The Asteroid Impact Mission

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The Asteroid Impact Mission (AIM) is a small and innovative mission of opportunity, currently under study at ESA, intending to demonstrate new technologies for future deep-space missions while addressing planetary defense objectives and performing for the first time detailed investigations of a binary asteroid system. It leverages on a unique opportunity provided by asteroid 65803 Didymos, set for an Earth close-encounter in October 2022, to achieve a fast mission return in only two years after launch October/November 2020. AIM is also ESA's contribution to an international cooperation between ESA and NASA called Asteroid Impact Deflection Assessment (AIDA), consisting of two mission elements: the NASA Double Asteroid Redirection Test (DART) mission and the AIM rendezvous spacecraft. The primary goals of AIDA are to test our ability to perform a spacecraft impact on a near-Earth asteroid and to measure and characterize the deflection caused by the impact. The two mission components of AIDA, DART and AIM, are each independently valuable but when combined they provide a greatly increased scientific return. The DART hypervelocity impact on the secondary asteroid will alter the binary orbit period, which will also be measured by means of lightcurves observations from Earth-based telescopes. AIM instead will perform before and after detailed characterization shedding light on the dependence of the momentum transfer on the asteroid's bulk density, porosity, surface and internal properties. AIM will gather data describing the fragmentation and restructuring processes as well as the ejection of material, and relate them to parameters that can only be available from ground-based observations. Collisional events are of great importance in the formation and evolution of planetary systems, own Solar System and planetary rings. The AIDA scenario will provide a unique opportunity to observe a collision event directly in space, and simultaneously from ground-based optical and radar facilities. For the first time, an impact experiment at asteroid scale will be performed with accurate knowledge of the precise impact conditions and also the impact outcome, together with information on the physical properties of the target, ultimately validating at appropriate scales our knowledge of the process and impact simulations. AIM's important technology demonstration component includes a deep-space optical communication terminal and intersatellite network with two CubeSats deployed in the vicinity of the Didymos system and a lander on the surface of the secondary. To achieve a low-cost objective AIM's technology and scientific payload are being combined to support both close-proximity navigation and scientific investigations. AIM will demonstrate the capability to achieve a small spacecraft design with a very large technological and scientific mission return.

The Double Asteroid Redirection Test (DART): NASA element of AIDA

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The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first demonstration of the kinetic impactor asteroid deflection technique for asteroid impact hazard mitigation. AIDA is a joint ESA-NASA cooperative project, that includes the ESA Asteroid Impact Mission (AIM) rendezvous mission and the NASA Double Asteroid Redirection Test (DART) kinetic impactor. The AIDA target is the near-Earth binary asteroid 65803 Didymos, which will make an unusually close approach to Earth in October, 2022. The ~300-kg DART spacecraft is designed to impact the Didymos secondary at ~7 km/s and demonstrate the ability to modify its trajectory through momentum transfer. DART and AIM are currently Phase A studies supported by NASA and ESA respectively.

The primary goals of AIDA are (1) perform a full-scale demonstration of the spacecraft kinetic impact technique for deflection of an asteroid, by targeting an object larger than ~100 m and large enough to qualify as a Potentially Hazardous Asteroid; (2) measure the resulting asteroid deflection, by targeting the secondary member of a binary NEO and measuring the period change of the binary orbit; (3) understand the hyper-velocity collision effects on an asteroid, including the long-term dynamics of impact ejecta; and validate models for momentum transfer in asteroid impacts, based on measured physical properties of the asteroid surface and sub-surface. The primary DART objectives are to demonstrate a hyper-velocity impact on the Didymos moon and to determine the resulting deflection from ground-based observatories. The DART impact on the Didymos secondary will cause a measurable change in the orbital period of the binary. Supporting Earth-based optical and radar observations and numerical simulation studies are an integral part of the DART mission.

The baseline DART mission launches in December, 2020 to impact the Didymos secondary in September, 2022. There are multiple launch opportunities for DART leading to impact around the 2022 Didymos close approach to Earth. The AIM spacecraft will be launched in Dec. 2020 and arrive at Didymos in spring, 2022, several months before the DART impact. AIM will characterize the Didymos binary system by means of remote sensing and in-situ instruments both before and after the DART impact. The asteroid deflection will be measured to higher accuracy, and additional results of the DART impact, like the impact crater, will be studied in great detail by the AIM mission. The combined DART and AIM missions will provide the first measurements of momentum transfer efficiency β from hyper-velocity kinetic impact at full scale on an asteroid, where the impact conditions of the projectile are known, and physical properties and internal structures of the target asteroid are also characterized.

The DART impact on the Didymos secondary is predicted to cause a ~4.4 minute change in the binary orbit period, assuming β=1, and is expected to be observable within a few days. The predicted β would be in the range 1.1 to 1.3 for a porous target material based on a variety of numerical and analytical methods, but may be much larger if the target is non-porous. The DART kinetic impact is predicted to make a crater of ~6 to ~17 meters diameter, depending on target physical properties, but will also release a large volume of particulate ejecta that may be directly observable from Earth or even resolvable as a coma or an ejecta tail by ground-based telescopes.

The Science of AIM and AIDA

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Introduction: The Asteroid Impact Mission (AIM) is a rendezvous mission and the European component of the Asteroid Impact & Deflection Assessment (AIDA) mission under study at ESA and NASA [1]. AIM is a small mission of opportunity demonstrating key technologies for future exploration missions while focusing on asteroid monitoring aspects i.e., the capability to determine in-situ the key properties of the small natural satellite of the near-Earth asteroid binary system Didymos used as the AIDA target [2]

AIM is under a Phase A/B1 study at ESA from March 2015 to the summer 2016. If funded for launch in 2020 with an arrival to Didymos in 2022, it will be the first mission to characterize a binary asteroid, including its internal structure. It will also give access to the detailed conditions of the impact by the Double Asteroid Redirection Test (DART, Fig. 1) under phase A study by NASA [3], as well as its outcome, allowing for the first time to get a complete picture of a collisional event at asteroid scale, a better interpretation of the deflection measurement and a possibility to compare with numerical modeling predictions.

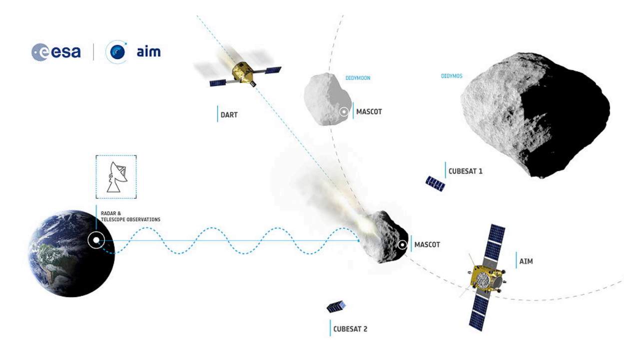

Figure 1: AIDA: AIM and DART

Baseline payloads: AIM is planned to carry the following remote sensing and in-situ instruments: a Visual Imaging System, a lander (based on the heritage of the DLR MASCOT onboard the Japanese mission Hayabusa 2), a thermal infrared imager, a high frequency (decimeter-wave) radar, and a low frequency (60 MHz) radar, to measure Didymos surface and subsurface physical properties and to study internal structures. AIM also includes an optical communication demonstration that can be used as a laser altimeter and CubeSat payloads.

Objectives: AIM has several objectives. First, it will characterize for the first time the secondary of a binary asteroid, allowing us to better understand the formation and properties of these systems that represent 15% of the NEA population. Second, AIM will demonstrate the technologies required by a simple monitoring spacecraft as well as establishing the suitability of binary asteroids as candidates for future explorations and asteroid deflection tests. Finally AIM will demonstrate, on the minimum expression of a deep-space mission, new technologies for optical communication, inter-satellite links, and on-board resource management.

Five studies of Cubesats are going on throughout the Phase A/B1, with various objectives, such as touching down to assess the surface material, gravity field, subsurface structure, perform near infra-red spectrometry, close range imaging, or characterizing and imaging the ejecta plume from the DART impact.

The characterization of Didymos' satellite by AIM will provide precious knowledge on the physical/compositional properties of a binary near-Earth asteroid. Physical and compositional properties of small bodies provide crucial information on the dynamical and collisional history of our Solar System. In addition, the formation mechanism of small binaries is still a matter of debate, although several scenarios have been proposed to explain their existence. In particular, rotational disruption of an NEA, assumed to be an aggregate, as a result of spin-up above the fission threshold due to the YORP effect (a thermal effect which can slowly increase or decrease the rotation rate of irregular objects) has been shown to be a mechanism that can produce binary asteroids with properties that are consistent with those observed. These properties include the oblate spheroidal shape of the primary, the size ratio of the primary to the secondary and the circular equatorial secondary orbit [4]. Other fission scenarios have been proposed which imply different physical properties of the binary and its progenitor [5]. Binary formation scenarios therefore place constraints on, and implications for the internal structure of these objects.

Small asteroids undergo substantial physical evolutions, and yet the geophysics and mechanics of these processes are still a mystery. AIM will allow us to address fundamental questions, such as: what are the subsurface and internal structures of asteroid's satellites and how does an asteroid's surface relate to its subsurface? What are the geophysical processes that drive binary asteroid formation? What are the strength and thermal properties of a small asteroid's surface?

What is the cohesion within an aggregate in microgravity? What are the physical properties of the regolith covering asteroid surfaces and how does it react dynamically to external processes, such as the landing of a surface package and/or an impact?

AIM within AIDA: AIDA will include both AIM and DART. The primary goals of DART are (i) to demonstrate a hypervelocity spacecraft impact on a small near-Earth asteroid (NEA) and (ii) to measure and understand the deflection caused by the impact. The DART mission includes ground-based optical and radar-observing campaigns of Didymos both before and after the kinetic impact experiment, as well as modeling and simulation programs. DART has the further objective to learn how to mitigate an asteroid threat by kinetic impact. AIM will make detailed measurements of the DART impact and its outcome, providing a fully documented impact experiment at asteroid scale to develop and validate models for momentum transfer in asteroid impacts.

AIM mission scenario and close proximity operations: two industrial consortia led by the industries OHB System and QinetiQ Space, respectively, are studying the AIM mission and spacecraft until summer 2016. The launch will take place in 2020 for an arrival at the asteroid in May 2022, allowing a first characterization of the target before the DART impact, planed in late September/early October 2022. Figure 2 shows the sequence of AIM close proximity operations before and after the DART impact.

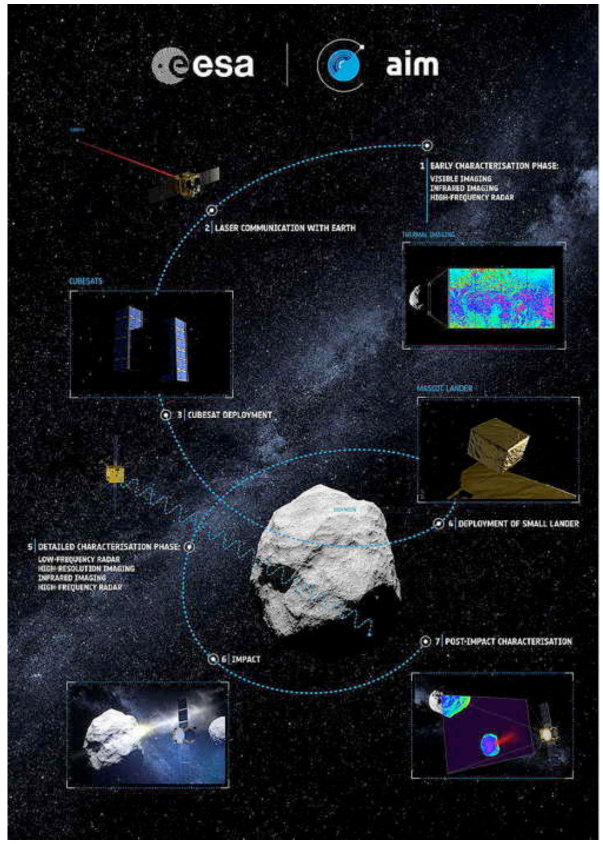

Figure 2: AIM close proximity operations.

Conclusions: AIM will return fundamental new information on a binary system, on the internal and surface structure and on the mechanical response of a small asteroid in the 100-meter-size range. Within AIDA with DART, it will be the first fully documented impact experiment at real asteroid scale, allowing numerical codes to be tested and used for similar and other scientific applications at those scales. In particular, it will ofer the possibility to improve greatly our knowledge on the impact cratering process at asteroid scale, and consequently on the collisional evolution of asteroids with implications for planetary defense, human spaceflight, and Solar System science.

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[1] Cheng A. F. et al. (2015) *Acta Astronautica, 115*, 262-269. [2] Michel, P. et al. (2016) *Advances in Space Research,* submitted. [3] Cheng, A. F. et al. (2016) *Planetary and Space Science*, in press. [4] Walsh K et al. (2008) *Nature, 454*,188-191. [5] Jacobson S. A and Scheeres D. J. (2011) *Icarus, 214*, 161-178.

Orbit stability in the Binary Asteroid System Didymos – An opportunity for spacecraft exploration

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We have analyzed particle motion in the binary asteroid system 1996 GT (Didymos), proposed as a target for the AIDA mission. The combined gravity fields of the odd-shaped rotating objects moving about each other are complex. In addition, orbiting spacecraft or dust particles are affected by radiation pressure, possibly exceeding the faint gravitational forces.

For the numerical integrations, we adopt parameters for size, shape, and rotation from telescopic observations. To simulate the effect of radiation pressure acting upon the spacecraft, we apply a spacecraft wing-box shape model. Integrations concerning spacecraft trajectory were carried out over at least 25 days beginning in near-circular orbits.

Most such orbits are unstable, escaping quickly or colliding with the asteroid bodies. However, with carefully chosen initial positions, we found stable motion in the orbiting plane of the secondary, associated with the Lagrangian points (L4 and L5), in addition to horseshoe orbits, where particles move from one of the Lagrangian point to the other. We also find stable orbits in commensurability with the motion of the orbital period of the secondary, implying a resonance in eccentricity. Stable conditions depend strongly on season, expressed by the changing inclination of the mutual orbit plane with respect to Didymos' solar orbit.

At larger distance from the asteroid pair spacecraft as well as dust moves in a non-Keplerian orbit, like the well-known "terminator orbits" where gravitational attraction is balanced against radiation pressure.

Stable orbits and long motion arcs are useful for long tracking runs by radio or Lasers and thus for modeling of the ephemerides of the asteroid pair and gravity field mapping. Furthermore, these orbits may be useful as observing posts or as platforms for approach. These orbits may also represent traps for dust particles, a possibly a hazard to spacecraft operation.

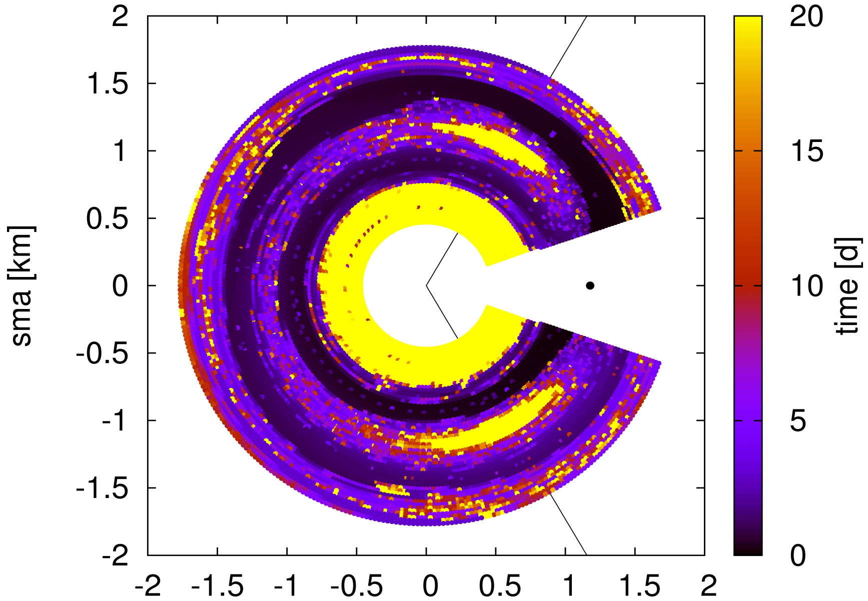

Figure 1: Stability analysis for orbits in the mutual plane of the 1996 GT system with different initial conditions. Different semi-major axis and mean anomalies are represented as radius and angel in polar coordinates. Initial eccentricity is 0.05. Colors indicate the time of stable orbiting. Initial conditions close to the primary (center) or the secondary (right dot) asteroid are cut out. The effect of solar radiation pressure is determined for a 2 x 2 x 2 m spacecraft with a 20 m^2 solar panel and 1275 kg mass.

