Small Spacecraft for Small Solar System Body Science, Planetary Defence and Applications

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Abstract— **Following the recent successful landings and occasional re-awakenings of PHILAE, the lander carried aboard ROSETTA to comet 67P/Churyumov-Gerasimenko, and the launch of the Mobile Asteroid Surface Scout, MASCOT, aboard the HAYABUSA2 space probe to asteroid (162173) Ryugu we present an overview of the characteristics and peculiarities of small spacecraft missions to small solar system bodies (SSSB). Their main purpose is planetary science which is transitioning from a 'pure' science of observation of the distant to one also supporting in-situ applications relevant for life on Earth. Here we focus on missions at the interface of SSSB science and planetary defence applications. We provide a brief overview of small spacecraft SSSB missions and on this background present recent missions, projects and related studies at the German Aerospace Center, DLR, that contribute to the worldwide planetary defence community. These range from Earth orbit technology demonstrators to active science missions in interplanetary space. We provide a summary of experience from recently flown missions with DLR participation as well as a number of studies. These include PHILAE, the lander of ESA's ROSETTA comet rendezvous mission now on the surface of comet 67P/Churyumov-Gerasimenko, and the Mobile Asteroid Surface Scout, MASCOT, now in cruise to the ~1 km diameter C-type near-Earth asteroid (162173) Ryugu aboard the Japanese sample-return probe HAYABUSA2. We introduce the differences between the conventional methods employed in the design, integration and testing of large spacecraft and the new approaches developed by small spacecraft projects. We expect that the practical experience that can be gained from projects on extremely compressed timelines or with high-intensity operation phases on a newly explored small solar system body can contribute significantly to the study, preparation and realization of future planetary defence related missions. One is AIDA (Asteroid Impact & Deflection Assessment), a joint effort of ESA, JHU/APL, NASA, OCA and DLR, combining JHU/APL's DART (Double Asteroid Redirection Test) and ESA's AIM (Asteroid Impact Monitor) spacecraft in a mission towards near-Earth binary asteroid system (65803) Didymos. DLR is currently applying MASCOT heritage and lessons learned to the design of MASCOT2, a lander for the AIM mission to support a bistatic low frequency radar experiment with PHILAE/ROSETTA CONSERT heritage to explore the inner structure of Didymoon which is the designated impact target for DART.**

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1. Introduction

Planetary defence related spaceflight missions come in two categories:

First, science missions to investigate the properties of small solar system bodies in general prior to any recognized threat.

Second, missions to characterize and possibly deflect one specific object that has become a recognized threat to such a degree and confidence that exclusively dedicated missions are warranted.

The main difference between those categories is that nature picks target and timeline for the latter, while for the former careful deliberation in scientific committees usually does.

Since science missions do not fly frequently, the spacecraft designers' aim is to maximize science output and consequently launch mass to the limit of accessibility of *any* suitable target object for affordable launchers within the space agency mission class. In threat-related missions, the only constraint is the target object itself including getting there in time.

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 in favour of propulsion and/or greatly extending flight time by planetary gravity-assists. However, this only prevails as long as interest in a specific object or a subset of possible targets outweighs more general considerations of the scientific communities involved in the mission. In most cases, a more easily accessible object of the same or a sufficiently similar class would be 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]

From Tunguska to Chelyabinsk: Bursts of Interest

The widely reported airburst of the Chelyabinsk bolide on February 15th, 2013, returned the focus on planetary defence. This ~500 kiloton TNT-equivalent range event caused by a ~20 m diameter chondritic body [2] was just barely non-lethal: Early reports stated that 1491 people including 311 children were seen by medical staff in the region [3] and 112 people were treated in hospitals, two of them in serious condition. One woman suffered broken vertebrae and was flown out for treatment; one man's finger was cut off by flying glass [4]. Most injuries were by glass shattered and scattered about or accelerated by the blast wave [5]. Property damage included massive destruction of window panes in the midst of the Siberian winter, mostly on appartment blocks, and several collapsed structures. [6]

The distribution of injuries also clearly demonstrated the value of preparedness in natural disasters. At one school and kindergarden site, 20 children were injured by flying glass as the blast wave hit during the break just after the first lessons were over. At another school, not recognizing the event for what it was, Ms Yulia Karbysheva, a 4th-grade school teacher, ordered her students to execute the duck and cover drill which is still customarily practised there – none of 44 was injured. She herself did not follow and suffered serious lacerations and a tendon cut by flying glass in one arm. [4]

It has to be noted that the main fragmentation occurred 31.8 km south of the city centre of Chelyabinsk approximately at the minimum distance to the ground track [7] at an altitude of 29.7 km [2], or at about 44 km line-of-sight distance between the largest release of energy in the event and a population of 1.13 million. Also, the most intense region of the shock wave propagating in the direction of the momentum vector originating from this area was already directed away from the city and most densely populated areas surrounding it. [8]

In the aftermath of this event, the size-frequency distribution of natural impactors at Earth and their potential for destructive effects on the ground, and technical options for near-Earth object (NEO) deflection were revisited extensively. [9]

The first wave of attention to the NEO threat had about three decades earlier recognized the rare but potentially globally catastrophic impacts of km-scale near-Earth asteroids (NEA) based on the observations of early photographic asteroid surveys and the emerging geological cratering record of the Earth. It drew strongly on the discovery of prehistoric indicators of impact such as the iridium anomaly at the cretaceous-tertiary boundary leading to the seminal Alvarez hypothesis [10], the recognition of Meteor Crater near Flagstaff, Arizona, [11] and the Tunguska event of 1908, [12] and other historical data as related to meteoritic impacts (e.g. [13] for a historical summary). This recognition of the impact threat was formalized into the goal to discover 90% of all NEAs larger than 1 km diameter, relatively quickly followed up by the definition of Potentially Hazardous Asteroids (PHA) of at least 140 m diameter which can approach Earth to within 0.05 AU. The ongoing dedicated NEO surveys based on mass automatic exposure and processing of CCD images [14] confirmed the significant contribution to the threat of the much more frequent small impactors with regional or locally devastating effects. [15] NEAs in the sub-PHA size range have recently become accessible enough to observation to enable estimates of the population based on re-discovery rates which indicate that their relative frequency is somewhat higher than expected from earlier extrapolations down from the PHA size range [16][17][18]. Also, modelling of the effects of atmospheric entry and asteroid fragmentation strongly suggests much higher yield to ground-level damage efficiency than previously expected from observations made e.g. at the 1908 Tunguska impact site. [19][20][21] U.S. government sensors recorded at least 556 fireball events from 1994 through 2013, ranging from about 5 ton TNT-equivalent to the Chelyabinsk superbolide. [22]

The shift of focus towards the threat posed by smaller, more frequent impactors also changed the approach towards deflection. The impulse necessary to deflect an object on a given orbit to a safe passage of Earth is proportional to its mass – a substantial reduction of requirements for the expected likely next event. The now unlikely case of a surprise civilization killer asteroid was replaced by impacts just slightly too large to be dealt with by practical application of preparedness and civil defence infrastructures but likely to occur on human timescales. For yet smaller impactors, the choice is to stand and stare or duck and cover.

This reappreciation of risk based on the success of NEO surveys and on the likelihood of occurrence on human timescales made deflection feasible within the present capabilities of the Earth's spaceflight infrastructure. However, smaller impactors are also much more difficult to detect. For the first generation of NEO surveys, reliable detection was only possible for km-sized objects. Thus, end-to-end mitigation concepts focused on the large objects that were detectable. To deflect these, correspondingly challenging large space segments were required. However, since the risk posed by Tunguska-sized impactors was accepted as real and much more frequent, there was a significant drive towards improvement in the global NEO observation and tracking capabilities. The resulting development of NEO surveys in the past decade greatly increased the likely lead time at which a reliable positive prediction of impact can be made; cf. [23] and ref. therein.

