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FROM SAIL TO SOIL – GETTING SAILCRAFT OUT OF THE HARBOUR ON A VISIT TO ONE OF EARTH'S NEAREST NEIGHBOURS

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ABSTRACT

The DLR-ESTEC GOSSAMER roadmap envisages the development of solar sailing by successive low-cost technology demonstrators towards first science missions. In this framework, the GOSSAMER-1 deployment demonstrator for a (5 m)² sail structure in low Earth orbit is followed by a (20 m)² sail effect demonstrator GOSSAMER-2 for higher Earth orbits, and the (50 m)² GOSSAMER-3 sailcraft to prove the principle within the Earth-Moon system. Missions requiring the unique capabilities of solar sail propulsion were studied by science working groups, including multiple NEO rendezvous and fly-by.

The GOSSAMER sail technology has been developed by DLR since the 1990s, with a successful (20 m)² deployment test in 1999 at DLR Cologne. The requirements for

GOSSAMER-3 demand the demonstration of sufficient trajectory and attitude control for science missions. Advances in boom, sail, and deployment mechanisms have already now increased the payload margin of baseline GOSSAMER-3 designs from a few to several kg. A camera to demonstrate attitude control and a magnetometer to study the space environment around a sail were first considered as payloads for GOSSAMER-3.

In addition to these, the shoebox-sized 10 kg asteroid lander MASCOT recently launched with HAYABUSA-2 also carries a hyperspectral infrared soil microscope and a surface thermal infrared radiometer. The camera‘s and radiometer‘s fields of view coincide on the asteroid surface.

Although designed for a mission on (162173) 1999 JU$_3$, with the necessary margins for the unknown the instruments are versatile enough to adapt. Thus, a minimal modification of MASCOT may be integrated as separable instrument module with GOSSAMER-3, first to observe the sail during the deployment and demonstration flight phases. In an extended mission and with experience previously gained, the mission could be concluded by the rendezvous with and the challenging drop of a ballistic lander onto a small asteroid near Earth.

For the exercise scenario on the mitigation of fictional Earth impactor 2015 PDC, it is assumed that the GOSSAMER roadmap keeps its 2 year mission interval after the last expected launch date for GOSSAMER-1; the HAYABUSA-2 mission proceeds successfully; the MASCOT Flight Spare become Ground Reference Model is preserved flightworthy and released from duty ½ year after the landing of MASCOT on 1999 JU$_3$ to be mated to a likely GOSSAMER-3 design prepared for but not depending on this opportunity. The combined spacecraft may: fly a technology demonstration mission extended to end at a nearby NEA; proceed directly to 2015 PDC for a fast flyby, a rendezvous and lander drop, or both; or abort the already begun tech-demo mission and midways change course towards the newly recognized threat.

INTRODUCTION

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 in 1999. This work was subsequently extended to the framework of the DLR-ESTEC GOSSAMER Solar Sail Technology Roadmap could provide such deployable structures.

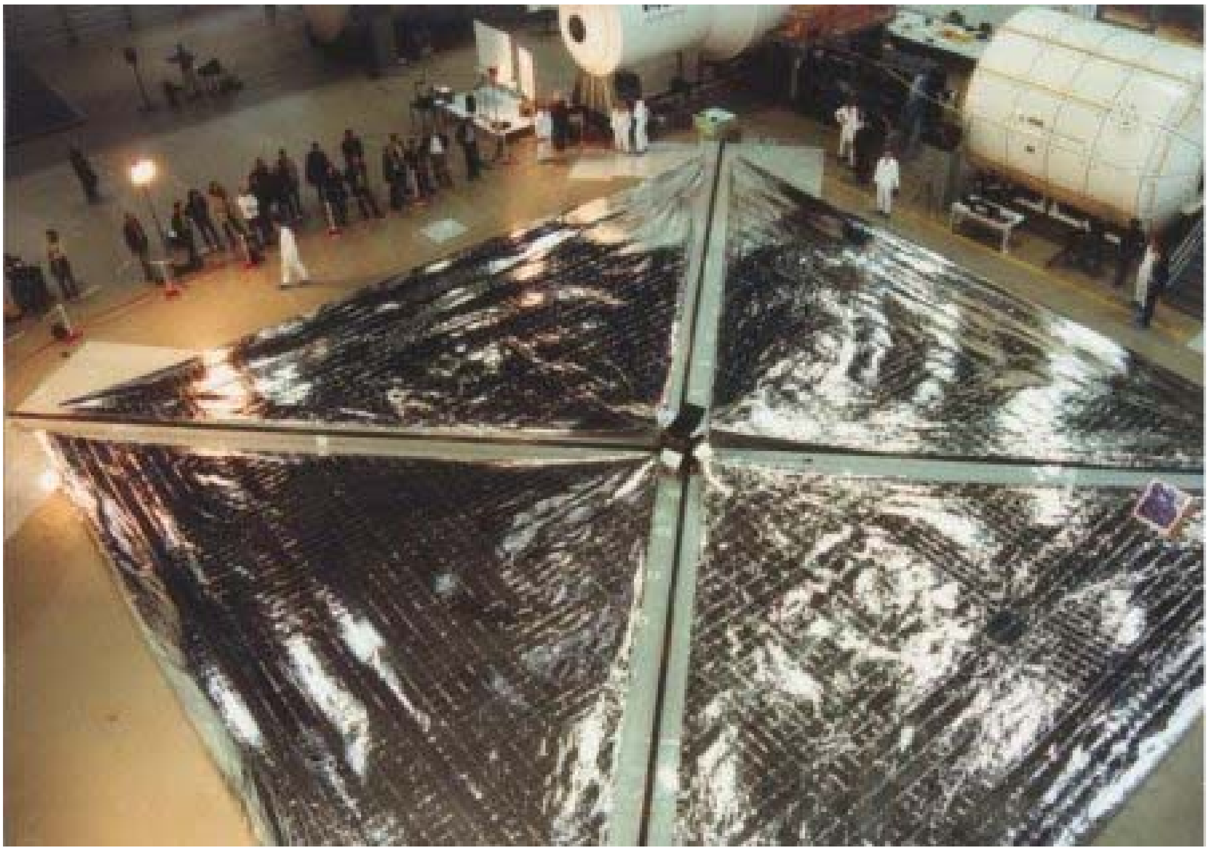

Figure 1 – Ground deployment test of a (20 m)² sail at DLR Cologne, 1999

However, space exploration projects are commonly funded primarily with the objective of fulfilling a planetary science objective. Interplanetary missions already are a rare occurrence when compared to the launch cadence of global spaceflight activities; not even a handful of the spacecraft launched each year leave Earth gravity behind. Missions to a specific interplanetary taget are a yet rarer occurrence; with the exception of the nearest planets a generation may pass before it comes to a revisit.