Post-mitigation risk assessment for the AIM+DART impacting mission

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The AIDA mission target (65803) Didymos – a binary asteroid – has several encounters with the Earth over the upcoming decades, some of which are closer than 20 lunar distances. Didymos, therefore, belongs to the dynamical class of Potentially Hazardous Asteroids (PHA). Although the kinetic impact (DART) is intended to change the orbit of Didymos' moonlet around the binary's centre of mass, net momentum is also imparted on the whole system. While small, the consequent change in the asteroid's velocity will change the heliocentric orbit of the system as well. Given the high degree of non-linearity of the near-Earth dynamical environment, even a small change in initial conditions can affect long-term predictions of the encounter distances between Didymos and the Earth.

In order to make sure that no planetary safety issues arise as a consequence of DART, we propose to conduct post-mitigation impact risk assessments (PMIRA, Eggl et al. 2015, 2016) similar to those already performed for the deflection demonstration scenarios elaborated in the framework of the European Commission funded NEOShield project. An essential part of the PMIRA is the evaluation of uncertainties in the deflection process, their influence on the final change in the asteroid's velocity, and the consequences for long-term impact risk assessment. A physical characterisation of the system, such as planned in the framework of AIM is essential to reduce such uncertainties the Didymos system, allowing for a more precise estimate of the long-term changes in Didymos' heliocentric trajectory. We discuss reconnaissance requirements to AIM that will optimize impact threat assessment before and after the launch and impact of DART.

Ref.:
Eggl et al. 2015. Post mitigation impact risk analysis for asteroid deflection demonstration missions. AdSR 56, 528.
Eggl et al. 2016. Dealing with Uncertainties in Asteroid Deflection Demonstration Missions: NEOTwIST. IAU-GA Meeting #29, eprint arXiv:1601.02103.

POPULATION OF SMALL ASTEROID SYSTEMS: BINARIES, TRIPLES, AND PAIRS

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Introduction: Binary and more complex systems are frequent among asteroids smaller than about 15 km in (primary) diameter. They are ubiquitous; we have found them among near-Earth, Mars-crossing as well well Main Belt asteroids – in fact in every group or family of asteroids where we searched for them. The fraction of binaries among near-Earth asteroids was found to be 15 ± 4% [1], and a similar fraction was suggested for main belt asteroid binaries [2]. There also exist pairs of asteroids on highly similar heliocentric orbits that are genetically related and that separated typically 10^5-10^6 yr ago. Currently we know more than 150 binary and triple asteroids and more than 200 separated asteroid pairs.

In my talk, I will first briefly outline the observational techniques that we use for detection and description of asteroid systems, and then I will review our present knowledge of their properties and understanding of their formation and evolutionary processes. I will put our current knowledge of Didymos' properties in context of the general population of small binary asteroids.

Observational techniques for asteroid systems: The three main techniques for remote detection and measurement of binary and multiple asteroid systems are radar observations, photometric lightcurve observations, and adaptive optics/direct imaging observations. Radar is efficient for detecting near-Earth asteroid binaries during their close approaches; the inverse dependence of the echo strength on the 4^{th} power of the distance between object and radar means that the existing radars (Arecibo, Goldstone) can effectively observe binary asteroids up to about 0.1 AU from the Earth. With the photometry method, we detect binary asteroids by observing mutual (eclipse/occultation) events between the system components even at large distances (limited by photometric S/N). An example of the photometric observations is shown in Fig. 1. The adaptive optics technique can resolve the components of wide binaries only, which represent a minority among binary asteroid systems. So far, most near-Earth asteroid binaries were detected by radar with about ¼ contribution from photometry. Almost all of the more distant binaries (among main belt and Mars-crossing asteroids) were detected by photometry, with a small fraction (a few percent) detected with adaptive optics. See [3] for a review of the binary asteroid observational techniques.

Main properties of small asteroid systems: The sample of more than 150 detected binary and triple asteroid systems allowed us to obtain certain interesting findings on their properties and to suggest how they formed and evolved. The most significant common features are following: The binary asteroid systems have a total angular momentum content very close to, but not generally exceeding, the critical limit for a single body in a gravity regime [4]. The primaries are mostly fast rotators (unless they were slowed down by spin-orbit interaction with large satellites, which are uncommon); they spin at rates close to the stability limit for cohesionless rubble pile aggregates. Close secondaries are on low (near-zero) eccentricity orbits and they are in synchronous rotations (in 1:1 spin-orbit resonance); more distant secondaries are more frequently on eccentric orbits and in asynchronous spin states [2]. There is a lower limit on the separation between the primary and secondary that is consistent with the Roche's limit for strengthless satellites; the semi-major axes of the mutual orbits are > 2.54 R_1 (primary radius), with the orbital periods > 11 hr [1]. The primaries have a "top" shape figures with an equatorial ridge [5, and references therein; see also Fig. 2]. The secondaries show an upper limit on their equatorial elongations with the axis ratios $a_2/b_2 \leq 1.5$ [2]. The mutual orbits are not oriented randomly, but they concentrate at low obliquities with the orbit pole latitudes being mostly within 30° from the ecliptic poles [6].

The properties of small binary asteroids strongly suggest that they formed from parent asteroids with low or zero tensile strength (a rubble pile structure) that were spun-up to the critical frequency. A strong candidate for the spin-up mechanism is the thermal Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect, that is a torque acting on rotating irregularly shaped asteroid due to asymmetric thermal emission from its surface (e.g., [7]). After fission of the parent asteroid, a formed secondary may remain in orbit around the primary or it may escape from the system due to a spin-orbit interaction with the primary, creating a separated asteroid pair (e.g., [8], and references therein).

Didymos in a context of the binary asteroid population: The binary asteroid (65803) Didymos is a typical member of the population of small binary asteroid systems in most of its properties, though a few are at the edge of their distributions in the binary population. In particular, the primary rotation period P_1 =

2.26 hr is one of the shortest observed (might be due to a slightly higher than average primary bulk density) and the mutual orbit is one of the tightest ($a/D_1 = 1.5$, $P_{orb} = 11.92$ hr). However, none of these two properties is really unique or anomalous and we consider Didymos being a good representative for small binary asteroid systems that probably formed by spin-up fission.

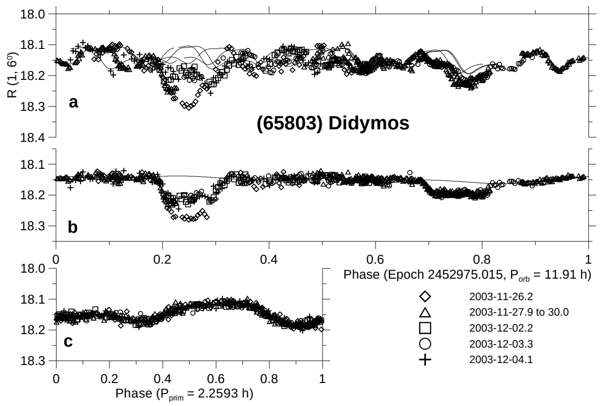

Figure 1: Lightcurves of (65803) Didymos of 2003-11-26.2 to 12-04.1. (a) The original data showing both lightcurve components. (b) The orbital lightcurve component showing the mutual events. The primary rotational lightcurve was subtracted. (c) The primary rotational lightcurve component. Figure taken from [1].

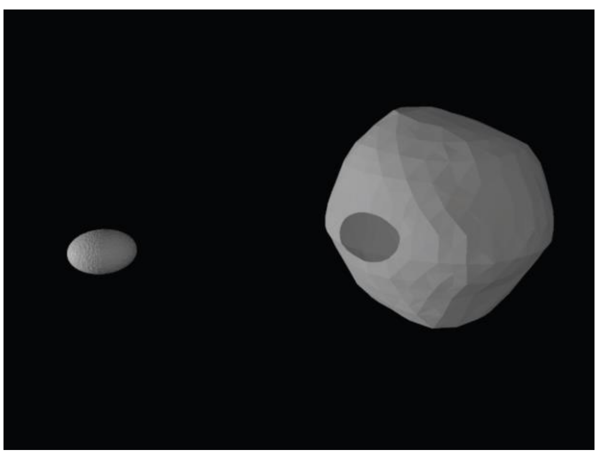

Figure 2: Preliminary shape model of the primary of Didymos obtained by L. Benner and S. P. Naidu from combined modeling of the radar and photometry data from 2003, shown with the secondary at scale with assumed ellipsoid axes [9]. Courtesy of L. Benner and S. P. Naidu, Jet Propulsion Laboratory.

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Physics of two Potential Hazardous Asteroids using groundbased observations

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Abstract: 1,640 objects among 13,800 Near-Earth Objects are classified as Potential Hazardous Asteroids (PHA). About 40 of them are characterized by reflection spectra in the visible and near-infrared. Their relatively small diameter make them visible from the ground just in the case of close encounters with the Earth, on average few times per century (Popescu et al, 2011). Thus it is vital to take advantage of such favorable geometries to records the largest amount of information concerning their physical properties such as the mass, internal structure, size, shape, surface composition, rugosity, mineralogy.

Spectroscopic observations of the PHAs 2007 PA8 and 2004 BL86 are analyzed during this presentation. Asteroid 2007 PA8 was observed in September 15, 2012 using SpeX/IRTF. Data analysis shows an object more akin to H-type chondites. Dynamical integration of 1,275 clones backward in time over 200,000 years show an express delivery of this chip from the main belt most probable from the 5:2 resonance region with Jupiter(Nedelcu et al 2014). The binary PHA asteroid 2004 BL86 was observed in February 6-7, 2015 using INT and IRTF facilities. Data analysis shows a mineralogy compatible to howardite-eucrite-diogenite meteorites. Spectroscopic observations allows to constrain the size of the system of about 300 meters in diameter, thus diminishing the previous estimation by 40% (Birlan et al, 2015).

References: Birlan et al, A&A vol 581, 2015; Nedelcu et al, A&A vol. 567, 2014; Popescu et al, A&A, vol 535, 2011;

DYNAMICAL PROPERTIES OF THE (65803) DIDYMOS BINARY

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Abstract

The near-Earth binary asteroid (65803) Didymos is the target of the AIDA/AIM mission; AIM is currently under Phase A/B1 study by ESA. Here we describe our preliminary assessment of the dynamical properties of the binary that are relevant for the mission. We have constructed an accurate model for studying the short-term dynamics of the system, in which each of the two components is represented by a rigid body, composed of ~1000 mass blocks that fit its known (or, in the case of the secondary, inferred from observations) shape. In particular, we use the latest shape solution for the primary and assume the secondary to be a triaxial ellipsoid, with axial ratios *a/b* and *b/c* varying between 1.1 and 1.5, as suggested by the latest ESA Didymos Reference Model. Our model solves for the orbital and rotational motion of the two rigid bodies, fully accounting for their gravitational interaction. Almost all solutions appear to be stable for a time corresponding to 1,000 orbits, in the absence of solar tides. The semi-major axis of the mutual orbit has very small variations (~1 m) and the eccentricity of the orbit (initially assumed ~0) stays smaller than 0.02 – increasing slightly with *a/b* and *b/c*. The orbital plane oscillates about the initial one very little (i<0.005°). The rotation axes also remain stable, as the obliquity stays <0°.02 for the primary and <0°.3, for the secondary. While the rotational period of the primary is extremely stable (δP_1 ~ 0.1 sec) the one of the secondary shows secular oscillations, whose amplitude and period depend on the assumed axial ratios and may range from δP_2 ~0.2 to 1.5 hr. An analysis of the system's secular evolution under the effect of solar and earth tides is underway.

The environment around (65803) Didymos: Conditions for loft regolith due to the fast spin of the primary.

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ABSTRACT

An increasing number of Near Earth Asteroids (NEAs) in the range of a few hundred meters to a few kilometers in size are found to have relatively high spin rates (less than 4 hr, down to ~2.2 hr, depending on taxonomic type). Due to their high spin rate local acceleration near their equator may in some case be directed outwards so that lift off of near-equatorial material is possible. In particular, this is the case of the primary of the (65803) Didymos binary system, target of the AIDA mission, spinning with a 2.26 h period. We study the effects of that phenomenon on surface material at any asteroid latitude.

MOTIVATION

Both coherent bodies and gravitational aggregates (GA) (often called “rubble piles”) may stand spin rates higher than the critical ones found for fluids by Chandrasekhar [1]. In the case of coherent structures that is due to internal solid state forces, while in the case of gravitational aggregates shear strength may easily appear as a consequence of friction among GA components [2] increasing structural yield. Near Earth Asteroids (NEAs) coming from the asteroid belt are believed to be mostly GA in the range ~0.5-1 km to ~50 km [3] due to their collisional history. Once in the inner Solar System, NEAs may undergo spin up evolution through the non-gravitational YORP effect [4] causing their components to disperse, to shed mass or to fission and eventually form binary, multiple systems and asteroid pairs [5, 6]. The end state of those events often is an object spinning above any Chandrasekhar stability limit, kept together by friction and characterized in some case by the presence of an equatorial “bulge”, as shown by radar images [7, 8]. This seems to be the case of the primary bodies of binary systems 1996 FG3 and 1996 KW4, and the single body 2008 EV5, among others. The Didymos primary has been spotted by radar in 2003, even if not at the precision level to evidence any such feature. The latest available shape model does not show such feature either. It is especially interesting to study this phenomenon in the case of Didymos, as it is the target of the AIDA mission. In particular, the ESA component AIM will orbit the system to entirely characterize it and it essential for navigation to have a characterization of its environment as good as possible.

In rapidly spinning bodies, in the rotating frame the centrifugal force acting on surface particles and boulders at near-equatorial latitudes may slightly overcome the gravitational pull of the asteroid itself, having the opportunity to leave its surface.

When particles leave the surface they are not necessarily lost form the asteroid, in fact, they leave the surface at negligible velocity and as soon as they lift off they only move under the gravitational field of the asteroid, the non-inertial apparent forces due to rotation, the Sun’s gravity and –in the case of binary systems- the secondary’s gravitational pull. Therefore, particles may levitate for some time, land on the surface and lift off again, repeating this cycle over and over. Alternatively, they may enter orbiting states or even transfer to the secondary. [9] have studied some of the features of this problem, relevant to binary dynamics. Non-inertial and gravitational forces have the same dependence on a given particle mass, their action is then independent on mass itself: small dust particles may leave the surface as well as large boulders. Other forces may act as well on small particles, like electrostatic forces or molecular forces (cohesion), with the likely result to stick them together and still undergo the same effects as dusty clumps. Moreover, small particles may be lost as they undergo solar pressure force able to subtract them to the asteroid's gravity while they are levitating.

METHODOLOGY

We have collected available data on binary asteroid systems with very good accuracy in spin rate determination and acceptable uncertainties in mass and have catalogued NEA binary systems according to their primary spin.

This study follows and develops researches made by the working group on mechanical properties of the "MarcoPolo-R" mission proposed to ESA in its past M3 call. In that case, the goal was to study regolith lift off features on both 1996 FG3, the former target of the mission, and 2008 EV5, its nominal target.

In this case we focussed on the binary system (65803) Didymos. In order to study the dynamics of particles, we use a numerical code that integrates, by a fourth-order Runge-Kutta method, the equations of motion of individual particles that are ejected from the asteroid surface when centrifugal acceleration is strong enough to overcome local gravity. The equation of motion is written in a non-inertial asteroid-centered reference frame, taking into account the asteroid (and the secondary, in this case) and solar gravity, radiation pressure, and inertial terms. A version of this code has been successfully tested and applied by Molina et al. [10] to the study of particles in comet environments.

We then study the motion of particles in the 1 μm to 10 cm range in the non-inertial reference frame of the rotating primary, accounting for centrifugal and Coriolis apparent forces as well as the gravitational fields of the primary, the secondary, the Sun and the radiation forces by the Sun itself. The eccentricity of the heliocentric orbit of the system and the obliquity of the system are taken into account.

The dynamics of particles of a wide mass range is calculated during many orbital cycles as a function of their initial position on the asteroid surface for each system under study. A relative mass density of levitating particles is calculated as a function of distance to surface, latitude, and longitude. In the very case of Didymos, the study is being extended and discussed in the ranges of size and mass of the primary.