The earliest space-based planetary defence scenarios envisaged nuclear payloads of unprecedented size to be put on the largest launch vehicles ever built – and long since decommissioned – for launch on very short warning lead times [24]. Now, flight hardware derived from already flown and currently developing interplanetary missions, some of which are discussed briefly below, can meet the various mitigation mission types' requirements on timelines of several years to a few decades from discovery to arrival at the target NEO. Advanced methods of deflection are being discussed, e.g. [25][26][27], which for all but the very largest impactors remove the non-technical burdens of nuclear mitigation and the justified concerns regarding their realization (cf. [23][28]). At the same time, advanced NEO surveys are working towards completion of the inventory of km-sized NEAs, largely eliminating the residual risk of surprise in this size segment [15].

2. Embracing Constraints

Whether it comes to a recognized threat situation which ties planetary defence related missions to one specific object, or whether a wider choice of target objects for scientific missions is desirable, there are two basic fundamentals of spaceflight:

First, reduce spacecraft mass by designing merely the best mission possible into the envelope of constraints ultimately driven by the object of interest, within the capabilities of the present spaceflight infrastructure; that is, decide to accept significant constraints beyond those which would commonly apply to a specific science mission and then stick by them.

Second, improve the delta-v of the spacecraft after launch from Earth; that is, decide to add propulsion-related functions to the spacecraft and to accept advanced or new technologies into such key functions to mission success, under mission responsibility.

Current Science Missions: Application of Pure Method

The first way out is none less than a paradigm shift in spacecraft design procedures. Scientific interplanetary missions are presently developed according to established agency and industry procedures and standards in a more or less linear fashion, following through from a basic set of stakeholder requirements that has already come out on top in a competitive peer-reviewed selection process. In a development process divided up into phases ranging from mission concept definition to hardware integration, those requirements are successively devolved or branched out to the next levels of detail from where in turn every detail requirement is traced back to the previously established higher levels for its justification. These levels, and therefore the justification of all following levels of finer detail, are confirmed by major reviews at least once at every phase transition, become frozen, and thus form the baseline design for the next phase. During testing, all previous connections of requirements are similarly retraced for the purpose of verification of fulfillment. Both processes inherently work as one-way roads. The requirements-driven technical design process lets the design expand from any given initital concept or current baseline into a generally open and unconstrained design space, but only within the limits of detail defined by the current project phase. The phased management of development leads to the creation of a succession of consolidated baseline designs from which the next phase or design cycle sets out. Each step in this succession of baselines needs to be formally certified by review to become frozen and thus allow the design to proceed. Technical as well as managerial work is commonly carried out in compartimentalized work packages with defined interfaces of data exchange and hierarchical communication which require formal data release processes. The division of work is often paralleled with contractual divisions of labour and contractual implications to be considered in the exchange of design data between the technical staff dealing with the purely technical content of the work packages, e.g. when some specific subset of the design data is not explicitly covered by the related contracts and/or intellectual property issues arise. In almost all cases work is carried out at widely separated sites for programmatical and other reasons. Change, which is mostly externally driven (e.g. by programmatic guidance, limitations or reorganization) can only be accommodated by going back to an earlier baseline and restarting development as a whole from there; in the extreme, though by no means rarely, effectively going back to start from scratch in the middle of an established major project. Often, when corrections or changes only apply to a subset of domains, other work packages have to idle until a common level of maturity and/or formal state of phased development is regained. Such change processes have to be implemented with care to ensure that every lane of communication is formally updated to the new baseline which is then not just a refined derivative of the previous one.

Constraints-driven Design: Small Organic Integrated

A planetary defence related mission can be expected to be developed in reaction to a small target Near-Earth Object (NEO) which is in some way newly discovered [14][15][16][29], i.e. in the broader sense in response to a mission target or objective that with the ongoing initial accumulation of knowledge on it poses fluid requirements, possibly until launch and thereafter. In this case, 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 requirements-driven development method that most in the industry and government agencies are used to. The accessibility of the target is defined by the laws of orbital mechanics, available launch and communication capabilities, and in the case of deflection also by the efficiency and timing of the selected method for impulse transfer [25]. Considering NEO accessibility studies related to science missions with comparatively stringent target selection constraints, e.g. [1], it appears quite likely that any other artificial burden beyond those imposed by nature and the serendipity of discovery could over-constrain such missions into infeasibility.

Efficient accommodation into an environment which poses a challenging and changing target definition however requires more than occasional re-tracing, tailoring or redefinition of requirements on paper. Even fundamental assumptions that would normally constitute long frozen and elementary mission requirements may have to be questioned rather frequently based on the need to maintain mission feasibility, immediately affecting the implementation of design or hardware production that follow from them. At later stages, changes may have to be implemented without the time to change hardware that already had to be produced due to lead times. Also, the design has to flow constantly into the – possibly also changing – constraits envelope related to a timely launch. These may, for example, be as simple as very clear cut limits of mass and geometrical size which immediately follow from launch vehicle capabilities and from the interplanetary transfer orbit that also sets the timeline to a fixed launch window. 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 thus blurs the interface boundaries of technical subsystems as well as the organizatorial structure and work package divisions. Also, since the efficiency of thorough optimization can depend on the implementation of relatively minor details, particularly when close to functional interfaces relevant for organic integration, attention to detail cannot be postponed until the appropriate project phase: The earlier hardware implementation can be exercised and tested, the more design space within the envelope of constraints is liberated from margins allocations by detailed knowledge and understanding of the design. Similarly, it is very unlikely that resource allocations defined at an early stage can be upheld simply because the blanket application of a structured margins philosophy (e.g. [30]) may already overconstrain the design. Every subsystem needs to be optimized as far as possible within 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, latest when that leaves the paper stage. Particularly those which can only affordably get into orbit as secondary or tertiary payloads by sharing a ride with other, usually much larger spacecraft reach a point of no return to requirements-driven design when they have to convert to a significant level or fraction of constraints-driven design. For these, the main passenger of the launch acts as the authority to set effectively immovable constraints. These effectively define feasibility of the small spacecraft’s design and mission concept, on the background of programmatic infeasibility of procurement of a dedicated launch of their own for the smaller payloads.

Once such a small spacecraft mission has reached sufficient maturity to be manifested into the spare capacity of a launch, also the launch window becomes fixed, at least relative to the progress of the main payload. Launch dates for Earth-orbital missions are known to drift considerably from the envisaged date at gaining funded project status till actual launch. But manifestation of the launch occurs only 12 to 18 months before the set launch date at that stage of the project, and secondary passengers are often only admitted later. This leaves about two years from the start of serious launch negotiations and about one year from a confirmed but by no means guaranteed launch opportunity to commit expensive, expirable and/or long lead time hardware to spacecraft integration and qualification, and get ready for launch. Margins are commonly in the not unlikely delays of a few weeks to months for key dates within this launch manifestation timeframe – but they may as well be zero.

These project conditions are about as poles apart as possible from mainstream interplanetary science mission project environments. But they are also currently the best approximation in living spacecraft design experience to the likely situation of threat-related planetary defence missions. Here, the tightest project timelines can be expected for the early precursor reconnaissance missions necessary to understand the potential Earth impactor as soon as possible before committing to or finalizing the flight hardware of possible deflection missions.