Thus, since the first robotic probes to the Moon [1] there has always been tendency to pack every possible instrument on what is perceived as the only bus out of town going ‘there’: Not surprisingly, most interplanetary missions strain the limits of their launch vehicles, and many still spend years among the terrestrial planest gathering momentum in a series of gravity-assist fly-bys. Consequently, the attempts to find an opportunity to fly a solar sail had follow the same path as any other propulsion module for interplanetary missions and found itself in a competition with those in science missions which had their science payload defined in a purely science requirements driven approach, as is common in design and engineering.

But the advantages of solar sails come to bear the better the lower the area loading of the whole spacecaft is. Given the traditionally defined instrument suites and the approach to creating and selecting science missions the very first sail-propelled mission would have required a giant technological leap to an unrealistically large sail and creation of all new technologies in one try. Or, when equipped with a sail of the very largest size that its proponents dared to commit to, it would hardly outperform the proven combination of chemical propulsion and multiple fly-bys, and then be discarded for the risks inherent in any new technology not justifying the marginal improvement. In this vicious circle, the widespread opinion manifested itself that solar sailing never really works in a mission, and, you know, anyway, it has never been tried and proven…

The GOSSAMER Roadmap

On the background of this experience, the solar sailing community in DLR went back to the drawing board and developed a scalable deployment technology with the focus on solar sailing and the application of thin film photovoltaics to provide a lightweight power source for sailcraft. Relatively minor adaptations of this technology extend this scalable and reliable technology to deployable membrane structures for space applications in general.
These developments on the background of the lessons learned in earlier attempts at getting solar sails into space led to the creation of the DLR-ESTEC GOSSAMER Roadmap: The key difference to previous national and European solar sail related studies and projects is its character as a pure technology development undertaking with the explicitly stated complete abandonment of any scientific payload – and thus mainstream big mission funding. Although they might initially seem interesting, tempting or of advantage when getting a project on the road, overriding scientific objectives at system or project level would introduce a higher complexity and thereby introduce additional risk where the fundamental interest is the development of thin film structures deployment technology to a readiness level that is sufficient for challenging applications. In the end, linking a largely new and first time technological development to in principle unrelated scientific objectives would lead to a project situation where design standard requirements for margins for the uncertainties of a new technology and science communities' justified demand for guarantees for the scientific output of the mission would escalate the design into a divergent spiral until it either shoots through the cost cap or its technical feasibility collapses or its residual performance is insufficient to win in a competition selection process. These mechanisms were the cause for previous failures of solar sail projects.

The GOSSAMER Roadmap consists of three steps:

- GOSSAMER-1 is a low cost technology demonstrator for the membrane deployment process, only. It deploys a (5 m)² sail using technology that is already suitable for the next step. It does not need attitude control and could fly in very low Earth orbit (LEO), even below the altitude of the ISS.
- GOSSAMER-2 is a validation mission for candidate solar sail attitude control technologies using a (25 m)² sail. It should also demonstrate sail effect but could do this in a somewhat higher LEO where air drag becomes insignificant, to take advantage of the bulk of "piggy-back" launch opportunities going to approximately polar Sun-synchronous LEO (SSO) but a higher orbit would also be possible, e.g. in the navigation satellite graveyard. At these altitudes a recovery attitude control system using magnetorquers would still be feasible.
- GOSSAMER-3 is a fully functional (50 m)² solar sail to validate the previously created design approach and prove sufficient guidance, navigation and attitude control to conduct planetary science and space weather missions.

The sizes of GOSSAMER-2 and -3 are approximate.

The first flight was planned in conjunction with the EU project QB50 which aims to deploy a flotilla of cubesats in very low LEO to study the upper atmosphere. While technically independent from the QB50 dispenser system, GOSSAMER-1 was integrated into the overall concept. Depending on the launch option it can be configured in several increments between an externally powered attached payload as shown in the figure below and a fully independent free-flyer which is the current configuration. [2]

Figure 2 – Early concept of GOSSAMER-1 coupled to a dedicated QB50 launch

The connection with QB50 put GOSSAMER-1 in a similar situation as another DLR Bemen centered project, MASCOT, in that it had to prepare for a relatively early launch date set by the main mission in the shared launch. [3][4] However, since the mission objectives are not linked as in the case of MASCOT and HAYABUSA2, and the free-flyer option of GOSSAMER-1 has become the baseline design, both schedules could be decoupled. This was taken advantage of when new interest in large-scale photovoltaics prompted a reorientation of the GOSSAMER project at DLR.

What next? – Science!

Although primarily a technology development project, the GOSSAMER Roadmap is not an end in itself: its purpose is to develop a new advanced fuel-free method of propulsion primarily for interplanetary spaceflight and photonic pressure augmented stationkeeping near bodies of the solar syste. To guide the development, three science working groups from different scientific communities were tasked to develop a candidate mission, each, for the first scientific solar sail mission envisaged after GOSSAMER-3 but still closely based on the expected state of the art reached by the end of the Roadmap development. The following three missions were identified:

- a spaceweather early warning mission stationkeeping with Earth ahead of the Sun-Earth Lagrange point L_1 towards the Sun, using the sail thust to augment Earth's gravity in the balance of orbital forces to generate an artificial Displaced L_1 point (DL1), and carrying a very lightweight suite of plasma instruments. The DL1 position was expected and required to at least double the warning time for oncoming solar storms which can disturb power grids, knock out spacecraft services, hinder radio communication, and increase high altitude radiation on Earth. Sail degradation during the mission would not lead to loss of stationkeeping, merely the displacement distance would recede in proportion. [5]
- a Solar Polar Orbiter for which the solar sail is used to raise the inclination of its heliocentric orbit much further than possible by gravity-assist fly-bys, chemical or electrical propulsion combined. A heavier helioseismic imaging payload could be raised in inclination sufficiently to observe the polar regions of the Sun, and a lighter plasma instruments payload could reach exact polar orbit within the required mission duration where the sail would be jettisoned; the sail does however not run out of fuel to continue in either case. [6]
- a multiple NEO rendezvous and fly-by mission to visit and rendezvous with at least three significant NEAs and to perform additional NEA fly-bys within the set lifetime of a decade. [7]

The requirements of all these missions can *only* be met using solar sail propulsion with a substantial margin to the second-best propulsion solution. Their requirements combined were intended to guide the Roadmap development towards GOSSAMER-3.

In other Projects…

MASCOT launched

Meanwhile, the small asteroid lander MASCOT was launched on December 3rd, 2014, aboard Hayabusa2 towards their target asteroid, the approx. 1 km sized (162173) 1999 JU_3. After a successful launch of the flight model (FM) of a spacecraft, it is common practice to de-integrate the flight spare (FS), if any, to return instruments to their providers for individual calibration. However, since MASCOT is a highly organic integrated and compact design, [3] there would potentially be an advantage for the calibration process if the MASCOT FS were kept fully integrated and functional to enable all-up calibration in continuation of the concurrent AIV approach established so far. [4]

The 2015 PDC Exercise Scenario

At about the same time, the organizers of this conference provided a hypothetical scenario in which a PHA-class asteroid is fictitiously discovered on the first day of the conference and it turns out that it is on a fictional impact trajectory to hit Earth in September 2022. This scenario mainly serves a tabletop exercise at the conference but it is also provided as a common resource to design a consistent set of concepts for observation and mitigation of NEAs against.

Synthesis: the Triple Fictional Scenario

With the reorientation of the GOSSAMER project, the flight of GOSSAMER-3 has for now become hypothetical. Adding to it the hypothetically not de-integrated MASCOT FS and the fictitious 2015 PDC scenario creates a *Gedankenexperiment*, an experiment in the mind, of constraints-driven design, concurrent engineering, and planning of concurrent AIV. In a study similar in concept and method to those carried out in the Concurrent Engineering Facility (CEF) at DLR Bremen, though not bound to a specific location, we will investigate a mission that combines the original GOSSAMER-3 mission as envisaged with the re-use of a minimally modified MASCOT FS that will haphazardly fall into the 2015 PDC turmoil – all hypothetical. This study take place in a little more than 1 month, from late March, 2015, to the end of April final paper deadline of the PDC. We provide 'live' updates on paper during the PDC timeframe. *Yes, this is what we do in our spare time!*

BIG SAIL, SMALL LANDER – CONCEPTUAL DESIGN

The envisaged mission of GOSSAMER-3, learning to fly, was to take place relatively close to Earth, essentially within its sphere of influence in the solar system, between the Sun-Earth Lagrange points L_1 and L_2 and around the Moon. This way the significant effort of implementing a truly interplanetary communication system using a large high-gain antenna could be bypassed. After all is proven and done, and to fulfill code of conducts for space debis mitigation [8] in partcular to keep the sail from ever drifting into the geostationary orbit region, a frequently returning idea was to decommission it into deep interplanetary space. And why then, as one supposedly had proven all capabilities, not try and fly to some conveniently accessible NEA? After all, the ultimate proof of sailcraft handling would be to rendezvous with a small object and land or drop something on it, perhaps a small beacon or a bean-bag target marker much like those used by the HAYABUSAS.

It is obvious that sailcraft and small mobile landers cover each other's weakness with their own advantages:

- the sail can provide a propellant-free transfer but it can't land safely, much less take off again
- the small lander is by definition and MASCOT experience an efficient payload which eases sail transfer but can't get anywhere on its own

There are disadvantages, though. A simple propulsion-free lander like MASCOT can not make precision landings. Its on-surface mobility has a timeline of landings that could replace pin-point touchdown by chance coverage in a random walk. It takes patience to get to a specific point.

HERITAGE

Deployable structures and small landers have some history in space. Well known is the most distant example, the Galileo Orbiter high-gain antenna which deployed only partially on its way to Jupiter, but thereby provided the impulse to develop efficient

low datarate interplanetary communication as may be necessary when sending an experimental near-Earth sailcraft out towards neaby interplanetary space.
Several larger structures are deployed on geostationary communication satellites where direct to satellite mobile phone services use lightweight deployable reflectors of 12 to about 20 m diameter, e.g. Thuraya 2 which serves Africa and the Middle East and is shown in the following figure as imaged by a telescope camera fixed to Earth's rotation which smears out all background objects.