RESULTS

We present the results of our ongoing study in the case of Didymos. We find that fine particles (< 100 μm) are quickly swept away from the system by solar radiation pressure, while larger particles may undergo landing and lift off cycles that form a dusty environment above the surface at near-equatorial latitudes. The relative density of floating particles drops by about one order of magnitude beyond 10-20 degrees of latitude. Consequences in the AIM navigation around the Didymos' primary can be derived from this study. We are currently updating our results to fully take into account the available shape model of the Didymos primary.

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Determining the mass of Didymos' secondary by visual imaging

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A critical requirement for the Asteroid Impact Mission (AIM) is the ability to determine the mass of Didymos' secondary with an accuracy of about 10 %. On one hand, this is necessary in order to plan the delivery of the lander MASCOT-2 with sufficient precision, on the other hand, it is needed to estimate the momentum transfer by the impact of the DART spacecraft and hence to verify the concept of asteroid deflection.

The conventional approach to estimate the mass of a solar system body through its gravitational effect by tracking the spacecraft trajectory is not viable for Didymos' secondary. With a diameter of only 163 m, its mass is too small to yield a significant impact on the spacecraft trajectory at reasonable fly-by distances. Instead, the idea to determine the mass of the secondary by measuring the "wobble" of the primary around the common centre of gravity has been put forward. The mass of the primary is about 100 times the mass of the secondary, thus the expected wobble radius is about one percent of the distance of 1180 m between the two, that is about 10 m. Such a wobble may be possible to measure either by means of using the optical communication device OPTEL-D as an altimeter or by direct observation with the visual imaging system VIS. Here, we investigate the latter approach.

The idea is to identify landmarks in VIS images and to simultaneously solve for the positions of the landmarks and the spacecraft in the body fixed frame of the primary. The temporary evolution of the spacecraft position comprises three components:

- the drift of the spacecraft due to gravitational disturbance and solar radiation pressure (and errors in the knowledge of the initial state),
- the apparent motion of the spacecraft around the primary (in the body fixed frame) due to its rotation,
- an apparent oscillation of the spacecraft position due to the wobble of the primary with a known period.

While the wobble component is quite small (about 10ṁ), its period is known and it is still possible to extract it under certain conditions.

In this preliminary investigation, we do not deal with the problem of landmark identification and the accuracy of landmark location in images. From the experience with the Rosetta mission, we know that landmarks locations can be measured with an accuracy of one pixel. We just arbitrarily generate landmark positions in the body fixed frame and simulate the viewing directions from the spacecraft (with some error), adding also some (unknown) spacecraft drift. We conduct Monte Carlo simulations for various scenarios and assess the accuracy of the determination of Didymos' secondary's mass.

Radio Science Investigations with Asteroid Impact Mission

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The Asteroid Impact Mission (AIM) is a candidate ESA mission to the binary Near-Earth Asteroid (65803) Didymos. While its main objective is to demonstrate new technologies for future deep-space missions, AIM will characterize for the first time a binary asteroid system, providing an understanding of its formation and of the origin of the Solar System. AIM can be conceived as a stand-alone mission, but it is also the ESA contribution to the proposed joint mission AIDA (Asteroid Impact & Deflection Assessment), which includes also NASA's spacecraft DART (Double Asteroid Redirection Test). DART will impact the secondary of Didymos, informally called Didymoon, to test and validate the kinetic impactor as a planetary protection strategy and greatly increasing the scientific return of both the missions through the detailed comparison of the Didymos system before and after the impact.

The precise orbit determination of the AIM spacecraft both in the Didymos system and in the Solar System will be crucial to achieve the scientific objectives of the mission, because it provides one of the very few direct measurements of its main dynamical and physical parameters.

As demonstrated by the recent Rosetta mission, the orbit determination and control of a spacecraft in the vicinity of a small body, like an asteroid or a comet, is a challenging problem because of the weak gravity accelerations exerted by the body and the consequently relatively large non-gravitational disturbances. Moreover, a binary asteroid system introduces new modelization and operational challenges because it is an intrinsically more complex dynamical environment, characterized by a strong coupling between the rotational and orbital dynamics of both the two bodies. Given the typical small relative velocities and accelerations near an asteroid or comet, the classical Doppler measurements, usually adopted as main observable in the interplanetary orbit determination process, provide a limited information content. Hence, the spacecraft navigation must be enhanced by means of additional observations, like optical measurements obtained by the onboard cameras. When aiming at a distant target, the picture of a body provides its relative direction with respect to the spacecraft, in the camera frame. Additionally, in a binary system the optical measurements provide also the accurate relative positions of the two bodies, posing a strong constraint on their relative orbital motion. When near, the camera may be used to identify optical features on the surface of a body, allowing to accurately estimate its rotational state. Hence, to precisely reconstruct the spacecraft orbit, the dynamics of the entire binary system must be accurately modeled and updated in a global estimation filter, using the information provided by all the available measured quantities.

We performed numerical simulations of the orbit determination of AIM within the Didymos system, providing a preliminary assessment of the accuracies achievable in the estimation of the scientific parameters of interest, by means of a covariance analysis, like the heliocentric orbit of the system, the masses and the extended gravity fields of Didymain and Didymoon, and their rotational states.

We built a realistic dynamical model of the system, on the basis of the most recent data available. The trajectories of both the spacecraft and Didymoon were numerically integrated taking into account the extended gravity of Didymain, modeled as an uniform-density polyhedral, the extended gravity of Didymoon, modeled as an uniform-density tri-axial ellipsoid, the gravity of the Solar System planets, and the solar radiation pressure. Simulated radiometric and optical measurements were computed assuming a simple mission scenario. The measurements were corrupted with an additive white Gaussian noise with realistic standard deviations.

Preliminary results show that the precise estimation of Didymoon orbit and rotational state, necessary to quantitatively test the asteroid deflection by kinetic impact, is strictly coupled to the detailed characterization of Didymain.

Possible improvements in the orbit determination accuracy may be obtained exploiting the optical communication system and the inter-satellite link payloads. The optical link may be used to accurately measure the absolute spacecraft distance from the Earth, significantly improving the estimation of the system's heliocentric orbit. The inter-satellite link between the spacecraft and the Didymoon lander may improve the knowledge of the moon's rotational state, while the inter-satellite link between the spacecraft and one or more CubeSats orbiting within the system may be of fundamental importance to disentangle the gravity and the dynamics of the two bodies. These will be the subject of future investigation.

However, despite these preliminary results, a comprehensive characterization of the Didymos system dynamics will represent a considerable challenge, because it relies on the development of accurate mathematical models of both non-gravitational perturbations and the coupling between the orbital and rotational dynamics.

Physical Bulk Properties of the Didymos binary system to be determined by the ESA Asteroid Impact Mission (AIM)

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The ESA Asteroid Impact Mission (AIM) spacecraft, to be launched in 2020, shall characterize the Didymos asteroidal binary system by means of remote sensing and in-situ instruments and shall monitor the impact of DART and its outcome. The masses, gravity fields, densities, porosities and the internal structures of both bodies can be determined from the attracting forces acting on the spacecraft by means of precise radio ranging and Doppler tracking. The proposing team has successfully performed similar experiments with Mars Express (many Phobos flybys), Rosetta (asteroid Lutetia; comet Churyumov-Gerasimenko) and New Horizons (Pluto flyby). Images taken from the AIM Visual Imaging System (VIS) and the ranging between the spacecraft, the lander and the cube-sats (inter-spacecraft links) can be used to determine the distances between the spacecraft and the centers of mass of both bodies, a requirement for a precise gravity field determination. A global solution for the individual gravity fields and the system gravity field, the orbital state and the rotational state can be obtained for the Didymos binary system from the combination of these observations. The observed gravity field coefficients are compared with those coefficients calculated from the shapes assuming constant bulk density. Differences from this comparison point to internal mass inhomogeneity. It shall also be tested how efficient and precise the optical communication link can be used for spacecraft tracking and applied optical (radio) science methods.

Natural seismic sources at the Didymos binary system

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Ground-based observations (e.g., [1,2]) and recent space missions (e.g., [3,4]) have significantly increased our understanding of asteroids over the last decade. It is now strongly believed that these bodies are covered by loose regolith and many may be rubble-piles (essentially made of regolith throughout). As a result of the unique micro-gravity environment that these bodies posses, a complex and varied geophysics has given birth to fascinating features that we are just now beginning to understand [5]. The processes that formed such features can be studied using theoretical, numerical and experimental methods. However, the only way to truly access the mechanical properties of an asteroid is to directly interact with the surface and measure how it responds to an external solicitation.

In addition, despite the successes of ground and space-based observations, there is still no clear understanding of the asteroid internal structure(s). Depending on their size, evolution and physical properties, many different asteroid internal structure models have been suggested from completely cohesive bodies, through to rubble pile objects. The internal structure of an asteroid has important implications for interpreting its evolutionary history (we may expect to find huge voids inside an asteroid that was formed from collisional disruption and re-accumulation of major fragments [6]) and also for understanding its continuing geological evolution (a microporous body may compact due to pore crushing during an impact whereas the voids in a macroporous rubble pile may protect the body causing more localised and less extensive damage [7]). In addition, such knowledge can also inform us about the collisional processes responsible for planetary formation and hence improve our understanding of the formation and evolution of the entire Solar System. The internal structure also has, of course, strong implications for possible mitigation and deflection techniques.

The Asteroid Geophysical Explorer (AGEX), a COPINS payload selected for study by ESA, will land geophysical instrument packages on the surface of Didymoon; the secondary object in the (65803) Didymos (1996 GT) binary system [8]. The instruments will characterize the asteroid surface mechanical properties and probe, for the first time, the sub-surface structure of an asteroid with a seismometer.

Factors such as crater erasure [9], destabilisation of regolith slopes [10], and regolith segregation [11] provide evidence for impact-induced seismic shaking of small bodies. However, seismic signals may also occur from other natural sources such as thermal cracks [12], internal quakes due to tidal forces [13] and other geophysical processes (see [5]). In this presentation, we will discuss the natural seismic sources that may occur on Didymoon and the expected characteristics of such signals.

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Thermal model of Didymos' secondary throughout the Asteroid Impact Mission

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Introduction

The thermal emission of the secondary in a binary asteroid system depends on the secondary's shape, size, spin vector, albedo, solar distance, surface roughness, and thermal inertia, as well as the shadowing effect and thermal radiation from the primary. All these parameters can be included in a thermal model to predict the secondary's thermal emission.

Modeling the daily temperature variation of Didymos' moon throughout the mission is important for calculating the operational temperatures of the Mascot lander and for predicting the output of the AIM thermal infrared imager and later analyzing the data.

Thermal modeling of Didymos' secondary is performed based on the current best knowledge of the physical properties of the secondary with the thermal inertia range of Γ=50–1000 J m^{-2} K^{-1} $s^{-1/2}$ [AD3: Asteroid Impact Mission: Didymos Reference Model 3.1].

Thermal model

As knowledge of the physical properties of the moon is very limited at the moment, we used a relatively simple thermal model. The model solves the one-dimensional heat conduction equation for an ellipsoidal body to provide longitude dependence. An adiabatic lower boundary is assumed, and the upper boundary condition is implemented to fulfill the conservation of energy with solar insolation depending on local coordinates, time, heliocentric distance and season. The surface is considered smooth in these preliminary calculations. Radiation from Didymos' primary is presumed negligible compared to the shadowing effect due to solar eclipses by the primary. The eclipses are included in the model under the assumption that the orbit of the moon lies in the equatorial plane of the primary with its z-axis normal to this plane. Simulations can be performed with or without eclipse conditions.

First results

Preliminary calculations have been performed for the temperature evolution of Didymos' secondary along the full orbit for a range of thermal inertia. A few examples of the results without eclipse can be found in figures 1 and 2. Including shadowing effects of the primary generally leads to lower maximum temperatures.

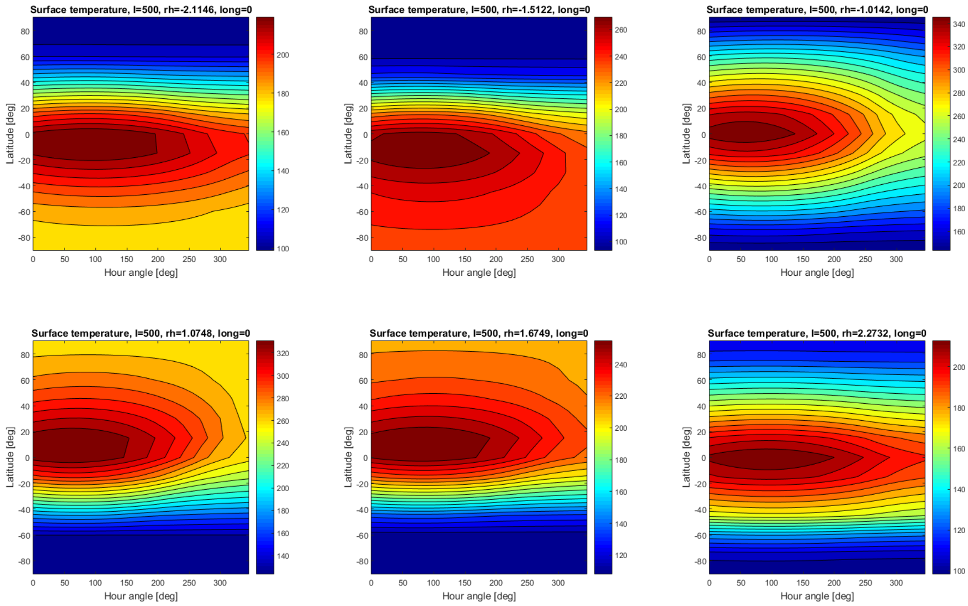

Figure 1: Contour maps of the daily surface temperature variation at longitude = 0 degree on Didymos' secondary for the case of a thermal inertia of 500 J m^{-2} K^{-1} $s^{-1/2}$. Contour maps for six different solar distances (rh, in AU) are shown. The northern winter can be seen in the first two and the northern summer in the 4^{th} and 5^{th} plot. The spin axis is given as 171±9 degrees [AD3]. Here, the extreme case of 162 degrees has been used.

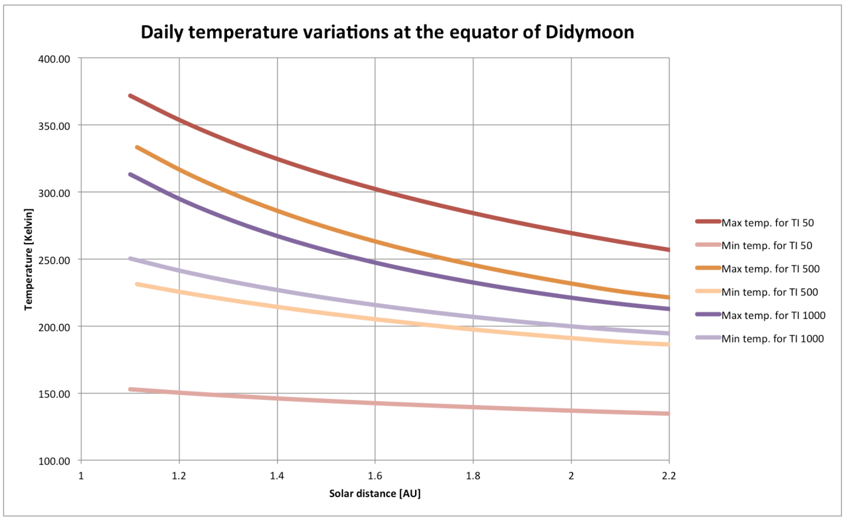

Figure 2: Daily maximum and minimum temperatures at the secondary's equator for different thermal inertia through the inward bound orbit.

Outlook

Currently, calculations are based on analytical formulations of an ellipsoid. The model however can also handle shape models with triangular and quadrilateral facets in common formats. Once available, a more detailed investigation of thermal conditions can be carried out. The model is also easily adaptable to updated physics.

Asteroid Surface Alteration by Space Weathering Processes

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Micrometeorite bombardment and irradiation by solar wind and cosmic-ray ions cause variations in the optical properties of small solar system bodies surfaces, affecting efforts to draw connections between specific meteorites and asteroid types. These space weathering processes have been widely studied for the Moon and S- and V-type asteroids, and they are currently being investigated for other asteroid types. Laboratory studies have been performed by several groups on different meteorite classes, aimed at simulating space weathering by using ion irradiation and laser ablation (Brunetto et al., 2015). Together with direct evidence of weathering of particles from asteroid Itokawa acquired by the Hayabusa mission, these results provide a fundamental contribution to the spectral interpretation of asteroid observations, to establish a solid asteroids–meteorites link, and to understand the energetic processes affecting the surfaces of minor bodies. In this presentation I will review the main recent results on asteroid surface alteration, with particular emphasis on the analysis of Itokawa particles (e.g. Bonal et al., 2015) and on the expected spectral trend of dark asteroids (Brunetto et al., 2014; Lantz et al., 2015). A general scheme for asteroid optical maturation is emerging. Spectral trends have confirmed that solar wind is the main source of rapid (10^4–10^6 yr) weathering, and that a number of rejuvenating processes (impacts by small meteorites, planetary encounters, regolith shaking, etc.) efficiently counterbalance the fast weathering timescales.