Propulsion: Beyond Hydrazine and Fly-by

The second way, improvement of overall delta-v, offers a growing choice of reasonably developed propulsion methods, from simply larger fuel fractions to 'alternatives' such as electrical propulsion. However, alternative methods, i.e. any other than storable chemical propellant based thrusters and the use of planetary gravity assists, are only slowly and 'from below' entering the segment of science missions. Often, these are primarily technology demonstration missions which are adapted to a planetary science objective to demonstrate compatibility of a new technology with science missions in general and their required quality of results. Early examples were the 373 kg DEEP SPACE 1 (DS1) which visited asteroid (9969) Braille and comet 19P/Borelly using solar-electric ion propulsion of 2.1 kW power [31][32][33], the 367 kg European Moon probe SMART-1 (Small Missions for Advanced Research in Technology) which used a solar-electric Hall effect thruster of 1.2 kW to raise its orbit from the initial geostationary transfer orbit (GTO) to capture into lunar polar orbit [34], and the first successful asteroid sample return by the 510 kg Japanese probe HAYABUSA using solar-electric xenon ion engines [35][36]. For the largest science missions, the transition towards electric propulsion is only beginning: 56% of the launch mass of the CASSINI-HUYGENS and MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging) spacecraft, each, was chemical propellant, but only 34% of BEPICOLOMBO of which more than half is xenon for solar-electric propulsion. [37]

The obvious next step is the use of large-area structures, either to generate more photovoltaic power for solar-electric propulsion or to employ solar sails. 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) which was launched as a secondary payload with the Venus Climate Orbiter (VCO) probe, AKATSUKI. [39][40][41] Although by unusual launch circumstances and 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. GETTING SMALL

This section provides a brief overview of the recent projects and activities at DLR. All these are either scientific missions to small solar sysem bodies or technology demonstrators. With respect to planetary defence, DLR at the Institute of Planetary Research also leads the NEOShield Project, funded by a 7th Framework Programme (FP7) grant from the European Commission (EC) [43].

PHILAE – Delete Lander, Add Instrument, Commit, Success

ROSETTA is a Cornerstone Mission of the previous Horizon 2000 ESA Programme. The mission was launched in 2004 and reached its target, comet 67P/Churyumov-Gerasimenko in 2014. [44][45] After an intense phase of remote investigation of the comet nucleus including the selection of an appropriate and safe landing site, Agilkia, all taking place during summer 2014 the ROSETTA Lander, PHILAE, (Fig. 1) performed the first ever landing on the surface of a comet on November 12th, 2014. [46][47]

The Lander, which has an overall mass of about 98 kg (including 26.7 kg of science payload) is based on a carbon fibre / aluminium honeycomb structure, a power system including a solar generator, primary and secondary batteries, a central data management system, and an S-band communications system, using the ROSETTA Orbiter as relay.

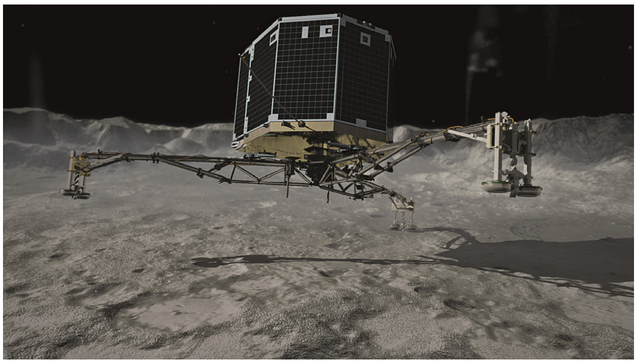

Figure 1: PHILAE just before a touch-down (artist's concept)

During cruise the Lander is attached to the Orbiter with the MSS (Mechanical Support System) which also includes the push off device, separating PHILAE from the Orbiter. [48] In this vantage position it was able to support ROSETTA during critical phases such as 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.

The selected landing scenario foresaw separation at an altitude of 20.5 km. The descent to the surface took just under 7 hours, as expected.

At touch-down anchoring harpoons were to be fired and a cold gas system should have prevented re-bouncing while ice screws were expected to drill into the surface to secure PHILAE in place [49][50]. However, in the reality of the unknowns of nature and engineering PHILAE arrived at its intended landing site, Agilkia, on 67P/Churyumov-Gerasimenko on November 12th, 2014, 15:34 UTC, and immediately left it again due to a combination of anchoring units' failures to finally settle after nearly two hours of bouncing at a heavily shadowed site now called Abydos. There, PHILAE successfully conducted its planned science mission until all energy was depleted on November 15th, 2014, 00:07 UTC. [51]

During a first scientific sequence of 57 hours while 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. Each experiment was operated at least once.

The expected long term operations phase foresaw the experiments to work mainly in sequence, one by one and to be scheduled according to power generation and data relay capacity. In this phase, data evaluation was expected primarily offline, while preplanning activities were to be performed in parallel; with various experiment operations for up to a few months on the comet surface. Expectations were off after the unexpected events upon landing(s) but telemetry from PHILAE was received again on June 13th, 2015, 20:28 UTC showing that it had been intermittently active already since May. Signals were received sporadically till July 9th, but even including attempts of 'blind commanding' and an adaptation of ROSETTA's orbit to impove radio visibility and distance regular operation could not be established. The communication conditions with ROSETTA have been unfavourable until recently because the orbiter had to retreat from the core of comet 67P/Churyumov-Gerasimenko due its much increased activity near perihelion. As this activity subsided, ROSETTA approached it again, mainly for close-up studies of the core, but also prepared for a possible second phase of science activities of PHILAE on the surface. As of this writing, the window of opportunity for any operations of PHILAE is closing and some final and more risky attempts are under way to reactivate it e.g. by spinning up its flywheel. [52]

In a historical sidenote, the ROSETTA Lander, now PHILAE, but for a long time merely known as ROLAND, was resurrected as an instrument proposal for the obiter by a grassroots movement of interested scientists and engineers, after being descoped from the mission, following the earlier deletion of an even more ambitious sample return option. This represents the first time that a lander, though in itself a complete spacecraft, and not a small one at that, is *not* the driving element of the main mission; here in that it was not considered essential *before* the call for proposals for instruments to fly aboard ROSETTA. The concept of integrating a small spacecraft style lander at the instrument level of the mothership mission has since been repeated by the unfortunately lost BEAGLE 2 on MARSEXPRESS, and the target markers, various MINERVAs and MASCOT on the HAYABUSA missions.

MASCOT – a Constraints Envelope come Alive

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. The Flight Model (FM) was delivered to JAXA mid-June 2014. It was launched aboard the HAYABUSA2 space probe on December 3rd, 2014, and appeared in good health at its first activation 2 weeks later. In June 2015, the first in-flight calibration session was completed successfully. In September 2015, the launch Preload Relief Mechanism was successfully actuated, putting MASCOT in a separation-ready configuration. Passing by Earth once more in late 2015 for a gravity-assist, HAYABUSA2 is carrying MASCOT along to asteroid (162173) Ryugu (formerly 1999 JU_3, [53]) using solar-electric propulsion. MASCOT, following

