IAC-16-C2.2.3.
114) T. Spröwitz et al, Qualification Testing of the GOSSAMER-1 Deployment Technology, ECSSMET 2016, #56220.
115) P. Seefeldt, P. Spietz, T. Sproewitz, J.T. Grundmann, et al., Gossamer-1: Mission Concept and Technology for a Controlled Deployment of Gossamer Spacecraft, Adv. in Space Research (2016), doi: http://dx.doi.org/10.1016/j.asr.2016.09.022.
116) F. Dannemann, M. Jetzschmann, Technology-driven Design of a Scalable Small Satellite Platform, 4S Symposium 2016.
117) P. Seefeldt, T. Spröwitz, E. Mikulz, S. Reershemius, K. Sasaki, N. Tóth, R. Jahnke, Controlled Deployment of Gossamer Spacecraft, ISSS 2017.
118) http://www.robex-allianz.de/en/about-robex/topic-2000-system-infrastructure/
119) http://www.dlr.de/dlr/desktopdefault.aspx/tabid-10212/332_read-19403/year-all/#/gallery/24429
120) B. Dachwald, R. Kahle, B. Wie, Solar Sailing Kinetic Energy Impactor (KEI) Mission Design Tradeoffs for Impacting and Deflecting Asteroid 99942 Apophis, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, AIAA 2006-6178.
121) B. Dachwald, R. Kahle, B. Wie, Head-On Impact Deflection of NEAs: A Case Study for 99942 Apophis, AIAA, PDC 2007.
122) B. Dachwald, B. Wie, Solar Sail Kinetic Energy Impactor Trajectory Optimization for an Asteroid-Deflection Mission, Journal of Spacecraft and Rockets, Vol. 44, No. 4, July–August 2007, DOI: 10.2514/1.22586.
123) S. Bhaskaran, B. Kennedy, Closed Loop Terminal Guidance Navigation for a Kinetic Impactor Spacecraft, IAA-PDC13-04-02.
124) J. Lyzhoft, et al., GPU-Based Optical Navigation and Terminal Guidance Simulation of a Hypervelocity Asteroid Intercept Vehicle (HAIV), IAA-PDC13-04-23.
125) J. Gil-Fernández, et al., The Challenge of Navigating Toward and Around a Small, Irregular NEO, IAA-WPP-301, 02_03.
126) R. Jaumann, N. Schmitz, A. Koncz, H. Michaelis, et al., The Camera of the MASCOT Asteroid Lander on Board Hayabusa2; Space Science Reviews, 2016 , DOI 10.1007/s11214-016-0263-2
127) M. Grott, J. Knollenberg, B. Borgs, F. Hänschke, et al., The MASCOT Radiometer MARA for the Hayabusa 2 Mission, Space Science Reviews, 2016 , DOI 10.1007/s11214-016-0272-1
128) D. Herčík, H.-U. Auster, et al. The MASCOT Magnetometer; Space Science Reviews, 2016 , DOI 10.1007/s11214-016-0236-5
129) L. Riu, J-P. Bibring, V. Hamm et al., Calibration of MicrOmega Hayabusa-2 Flight Model – First Results, 47th LPSC 2016, #2109.