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Title: Small Bodies: Near and Far (SBNAF)

Abstract:

We are about to start an EU Horizon2020-funded benchmark study (EU reference number: 687378; Apr-2016 to Mar-2019) that addresses critical points in reconstructing physical and thermal properties of near- Earth, main-belt, and trans-Neptunian objects. The combination of the visual and thermal data from the ground and from astrophysics missions (like Herschel, Spitzer and Akari) is key to improving the scientific understanding of these objects. The development of new tools will be crucial for the interpretation of much larger data sets from WISE, Gaia, JWST, or NEOShield-2, but also for the operations and scientific exploitation of the Hayabusa-2 mission.

Our approach is to combine different methods and techniques to get full information on selected bodies: lightcurve inversion, stellar occultations, thermo-physical modeling, radiometric methods, radar ranging and adaptive optics imaging. The applications to objects with ground-truth information from interplanetary missions Hayabusa, NEAR-Shoemaker, Rosetta, and DAWN allows

us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. The SBNAF project will derive size, spin and shape, thermal inertia, surface roughness, and in some cases even internal structure and composition, out to the most distant objects in the Solar System.

Another important aim is to build accurate thermo-physical asteroid models to establish new primary and secondary celestial calibrators for ALMA, SOFIA, APEX, and IRAM, as well as to provide a link to the high-quality calibration standards of Herschel and Planck. The target list comprises recent interplanetary mission targets, two samples of main-belt objects, representatives of the Trojan and Centaur populations, and all known dwarf planets (and candidates) beyond Neptune. Our team combines world- leading expertise in different scientific areas in a new European partnership with a high synergy potential in the field of small body and dwarf planet characterization, related to astrophysics, Earth, and planetary science.

Our experience in modeling benchmark near-Earth objects 433 Eros, 25143 Itokawa and 162173 Ryugu can also be applied to the binary object 65803 Didymos, with the goal to obtain the best possible characterization of the object in the AIM planning phase, and also to combine disk-integrated remote observations with disk-resolved in-situ measurements during the operational phase.

IMPACT CRATERING ON SMALL ASTEROIDS: EXPECTATIONS AND OPPORTUNITIES FOR AIM. G. S. Collins[1], [1]Impact and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College, London, UK (g.collins@imperial.ac.uk).

Introduction: A principal objective of ESA's proposed Asteroid Impact Mission (AIM), is to observe, measure and characterize the impact deflection (by NASA's DART spacecraft) of asteroid 65803 Didymos' satellite ("Didymoon") from orbit [1]. Apart from being the first, important test of asteroid deflection using a kinetic impactor, the mission would be the first artificial hypervelocity impact on an asteroid and the first time such an impact was observed, recorded and measured, which affords a unique opportunity to study—close-up and in detail—the hypervelocity impact cratering process on a low-gravity asteroid surface. The results will advance our understanding of crater scaling on small bodies, a fundamental component of accurate surface dating; accretional efficiency during collisional evolution of the asteroid belt; and how we might use craters on asteroid surfaces to infer their interior structure.

In this presentation, we will briefly review current understanding of impact cratering on small asteroids, based on theory, experiments and numerical modelling to provide context and expectations for AIM.

Impact cratering on small asteroids: Asteroid 65803 Didymos and its satellite are ~800 m and ~150 m diameter asteroids, respectively, that are likely to be rubble-pile aggregates with high internal porosity (density ~2 g/cc) and low strength. With a surface gravity and escape velocity of ~4×10^{-5} ms^{-2} and ~7.5 cms^{-1}, respectively, the surface of Didymoon is an extremely low-gravity environment; hence, even a small cohesive strength of the surface materials may play an important role in modulating crater growth, ejection speeds and, consequently, impactor-target momentum transfer.

For a given set of impactor parameters (size, speed, density) crater size is a function of the gravity and cohesive strength of the target surface [2]. For cohesionless materials, such as dry sand, impact craters form in the so-called gravity regime, where the principal force arresting crater growth is the weight of the displaced target. In this case, a scaling line defined by numerous impact experiments in sand provides a robust estimate of crater size (cratering efficiency; Fig. 1). However, at the extremely low gravity of the DART-Didymoon impact scenario, lithostatic stresses around the crater are much less than the cohesion of lunar regolith (1-10 kPa) and even the weakest estimates of the cohesion of asteroid surfaces (~10 Pa). Hence, AIM is likely to observe a strength-dominated cratering process that forms a crater somewhat smaller than the ~100 m predicted by gravity scaling (Fig. 1).

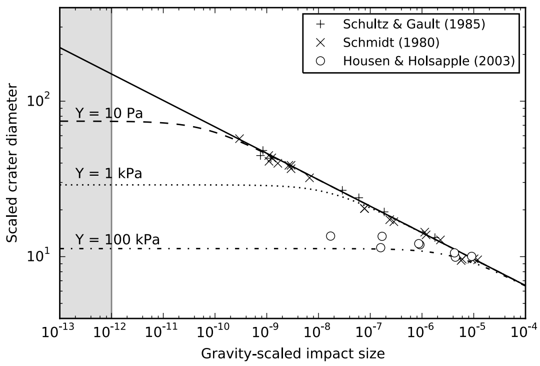

Figure 1: Crater scaling in the gravity regime. Scaled crater diameter (aka cratering efficiency, $D(\rho/m)^{1/3}$) versus gravity-scaled impact size (ga/U^2) for impact experiments in sand [3,4] (open) and sand-fly-ash mixture [5] (closed). Solid line shows canonical scaling law for cohesionless sand; broken lines show effect of small cohesive strength (for U = 6.5 km/s; ρ = 2.1 g/cc). Grey rectangle demarks likely range in gravity-scaled impact size of DART experiment.

Experimental constraints on porous, low-strength, but strength-dominated cratering are limited and lie outside the expected regime of the DART impact (Fig. 2). If the bulk cohesive strength of the Didymoon surface is less than a few kPa (the strength of lightly packed mountain snow), the best analogs are suites of experiments in a high porosity sand-fly ash mixture [5] and weakly-cemented basalt [6]. Scaling laws based on these experiments suggest a crater diameter between 10 and 60 m, depending on surface strength (Fig. 2).

Impact ejecta and momentum transfer: The efficiency of momentum transfer, and hence orbital deflection, in a hypervelocity impact on an asteroid is governed by the component of the total momentum of ejecta that escapes the asteroid surface in the opposite direction to impact [8]. In favourable deflection scenarios this ejected momentum may exceed the impactor momentum several times, greatly amplifying the imparted velocity change. Impact experiments and numerical models have provided insight into mass-velocity distributions of impact ejecta; however, as with crater size the results appear to be very sensitive to the material properties—porosity and strength—of the impacted surface [7,8]. As a result, estimates of the Δv that DART will impart on Didymoon vary by an order of magnitude [9]. The compaction of pore space, in particular, has been shown to dramatically reduce ejection speeds compared to those in a nonporous target [10, 11]. Based on models and experiments, the expectation for moderately porous targets, such as the surface of Didymoon, is that the ejecta momentum will be comparable to, but somewhat less than the impactor momentum, thereby amplifying momentum transfer by less than a factor of 2 [1; 8; 9; 11].

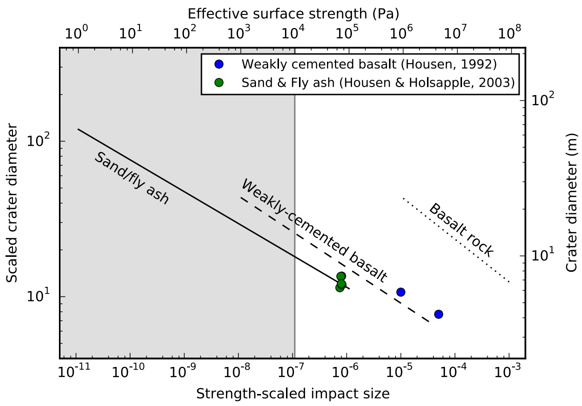

Figure 2: Crater scaling in the strength regime. Scaled crater diameter ($D(\rho/m)^{1/3}$) versus strength-scaled impact size ($Y/\rho U^2$) for impact experiments in low porosity basalt rock, moderate porosity, weakly cemented basalt aggregate [6] and a high porosity sand-fly ash mixture [5] and their corresponding scaling laws [7]. Right axis shows crater diameter and top axis shows equivalent effective surface strength of Didymoon for the DART impact scenario (U = 6.5 km/s; ρ = 2.1 g/cc). Grey rectangle demarks likely range in surface strength/strength-scaled impact size.

A challenge and opportunity for numerical modeling: The sensitivity of the outcome of the DART impact to the near-surface properties of its target present both a challenge and an opportunity for numerical impact modelling. Simulations of the impact will be critical for interpreting the observations of the AIM experiment, but will also test the robustness and accuracy of the material models that they employ. The high cratering efficiency and slow crater growth in such a low-gravity environment also makes such calculations computationally demanding. In addition, as the ejected momentum is dominated by the slowest ejecta, which is last to leave the growing crater and moves at speeds six orders of magnitude slower than the initial impact velocity, accurate and robust predictions of momentum transfer are a considerable challenge. The use and cross-comparison of multiple codes will strengthen the robustness of predictions, which calls for wide participation by the numerical modeling community—an endeavour that is already underway [12].

Conclusions: AIM will observe an impact scenario well outside the range of our experimental experience, thereby testing both our theoretical understanding of crater scaling and the accuracy of numerical impact models. Crater size, ejection speeds and momentum transfer are very sensitive to the strength and porosity of the asteroid's surface. Hence, characterising the bulk surface properties of Didymoon is imperative for maximizing the scientific value of the impact experiment. Replicating the AIM scenario is a challenge for numerical impact models, but offers a unique test of their capabilities that should provide great rewards in scientific understanding of impact cratering on small bodies.

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Laboratory investigations of impact momentum transfer

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Numerous strategies for preventing a collision of a potentially hazardous Near Earth Object (NEO) with the earth are currently discussed. The most mature of all proposed methods is the kinetic impactor approach, potentially suitable for deflection of celestial bodies in the size range 100 – 300 m [1]. The working principle of a kinetic impactor is based on momentum transfer caused by hypervelocity impact to modify the trajectory of a celestial body in a defined manner. Since our understanding of the impact momentum transfer process in rocks stems only from a limited number of small-scale experiments and hydrocode simulations performed in a few laboratories worldwide, artificially created impact events at full scale as planned in the AIDA mission [2] provide a unique opportunity of real-time observation of all impact related phenomena, such as crater formation and ejecta dynamics during hypervelocity impact as well as the impact momentum transfer to the celestial body. From in-situ observation of the impact process and from post-impact measurement of crater morphology and -size in the AIDA mission, eventually conclusions will be drawn concerning the physical and mechanical properties of the impacted celestial body, including the surface and subsurface material properties as well as porosity and structure of the subsurface material. Such an in-depth characterization is critical to correctly anticipate and explain the observed impact phenomena, and requires sub-scale laboratory experiments as an integral part of the whole mission, supporting the mission planning phase, the implementation phase and the post-mission scientific analysis phase.

Crater growth and -morphologies as well as ejecta dynamics have been measured in the NEO-Shield [1] and MEMIN [3] projects for several solid brittle materials, covering a wide range of porosities and material densities. Significant findings from these experiments are reported below.

Hypervelocity impact experiments were conducted on four different target materials. The target materials were selected to cover a wide range of densities ρ and porosities ϕ, ranging from almost non-porous quartzite ($\rho \approx 2.6$ g/cm^3, $\phi \approx 2.9$ %), porous sandstone ($\rho \approx 2.0$ g/cm^3, $\phi \approx 25.3$ %), porous limestone ($\rho \approx 1.8$ g/cm^3, $\phi \approx 31.0$ %) to a highly porous aerated concrete ($\rho \approx 0.4$ g/cm^3, $\phi \approx 87.5$ %). The targets were cubes with edge lengths of 20 cm.

A common feature for rock targets is the cone-shaped ejection (Figure 1, left). The ejecta cone angle can vary significantly depending on the physical properties of the target material. Impact tests revealed that the ejection angle is shallower in porous targets compared to less porous targets [4], [5]. Impacts into highly porous materials such as aerated concrete, do not show a cone-shaped but a rather diffuse ejection behavior [5] (see also Figure 1, right). Furthermore, these experiments show that porosity reduces ejection velocities and produces brighter ejecta.

The morphology and size of the resulting impact crater is also influenced significantly by the target material properties. Figure 2 shows the results of four hypervelocity impact experiments into targets with different porosities [5]. Impact velocities were about 6 km/s, i.e. velocities similar to the planned encounter velocity of the DART impactor spacecraft. The depth-diameter ratio (d/D) of the resulting impact crater increases with growing projectile-target density ratio. Impacts into

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quartzite, having low porosity, generated shallow craters. In contrast, impacts into the aerated concrete, a highly porous material, generated deep and “tube-like” craters [5]. In [6], detailed morphological investigations of the experimental craters are reported. [6], [7] observe that porosity reduces the cratering efficiency, where cratering efficiency is defined as the ratio of target density multiplied with crater volume to the mass of the projectile. For non-porous materials, the product of target density and crater volume equals the ejected mass. For porous materials, where a significant proportion of the crater volume can be formed by compaction of pore space, the ejected mass is smaller.

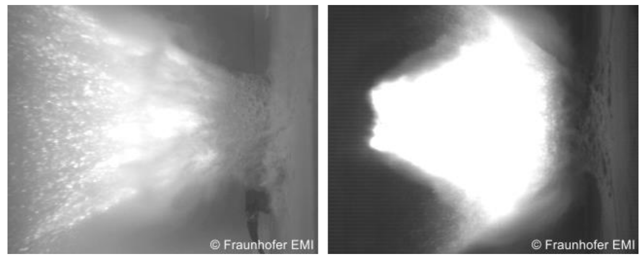

Figure 1: Comparison of the ejecta clouds obtained from impacting a 12 mm steel projectile at a velocity of about 4.7 km/s into non-porous quartzite (left) and porous sandstone (right). Images were taken at the same delay time with regards to the projectile impact. Porous materials like sandstone produce shallower and slower ejection clouds compared to non-porous materials like quartzite. Furthermore, porous materials show brighter ejecta.

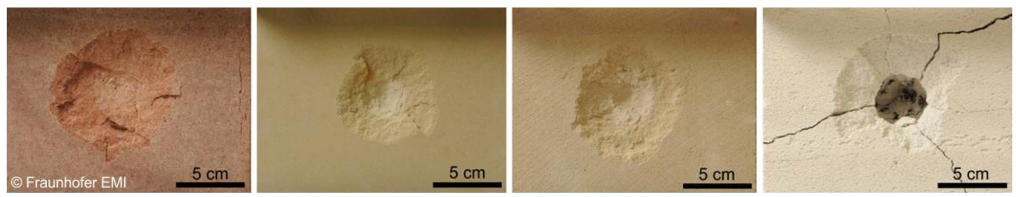

Figure 2: Comparison between four impact craters formed in target materials with different physical properties (quartzite, sandstone, limestone and aerated concrete). Porosity increases from left to right. Aluminium spheres with a diameter of 5 mm were impacted at velocities of ca. 6 km/s.

For precise measurement of the momentum transfer a ballistic pendulum was designed and constructed including a fast-closing valve. Target displacements were measured by means of a laser vibrometer. A high-speed camera was used to investigate the highly transient ejection process. The momentum multiplication factor (the so-called “beta value”, β) is defined as the ratio of the change in target momentum after the impact to the momentum of the projectile. The highest beta values were measured for the low-porous quartzite (e.g., beta ~ 3 for a projectile velocity of about 4.05 m/s). Porous materials like sandstone, on the other hand, show lower beta values (e.g., beta ~ 1.8 for a projectile velocity of about 4.11 km/s). Besides the different amount of ejected mass, the material-specific behavior of β is explained here by the ejection characteristics: Quartzite and sandstone show a cone-shaped, directional ejection (cf. Figure 1, left) whereas limestone and aerated concrete show a diffuse ejection behavior (cf. Figure 1, right). Quartzite shows the highest ejection velocities and the steepest angle of ejection, i.e. the largest normal component with reference to the target surface.