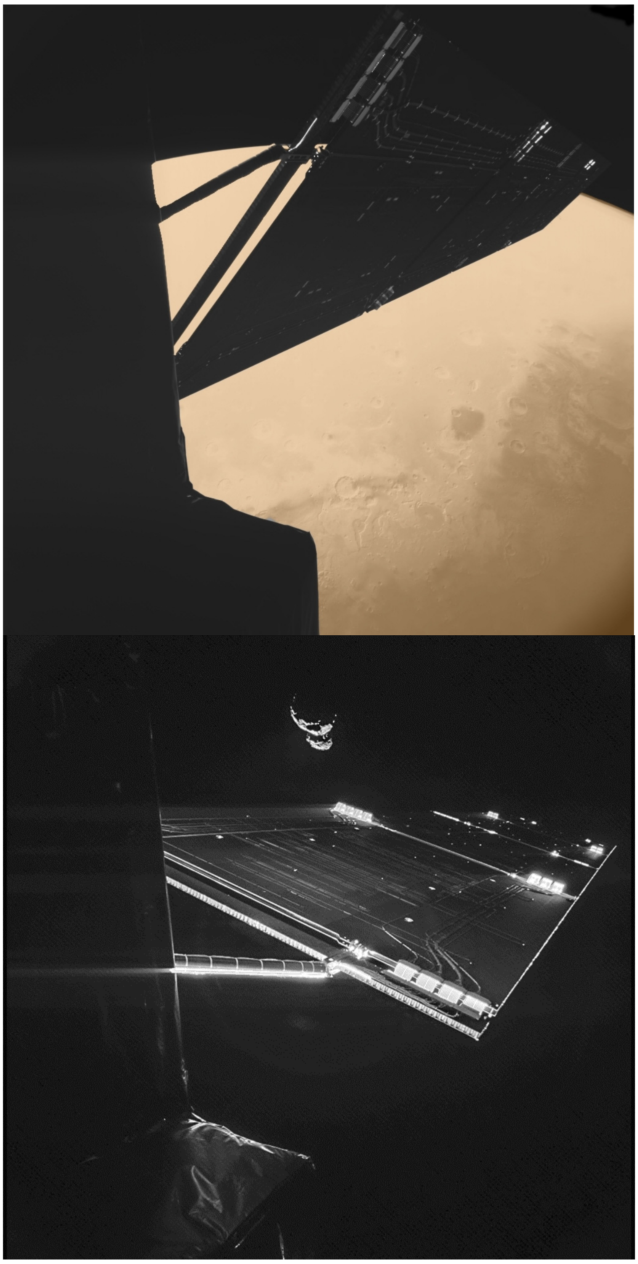

Figure 2: Worlds viewed from a small spacecraft's perspective – Mars and 67P/Churyumov-Gerasimenko – © ÇIVA/PHILAE/ROSETTA

constraints set by its mothership and target asteroid, is an organically integrated high-density design. [54][55][56][57][58][59]

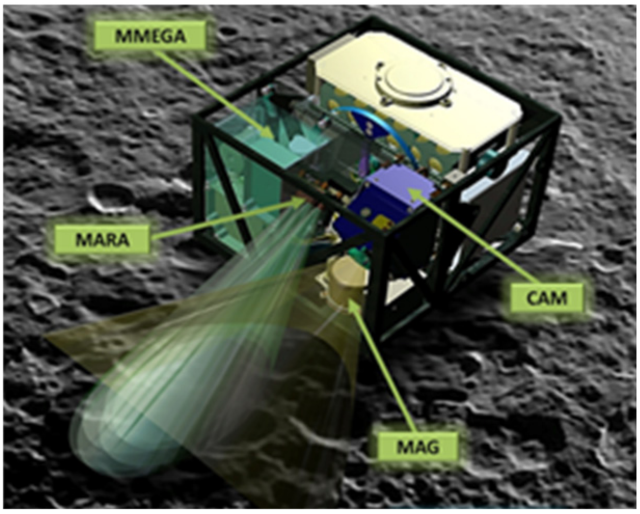

Figure 3: The MASCOT Lander and its science instruments on the asteroid (Outer single layer insulation foil is removed for clarity)

Main MASCOT subsystem features are as follows:

- Structure: The MASCOT structure is a highly integrated and ultra-lightweight truss-frame made from a CFRP and Rohacell® foam sandwich. [60][61]

- Mechanisms: MASCOT has three internal mechanisms: (i) the Preload Release Mechanism to release a controlled kN-range preload in the structure and across the separation mechanism interface which suppresses detrimental vibrations; (ii) the Separation Mechanism to realize the gentle push-off of MASCOT at ~5 cm/s out of the Mechanical Support Structure, MESS, recessed inside the HAYABUSA-2 envelope; and (iii) the Mobility Mechanism for uprighting and hopping across the asteroid surface over distances from less than a metre up to 220 m. [62]

- Thermal: MASCOT uses a semi-passive thermal control concept, with two heatpipes, a radiator, and Multi-Layer Insulation (MLI) for heat rejection during active phases, supported by a heater for thermal control of the battery and the main electronics during passive phases. [63]

- Power: MASCOT is using a primary battery for the power supply during its on-asteroid operational phase. During cruise, it is supplied by HAYABUSA2. The Power Conversion and Distribution Unit (PCDU) applies a mixed isolating/non-isolating conversion concept adapted to grounding within a nonconductive structure. [64]

- Communication: All housekeeping and scientific data is sent to Earth via a relay link with the HAYABUSA2 main spacecraft. The link is set up using a redundant UHF-Band transceiver and two patch antenna, one on each side of the lander, with omnidirectional coverage.

- OBC: The MASCOT OBC is a redundant system providing data storage, instrument interfacing, command and data handling, as well as autonomous surface operation functions. The operational redundancy mode is configurable in a four module set of two CPUs and two I/O and mass memory boards to optimize power consumption and robustness on the background of an exclusively primary battery powered mission.

- Attitude Determination: The knowledge of the landers attitude on the asteroid is key to the success of its uprighting and hopping function. The attitude is determined by a threefold set of sensors: optical distance sensors, photo electric cells and thermal sensors.

Looking at the worldwide planetary defence and science-related planning for missions to small bodies in the next years, it is inherent that future flight opportunities will arise for such a small versatile add-on landing package which has the capability to complement, complete and counterbalance the main missions objectives at a comparably low cost.

This is why at DLR, we are using our knowledge [65] to build on this heritage by carrying forward the idea of further MASCOT derivatives. Such derivatives or variants will be differing in their main features such as lifetime (long-lived vs. short-lived), feasible landing velocity (small or high velocity landing) or instrument suite (e.g. radar tomography vs. geology vs. geochemistry), but will all be based on a common platform. [66]

The main goal is to advance the current design from the dedicated lander MASCOT, to a generic instrument carrier able to deliver a variety of payload combinations on different mother-missions to different target bodies. To minimize the effort of redevelopment and the time to obtain a new design, we are employing principles of Model Based Systems Engineering (MBSE) [67] and Concurrent Engineering [68][69][70]

GOSSAMER-1: "So hoist the foil and booms…"[*]

In the final stages of qualification testing preparations is the GOSSAMER-1 large lightweight structures and solar sail deployment demonstrator.

The idea of an outward propulsive force of sunlight goes back to Kepler's observations and remarks published in 1619 on the directionality of comets' tails [71]. It was predicted to equal magnitude in 1873 by Maxwell on the basis of his electromagnetic theory [72] and in 1876 by Bartoli based on the Second Law of Thermodynamics [73] but could only be experimentally demonstrated as pressure due to radiation by Lebedev in 1901 [74] and by Nichols and Hull in 1903 [75].

The development of solar sail technology has been ongoing at DLR for many years at varying levels of intensity since the 1990s. A first phase culminated in a successful ground deployment test of a (20 m)² boom-supported sail on December 17th,1999. [76]

Figure 4: GOSSAMER-1 solar sail deployment demonstrator in Earth orbit

In its solar sail application, the GOSSAMER-1 deployment demonstrator (Fig. 4) was to have been the first step in the DLR-ESTEC GOSSAMER roadmap [77], leading to sailcraft of sizes enabling unique science missions that are presently difficult to achieve or not feasible using other post-launch propulsion methods. Among these mission types, three were studied in detail:

- a multiple NEO rendezvous mission with the capability of additional fly-bys between stays at 3 NEAs within 10 years of flight time (Fig. 5) [78],

- a displaced-L1 spaceweather mission which bears some similarity to a co-orbital NEA rendezvous flight profile [79], and

- a solar polar orbiter mission which bears some similarity to a highly inclined and eccentric orbit NEA rendezvous flight profile [80].