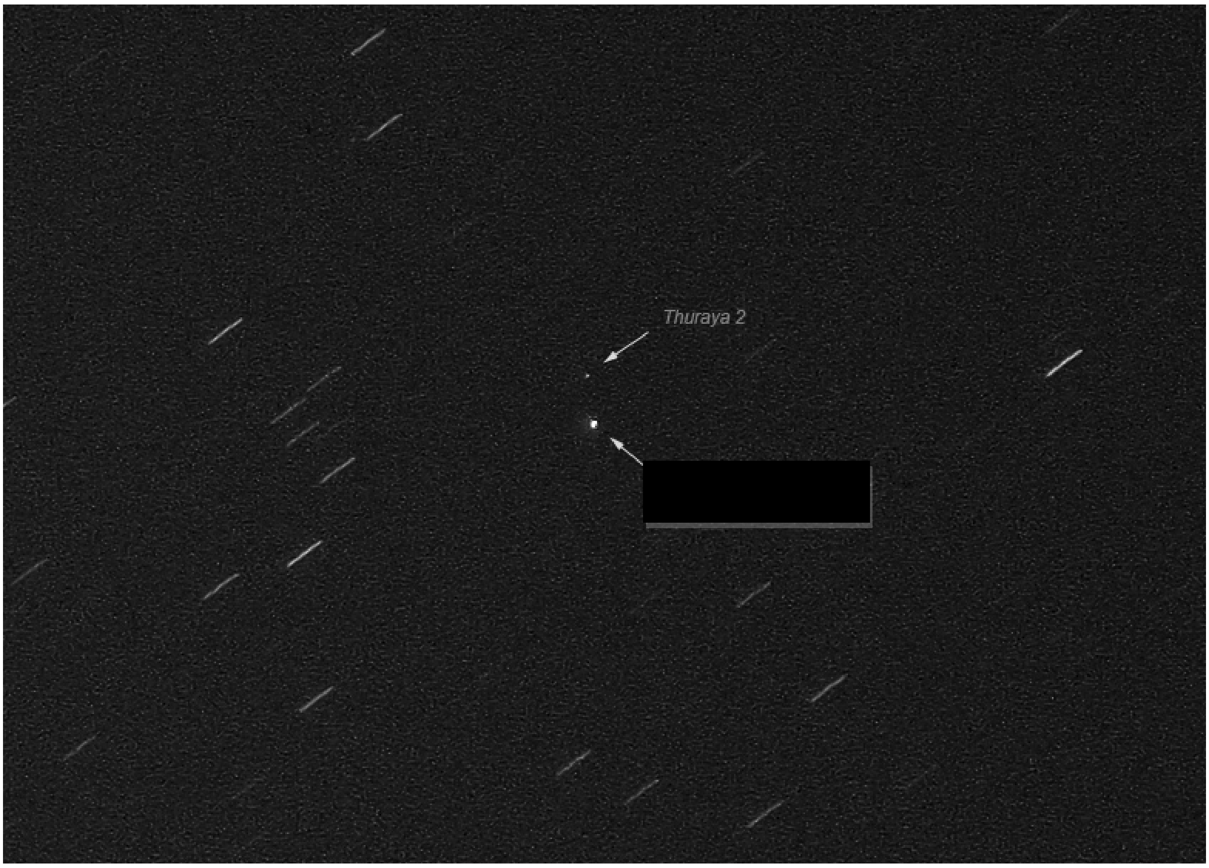

Figure 3 – Thuraya 2 and a second nearby geostationary satellite, photographed on 8 December 2010 from the Netherlands [image: Marco Langbroek]

DESIGN ASSUMPTIONS

To enable a series of low-cost missions, the GOSSAMER Roadmap baselined a small spacecraft approach and the use of secondary payoad "piggy-back" launch. Beyond the high LEO orbit envisaged for GOSSAMER-2, such opportunities exist mainly to geostationary transfer orbit (GTO) but could also become available to navigation satellite orbits e.g. of the Galileo system presently under construction and to related transfer and upper stage disposal orbits. A similar method has been discusse for the PROBA-3 mission.

The GOSSAMER-3 sailcraft in launch configuration shall be compatible with the Arianespace ASAP-micro envelope which has been used for secondary payloads on the Ariane 5, the Soyuz in general (e.g. for the German on-orbit validation satellite

TET), and Vega. It is quite similar to secondary payload sizes feasible on the ESPA platform implemented on several U.S. launch vehicles. It shall also be compatible with a launch on other medium-size launchers such as the frequently used PSLV, Dnepr or Rokot-KM (Eurockot) with no significant restrictions in the choice of launch opportunities.

The GOSSAMER-3 sailcraft design, in particular all elements directly related to the sail, shall be based on presently existing hardware such as already sample-built and tested boom technologies, readily available sail foil, and MASCOT-style electronics and motorized mechanisms for deep space compatibility.
The sail shall be fully flyable from both sides and shall be able to recover from edge-on attitude without losing power, control, or ground communication.

SPACECRAFT DESIGN

“So hoist the foil and booms…”* – a first lightweight sailcraft

The notional design is a ‘box design‘ within ASAP-micro envelope of 80x80x100cm³ available in principle on all three Arianespace launchers.

- 4 „tall“ Boom Sail Deployment Units (BSDU) in 2x2 array of 40x40 cm² cross-section x TBD height beneath the Central Spacecraft Unit (CSCU),
    - 1 with launch adapter (to discard that, as well)
        - spun-up separation pointing ring in-flight in perigee, against-flight in apogee,
    - 1 with optional green propellant (1 N engine & tank from Prisma) or cold gas boost stage to get out of low GTO perigee to sailable perigee (design case e.g. 185 km perigee GTO to >2000 km perigee GTO with burn(s) at apogee)
        - optional magnetorquer
- CSCU flat box design with 80x80 cm² base and (100 cm – MASCOT – TBD BSDU) height on top of BSDUs
- MASCOT on top of CSCU
    - tilted so that MASCOT CAM sees about ½ sail and boom in foreground & ½ deep space
    - mounted on pedestal (mostly) above CSCU surface: Support Structure and Elevated Mount (SSEM, i.e. inverted MESS)

All sail attitude control including roll control shall be propellant free.

The CSCU electronics, which has to operate much longer than the BSDUs which are only required to work until they are separated after deployment, is a synthesis of the MASCOT mechanical integration concept wedgelock-mounted PCB cards for suffcient heat rejection capability to drive 10s of W sail control motors, comparable to the MASCOT Mobility Controller. A low-power cruise supervision and housekeeping computer based on GOSSAMER-1 designs handles communication to the ground and coordinates the deployment control network for the four BSDUs on a 50 m scale sail

Power on CSCU and BSDUs is provided by all-round coverage with triple-junction photovoltaic cells, because the sail should be optimized for reflective power, not electrical power generation. A thin-film photovoltaics option can be carried to augment power generation but should not yet be mission-critical.
The thermal balance is thus expected to be more cubesat-like, somewhat warm environment at ~1 AU that keeps motor and gear friction low, cf. MASCOT Mobility, and improves power delivery capability of the battery but also increases battery ageing to some extent. This considered acceptable for a short term technology demonstraion mission with about a year design lifetime.
But it could be possible to use the assumed flip-over capability of a Gossamer-style sail to have a warmer and cooler orientation that differ by 180° with respect to the Sun vector. One orientation puts the attached MASCOT in shadow, the other in sunlight.