These results show that the kinetic impactor can be a promising method especially for low porous targets due to the large momentum multiplication factor. The deflection performance and the induced ejection effects depend strongly on the asteroid material characteristics. In view of the uncertainty of the composition of asteroids, it shows that experimental studies involving high-performance hypervelocity impact test facilities including various high-speed diagnostics, as well as characterization of material properties are a pre-requisite for understanding and predicting these complex impact processes.

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Laboratory impact experiments at varied gravitational acceleration combined with 3D numerical simulation to determine the effect of a layered target on the efficiency of projectile impacts as a mean for asteroid deflection.

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Most asteroids are either completely composed of relatively poorly consolidated rock fragments (i.e. rubble pile), or have such materials forming a regolith layer that may have substantial thickness relative to the size of the asteroid. During a projectile impact event a porous, unconsolidated target material strongly affects the transfer of kinetic energy and the shock wave propagation, thus greatly influencing the cratering efficiency [1, 2] This is of paramount importance when estimating the effects of an artificial projectile impact to change the trajectory of an asteroid on a collision course with the Earth.

For simplicity, we may here consider the relatively poorly consolidated materials of an asteroid to form a layer, which thickness can vary from being a thin surface layer to comprise the whole asteroid. Pioneering work on the effects of target layering on the cratering process was done by Quaide and Oberbeck [3] in their studies on the lunar regolith thickness, and by Gault and Sonett [4] in experiments with targets including a surface layer of water. The latter was later successfully developed into a method to determine the depth of the target seawater in past marine-target impact events by Valery Shuvalov [e.g. 5] and members of this proposal team [e.g. 6, 7]. The study by Quaide and Oberbeck [3] describes how so-called concentric craters (i.e. craters with a nested, deeper crater in a rigid basement surrounded by a wider, shallow crater in a weaker surface layer) develop in layered targets such as regolith covered lunar basalts.

If the dynamic yield strength of the substrate exceeds the pressure of the shock wave transferred to the substrate then cratering will only occur in the upper layer causing a relatively wide, flat-bottomed crater. When the surface layer is so thin that the energy transmitted to the substrate overcomes its dynamic yield strength a concentric crater develops. Both the crater in the weak layer and the nested crater in the substrate grow simultaneously but the crater in the weaker surface layer grows to a greater size. While much of the kinetic energy of the projectile is released in the upper weak layer, this layer also requires relatively less energy to be cratered, i.e. less energy is consumed by the crushing and melting of rock. Therefore, the crater in the weak layer (e.g. regolith on the Moon or an asteroid) gets relatively wider than a corresponding crater in a homogeneous basement.

The Quaide and Oberbeck model is possibly applicable only to strength dominated cratering. In recent papers team members of this proposal describe how target layering seems to affect also gravity dominated craters on both Earth and Mars [8] and Moon [9]. Gravity dominated craters in rock have not been analysed in detail although they a frequently observed on both Earth and Mars (Ormö et al. 2013). The transition from strength dominated to gravity dominated cratering is a function of the gravitational force of the cratered body, being for the Earth at craters of about 70m diameter, Mars about 130m diameter, and the Moon at about 300-400m diameter, whereas these estimates strongly depend on the actual strength properties of the impacted target. For a 2 km in diameter asteroid the transition crater diameter may be well above the size of the target, giving that all impacts on such small objects would be strength dominated, although for large asteroids such as Vesta the transition diameter allows both strength and gravity dominated cratering. Nevertheless, even in the case of strength dominated substrates, the weak layer consisting of granular cohesion-less material will still be gravity-dominated. Obviously, the cratering process behind the concentric craters with diameters well above the transition size-range must be different from that suggested for the small strength dominated craters in lunar regolith and previous experiments.

Even though strength can be considered of less importance for gravity dominated craters, there will still be differences in the density and the wave speed between the weaker upper layer and the rigid substrate. The product of these two factors is the mechanical impedance of a material. It determines how a shock wave reflects when it hits a boundary between two materials with different densities and wave speeds. Possibly, for large gravity-controlled craters, the differing impedances of the two layers could result in reflection of the shock, with a reduction of the energy transferred into the basement. It may be that it is the wave speed, the density, or the combination of both (i.e. impedance) that is the critical factor. If the kinetic energy is dissipated into a porous, low-strength target it may have the consequence that the necessary magnitude of the artificial impact needs to be significantly greater than anticipated in order to achieve the demanded effect.

Notwithstanding that most cratering on asteroids, and especially of the magnitude of artificial impacts such as DART, will occur in the strength dominated regime, we here propose a project that will aim to determine the influence of a weak and/or low density layer on the kinetic energy transfer in both strength and gravity dominated cratering. The studies will be carried out as projectile impact experiments in the new Laboratory for Experimental Impact Cratering at Centro de Astrobiología (CAB), Spain, and at the centrifuge impact lab of the Boeing Corporation, Seattle, USA. The results will be compared with advanced 3-D numerical simulations performed at the Museum für Naturkunde (MfN), Berlin, Germany, as well as with remote sensing performed at the Jacobs-University, Bremen, Germany, on publicly available data of natural impact craters on low-gravity celestial objects (e.g. asteroids, moons).

The anticipated outcome of the study will be a better assessment on the effects of an artificial impact on an Earth-threatening asteroid in order to change its trajectory.

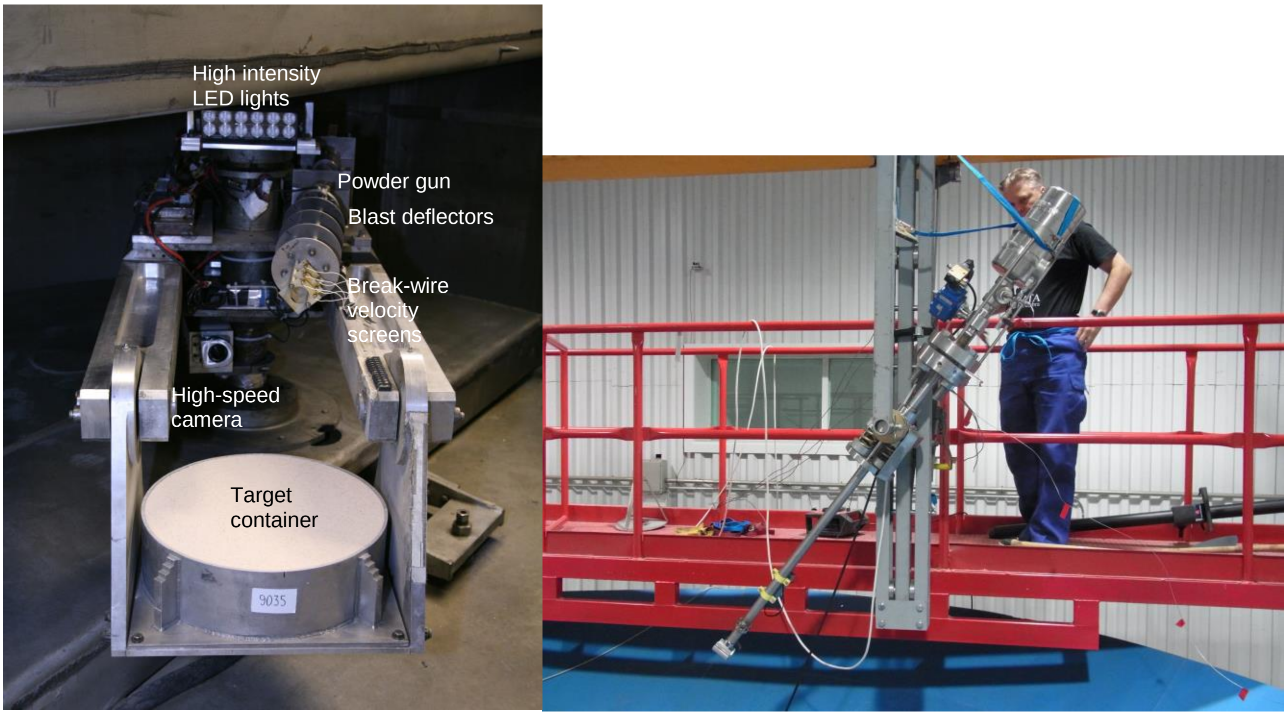

Fig. 1. Left: The Boeing geotechnical centrifuge, Boeing Corp., Seattle, USA. Right: The projectile launcher of the Experimental Projectile Impact Chamber (EPIC) at Centro de Astrobiología (INTA Torrejon de Ardoz), Spain.

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Abstract
AIM Science Meeting, 1-2 March 2016, ESA/ESAC, Villanueva de la Cañada, Madrid, Spain

NEOShield-2

Science and Technology for Near-Earth Object Impact Prevention

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Keywords: Near-Earth object, Asteroid deflection, Impact threat mitigation, Kinetic Impactor, Gravity Tractor, Material sampling, NEO observation and characterisation, NEO simulation and modelling

Abstract

In late 2013 the European Commission issued a call for proposals addressing "access technologies and characterisation for Near Earth Objects (NEOs)", to succeed the activities started by the NEOShield project in 2012. This new call for proposals, in the framework of the Horizon 2020 program, resulted in the granting of funding for the 11-partner NEOShield-2 project for 2.5 years from March 2015.

The project work packages are integrated into a coherent programme of research and technology development. Building on NEOShield experience, the project is investigating in more detail key technologies crucial to space missions to deflect NEOs, including autonomous guidance, navigation, and control systems to allow increased targeting accuracy and relative velocity of a kinetic impactor spacecraft into a small (e.g. 100-300m diameter) asteroid, to facilitate navigation close to a low-gravity, irregularly shaped asteroid, demonstrate techniques for precise and rapid NEO orbit determination, and develop mechanisms for the collection of material samples. Moreover astronomical observations of selected NEOs are being carried out for the purposes of broadening our knowledge of their mitigation-relevant physical properties, concentrating on the smaller sizes of most concern for mitigation purposes, and increasing the list of suitable candidate targets for deflection test missions. On the scientific front, statistical analyses of recently published NEO survey data, which have already been very successful in the course of NEOShield research, are being further explored in NEOShield-2. The current focus is on detailed analyses of relevant individual objects (e.g. potentially hazardous objects) on the basis of published data from different observing techniques (radar, infrared, spectroscopy, etc.) and new data obtained during the course of NEOShield-2. Furthermore, modelling work and computer simulations will be enhanced to explore the effects of large spin rates, shattered and rubble-pile structures, and mineralogy on an object's response to a deflection attempt.

We will present an overview of the NEOShield-2 project and results achieved to date, and provide a brief summary of plans for the future.

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Mission and Asteroid Operations Strategy of the Asteroid Impact Mission

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This paper presents OHB's current mission and asteroid operations strategy for the Asteroid Impact Mission (AIM) as a part of AIDA. The Asteroid Impact & Deflection Assessment (AIDA) mission is an international collaboration of ESA and NASA, with the primary goals to test the ability to perform a spacecraft impact on a near-Earth asteroid and to measure and characterize the deflection caused by the impact. The AIM mission is currently studied in a Phase A/B1 under ESA contract. One of the two parallel industrial studies is lead by OHB System. This paper focuses on the current Phase A mission and local asteroid operations concept for AIM, addressing system design and operational challenges. Special focus is placed on asteroid local operations and the planned payload operation strategy. In addition, the spacecraft navigation performance is presented together with the expectable resources being available to the payloads.

Design and development of the GNC subsystem for the AIM mission

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Guidance Navigation & Control Section
ESA/ESTEC

The challenging mission of AIM puts high demands on the GNC subsystem in terms of performance and reliability, particularly during the close proximity operations phase and during the MASCOT-2 and COPINS release phases.

The Guidance, Navigation and Control Section of ESA has previously developed Guidance, Navigation, and Control techniques for missions to Near Earth Objects (Rosetta, Don Quijote, Marco Polo and Marco Polo-R) addressing several mission types (orbiters, impactors, sample-return probes) and covering all mission phases. The wealth of knowledge that has been accumulated in developing these technologies is an important asset upon which the design of the GNC subsystem for AIM shall be based. This presentation will provide a survey of the GNC techniques developed by ESA in recent years which have a direct application on AIM, in some cases as mission enablers, like vision-based navigation techniques and image processing algorithms.

Equally important in the development and verification of a GNC subsystem is the use of suitable test facilities. The Guidance, Navigation and Control Section of ESA has developed test facilities to incrementally verify (in a rapid prototyping context) Guidance, Navigation, and Control techniques for missions to Near Earth Objects in Model-in-the-Loop (MIL), Processor-in-the-Loop (PIL), and Hardware-in-the-Loop (HIL) test setups. An overview of these facilities, together with their intended use for AIM and with the upgrades currently foreseen will be presented.

The AIM scientific instruments as GNC sensors

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The Asteroid Impact Mission (AIM) is a mission of opportunity which has a very tight cost and schedule constraints. AIM has scientific and technology demonstration objectives. These characteristics convert AIM a one-of-a-kind deep space mission which requires novel approaches for the design, implementation and operations.

The scientific payload includes a Thermal Imager (TIRI), Low and High Frequency Radars, an Optical Communication Terminal (Optel-D), the MASCOT-2 micro-lander, two cubesats (COPINS) and a Visual Camera (VIS) which has a dual use as main navigation sensor.

The proximity operations in the vicinity of the binary asteroid defines the spacecraft Guidance, Navigation and Control system (GNC) and the ground Flight Dynamics System as critical systems for the mission. In particular, the close distance (less then 10 km) required to acquire scientific data of some payloads, and the deployment of MASCOT-2 lander and the cubesats require some degree of autonomy.

Given the tight cost objective, maximum re-use of previous ESA heritage is intended, namely ROSETTA FDS and operations and GNC technology research for Marco Polo and similar missions.

This limits the possible strategies for the proximity operations which in turn reduces the achieved science performances and MASCOT-2 landing success.

In this paper an analysis of the potential improvements in the navigation performances by measurements from the science payload is performed. First a nominal trajectory (Figure 1 and Figure 2) is analysed using baselined GNC technologies (i.e. only the VIS navigation camera). Then the potential benefits introduced by the inclusion of few measurements derived from one payload. The payloads that are considered in this analysis are Optel-D and a radar. TIRI infrared images are also assessed in particular for the MASCOT-2 localization after landing.

Optel-D and radar payloads can provide altimetry measurements but of quite different characteristics. Optel-D terminal can provide LIDAR ranging with narrow beam (orientation of the SC relative to the illuminated body is very demanding), while the radar will provide distance to the narrowest part of the surface. These measurements are properly modelled in a high-fidelity simulator. The distance at which the payloads can provide these measurements as well as their performances are based on preliminary assessments by the payload teams.

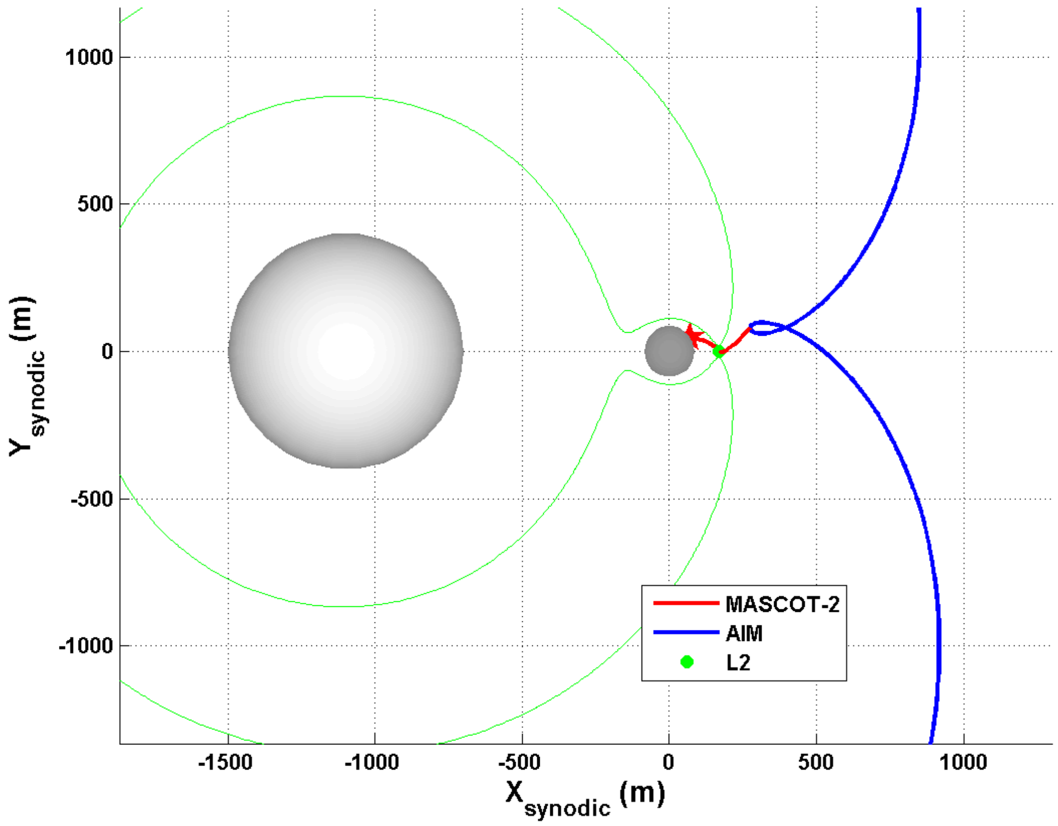

Figure 1 Zoom of the trajectory used to assess the GNC performances in synodic (rotating) frame.