All these missions are small spacecraft that could ride as secondary passengers to GTO and proceed from there with a small kickstage. They are all within the capabilities of currently available sail film and boom technology. [81] One advantage of solar sail as a propulsion method is the relative ease of target object change during the mission. It would for example be possible to re-direct a multiple NEO rendezvous mission similar to [78] to a newly discovered target of urgent interest or change the priority of target objects when the progress of science or other missions makes this desirable. Some flexibility of this kind is, within the limits of fuel and photovoltaic power, also possible for some lightweight solar-electric missions, as was shown e.g. by the target object changes of DEEP SPACE 1 throughout its project and flight history. Also, the adaptation of the cruise

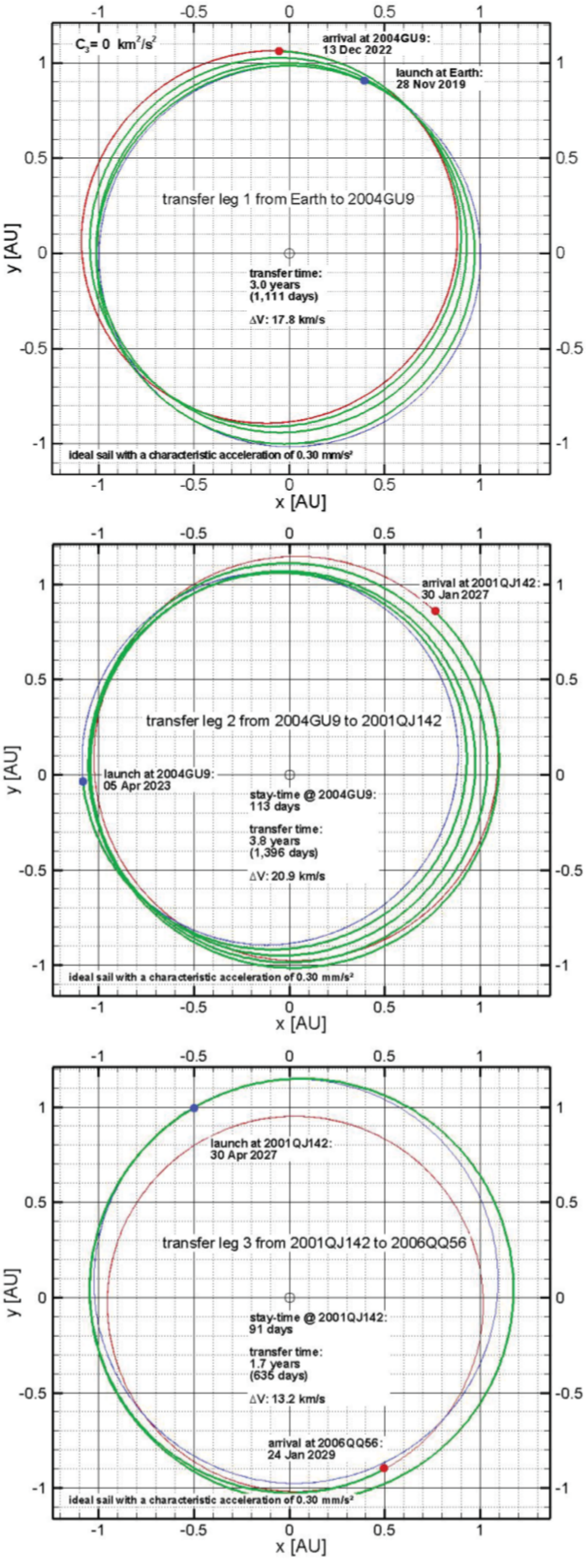

Figure 5: GOSSAMER-based multiple NEA rendezvous mission visiting 2004 GU_9, 2001 QJ_{142}, and 2006 QQ_{56}

trajectories of HAYABUSA was only possible due to advanced propulsion capabilities, as is the double rendezvous of DAWN with the two largest main belt asteroids, (4) Vesta and (1) Ceres. Among other uses closer to Earth, this has generated interest in high power electric propulsion for which very large lightweight deployable structures seem attractive for photovoltaic supply. [38][40][81]

However, the unique capability of accelerating without having to consume or carry propellant that is characteristic of solar sailing remains a mission enabler for high delta-v and hypervelocity missions beyond the range of any fuel-based propulsion method. [82][83]

AIDA – Combined Operations

The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid. AIDA is a joint NASA-ESA mission in pre-Phase A study, which includes the NASA Double Asteroid Redirection Test (DART) mission and the ESA Asteroid Impact Monitor (AIM) rendezvous mission. The primary goals of AIDA are first to test our ability to impact a small near-Earth asteroid by a hypervelocity projectile and second to measure and characterize the deflection caused by the impact.

The AIDA target will be the binary asteroid (65803) Didymos, with the deflection experiment to occur in October, 2022. The DART impact on the secondary member of the binary at ~6 km/s will alter the binary orbit period, which can be measured by Earth-based observatories. The AIM spacecraft will monitor results of the impact in situ at Didymos. AIDA will return fundamental new information on the mechanical response and impact cratering process at real asteroid scales, and consequently on the collisional evolution of asteroids with implications for planetary defense, human spaceflight, and near-Earth object science and resource utilization.

The AIM component of AIDA has also been studied in variations of spacecraft and payload sizes for different classes of launch vehicles which would enable the accommodation of landers within a size range approximately between MASCOT and PHILAE on instrument level, where in the latter's envelope a number of smaller landers could be carried as an alternative. [84]

DLR is currently applying MASCOT heritage and lessons learned to the design of MASCOT2 or MASCOT@AIM, a lander for the AIM mission to support a bistatic low frequency radar experiment with PHILAE/ROSETTA CONSERT [85] heritage to explore the inner structure of Didymoon which is the designated impact target for DART. The current MASCOT2 baseline design envisages only the minimum of modifications necessary to adapt the short science mission lifetime optimized design of MASCOT at HAYABUSA2 to a long-life photovoltaically powered mission more similar to the once envisaged extended operations phase of PHILAE. Also, some modifications necessarily follow from changes in the suite of instruments of which only some are expected to be re-used from the first MASCOT. The fundamental changes in the power supply and instruments concept have lead to some growth but it remains well within the margins to be applied on top of the respective original MASCOT's parameters for a partially new, partialy modified design. [30] However, the basic constraints-driven design and concurrent engineering approaches characteristic of MASCOT seem set to be continued due to the resources envelope constraints and timeline requirements of the AIM mission. [86]

Everyone's Favourite MASCOT

The attention caused by the coincidence of PHILAE's landing(s) and MASCOT's launch in late 2014 resulted in a whole host of small SSSB lander studies at DLR. They range from spacecraft considerably smaller and somewhat simpler than MASCOT to fully PHILAE-sized and even more complex and 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 design features at unit level. However, as demonstrated by the work on MASCOT2 for AIM, the original MASCOT design appears quite well prepared for strategic re-use [87] even though this was not an important factor during its design phase which out of necessity built on concepts of successively smaller derivates of PHILAE [47]. One key feature is shared by all these fresh branches on the MASCOT family tree: they are self-contained spacecraft integrated at the instrument level from the perspective of their respective mothership missions.