For precision guidance, navigation and control (GNC) the sailcraft uses coarse and fine sun sensors and 2 small lightweight startrackers or adaptations of MASCOT CAM for that purpose mounted within the CSCU, e.g. one in parallel to each sail normal as the sail is rarely face-on to the Sun.
Spin-up and despin for a possible perigee lifting burn by a BSDU-mounted thruster is achieved by tuned separation mechanism springs and/or a magnetorquer set in one BDSU, e.g. that carrying the engine

The communication design is scaled solely for a technology demonstrator operating in the Earth-Moon system. GOSSAMER-3 would be designed for good telecommand (TC) and housekeeping (HK) telemetry (TM) communication with Earth within 1 t 2 lunar distances, i.e. about ½ million km, and with some minor restrictions acceptable for operation out to the Earth-Sun L_1/L_2 distances, i.e. about 1.5 million km. Communication performance in the extended mission to a distance of a few tenths of an AU would be correspondingly reduced. Hence, the data rate shound not be fixed.

For sail degradation analysis and (deep) space debris detection, a very lightweight method to detect hits on the membrane shall be used.

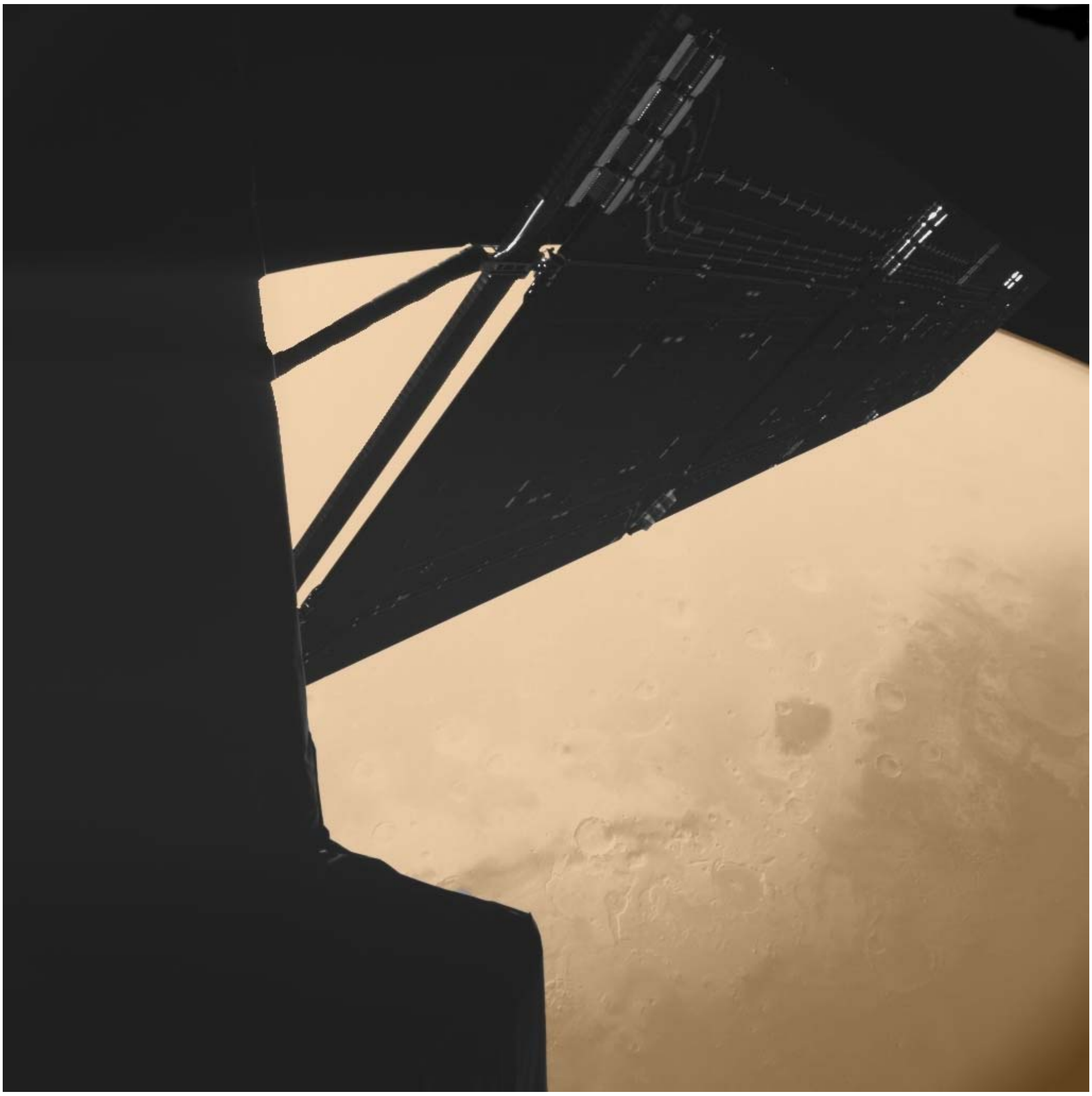

Figure 4 – Planetshine for mothersip diagnostic images example: Mars as seen from PHILAE along the rear side of the photovoltaic panels of ROSETTA