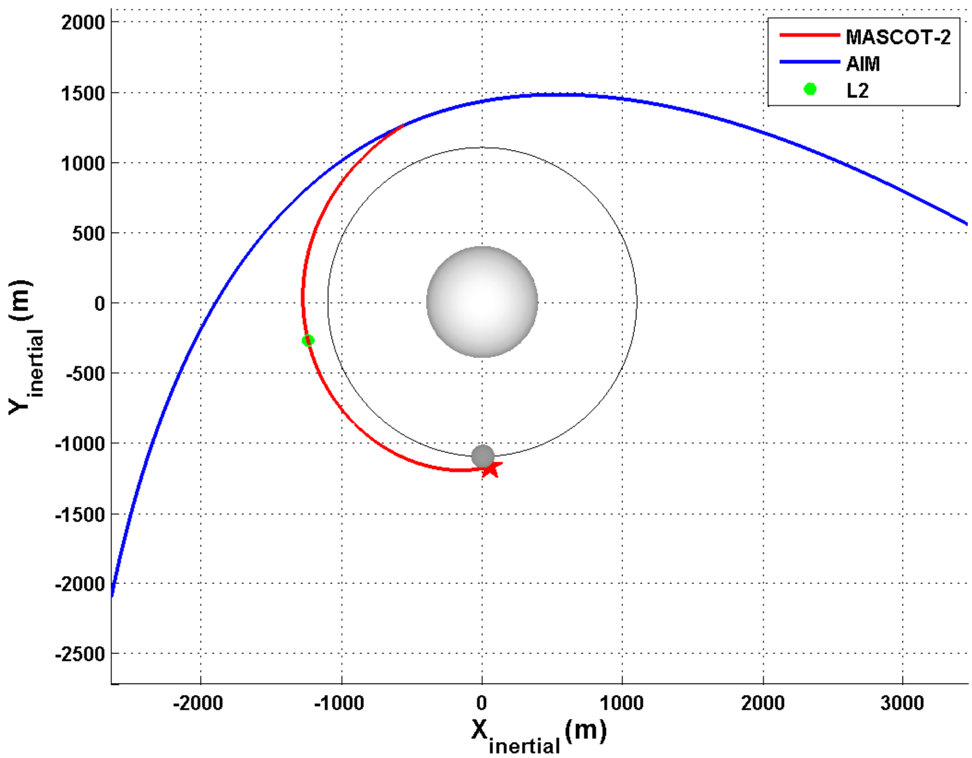

Figure 2 Zoom of the trajectory used to assess the GNC performances in inertial frame.

Asteroid Impact Mission (AIM) Science Meeting, 1-2 March 2016, ESA/ESAC

AIM Autonomous Vision Based GNC

A. Pellacani (GMV, Spain), J. Naudet (QinetiQ Space, Belgium), Matteo Suatoni (GMV, Spain) and Raluca M Stefanescu (GMV, Romania)

1st – 2nd of March 2016

Abstract

The Asteroid Impact Mission (AIM) is a small ESA mission of opportunity which objective is to perform scientific observations of a binary asteroid (Didymos) while demonstrating technologies for future missions and addressing planetary defence.

The distance to the Earth during the proximity operations and the binary system characteristics, together with the expected navigation performance, are the main reasons that push the AIM mission towards a high level of autonomy during critical phases.

Probably one of the main challenges for the AIM mission, is the delivery of the MASCOT-2 lander on the surface of the secondary asteroid. This payload will be released from the AIM spacecraft at a short distance from the surface, requiring advanced and complete on-board autonomy (speaking about Guidance, Navigation and Control algorithms). This can be achieved thanks to vision based navigation that provides high accuracy relative measurements with respect to the asteroid. The presentation will address to the performed work related to this type of navigation, also dealing with the GNC and the FDIR functions needed to have a robust and safe on-board autonomy.

The results of NEOGNC2-NPAL will be presented, which is a AIM parallel activity run by GMV). Its objective has been to perform hardware-in-the-loop (HIL) validation tests with a HW representative of a true navigation camera, the NPAL bread board. The activity also assessed the possibility of re-using the GNC system designed and developed for the Marco-Polo R mission to the AIM mission, showing that the system, once tailored to the specific needs of the mission, is able to fulfil the strict requirements of the AIM mission. HIL tests have been performed in two different facilities at GMV premises. A first validation step has been realized in the HIL optical facility, in which the camera is stimulated through the use of a screen with images generated by a rendering SW (PANGU). A last step has been performed in the HIL robotic facility, in which the camera is stimulated by a real scene of an asteroid mock-up and the kinematic and illumination conditions of the scenario are provided by the motion of robotic arms. The HIL validation results showed that the performances obtained in the HIL tests are really consistent with the ones expected from the model-in-the-loop (MIL) validation, thus demonstrating that the GNC system (including the image processing) is robust to the use of a space-representative navigation camera.

Also the preliminary outputs of DAFUS (ongoing AIM parallel activity run by GMV Romania) will be given. Its objective is the development and testing of new GNC and FDIR algorithms that may be included in the AIM mission. The scare equipment available on-board forces some innovative data fusion strategies in order to perform the GNC tasks to achieve the mission objectives and for the FDIR to perform independent validation of the GNC performances and assure safety of the operations (e.g. identify collision risk and

perform collision avoidance manoeuvre). The inclusion of sensors like the thermal camera and the laser altimeter in the GNC or FDIR chain will be tested to assess its impact on the navigation performances and robustness, giving valuable input to AIM. Indeed, in the current baseline the most challenging aspect of the MASCOT-2 release is the lack of a direct range measurement available for the nominal GNC loop due to mass/budget trade-off (and low TRL level of on-board instruments which are considered experiments). This strategy requires an accurate navigation initialization from ground and a reduced autonomous phase not to accumulate a significant navigation error that may jeopardize the MASCOT-2 landing conditions.

Mobile Asteroid Surface Scout (MASCOT-2) for the AIM Mission

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and the MASCOT-2 Study Team

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MASCOT-2 is a small (~10kg) surface package, delivered by the AIM spacecraft onto Didymoon, the secondary object in the (65803) Didymos binary near-Earth asteroid system.

The design of MASCOT-2 is based on the MASCOT lander onboard the Japanese (JAXA) Hayabusa2 Mission to the near-Earth asteroid (162173) Ryugu [1,2]. Hayabusa2 was launched in December 2014. Equipped with a mobility mechanism, MASCOT-2 (as MASCOT) is able to upright and relocate on the targeted asteroid; thus providing in-situ data at more than one site.

The payload of MASCOT-2 consists of four scientific instruments:

- a low frequency radar (LFR), based on CONSERT, a similar instrument of Rosetta/Philae, to characterize the internal structure and porosity of Didymoon [3]
- a Camera (CAM, identical [tbc] to the one aboard MASCOT) to image the near surrounding of the lander with up to sub-mm resolution [4]
- a radiometer (MARA, identical [tbc] to the one aboard MASCOT) determining the thermal properties of the asteroid surface material in the vicinity of the lander and
- a set of accelerometers (DACC) to characterize surface properties of the asteroid by determining the bouncing of the lander after delivery or during mobility activation, respectively.

It is currently foreseen to deliver MASCOT-2 prior to the DART impact to the surface of Didymoon, allowing the characterization of possible changes of the moons physical properties [5]. The lander will be equipped with a solar generator that shall allow long term operations.

The scenario, to land on such a small (low gravity) object as Didymoon in the dynamic gravitational environment of a binary asteroid requires a sophisticated delivery strategy, unprecedented for any lander mission so far.

The paper will summarize science objectives and the status of the development study.

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A DIRECT OBSERVATION OF THE ASTEROID'S STRUCTURE FROM DEEP INTERIOR TO REGOLITH: TWO RADARS ON THE AIM MISSION

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The internal structure of asteroids is still poorly known and has never been measured directly. Our knowledge is relying entirely on inferences from remote sensing observations of the surface and theoretical modeling. Is the body a monolithic piece of rock or a rubble-pile, an aggregate of boulders held together by gravity and how much porosity it contains, both in the form of micro-scale or macro-scale porosity? What is the typical size of the constituent blocs? Are these blocs homogeneous or heterogeneous? The body is covered by a regolith whose properties remain largely unknown in term of depth, size distribution and spatial variation. Is it resulting from fine particles re-accretion or from thermal fracturing? What are its coherent forces? How to model its thermal conductivity, while this parameter is so important to estimate Yarkowsky and Yorp effects?

After several asteroid orbiting missions, theses crucial and yet basic questions remain open. Direct measurements of asteroid deep interior and regolith structure are needed to better understand the asteroid accretion and dynamical evolution and to provide answers that will directly improve our ability to understand and model the mechanisms driving Near Earth Asteroids (NEA) deflection and other risk mitigation techniques. There is no way to determine this from ground-based observation. Radar operating from a spacecraft is the only technique capable of achieving this science objec-tive of characterizing the internal structure and heterogeneity from submetric to global scale for the benefit of science as well as for planetary defence or exploration [1].

Low Frequency Radar: The deep interior structure tomography requires low-frequency radar to penetrate throughout the complete body. The radar wave propagation delay and the received power are related to the complex dielectric permittivity (i.e to the composition and microporosity) and the small scale heterogeneities (scattering losses) while the spatial variation of the signal and the multiple paths provide information on the presence of heterogeneities (variations in composition or porosity), layers, ice lens. A partial coverage will provide "cuts" of the body when a dense coverage will allow a complete tomography. Two instruments concepts can be considered: a monostatic radar like Marsis/Mars Express (ESA) that will analyze radar waves transmitted by the orbiter and received after reflection by the asteroid, its surface and its internal structures; a bistatic radar like Consert/Rosetta (ESA) [2],[3] that will analyze radar waves transmitted by a lander, propagated through the body and received by the orbiter. Monostatic radar requires very low frequencies in the range 10 to 20 MHz necessitating the use of large antennas and is more consuming in term of mission resources (mass, data flow), driving all the mission specification. On the other hand, bistatic radar can use slightly higher frequencies in the range 60-90 MHz, simplifying the accommodation on mission carrying a surface package. This concept is fully compliant with medium class planetary missions.

Hight Frequency Radar: Imaging the first tens meters of the subsurface with a metric resolution to identify layering and to reconnect surface measurements to internal structure can be achieved with a higher frequency radar on Orbiter only with a 300MHz – 800MHz frequency range typically.

An enlarged frequency range up to 3GHz, like the WISDOM radar designed and developed for the ESA ExoMars 2018 Rover mission [4] adds valuable science return contributing into the shape modeling, mass estimation, orbital parameters determination or close asteroid navigation with an altimeter mode.

AIM Mission: Bistatic tomography radar and high frequency radar are presently under phase A/B1 study in the frame of the ESA's Asteroid Impact Monitoring mission. AIM as a stand-alone mission or constituting the Asteroid Imact & Deflection Assessment (AIDA) with the Double Asteroid Redirection Test (DART) mission under study by APL is a mission to characterize "Didymoon", the secondary of the binary NEA Didymos and to contribute to the evaluation of impact mitigation strategies [5],[6].

AIM will carry Mascot2, a lander inheriting from Mascot/Hayabusa2 [6] to land on Didymoon. On Mascot2 and AIM, the bistatic will porbe the Didymoon's internal structure, with a typical resolution of 30 meters to characterize the structural homogeneity in order to discriminate monolithic structure vs. building blocks, to derive the possible presence of various constituting blocks and to derive an estimate of the average complex dielectric permittivity, which relates to the mineralogy and porosity of the constituting material. Assuming a full 3D coverage of the body, the radar will determine Didymoon's 3D structure: deep layering, spatial variability of the density, of the block size distribution, of the average permittivity.

When AIM is combined with DART, the bistatic experiment will characterize possible structural modification induced by DART impact. It will also support mass determination and orbit characterization with range measurements during and after descent. Finally, it will contribute to the characterization of the primary (called "Didymain").

On AIM mothership, the shallow subsurface radar will determine the structure and layering of Didymoon and Didymain shallow sub-surface down to a few meters with a metric resolution and will map spatial variation of the regolith texture which is related to the size and mineralogy of the constituting grains and macro-porosity and spatial distribution of geomorphological elements (rocks, boulders, etc) that are embedded in the subsurface.

With DART, it is a key instrument to assess the regolith tomography before and after impact in order to characterize the crater topography, the internal structure modifications and the mass loss. Then it is also a monitoring of the impact ejecta generated by the collision of the DART spacecraft in the vicinity of the secondary asteroid in order to estimate size distribution, speed, and total mass.

It will also contribute to shape modeling, mass determination and orbital characterization with altimeter mode. And finally, more prospective objectives will be considered, such as the support to ground-based radar measurements like Arecibo or Goldstone: orbital radar measurement is indeed a unique opportunity to cross-validate ground-based NEA characterization with radar signal in the same frequency range and with better resolution, better SNR and more favorable geometry.

	HFR	LFR
Target	Regolith	Deep interior
Radar	Monostatic	Bistatic with Mascot
Signal	Step Frequency	BPSK
Heritage	WISDOM / Exomars	CONSERT / Rosetta
Wave propagation	Reflection/Scattering	Transmission
Antenna	Vivaldi	Dipoles
Tx Polarization	circular	Linear
Rx Polarization	2 linear	Circular
Penetration (m)	10 to 20	170
Resolution (m)	~2	15 - 30
Nom. BW (MHz)	300-800	50-70
Ext.. BW (MHz)	300-2500	45-75
PRF (Hz)	0.5-5	0.1-0.3
Step durat. (µs)	60	0.05
Integration	3000	261120
Tx Power (W)	20	16
Primary pow (W)	88	10 (each unit)
data rate (kbit/s)	300	5

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Taking AIM at asteroids in the thermal infrared

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Abstract

A thermal infrared imager system is one of the interments planned for the the AIM spacecraft of the AIDA mission. This instrument – described in accompanying abstracts by Bowles/Licandro – is sensitive to the surface temperatures of the asteroid and can be used to discriminate between different possible surface properties of the primary and of the secondary component of the Didymos asteroid system.

In this presentation, I will describe how analysis of thermal infrared data by means of asteroid thermophysical models [1] can be used to discriminate between bare rock versus granular or dusty surfaces. A key parameter for these studies the measurement of the value of the thermal inertia of the surface.

I will also present intriguing results suggesting that binary near-Earth asteroids have higher thermal inertia than non binary systems [2], and the what we can learn from these findings about the formation mechanism(s) of small binary asteroids.

I will also detail how thermal properties of the asteroid surface are important to the characterisation of the soil structure and cohesion, and those how these properties determine thermal effects on the orbital and spin state evolution of asteroids, such as the Yarkovsky and the YORP effects, respectively.

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Design concepts and options for the Thermal Infrared Imager (TIRI) as part of ESA's Asteroid Impact Mission.

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ESA's Asteroid Impact Mission (AIM) is being studied as part of the joint ESA/NASA AIDA mission for launch in 2020. AIDA's primary mission is to investigate the effect of a kinetic impactor on the secondary component of the binary asteroid 65803 Didymos in late 2022. AIM will characterise the Didymos system and monitor the response of the binary system to the impact.

A multi-spectral, thermal-infrared imaging instrument (TIRI) will be an essential component of AIM's remote sensing payload, as it will provide key information on the nature of the surfaces (e.g. presence or absence of materials, degree of compaction, and rock abundance of the regolith) of both components in the Didymos system. The temperature maps provided by TIRI will be important for navigation by allowing imaging of the night side of the asteroid and spacecraft health and safety during surface proximity/lander operations. By measuring the asteroids' diurnal thermal responses (thermal inertia) and their surface compositions via spectral signatures, TIRI will provide information on the origin and evolution of the binary system.