ASTEROIDFINDER – Breaking the Sunlight Barrier

In 2008, DLR selected the AsteroidFinder Instrument (AFI) to be studied extensively for a mission on the satellite platform being developed at the time in the frame of the German national 'Kompaktsatellit' (compact satellite) Program. The scientific goal was to contribute to the understanding of the dynamical evolution and the cratering history of the innermost region of the Solar System, and the assessment of the impact hazard posed by objects Interior to Earth's Orbit (IEOs). Also called Inner Earth Objects, Apohele or Atira asteroids, these NEOs' orbits are completely contained within the Earth orbit's perihelion distance, 0.983 AU. If at all, IEOs are only observable from the ground at dusk or dawn which makes them difficult to discover. Currently, only 14 IEOs have been detected out of an estimated population of about 1000 down to a size of 100m. Most of these graze the Earth's orbit from within. An Earth-orbiting search telescope is an efficient and cost-effective tool for discovering these objects. ASTEROIDFINDER was planned to use a body-fixed 25cm wide-field telescope to continuously scan the sky in the range of 30° to 60° solar elongation. (Fig. 6) An off-axis telescope design was chosen which combines an efficient aperture, without the occultation loss due to a conventional on-axis central secondary mirror, with very high straylight suppression. (Fig.7) As in ground-based surveys, asteroids are identified through their apparent motion. The instrument was optimized for point-source detection. It used unfiltered electron-multiplied CCD sensors (EMCCD) to suppress read-out noise combined with onboard stack-register pre-processing to enable the use of a small and agile spacecraft platform. It was expected that ASTEROIDFINDER could double the number of known IEOs and particularly increase the discovery rate for those with deep-interior orbits, and would also discover a much larger number of Aten asteroids.

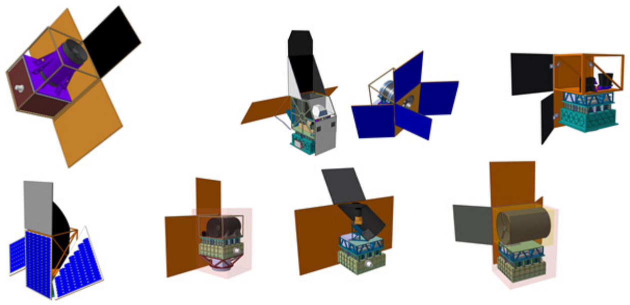

Figure 6: Some ASTEROIDFINDER configurations evaluated during early phases sessions in the DLR Bremen Concurrent Engineering Facility (CEF)

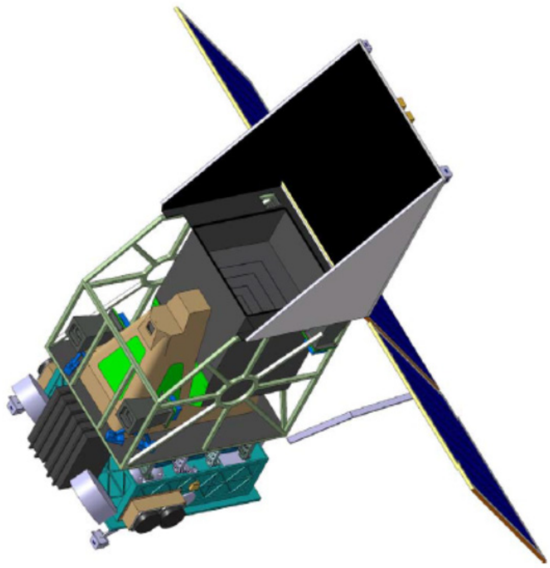

Figure 7: ASTEROIDFINDER in standardized secondary payload launch envelopes compatible configuration with deployable sunshield (spacecraft bus surface structural panels and thermal insulation foil not shown)

From the start, the spacecraft was designed to fit pre-defined secondary payload envelopes of several launch providers (Figs. 6 & 7), and to be compatible with frequently used Sun-Synchronous low-Earth orbits (SSO). [88][89][90]

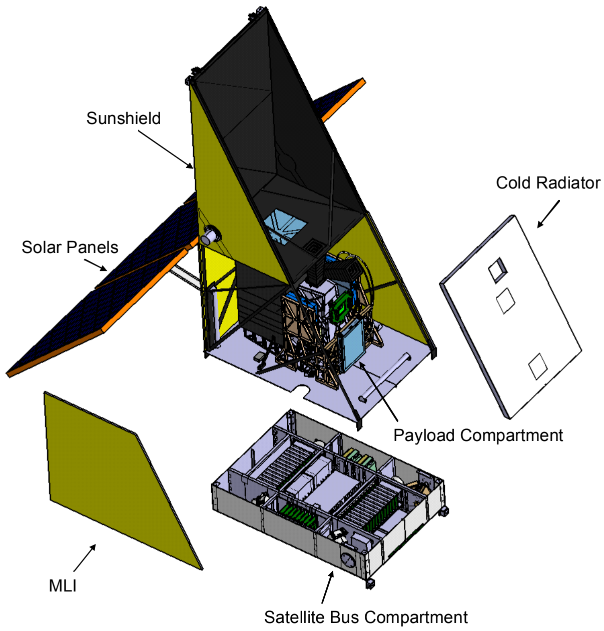

Figure 8: ASTEROIDFINDER in dedicated launch configuration with fixed sunshield

However, the design was flexible enough to be enlarged, simplified and adapted to a later envisaged dedicated launch on a FALCON-1e launch vehicle. (Fig. 8) [91][92][93][94]

ASTEROIDSQUADS/iSSB – More of the Same

In an ad-hoc effort for the 2011 Planetary Defence Conference, a PHA multiple flyby/impact mission concept was studied that combines a heavy lauch vehicle test launch opportunity (Fig. 9) with a concerted practical exercise of the NEO observation and interplanetary spaceflight infrastructure.

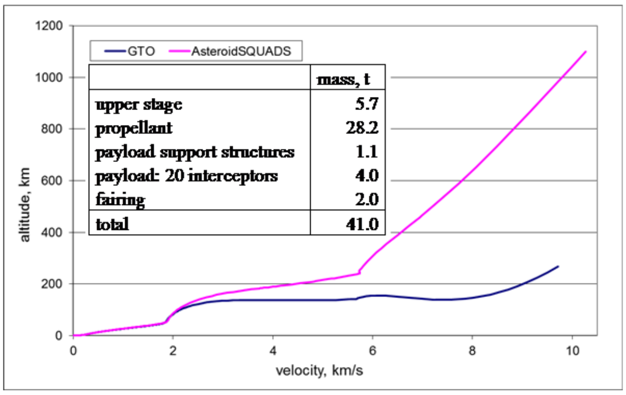

Figure 9: ASTEROIDSQUADS/*i*SSB launch profiles: altitude-velocity comparison of a maximum payload mass launch to GTO and a launch of the lighter ASTEROIDSQUADS/*i*SSB stack using an identical burns

In this concept, the timing of the launch vehicle test replaces the coincidence of discovery of a genuine threat and drives the selection of a target object at relatively short notice. Also, the mission profile is restricted to operations relatively close to Earth to minimize mission duration and infrastructure requirements. This study employed a simplified derivate of the then-current ASTEROIDFINDER spacecraft design equipped with a propulsion module but still fitting the originally envisaged secondary payload envelope. (Fig. 10)

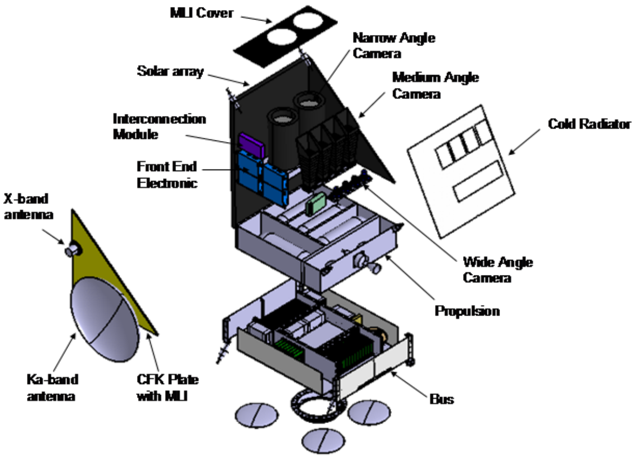

Figure 10: ASTEROIDSQUADS/*i*SSB impactor concept

Thus, up to approx. 20 small spacecraft could be launched at once, using existing launcher payload accommodation options (Fig. 11), to exercise deep space flotilla operations that can be expected in a real asteroid deflection case. It preserved some of the AFI features, particularly the EMCCD sensors, though in this case to achieve close-up imaging of the target NEA right down to impact at up to 1000 frames/s. [28]