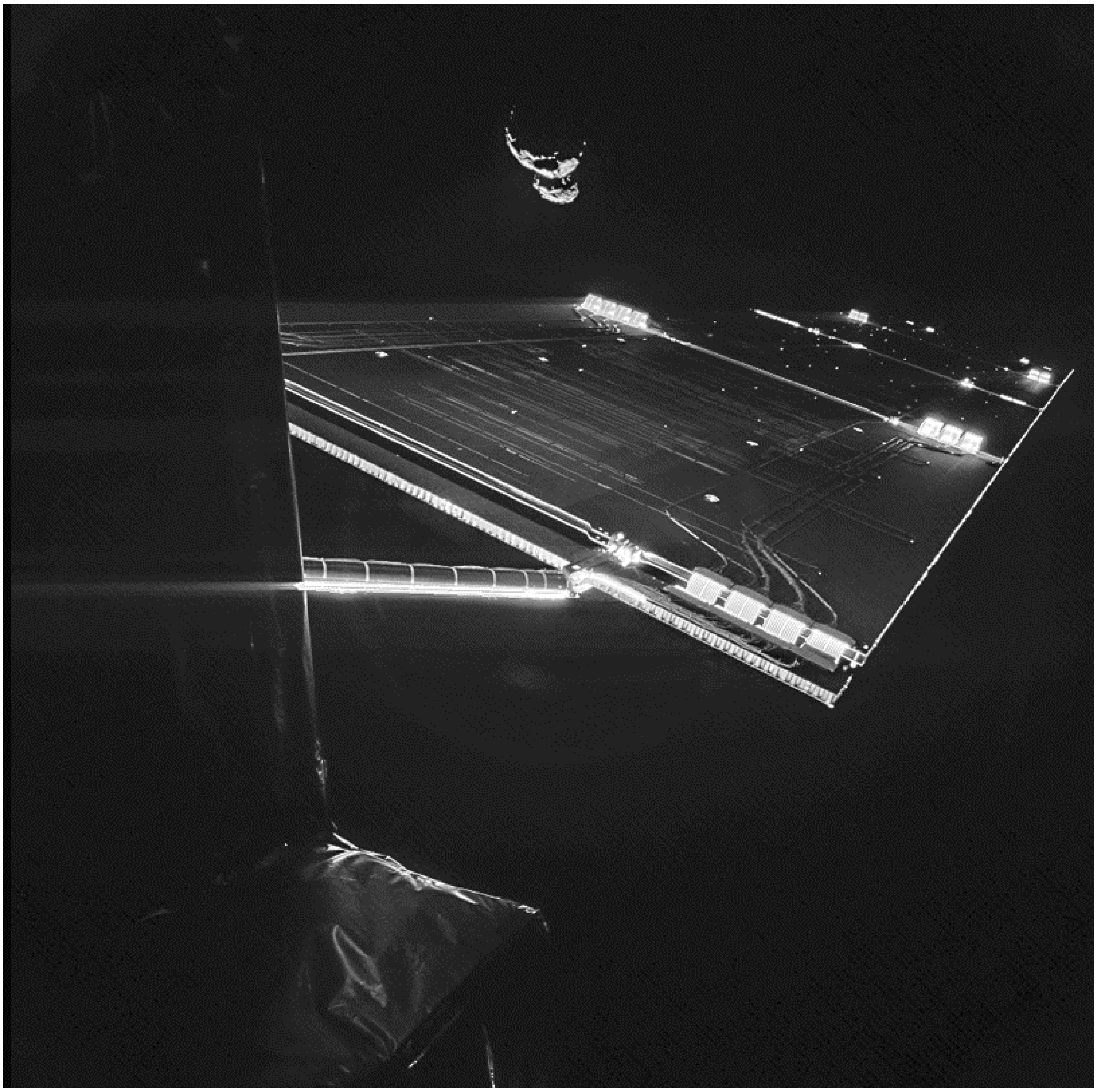

Figure 5 – Flyby image targeting practice example: 67P seen from PHILAE along the photovoltaic panels of ROSETTA