Due to the difference in the expected rotation rates between the primary (2.26 h) and the secondary (likely to be synchronous with its orbital period of 11.9 h, Scheirich and Pravec, 2009) objects thermal modelling (after Delbo et al., 2015) shows that the night-time surface on the Didymos moon can be lower than 150 K even for equatorial regions. Mapping these potentially low surface temperatures (<150 K) on the secondary are one of the key design challenges for the TIRI instrument.

In this presentation we will discuss possible instrument designs for TIRI, exploring options that include imaging spectroscopy to broadband imaging. By using thermal models and compositional analogues of the Didymos system we will show how the performance of each design option compares to the wider scientific goals of the AIDA/AIM mission.

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OPTEL-D System Description, Auxiliary Functions and Key Parameters

A preliminary system architecture of the Direct-to-Earth (DTE) lasercom solution is presented. It comprises the ground segment and a payload terminal named “OPTEL-D” in space segment. Expected temporal variations of optical signal amplitudes and corresponding distribution statistics, as well as atmospheric channel attenuation are shown.

The functional architecture of the OPTEL-D space terminal provides generic features that provide laser communications downlink solutions for a variety of deep space missions. Hence the AIM mission provides the possibility to flight-qualify a deep space laser communications system that allows utilization on other deep space missions as well.
In this context, an outlook to key performance parameters of a potential extension to a proximity Lidar and to an imaging camera in the NIR band (for 1064nm) is presented.

AN EMISSION SPECTROMETER, AND OTHER INSTRUMENTS FORMING PART OF *AIM-PALS* PAYLOAD TO STUDY *DART* SPACECRAFT IMPACT IN ASTEROID 65803 DIDYMOS' SATELLITE.

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Introduction: The *Asteroid Impact & Deflection Assessment (AIDA)* mission is a joint project of ESA and NASA conceived to quantify how a kinetic impactor can deflect a small asteroid and to characterize its physical properties. *AIDA* is composed of the projectile called *DART* (Double Asteroid Redirection Test) and an observer satellite called *AIM* (Asteroid Impact Mission), each under study by NASA and ESA, respectively.The combination of both spacecrafts is referred to as AIDA. As in the separate *DART* and *AIM* studies, the target of this mission is the binary asteroid system (65803) Didymos. There is no doubt that this join effort is conceived as a technological challenge that can demonstrate the utility of new scientific approaches. Being *AIM* conceived as a technology demonstration mission, it will offer the possibility of testing various technologies and techniques needed to better understand the physical properties and composition of near-Earth Asteroids (NEAs). A key point of *AIM* mission is the interest for using CubeSats in order to act as platforms for carrying advanced payloads and test intersatellite links in deep space.

The two cameras outlined here are part of the Payload for *Advanced Little Satellites (PALS)* proposal answering AIM-COPINS ESA call. *PALS* is leaded by a group of planetary and asteroid scientists from the Swedish Institute of Space Physics, the Institute of Space Sciences (IEEC-CSIC) in Spain and the Royal Institute of Technology in Sweden. We have designed a deep space exploration mission where the unique capabilities of two 3U CubeSats are exploited to the limits in order to obtain close range measurements of the two bodies constituting the Didymos binary asteroid system. The Cubesats that carry two imagers, a double fluxgate magnetometer (*MAG*) and a Volatile Composition Analyser (*VCA*) will be carried to the Didymos system by the ESA AIM (Asteroid Impact Mission) where they will be ejected for proximity operations in the asteroid sphere of influence. The CubeSats will operate closer to the asteroids than the AIM spacecraft can, and this can result in a complementary and unique scientific outcome. We focus here in the scientific interest behind the development of a narrow angle camera (*NAC*) and the video emission spectrometer (*VES*) to provide new insight into the physics and chemical consequences of *DART* impact, and subsequent crater excavation, in Didymos satellite (hereafter refered as Didymoon).

We focus here in discussing the scientific relevance of operating a high-resolution camera and an emission spectrometer at close range of Didymoon. With these experiments, we wish to gain insight into the high-speed impact, the associated impact plume and the magnetic environment of the asteroid before and after the impact. We have three main goals: 1) To provide an additional camera perspective of the impact in order to investigate the collision and plume development with the added value of calibrating the luminous efficiency with the camera on board the spacecraft, 2) to get a better understanding of plasma physics associated with the evolving plume, and 3) to get measurable information about the temperature and chemical composition of the hot gas produced by *DART* spacecraft impact into Didymoon's surface.

Proposed Instruments: A general outline of the instruments proposed to be onboard the two proposed PALS CubeSats are:

- *NAC* will provide a high resolution mapping of the secondary asteroid of Didymos system at a cm-sized resolution in which the regolith can be characterized. This can be achieved thank to the close range in which we expect to image Didymoon (about 100 m). Additional observations of the NASA DART (Dual Asteroid Redirect Test) impact from second and third vantage points can provide significant insight in the evolution of the impact plume.

- *VES* will provide a video sequence up to 30 frames/s of the impact flare. Light emitted from the impact site will be mostly provenant from the hot gas produced by the quick evaporation of the target and projectile (impacting at ~6 km/s). Spectral measurements on the ejecta temperature and derivation of bulk chemical composition of the gas will be achieved by using the camera as emission spectrometer. A diffraction grating will disperse the light in the different emission lines associated with each element multiplet [see e.g. 2-3]. From the sequential data we will try to decipher how these lines contribute to the luminous efficiency, found to be quite small (10^{-4} to 10^{-5}) in laboratory impacts into silicate targets [4]. The spectrometer will provide a medium resolution (~3 nm/pixel) spectrum of the impact flare, but also from the evolving plume as a function of time (frame to frame sensor detection). IEEC-CSIC has expertise in the development of such camera systems in the framework of the SPMN network [5-8]. Having *VES* a wide field lens, we don't need directionality, but only the camera side orientated to the asteroid target at the time of the impact. The spectra will be extracted from the images in order to provide the emission lines of the main rock-forming elements. Therefore, we expect to get data on Didymoon bulk chemistry, by analyzing the light coming from the impact-released hot gas, and the chemical evolution of the plume (see e.g. experiments described by Schultz et al. [1]). From the sequential spectra additional clues will be obtained about the fraction of vaporized target and projectile, and the amount of non-thermal radiation released after the impact by hot particles. Most of the dust released at high temperature will contribute to the spectrum as background. By measuring that component we could get clues about the mass fraction vaporized that is related with our ability to deflect the target. The presence of volatiles in Didymoon surface, perhaps implanted by micrometeorite impacts, could be also inferred by elemental overabundance or molecular bands noticeable in the spectra if the amount is significant.

- *MAG* will provide information about possible magnetization and metallic content of asteroids by measures of their magnetic environment. These measurements will be carried out during approaching to the double system then before and after impact in close orbits to the main asteroid body and its moon. Two sensors mounted on one deployable boom will be used to eliminate influence of residual magnetization of the CubeSat giving possibility for very low magnetic field registration. The scientific goals are characterization of the intrinsic magnetization of D1 and D2 and the solar wind interaction with asteroids magnetic fields and with the impact plume.

- *VCA* will provide a continuous, lower resolution, ambient ion measurements in the vicinity of the binary system, also informing about the presence of subsurface volatiles and solar wind interaction.

Instrument	Goals
Narrow Angle Camera (NAC)	Close range imaging, regolith characterization, impact ejecta, etc..
Video emission spectrometer (VES)	Emission spectra, luminous efficiency
Double flux-gate magnetoemter (MAG)	Magnetic environment and asteroid properties
Volatile Composition Analyser (VCA)	Sub-surface properties

Table 1. AIM-PALS payload described in the text.

Discusion and conclusions:

The complexity of *AIM-COPINS* mission lies in the diverse payloads as well as operating at far ranges from the Earth inside the sphere of influence of a low gravity system places challenges on the CubeSat designs. Our *AIM-PALS* CubeSats are designed for high autonomy and high reliability by ÅAC Microtec with a preference for state-of-the-art equipment and packaging technology where minimum form factor and high reliability avionics are necessary. The spacecraft will communicate with Earth through the AIM spacecraft and possibly also use the main spacecraft for positioning in the dual asteroid system. The DLR, the German Space Agency are responsible for mission analysis and for preparing a conceptual attitude and orbit control system design that can operate the spacecraft in the challenging environment

The studies to be performed by the two envisioned cameras onboard the AIM-PALS mission will provide a significant scientific outcome in our knowledge about crater excavation and momentum transfer to gain insight in impact physics. Both issues are relevant in a key aspect as asteroid deflection. NAC can provide a high resolution mapping of the secondary asteroid of the system at a cm-sized resolution in which the regolith can be characterized. Observation of the NASA DART impact from second and third vantage points can provide significant insight in the evolution of the impact plume. On the other hand, VES spectral measurements on the ejecta temperature and composition from the impact by using emission spectroscopy can provide additional insight on the physical mechanisms at work in light production [7]. *MAG* and *VCA* instruments will also provide unique information about Didymoon after *DART* impact. Consequently, a successful *AIM-PALS* mission will nicely complement *AIM* goals, and enhance significantly our understanding of the asteroids in general and Didymos in particular.

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The Asteroid Geophysical Explorer (AGEX); Proposal to explore Didymos System using Cubesats.

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We present a novel concept for ESA's CubeSat Opportunity Payload Intersatellite Network Sensors (COPINS) planned to be deployed from the ESA AIM spacecraft at the Didymos System: the Asteroid Geophysical Explorer (AGEX). AGEX includes two 3-U CubeSats with geophysical packages that will land on the surface of the secondary; Didymoon. These geophysical packages will work in synergy on the secondary's surface to fulfil a rich set of scientific and technological mission goals. This includes the measurement of mass during the ballistic descent, and determination of dynamical state, local gravity, geophysical surface properties and sub-surface structure following the landing. As a secondary objective, the assessment of the DART impact on the asteroid dynamical properties will be performed. AGEX will help AIM to meet its science and technology objectives, and will demonstrate the benefits of the deployment of a network of sensors while simultaneously developing technology of relevance to future ESA missions.

ASPECT SPECTRAL IMAGING SATELLITE PROPOSAL TO AIDA/AIM CUBESAT PAYLOAD. T. Kohout[1, 2], A. Näsilä[3], T. Tikka[4], A. Penttilä[1], K. Muinonen[1, 5], A. Kestilä[4], M. Granvik[1], E. Kallio[3], [1]Department of Physics, University of Helsinki, Finland (tomas.kohout@helsinki.fi), [2]Institute of Geology, The Czech Academy of Sciences, Prague, Czech Republic, [3]VTT Technical Research Centre of Finland, Espoo, Finland, [4]Aalto University, Espoo, Finland, [5] Finnish Geospatial Research Institute, Masala, Finland.

Introduction: ASPECT (Asteroid Spectral Imaging Mission) is a part of AIDA/AIM project and aims to study the composition of the Didymos binary asteroid and the effects of space weathering and shock metamorphism in order to gain understanding of the formation and evolution of the Solar System.

AIDA mission: The joint ESA/NASA AIDA (Asteroid Impact & Deflection Assessment) mission to binary asteroid Didymos consists of AIM (Asteroid Impact Mission, ESA) and DART (Double Asteroid Redirection Test, NASA). DART is targeted to impact Didymos secondary component (Didymoon) and serve as a kinetic impactor to demonstrate deflection of potentially hazardous asteroids. AIM will serve as an observational spacecraft to evaluate the effects of the impact and resulting changes in the Didymos dynamic parameters.

ASPECT mission: The AIM mission will also carry two CubeSat miniaturized satellites, released in Didymoon proximity. This arrangement opens up a possibility for secondary scientific experiments. ASPECT is one of the proposed CubeSat payloads.

ASPECT objectives: Whereas Didymos is a space-weathered binary asteroid, the DART impactor is expected to produce a crater and excavate fresh material from the secondary component (Didymoon). Spectral comparison of the mature surface to the freshly exposed material will allow to directly determine space weathering effects. It will be also possible to study spectral shock effects within the impact crater.

ASPECT will also demonstrate for the first time the joint spacecraft – CubeSat operations in asteroid proximity and miniature spectral imager operation in deep-space environment.

Science objectives:

- Study of the surface composition of the Didymos system.
- Photometric observations (and modeling) under varying phase angle and distance.
- Study of space weathering effects on asteroids (comparison of mature / freshly exposed material).
- Study of shock effects (spectral properties of crater interior).
- Observations during the DART impact.

Engineering objectives:

- Demonstration of CubeSat semi-autonomous operations in deep space environment.
- Navigation in the vicinity of a binary asteroid.
- Demonstration of a satellite survival during impact.
- Demonstration of joint spacecraft – CubeSat operations.

ASPECT configuration: ASPECT is a 3U CubeSat (size of 3 units, Fig. 1) equipped with a spectral imager from 500 nm to 1600 nm (spatial resolution < 2 m, spectral resolution 10 – 30 nm; VIS channel 512 x 512 pixels, NIR channel 256 x 256 pixels), and a non-imaging spectrometer from 1600 – 2500 nm. The design is based on the Aalto-1 CubeSat Spectral Imager heritage. ASPECT will also demonstrate the capabilities of a CubeSat and a miniature spectral imager for the first time in deep-space environment.

Acknowledgements: This work is done under SysNova: R&D Studies Competition for Innovation contract with ESA.

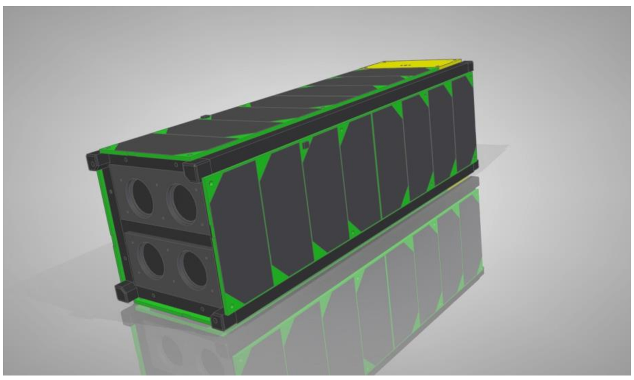

Fig. 1. Proposed ASPECT CubeSat.

CUBATA – Cubesat mission for Asteroid characterisation in collaboration with AIM

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Abstract

CUBATA (CUBesat At Target Asteroid) is a cubesat based mission to be flown in combination with the AIM (Asteroid Impact Mission) mission within the AIDA (Asteroid Impact & Deflection Assessment) ESA-NASA joint mission. It is composed by two 3U cubesats to be released by AIM spacecraft in the vicinity of the Didymos system. The main objective of the mission is to determine the gravity field of the Didymos system before and after the impact by means of Doppler measurements and to observe the impact at close range with a visual camera.

Cubesats have demonstrated to be an inexpensive and easy way to reach space and have been mostly used for educational purposes, technology demonstration and scientific investigations. Till now, Cubesat have been Earth bounded missions, with a limited number of proposals being made for outer space missions. AIM is offering the first opportunity in Europe to expand the range of utilisation of cubesat technologies to deep space missions with scientific applications. In this context, the goal of the CUBATA mission is to complement the scientific objectives of AIM with it is own measurements so the overall value of the combined mission is increased with a minimum impact on the nominal mission.

The main objective of the mission is to determine the gravity field of the Didymos system. In order to achieve this goal, Doppler measurements will be done between the spacecraft. To this purpose a very good time reference and coherent transponder will be required, becoming the main payload for the mission. Given the constraints of the mission in terms of schedule, integration of existing units is the preferred option vs development of components for the payload. A further constraint comes from the platform in terms of size, power and mas available for the system. This limits the choice of time references to Mini Ultra Stable Oscillators, usually based on OCXO technology.

The goal is to have a system with an Allan deviation in the order of 10^{-12} at integration times of 1000s. This will provide enough sensitivity to determine with a very good accuracy the main gravitational parameters of the main body (GM, J2 and J3) and possible the GM of moon of Dydimos.

		Gm_{main}	J_2	J_3	GM_{moon}
Expected Accuracies	**Best**	0.03%	0.2%	0.7%	0.7%
	Worse	2%	10%	35%	36%

Table 1: Expected performances

In order to generate the measurements, the cubesat will need to be inserted in an orbit around the asteroid with an altitude as low as possible. Given the limited capabilities of the spacecraft and the operational constraints (response time), inherently safe orbits will need to be selected, leading to Sun Synchronous Terminator Orbits with semi major axis ranging from 1.5 to 3 km. the duration of the observation period is expected to be one month prior to the impact and one month after the impact of DART.