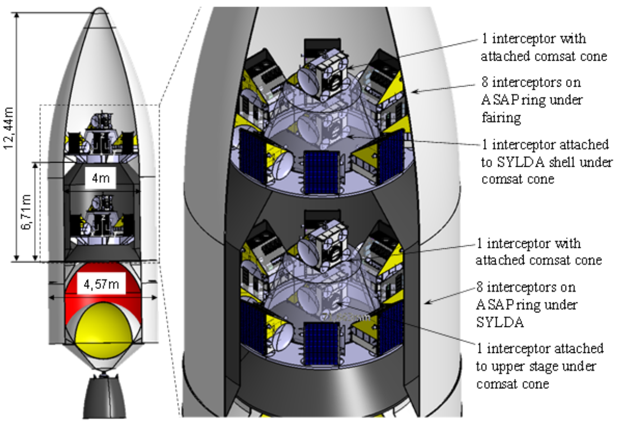

Figure 11: ASTEROIDSQUADS/*i*SSB launch configuration with 20 impactors, all mass except the launch vehicle's fairing is carried to impact

The comprehensive exercise of a massively parallel deflection scenario combined with cameras and other instruments using the required high-speed data link would provide planetary science and civil defence with Asteroid Serendipitous Quantitative Understanding and Assessment of Deflection Strategies, based on an improved interplanetary flight capable Standardized Satellite Bus kit which provides a wide choice of functional units from past and present projects and studies that serves as a point of departure configuration for the next step.

4. GETTING THERE

Recent interplanetary missions have brought developments that favour small spacecraft. But small spacecraft also 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.

A little Far Out – Launch to Earth Escape Capabilities

Many launch vehicles have a minimum payload weight that is due to the advances in spacecraft miniaturization no longer filled by smaller interplanetary missions. For example, IKAROS was added as ballast to achieve minimum lauch mass of the H-IIA launch vehicle of the Japanese Venus probe AKATSUKI, and therefore not mass-optimized. [42] Additionally, one interplanetary and three Earth-orbiting cubesats were carried. The launch of HAYABUSA-2 followed this template by carrying three additional payloads: the 59 kg Proximate Object Close flyby with Optical Navigation (PROCYON), the 2.85 kg SHIN'EN 2 student-built interplanetary communication experiment, and ARTSAT2: DESPATCH (FO-81), also an interplanetary radio experiment [95]. Future launches may follow the same concept and have ballast added in the form of secondary passengers that go along into parking orbit or even all the way into the final escape trajectory.

This trend will likely offer affordable launch opportunities also to small interplanetary missions as those discussed above, though under similar constraints as for secondary passengers to Earth orbit. It will pose significant time constraints, physical size constraints, and AIV challenges to these projects which will be highly unusual to the established interplanetary missions and science community, but have been mastered in the course of PHILAE and MASCOT.

Here and Now – the AIV/AIT Challenges

The Assembly, Integration and Test/Verification (AIT/AIV) is the final stage in producing a spacecraft and readying it for launch. It includes the simulation and test of the expected space environment and flight operation to verify and demonstrate the overall performance and reliability of the flight system. 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 verification approach (Prototype Approach) which evolves in a mostly sequential and also successive fashion would be of course the most reliable method to choose as it gives the highest confidence that the final product performs well in all aspects of the mission [97]. However, if the schedule is heavily constrained in time, this extensive and time consuming method cannot be applied.

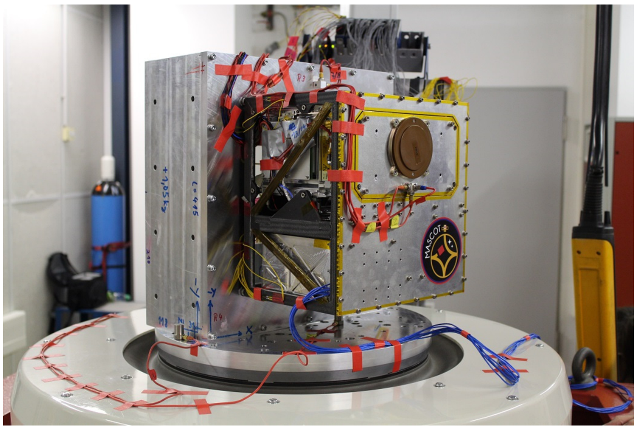

Figure 12: The MASCOT Structure Thermal Model 2.1 during vibration tests

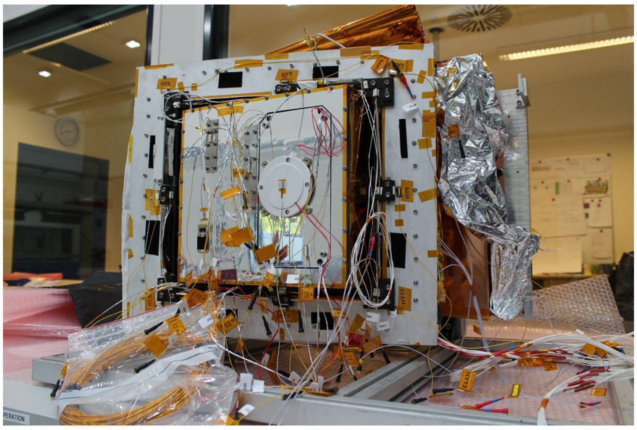

Figure 13: The MASCOT Structure Thermal Model 2.2 in preparation for Thermal Vacuum Test

On the other hand, 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. The project can start with a baseline on the classical sequential approach to ensure a minimum number of physical models required to achieve confidence in the product verification with the shortest planning and a suitable weighing of costs and risks. But this approach can be adapted on a case by case scenario, where the model philosophy evolves along the verification and test process depending on the particular system and subsystem readiness. This includes test models reorganization, refurbishing and re-assigning previous models for other verification tasks if appropriate, skipping test cases, parallel testing of similar or equal models and for some components allowing the qualification on system level.

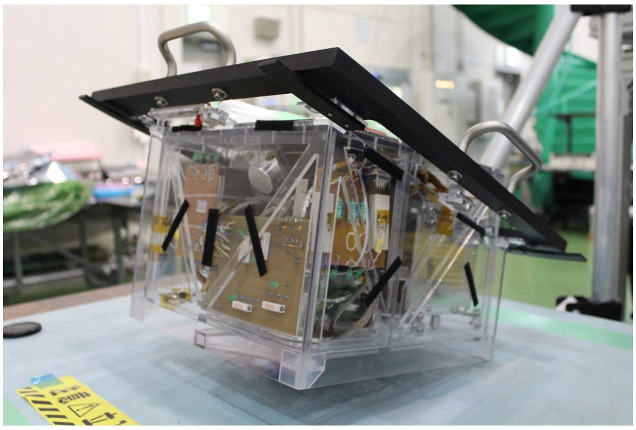

Figure 14: The MASCOT Engineering Model (EM) awaiting the Initial Integration Test

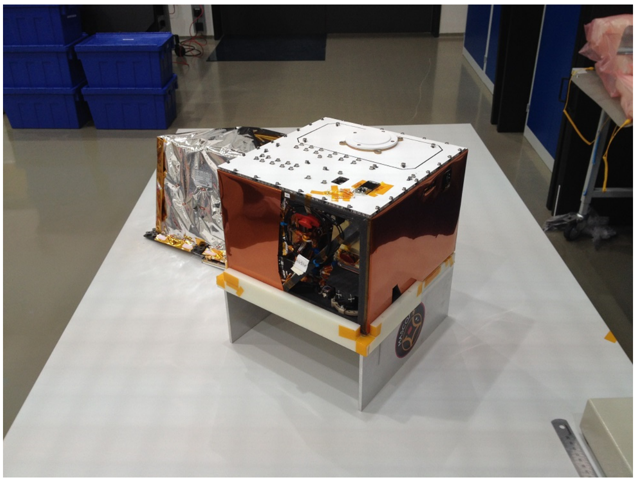

Figure 15: The MASCOT Engineering Qualification Model (EQM) ready for the Advanced Engineering Test

More specifically, parallelization of testing activities using identical copies and flexibility in the model philosophy will create independent unique test threads only joining their dependencies at key points where other optional roads could be chosen. Like Concurrent Engineering, a methodology based on the parallelization of engineering tasks nowadays used for optimizing and shorten design cycles in early project phases, the term “Concurrent AIV” has recently been introduced to express many simultaneous running test and verification activities [98].

