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CO-ORBITAL CONVERGENCE – RALLYING SOLAR SAILS, SMALL SOLAR-ELECTRIC SPACECRAFT AND NANOLANDERS TO HELP SAVE US FROM A NASTY NEIGHBOUR SOON

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Extended Abstract—

1. Introduction

Out of the shadow that ever since the beginning the Sun's glare cast on the telescopes of Earth, *fictitious* asteroid 2023 PDC enters the stage on January 10th to be recognized over the next few months as a serious threat with potential for impact on Earth. It is trailing Earth but catching up, and seen from Earth's hazy sky at dusk, it slowly but steadily corkscrews in over the next 13¾ years towards an impact corridor that wraps itself nearly all the way around Earth.

Unlike the vast majority of near-Earth asteroids (NEA), it is in a virtually co-orbital heliocentric motion with Earth (though not perfectly so, because then it would not impact) and it is fairly large (as far as we know early on).

2. Background to the Future

In 2015, we drew a mission sketch combining the last planned in our series of our then just freshly cancelled solar sail demonstrators, GOSSAMER-3, with the Flight Spare (FS) of MASCOT (which still is by and large available) on a one-way journey to visit one of the larger (and much more friendly) of Earth's nearest neighbours. Back then (and probably still today), we would be aiming at (419624) 2010 SO_{16} or 2010 TK_7 which were at the time and still are today the largest genuinely co-orbital NEAs, in the sense that they are not just distant commensurates like (3753) Cruithne but more tightly gravitationally coupled to Earth as a horseshoe liberator and a Lagrange L_4 Trojan, respectively. Their estimated size of some 350 m, each, makes them relatively bright for optical rendezvous navigation (perhaps comparable to (25143) Itokawa or (99942) Apophis) and suitable for MASCOT nanolanders because by their minimum estimated size alone they are unlikely to be fast rotators, even in the absence of lightcurve observations.

In 2017, we further explored the capabilities of such small spacecraft solar sails and nanolanders, working cooperatively and in larger numbers, for in-situ surveying and characterization of NEAs, also taking a peek towards their utility in space resources utilization by fathoming the interior of such rocks and rubble piling up as unstaked claims in the sky. The resurgence of interest in asteroid mining at the time added impetus, and a third 'asteroid user community' next to planetary science and planetary defense.

In 2019, benefiting much from all the paths not taken during our solar sail development of the GOSSAMER Roadmap period, we found that the exploration of NEAs is one of the no-limits of even "now-term" technology solar sails: As soon as you fly on the power of your own sail, you can go see asteroids. Once solar sail technology is mastered and with it also all that it carries is up to a few thermal challenges, high-Δv high-eccentricity targets like the Taurid Stream are within reach for rendezvous within a tolerable flight duration. However, like the PDC 2019's Comet Scenario, the Taurids did not really show up when scheduled and astronomers did look up, but later at least the former hit the movies.

In 2021, we added to our Multiple NEA Rendezvous solar sail mission concepts another dimension that we nicked from the well-emerged new space sector, massively serial kinetic impact – think *ASTEROIDS*™ – of hardly modified commercial solar-electric spacecraft. While desperate, this may be a viable option in a last-ditch attempt at deflecting or at least eroding a bit an incoming asteroid discovered only a few months out on its fatal swan dive, other than stand and stare and duck and cover. As a reprise, this also celebrated the 10th anniversary of our contribution of 2011, ASTEROIDSQUADS, where we introduced this as a low-cost acceptable-risk test payload concept for the first launches of new heavy launch vehicles, at least those capable of escape trajectories. Unexpectedly, just a few months later, Earth in reality kindly provided to its Earthlings the experience of an entirely unpredicted major multi-megaton explosive event in the shape of the Hunga Tonga–Hunga Haʻapai eruption and tsunami of January 15th, 2022. The lessons learned from such explosive volcanic events since the Mt St Helens eruption of 1980, at best vaguely predictable at shortest notice, could guide the geophysical instrumentation and monitoring of a no longer avoidable but much more predictable asteroid impact.