Few days before the impact the cubesats will be transferred to the impact observation orbit from where the impact and its ejecta cloud will be analysed by means of a miniaturised optical camera from two different locations. This camera will also be the main navigation sensor during the mission.

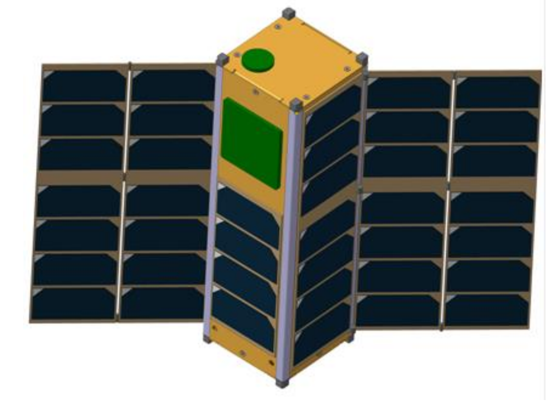

Figure 1: CUBATA spacecraft

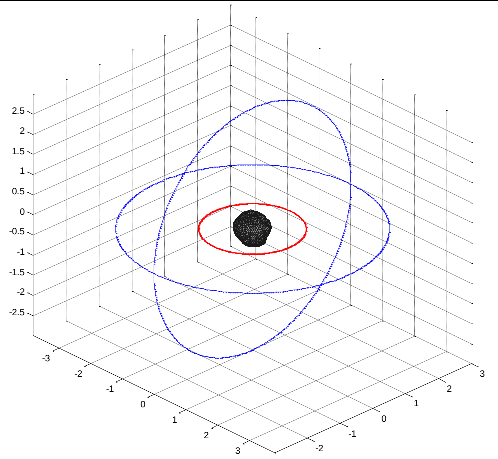

Figure 2: Possible orbits around Didymos

Asteroid Impact Mission (AIM) Science Meeting
1-2 March 2016, ESA/ESAC

Didymos System Gravity Field Reconstruction and DART Impact Characterization with COPINS Radio Science Experiment

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ABSTRACT

The Asteroid Impact and Deflection Assessment (AIDA) joint mission has been conceived to both study the binary asteroid system 65803 Didymos, and test whether an impacting spacecraft could successfully deflect a hazardous asteroid, virtually on a collision course with the Earth. NASA DART spacecraft will impact the asteroid's moon in 2022, whereas the Asteroid Impact Mission (AIM), currently under study by ESA, will perform asteroid science, prior and after the impact.

In the context of AIM study, the CubeSat Opportunity Payload Intersatellite Network Sensors (COPINS) is a payload made up by a set of 2 CubeSat (up to 3U each) which exploits an intersatellite link with the AIM main spacecraft for communications and to transmit basic telemetry and sensor data.

In the frame of the Cubata Sysnova ESA Study, of which the company GMV is the prime contractor, a radio science experiment has been conceived, with the following scientific objectives:

- Determine the gravity field of the Didymos system;
- Determine the orbital change of the moonlet after DART impact.

The estimation of the masses and gravity field of the Didymos system will be attained by means of space-to-space Doppler tracking. The two cubesats will be tracked alternatively in a coherent, two-way mode, from the AIM spacecraft, by means of a dedicated inter-satellite link, in S or L band. Alternatively, a cubesat-to-cubesat link may also be implemented, depending on the best scientific return. The transmitting and receiving antennas for the inter-satellite link can be nearly isotropic, given the small relative distance between AIM and each cubesat. This avoids pointing issues and has only loose requirements on the attitude reconstruction.

In order to perform accurate space-to-space Doppler tracking, an on-board Ultra Stable Oscillator (USO) is required. However, its frequency stability is not critical, because the very small two-way light time of the tracking line of sight ensures a high level of correlation between the jitter of the received signal and the one of the frequency reference, at much higher time scales than the round-trip light time. Thus an effective cancellation of frequency instabilities occurs and the expected two-way range rate accuracy is much better than 0.4 mm/s with integration time of 1000 s (corresponding to an Allan deviation of 10^{-12} @ 1000 s).

The performances of the gravity field experiment are assessed, exploring different orbit geometries for the two cubesats, and considering a baseline experiment duration of 4 weeks

before the impact and 4 weeks after. The selected orbital scenarios to evaluate the performances of gravity field reconstruction are the following:

1. The two cubesats lie in the same circular nearly polar orbit on Sun terminator, with a nominal constant difference in anomaly;
2. The two cubesats lie in two different orbits, which share all the orbital parameters except the inclination.

The performances with AIM-to-cubesat or cubesat-to-cubesat line of sight for Doppler tracking are evaluated for both scenarios.

The deployment of the two cubesats allows to estimate the gravity field of the major body of Didymos system (at least the degree 3 spherical harmonics are expected to be recovered), the gravitational parameter of the moonlet, and to determine the variation of moonlet's orbit after the impact with DART. The last quantity is related to the effectiveness of the momentum transfer during the impact and it will contribute, together with the data from on-board camera, to the characterization of the ejecta after DART impact.

The dynamical model of the two cubesats include the gravitational effect due to the main asteroid and its gravity field, to the required degree of spherical harmonics expansion, the point mass attraction due to the moonlet, the solar radiation pressure, and the third body effect of relevant solar system planets.

VISTA, a thermogravimeter to measure dust and volatile from Dydimos

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VISTA is a miniaturized thermogravimeter able to detect and analyze material (dust and water vapor) emitted from the asteroids.
The instrument is based on a Piezoelectric Crystal Microbalances (PCM) - see Figure 1 -, oscillating at a resonant frequency linearly depending on the mass deposited on its sensible area. PCM can be locally heated/cooled allowing the ThermoGravimetric Analysis (TGA).
TGA measures the change in mass of a sample as a function of temperature and time and can characterize materials that exhibit weight loss or gain due to kinetic processes, mainly decomposition, oxidation or dehydration.

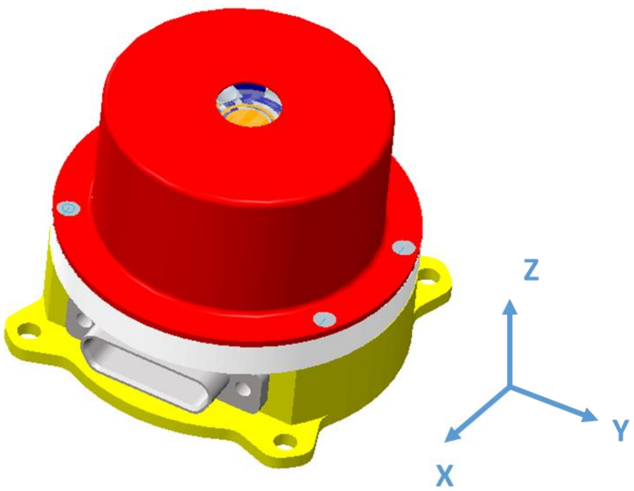

Figure 1. Design of the VISTA Engineering Model

VISTA is composed of two sensor heads, including the PCM and related Proximity Electronics. Each VISTA PCM is equipped with two built-in resistors, whose resistance is a linear function of temperature: the first one acts as temperature sensor, i.e. allows inferring the crystal temperature from a resistance measurement (Palomba et al. 2015), whereas the second one acts as heater, i.e. heats the crystal when a voltage is applied.
Proximity Electronics include an oscillator circuit, which reads the PCM frequency, and a temperature-readout circuit, which allows reading the temperature of the crystal, by means of the built-in resistor.
The two sensor heads include two different types of PCM:

• a Quartz PCM for VISTA sensor head 1 (SH1), in order to perform measurements at low temperatures

• a GaPO4 PCM for VISTA sensor head 2 (SH2), in order to perform measurements at high temperatures.

The Main Electronics Unit, including a DC-DC converter, an A/D converter, a serial bus interface and a memory to store data, can be shared with other sensors of the scientific package.

In the AIM scenario, the VISTA main goals are:

1. to monitor the flux emitted from the asteroid (i.e. plume) temporally, in terms of fine dust (i.e. size lower than 10 μm) and water vapour (VISTA Sensor Head1)
2. measure the volatile (e.g. water and organics) content in the dust emitted (VISTA Sensor Head2)
3. monitor the spatial distribution of the plume, by combining SH1 and SH2 measurements.

It is expected to observe a low flux before the impact, which would be caused by material loss from asteroids due to a fast rotational state or to a possible cometary activity. It is not expected to observe water emission in this phase, due to the low presence of water ice on the NEA surface. After the impact water ice possibly stored in the subsurface can be released and measured, allowing providing useful information about the subsurface composition.

The measurement of volatile amount of the asteroid dust will allow obtaining information about the possible presence of pristine and/or carbonaceous chondrites materials, such as water and organics, that can be related with models of water delivery to Earth from asteroids.

In order to measure water vapour emission (goal #1), VISTA requires to be in conductive contact with a cold finger, since when the sensor is at a temperature lower than the ice sublimation point in vacuum, i.e. 180 K (Townrow and Coleman 2014), the condensation of water molecules on the QCM sensible area is favored. However, if the crystal works at a temperature larger than 180K it is still possible to measure dust flux emitted from asteroids.

The goal#2 is achieved by performing TGA. This is obtained by heating the crystal up to desorption temperature of physically adsorbed water, i.e. 423 K (Bruckenthal and Singer 1987), and organics, i.e. 473-573 K (Grady et al. 2002).

The goal #3 requires that either the two sensor heads would be located on different parts of the mother spacecraft or different cubesats to be completely redundant both of them located on at least two vehicles, to measure dust flux in different locations.

Table 1 reports the most relevant performance and requirements for the VISTA sensor.

Sensitivity (flux)	4.4 ng cm^{-2} s^{-1}
Sensitivity (volatile content)	100 ppm
Temperature range	up to 180K (SH1) up to 573K (SH2)
FOV (each sensor head)	143°
Detector	QCM
Responsivity	1.6 ng/Hz
Main Electronics	Shared with other sensors
Other technical characteristics	A conductive contact with a cold finger would allow to measure water vapour emission from the asteroids
Mass (each sensor head)	90 g
Volume (each sensor head)	Ø 35 mm; height: 25 mm
Power	0.2-1 W
Data Rate	30 bit/meas
Alignment	No constraint but it should be favourable to point toward the plume

Table 1. VISTA technical requirements

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Compositional Mapping of Interplanetary Dust with a Small Dust Telescope

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Abstract

Asteroids are embedded in the zodiacal dust cloud and collisions with interplanetary dust particles generate smaller ejecta and alter their surfaces. Compositional studies are a key method to investigate the diversity of small bodies in our Solar System. Here we report about the performance of a reflectron-based ToF mass spectrometer for the in-situ study of interplanetary micrometeoroids. The Dust Telescope was developed for inner Solar System measurements and it is currently under test and development for the NASA Europa Mission. The trajectory and composition of individual micrometeoroids is measured in the speed range between 2 and 50 km/s. The spectrometer mass range is between 1 and 250 amu and the mass resolution is above 150. The instrument has a mass of 2.9 kg and consumes a peak power of 12 W.

Introduction

Collisions between meteoroids or between meteoroids and asteroid surfaces are important processes which lead to space weathering effects and the generation of fragments. Collisions also limit the life time of objects in the inner Solar System. Micrometeoroids are typically cometary or asteroidal fragments and their dynamical and compositional properties are essential for the Solar System evolution.

There is high interest in new planetary missions to small bodies, the moon and the jovian and saturnian systems. Here the in-situ characterisation of surface ejecta, volcanic or geyser plume particles provide an excellent method for geochemistry and mineralogy. The link between the dust grain properties and their origin (surface properties of planetary bodies) is achieved by the combined knowledge of dust composition and dust trajectory. No high-resolution compositional data of interplanetary meteoroids between Earth and Jupiter exist. Former missions focused on particle fluxes and mass distributions. The missions Giotto and Stardust were driven by cometary science and Cassini-CDA achieved only limited results between Earth and Jupiter due to the constrained pointing profile of the 3-axis stabilised spacecraft [1].

New developed dust telescopes provide the dynamical and elemental properties of impacting micron sized dust grains [2,3]. This technology was developed with the requirement of large sensitive areas to be suited for the detection of low interstellar and interplanetary dust fluxes ($<10^{-4}$ m^{-2} s^{-1}). However, later instrument studies resulted in smaller instruments which are better suited for certain regions in the Solar System. A flight instrument of a small dust telescope will require a mass of 2.9 kg and a peak power of 12 W. A twin instrument for the Europa Mission, the small dust telescope SUDA (Surface Dust Analyzer), is currently in the design and test phase at the Univ. of Colorado [4]. This instrument will map the surface composition of the icy moon Europa by flying through the ejecta clouds.

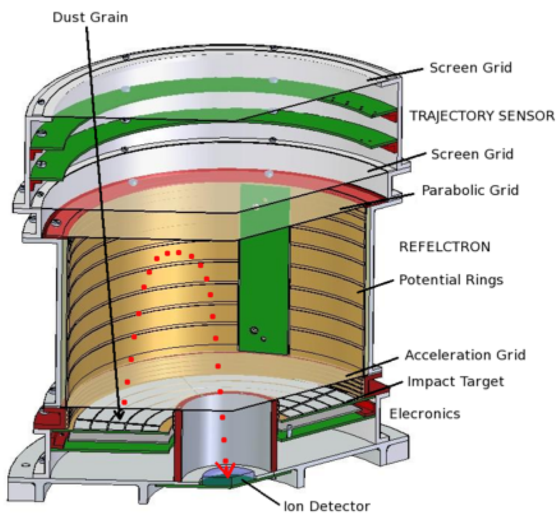

Fig. 1 *Cross section of the compact dust telescope and its integrated time-of-flight spectrometer. Ions generated by a hypervelocity impact (red dots) are extracted and focused onto the ion detector providing the composition of the dust grain.*

Instrumentation

A laboratory model of a small dust telescope with a diameter of 20 cm was designed and fabricated (Fig. 1). The spectrometer subsystem contains a ring shaped gold plated impact target, a plane acceleration grid, a reflectron employing a parabolic shaped grid and potential rings for field smoothing. Hypervelocity impacts of micrometeorites generate an impact plasma which is separated by a field of 2000 V and the positive ions are extracted and focused to the central ion detector. The ion optics and instrument design was optimised for a very compact size and low mass [2]. The integrated spectrometer of the dust telescope was tested at the Heidelberg and at the Boulder dust accelerator facility (Fig. 2). An integrated system of charge sensing grids provide a trajectory information of individual dust particles which are larger than approx. 1 µm. For the first time, compositional particle measurements can be combined with particle trajectory information. A variety of projectile materials were used during impact tests and mass spectra generation including metals (Ni, Fe), organics (latex) and silicates (olivine, pyroxene) [3].

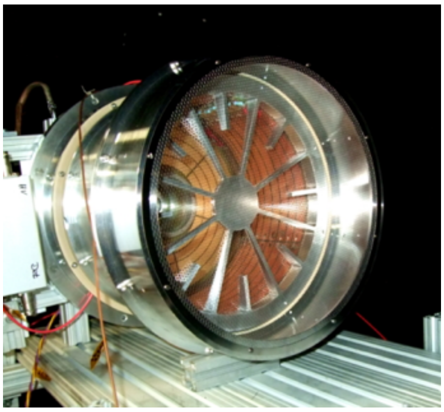

Fig. 2 Laboratory instrument of the small dust telescope in the vacuum chamber of the Heidelberg dust accelerator.

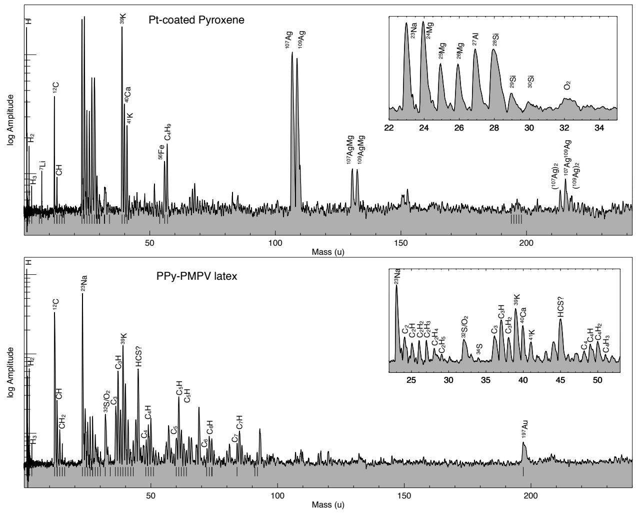

Fig. 3 Example spectra of a pyroxene particle impact on a silver target and of a latex particle on a gold target recorded with the SUDA Dust Telescope for the Europa Mission.[4]

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