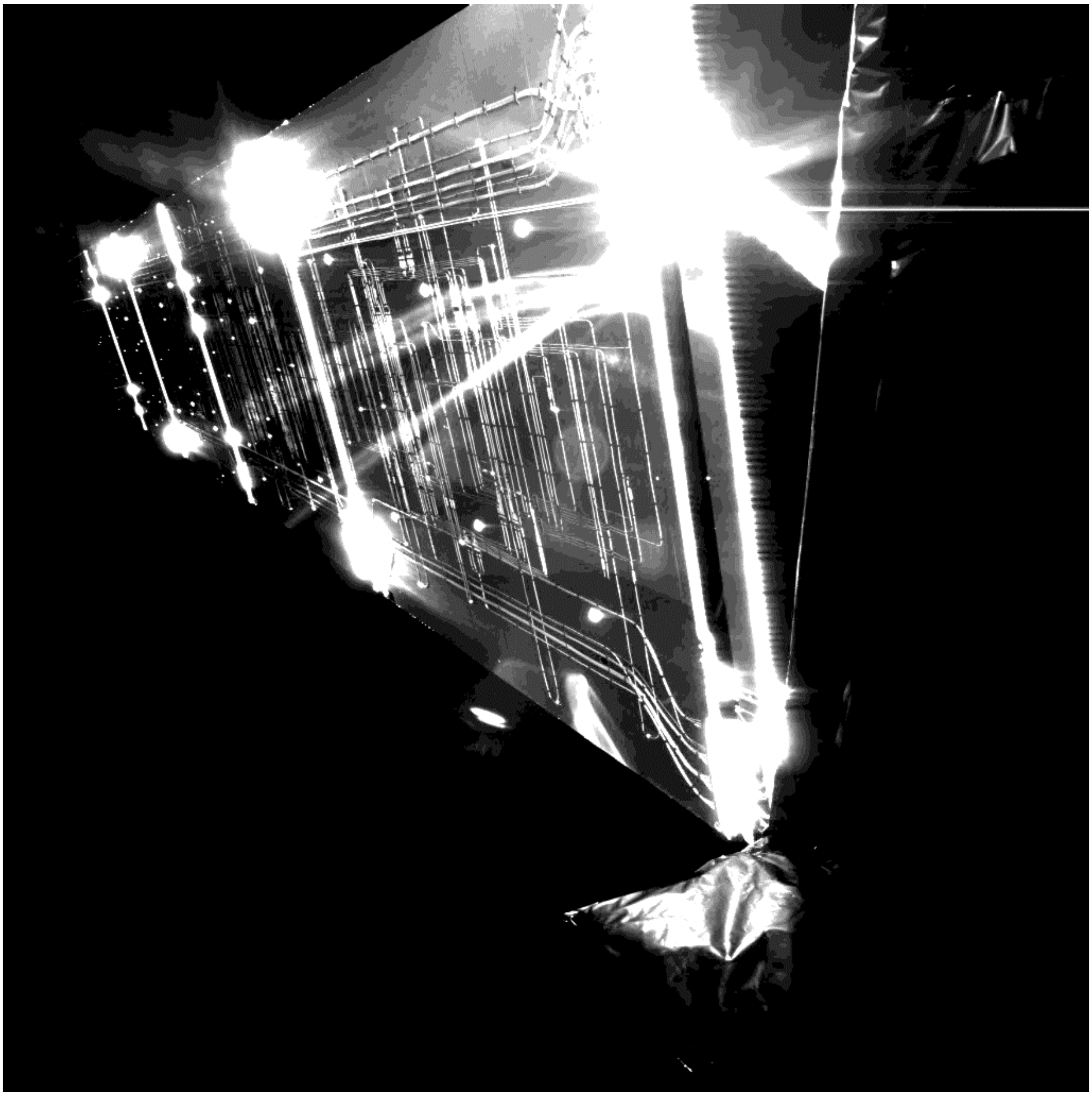

Figure 6 – High Dynamic Range photography example: First Light of PHILAE looking at Sun glints on the photovoltaic panels of ROSETTA against the black of space

REFURBISHING THE MASCOT FLIGHT SPARE FOR FLIGHT

Reduce, Reuse, Recycle – Advantages of an Integrated Flight Spare

A flight spare (FS) has already passed through all acceptance tests and post-launch calibration campaigns. It has seen all updates of the flight software, all known bugs were already ironed out along with the flight model's maintenance in space. Also, the integration is already done and payed for, unless instruments or other units are de-integrated for separate calibration as it is usually the case.

Adaptation by Minimum Modification of MASCOT FS

The HAYABUSA2 (HY2) interface to MASCOT provides

- cruise power supply at 50 V, hot-redundant and tolerant to about 30 V in MASCOT
- cruise heater power lines (redundant)
- cruise temperature sensors lines (redundant).

Late-Access Options

Step 1 – Battery replacement and accessibles of opportunity

The battery of MASCOT is using primary cells requiring cold -40°C storage to minimize self-discharge. The battery is therefore installed just before launch in a late access operation. Therefore, it could be replaced by a same volume, similar mass secondary battery also using a small-cell design.

A rechargeable battery would need some adapter electronics to provide a battery charge regulator (BCR) and a load-shedding switch to protect the battery from deep discharge because MASCOT has no turn-off once separated; it is forced on from the point of actuation of the separation mechanism.

It is possible that the heater lines leading to the battery can be used for combined charger/heater control and power supply independent of the 50 V cruise power line wich always turns MASCOT on. A reduced end-of-charge voltage (REOCV) concept should be implemented to minimize battery ageing.

Backward compatibility to the present MASCOT heater control concept shall be preserved since additional heaters are connected in parallel to those in the battery.

Since some electronics has to be implemented in the exchangeable battery, it is possible to provide a wired data interface to the mothership by re-routing the MASCOT On-Board Computer test connector through a serial interface switch to the re-purposed thermal sensor lines. This interface shall also remain backward-compatible.

A small accelerometer was once considered for MASCOT as an add-on payload, however, suitable hardware was not available in time. Shortly before MASCOT FM integration was to commence, a sufficiently small and low power sensor became available and was selected for the GOSSAMER-1 demonstrator. Sufficient A/D channels, control lines and power, tapped from the GNC supply, for a non-redundant tetraedric seismometer based on this sensor are available as spares in the MASCOT design. For other test purposes, they are accessible in the battery compartment of the MASCOT FS, only. However, the maximum sample rate is 10/s, so this add-on instrument would be limited to impact deceleration envelope detection and could not record structural resonances.

Step 2 – Thermal Surfaces and Photovoltaics

It is possible to replace the single-layer insulation (SLI) foil on the outside of MASCOT by photovoltaic panels, rigid or flexible. From other studies the application of 2x2cm² triple-junction photovoltaic cells such as used for the MASCOT GNC attitude sensors (PEC) appears most efficient. When grouped into short strings the effect of sigle cell damages stays limited. Since a battery charge regulator (BCR) is already required in the exchangeable battery, a maximum power point tracking (MPPT) control loop can be added to it. The additional photovoltaic pane harness needs to be routed through the very tight interior of MASCOT to the battery compartment.

Partial Deintegration Options

Step 3 – changing the channel

MASCOT uses the HAYABUSA2 infrastructure for communication with its mothership. Either, a terminal has to become available for the sailcraft (perhaps a flightspare or refurbished QM), or an alternative solution needs to be developed on the CSCU side, or the communication modules and possibly antennae need to be replaced by an entirely new communication subsystem for both sides. Changing the communication hardware on the MASCOT side requires deintegration to the level of E-Box removal, i.e. an almost complete de-integration of MASCOT. In this case, the integration of MASCOT into the CSCU-BSDU communication network with omnidirectional antennae could be considered, but its working distance would have to be significantly expanded beyond the GOSSAMER-1 system, to a range of order >>1…20 km.

SSEM – Integration of an existing lander on a new Sailcraft

Of the MASCOT Mechanical Electrical Support System (MESS) equipment at HAYABUSA2, the MESS baseplate, ejection mechanism and harness can be preserved, and parts be reused where possible. To use MASCOT as an observation package also in cruise, the MESS frame needs to be replaced by a new design, a pedestal that raises MASCOT well above the mothership surface to an angle and position which gives the MASCOT camera (CAM) Field of View (FoV) a shared coverage of ½ sail, ½ space with one boom safely in the FoV.

MASCOT as an Instruments Package for a Solar Sailing Cruise

- CAM – the camera views the sail, a boom and possible target objects, with emphasis on black-and-white HDR photography because of foreground glints and shadows
- MARA – the thermal IR radiometer views the sail foil thermal emission as an indicator of ageing
- MAG – the magnetometer observes the external and internal magnetic fields and could be augmented by two boom tip magnetometer sensors near a boom tip
- MicrOmega (MMEGA) – the hyperspectral near-IR soil microscope could receive a cover of its optics nose that also contains a moveable strip of sail foil (aluminized 2-side, 1-side, coated and/or bare) which is exposed to space elsewhere and can be inspected regularly by being rewound past the MMEGA optics for near-IR hyperspectral, 10µm resolution characterization

SAME SHIP, DIFFERENT PORT – SCIENCE WITH HARDWARE AS-IS

MASCOT appeared as a handy instruments package, implementing all the not-so-remote sensing capabilities a solar sailor would like to have to watch a new sail perform and age in space in one proven box with a unified interface.
But even recycled, it still is an asteroid lander.