Nano-scale spacecraft concepts, robust design by simplicity in complex (and not just complicated) architectures, and instrument-scale integration, which we described along with MASCOT for the first time at the PDC 2013 has in parallel meanwhile been established and field-tested in geophysical applications in the ROBEX Lunar Analog Demonstration Mission on Mt Etna, in 2017.

Finally, the Earth is still missing an eye for asteroids on the dayside. Contemporary with the Canadian NEOSSAT mission, we developed ASTEROIDFINDER/SSB, a microsatellite to discover and track asteroids down to 30° solar elongation, also to give more lead time to mitigation on objects like 2023 PDC. Several aspects of the high-density organic integration and high-efficiency design features later evolved for MASCOT, the ROBEX Remote Unit, and the 5 nano-scale sub-spacecraft of GOSSAMER-1 had their origin here, in the quest for the invisible asteroids and a highly agile and stable telescope platform.

3. Common Denominators

All these concepts leverage agile and responsive, high-density organically-integrated design and construction of small, and in particular nano-spacecraft that combine the carefree handling of cubesats with the dependability of larger spacecraft while implementing fully fledged planetary science missions. In all elements, the cooperatively connected sub-spacecraft are designed with strategic re-use in mind, while ad-hoc (or 'tactical') re-use is well possible and frequently employed for the compressed timelines of asteroid deflection exercises as well as in concurrent engineering studies or for responsive space missions like MASCOT2@AIM.

As in this example, all this would also be of much use and benefit for, and could well accelerate the near and far future industrial and scientific exploration of small solar system bodies, at real asteroids, not just the *fictitious* 2023 PDC.

4. Beyond Exercises

Currently, and in particular seen on the background of the AIM experience, the preparation for Earth's close encounter with (99942) Apophis on Friday, April 13th, 2029 21:45 UT seems as a good case to put agile and responsive mission development into action. It's high time, at least on the scale of spaceflight projects, to get going – we're way into the typical 8 years between first significant budget release and Flight Model (FM) delivery. If a visit to Apophis is intended, whether fast or slow fly-by or a rendezvous brief or long, it is now less than 6 years to closest approach. Launch for a pre-encounter arrival might be anywhere from 2 to 5 years away. Such lead times from money in the bank to rocket off the pad are not known in recent times for interplanetary missions; in fact, one has to go back to the very beginning of the space age to find such projects launching to the Moon and the nearest planets. But they are regularly achieved by not just Earth-orbiting cubesats, have been demonstrated by MASCOT in the 2-year race to catch up with HAYABUSA2, and were mastered by the first interplanetary solar sail, IKAROS, which was developed from scratch in only 18 months to give sense and meaning to a launch vehicle trim weight of 310 kg. Designed for a few months of sail control demonstrations in near-Earth interplanetary space, and built largely from the leftovers of other missions and cancelled projects by a tiny team, it operated for 5 years near the orbit of Venus and provided valuable science.

5. A Glance at the Portfolio

5.1 MASCOT

Cuboid on the outside, sized just under 17U, lightweight at 0.57 kg/U, and developed by DLR in collaboration with the French space agency, CNES, the Mobile Asteroid Surface Scout, MASCOT, successfully completed its mission on the nearly km-sized C-type potentially hazardous asteroid (162173) Ryugu on October 3rd, 2018. It scouted the rugged landscape for 17 h together with two smaller but longer-lived photovoltaic-powered MINERVA-II