In effect, the development, test and verification track 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 reduced potential delays. Seven models of MASCOT used in parallel are shown in Figs. 12 to 18. In addition, the development of the onboard software including individual instrument and subsystem software, can be performed completely independent with first simulated payloads and later with real hardware-in-the-loop electronic when they become available. This way, every payload and subsystem can freely do debugging tests which can take longer time independently. With this approach, most of the problems for the interfaces and functionality of each subsystem can be found before flight model integration.

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 test could be performed in parallel. In addition, this philosophy is also more complex as it requires the 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.

It may sound unreasonable to perform the development of a spacecraft in such a manner, whereas well established methods form a 'standard way'. But if a certain project is left with no choice of having the luxury of excessive testing, such an approach may be the only option. That this method is not just a theory can be seen in the DLR MASCOT project – a fast paced and high performance deep space project. It applied a unique mix of conventional and tailored model philosophies and it was possible to dynamically adapt the test program, limited by a fixed launch date, to accomplish for the shortest planning and a suitable weighing of costs and risks. A dynamically adapted test programme using Concurrent Assembly Integration and Verification (AIV) kept project risk within acceptable bounds and shortened the system-level AIV phase from the typical 4 to 5 year to 2½ years within a project timeline of 3 years focused on the specific launch opprotunity. When the definite launch opportunity was confirmed, MASCOT already was in the position to benefit from a preceding phase of a range of lander concept studies at the DLR Bremen Concurrent Engineering Facility since 2008. (It is this situation that is not unlike that of an Earth-orbital small spacecraft awaiting manifestation for a shared launch with another, larger main payload, as described earlier.)

Within this 2½-year AIV phase, from the start with the first breadboard model, the MASCOT team has successfully completed approx. 30 MASCOT system level tests, including Shock and Vibration, Thermal Vacuum, Full System Functional, EMC and Integration campaigns. On its carrier satellite HAYABUSA-2 it has fulfilled additionally approx. 10 test campaigns for Sinusoidal Vibration and Mass Balance, Acoustic Vibration, Thermal Vacuum and System End-to-End tests. To develop the MASCOT system

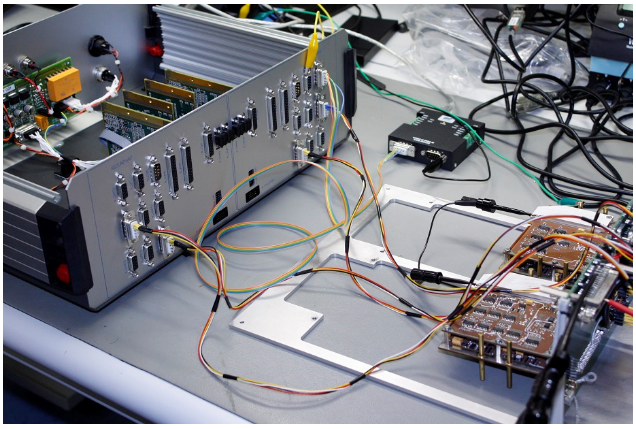

Figure 16: The MASCOT Software Development and Validation Facility (SDVF) in operation

and to make it flight ready, more than 50 additional System Unit tests were performed, excluding any test performed by the Payloads or other subsystems provided by the collaborating partners during subunit development. This culminates in amost 100 different test campaigns performed in roughly half the time usually allocated for such a prototype project which would follow a standardized way.

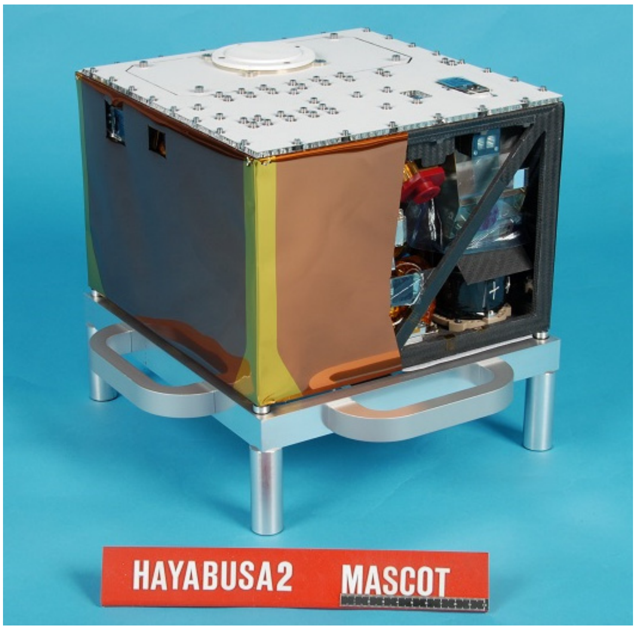

Figure 17: The MASCOT Flight Model (FM) ready to go

Currently, the fully integrated MASCOT Flight Spare (FS) is used as a precision reference model in addition to the mainly functional Ground Reference Model. They continue in functional and environmental testing on system level, with the SDVF (Fig. 16) for software and operations development. If required, these could be joined by more still to be (re-)built partial hardware models. Also, some subsystem test campaigns necessary for optimized operations planning are ongoing or are being planned. With the fully integrated FS, engineering aspects can be covered during science calibration campaigns and vice versa. All these activities expand the experience base for future MASCOT activities leading up to the asteroid surface science mission. [99][58]

Figure 18: The MASCOT Structure Thermal Model 1 on public relations assignment at the ILA, Berlin

5. Doing Things

Planetary defence is still a new and developing field. [9] Related instruments to be carried on spacecraft as those discussed above can also extend in their operating and design principles beyond those commonly carried on science missions. It is, as in AIDA or Deep Impact, possible to conduct impact impulse transfer studies (i.e., employ a "very fast lander") for the promising deflection concept of kinetic impactors. A ranging beacon for extended precision orbit determination by Earth-based facilities can be deployed, also in a MASCOT-like solar-powered lander dropped by solar sail or other low-thrust propelled main spacecraft which can not be used as easily as a ballistic orbiter to do precision orbit determination ranging of an asteroid but can reach targets inaccessible to conventionally fuelled propulsion missions.

6. Conclusion

In this paper we present an overview of the characteristics of small spacecraft missions, from Earth orbit and interplanetary mission experience 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.

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Stephan Ulamec *has more than 20 years of experience in the development and operations of space systems and instruments. After finishing his PhD at the University of Graz, 1991, he worked as a Research Fellow at ESA/ESTEC until 1993 and is since then at the German Aerospace Center, DLR, in Cologne. Besides of his activities in system engineering and project management of the* Rosetta *Lander,* Philae*, he is engaged as payload manager of MASCOT for the* Hayabusa*2 mission. He was involved in numerous studies for in-situ packages and landers for space research as well as the definition and performance of tests for various systems to be operated on planetary surfaces.*