The primary mission of GOSSAMER-3 is learning to fly, out of the harbour that is Earth orbit. This can be done in the Earth-Moon system, transitioning between the spheres of influence of two planet-sized bodies without months of interplanetary cruise to even the nearest planets and without the need for deep-space communication. But then, there are other near-Earth targets – small asteroids, notorius for their Earth-crossing and sometimes hardly well-defined orbits of high inclination and high eccentricity.
As a first-time flying practice and technology demonstration mission, GOSSAMER-3 should be on a notoriuosly unpredictable timeline and trajectory. Interplanetary spaceflight, on the other hand, is commonly tied to precise trajectories and highly constrained launch windows for Earth departure.
But there is a small group of near-Earth asteroids seemingly made for this triple-fictional mission scenario: co-orbitals. These asteroids follow Earth on average with a very low differential motion, although with a superimposed large annual cyclical motion. But seen from Earth, they stay nearby circling in the morning or evening sky for decades near the turning points of their libration cycles lasting several decades to a few hundred years.
The first Trojan and horseshoe-librating asteroids of Earth have been discovered in recent years. Among this group, the largest known target asteroids are around 300 m in diameter, barely half of the target body MASCOT was designed for, the 980 m (162173) 1999 JU_3. They are also unlikely to be a dark, C-type object and therefore likely colder at a similar heliocentric distance.
Prime candidates for a visit concluding our fictional very much extended GOSSAMER-3 mission with a possible MASCOT drop and landing, i.e. by a proof drop of a propulsion-free test particle onto a small solar system body, are the largest know co-orbital NEAs which due to their size likely are not fast rotators:

- 2010 TK_7 – 300 m, L4 librator, turning at ~0.2 AU distance
- 2010 SO_{16} – 200…400 m, horseshoe librator, 14.5° inclination

MISSION DESIGN

Launch

- Secondary payload launch, “piggyback”
- GTO Ariane 5, 200 x 36000 km
- MTO Soyuz CSG, e.g. Galileo transfer orbit ? x 23000 km
- HEO, e.g. Galileo upper stage disposal orbit >23000 km
- like PROBA-3: 600x60000 km
- up-high disposal of a Vega AVUM at >2000 km circular
- raised-perigee GTO such as provided by Proton-M, e.g. ~5000 x 36000 km

Trajectory

101 small steps for a solar sailor… – a nominal trajectory wishlist

minimum mission

- spiral-up from launch orbit
    - advantage by flip-over capability enabling a constant-rotation mode that puts the sail edge-on at low perigee (usually in shadow) and generates thrust near apogee?
- multiple pointing and navigation tests – image Earth limb, Moon, specific locations on Earth, Venus, bright stars…
- targeted flyby proof test: image a Chelyabinsk- to Tunguska-sized (by brightness, absolute magnitude H) object on a well known trajectory, e.g. Thuraya-2 or another comsat with large deployed antenna in GEO with >1 pixel if safely possible (cf. Rosetta misidentified as NEO and likely Saturn V upper stage J002E3 appear bright compared to rocky NEO)
- inclined passage through GEO region to minimize risk (e.g. can keep inclination of Galileo orbit or build up inclination from Ariane GTO)
- spiral up further, at least into GEO upper graveyard

expected or nominal mission

- spiral up to lunar distance
- navigation in the Earth-Moon system tests
- explore Earth-Moon Lagrange points, e.g. look for Kordylewski clouds in L_4/L_5
- lunar flyby(s) – also in the following

extended mission

- slingshot to Earth-Sun L2
- targeting flyby test: find decommissioned L2 spacecraft, e.g. Planck, and image at >1 pixel
- return near Earth for pole-sitter try
- slingshot to Earth-Sun L1
- try out Displaced L1 mode

extended extended mission

- fly out to coorbital asteroid – prime candidates: larger, non-fast rotators
    - 2010 TK_7
    - 2010 SO_{16}
- rendezvous directly, or fast flyby and then return for rendezvous
- drop MASCOT and stay close enough to relay data until MASCOT EOL

safe disposal

- continue at NEA fly to another nearby NEA (i.e., within reach, also coorbital, on same L_4 or L_5 side of Earth, but e.g. not suitable for MASCOT landing)
- beach sailcraft on that asteroid, if possible so that Sun glints are visible from Earth periodcally

Exercise – Emergency Diversion to 2015 PDC

assumptions: yes, we can fly, i.e. the minimum mission to >GEO altitude passed successfully, spiral out and lunar flyby will likely be successful.

- Launch date 2020

Possible triggers for an emergency divert:

- precursor mission to 2015 PDC failed before deflection attempt
- deflection failed or did not impart sufficient momentum

- fragmentation occurred unexpectedly, a significant fragment is still on impact trajectory
- post-deflection assessment needed fast, e.g. postcursor mission failed or need not anticipated

Options:

- Do 2015 PDC (fast) flyby on the way, then resume extended mission as above
- try to catch up and chase 2015 PDC to rendezvous and drop MASCOT on it (before drop at coorbital NEA)
- as soon as possible flyby and then loop back for somewhat later rendezvous, accompany to near impact, and/or drop MASCOT on it (i.e., the two options before combined)
- try to chase 2015 PDC after drop of MASCOT FS at coorbital NEA to rendezvous and beach on it, to modify Yarkovsky characteristcs of successfully deflected impactor

SUMMARY

We hope to have provided a ficttious carefree handling sailcraft and to have been able to fly it to a small Earth-coorbital NEA, demonstrating flexibility in mission design including an unexpcted change of target after launch. It appears from our investigation so far that solar sails and small mobile landers match like hand in glove. We expect that we can complete this fictitious journey within about a month – by the final paper deadline, 7½ years before the hypothetical impact of 2015 PDC.

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