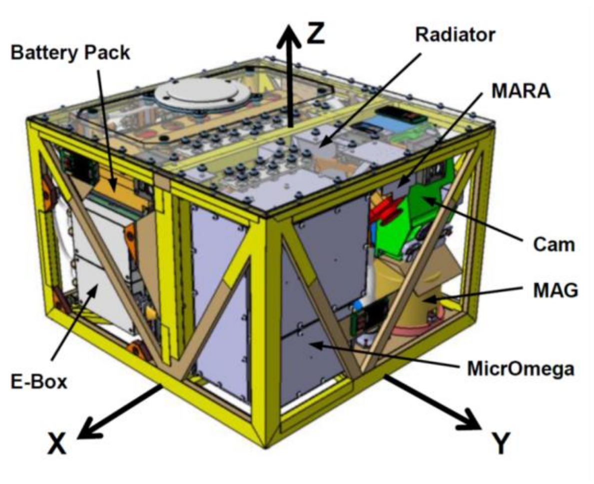

Fig.1 – The MASCOT Landing Module

landers before the asteroid surface was sampled by their mothership, JAXA's HAYABUSA2. MASCOT carried four full-scale science instruments, and provided them with controlled relocation and orientation capability. [1-5] The full-scale hardware development of MASCOT for HAYABUSA2 was done within 2 years from its Preliminary Design Review on June 6th, 2012, the day of the Venus transit, to FM delivery in mid-June 2014 for integration and launch to Ryugu aboard HAYABUSA2 on December 3rd, 2014. [6-8] On the inside, MASCOT was partitioned into a cold compartment for the science instrument front-ends and a warm compartment for the avionics, mechanisms and the battery. The latter was dominated by the 'E-Box' containing all bus avionics and instrument back-ends accommodated on card modules plugged into a backplane. While entirely custom-developed and ruggedized for repeated bouncing across a thermally challenging asteroid for several local days, these card modules were sized to enable the straight transfer of the functional section of a CubeSat PC104 card PCB layouts to the MASCOT E-Box & Backplane interfaces, and vice versa.

Fig.2 – MASCOT E-Box, Mobility & card modules

5.2 MASCOT2

In a study for ESA, MASCOT2 was designed in 2016 to land, accurately position and locate, and repeatedly operate the surface element of the bistatic low-frequency radar of the AIM mission, LFR. Until then, AIM was the planned observer for the spectacular kinetic impactor spacecraft, DART, in the joint NASA-ESA AIDA mission to perform and study a kinetic impact on Dimorphos, the moonlet of binary NEA (65803) Didymos. MASCOT2 was expected to operate on Dimorphos before, during, and after DART's impact, i.e. within ~85 m of the bull's eye. It was based on extensive re-use of MASCOT technologies and flight designs with tailored capability upgrades and mission-specific tuning in the details of most subsystems. [9]

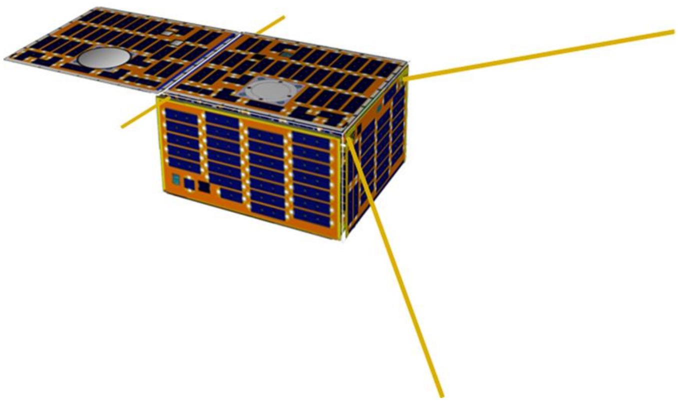

Fig. 3 – MASCOT2 for AIM with LFR deployed

Although time ran out for AIM to make it to Didymos in time for DART's impact, we are pursuing a wide range of MASCOT nanolander design options and keep collecting lessons learned from nanospacecraft and interplanetary missions. From maximum as-is re-use for near-term opportunities to entirely new developments of the MASCOT concept for challenging targets, tailored re-use with optimization in detail offers many roads to space for small solar system body science. [10]

5.3 New Trends for 'small' in interplanetary space

CubeSat accommodation is becoming an increasingly popular feature of small research satellites and interplanetary probes: DART carried and deployed the 6U LICIACube sub-spacecraft to recover some of the live impact observation capabilities lost with the demise of AIM. AIM's successor, the impact damage assessment mission, Hera, is designed to carry two 6U-XL cubesats to explore the Didymos system, Milani and Juventas, which cover some of the riskier close-in operations aspects that would have been performed by AIM itself, allowing Hera to stay at a safer distance at all times, and thus de-risking the main mission.

5.4 CubeSats of a different shape

Cubes of a different shape not only include the many variants of 'U' sizes or deployable photovoltaic panels but also deployment technology demonstrators such as Nanosail-D2 which itself was deployed as a 3U cubesat from the small satellite, FASTSAT in 2010, and then unfolded a 10 m² solar sail. Conversely, spacecraft that on the outside appear all but 'cubesat-ish' can be built using cubesat subsystems and units, to benefit from their small size and efficient design, their low cost, or to avoid unnecessary duplicate development effort.

5.5 GOSSAMER-1: towards interplanetary Cubesats

The GOSSAMER-1 solar sail deployment demonstrator project, itself a small 'micro' spacecraft composed of 5 independent 'nano' spacecraft, followed such an approach for the avionics which were ~1U PC104 stacks in the 4 Boom Sail Deployment Units and a Central SailCraft Unit using the CLAVIS 'interplane' integration concept for different PC104 cards. [10-16] This concept was also used on the DLR nanosatellite AISat equipped with a large deployable helix antenna to monitor AIS transmissions of ships from orbit. [17]

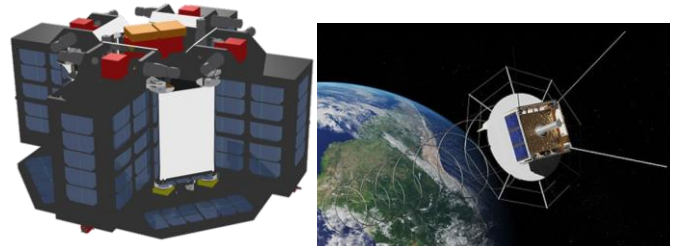

Fig.4 – GOSSAMER-1 and AISat: cubesats inside

Small interplanetary probes for 'mini' and 'micro' rideshare payload slots on launch vehicles can benefit from resource-sharing, shell-lander and self-transfer propulsion concepts in the MASCOT portfolio, allowing the main spacecraft to stay at a safe distance from the unknown unknowns of the asteroid. [18-20]

6. Work for the Future

A large asteroid impact is an unlikely but severe event that can be prevented if the impactor is discovered in time. Climate change is a certain and severe human-made process that can be stopped and reversed if there is enough time left before its consequences incapacitate humanity's capabilities to do so. From communication to the public and legal considerations to international processes, it bears striking resemblance to the challenges and solutions found in the field of planetary defense in the recent decades. Promising technologies are another commonality: although much development work in detail and mass is still required, it is possible with the 'now-term' technological basis of solar sailing and interplanetary exploration to build a planetary sunshield to clip the peak of climate-driven disasters without messing with the Earth as an ecosystem any further, thus preserving our ability to change all we do on Earth which we must. While massive and orders of magnitude beyond the current space capabilities of Earth, it is not beyond the industrial capabilities of production of everyday goods such as cars or mobile phones. And unlike those, it can be built mainly 'from above' drawing on space resources that, next to the Moon, close another circle to the near-Earth asteroids, through mining and small solar system body science. [21-22]
And then, to paraphrase Lord Byron's note on comets, who knows whether, when climate change shall approach this globe to destroy it, as it often has been and will be destroyed, people will not tear rocks from the vacuum of space by means of light, and unfurl mountains, as the giants are said to have done, against the searing light? - And then we shall have traditions of sailors again, and of adventures in space.

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