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THE ASTEROID IMPACT MISSION: TESTING LASER COMMUNICATION IN DEEP-SPACE

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INTRODUCTION

In October 2022 the binary asteroid system 65803 Didymos will have an exceptionally close approach with the Earth flying by within only 0.088 AU. ESA is planning to leverage on this close encounter to launch a small mission of opportunity called Asteroid Impact Mission (AIM) to explore and demonstrate new technologies for future science and exploration missions while addressing planetary defence and performing asteroid scientific investigations. AIM is part of an international cooperation between ESA and NASA currently completing Phase B1 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. AIM will be the first mission to demonstrate optical communication in deep-space. In addition, several other new technologies will be embarked on the spacecraft using this opportunity to acquire validation for future flagship missions. By combining AIM's technology and scientific payload to support both close- proximity navigation and scientific investigations together with a fast development schedule and short mission operation, AIM will demonstrate the capability to achieve a small spacecraft design with a very large technological and scientific mission return.

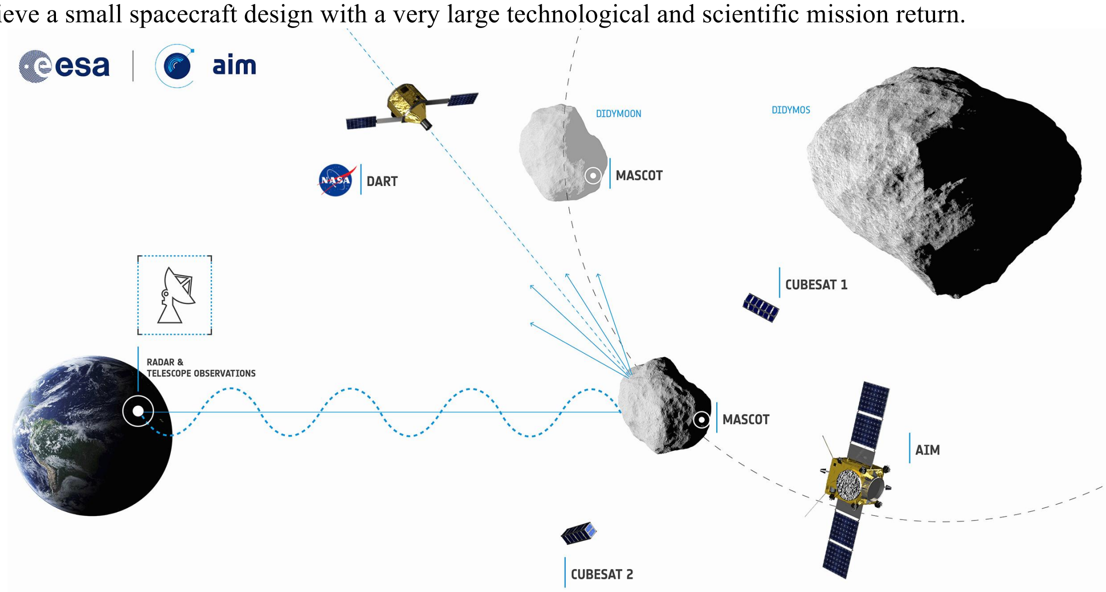

Fig. 1. AIDA international collaboration

By participating to the AIDA collaboration, the result on investment of the AIM mission is doubled thanks to the additional experiment resulting from the DART hypervelocity impact. In particular, the observation of the plume, the crater, and the freshly exposed material will provide truly unique information for asteroid deflection, science and mining communities.

ASTEROIDS, THREAT AND OPPORTUNITY

Asteroids are fascinating objects, they hold unique information about the solar system formation and ultimately about our own origins. Asteroids are also tracers of the solar system history where collisions played a fundamental role. Understanding the impact processes at large scale (beyond laboratory) provides important clues on the evolution of the solar system, including our own planet. There are currently over 14000 known Near-Earth Objects (NEOs) out of which over 500 are considered potentially hazardous (PHOs). More that 90% of asteroids of 1km in diameter or larger, capable of producing damage at planetary scale, are considered to be known by current search programs. Instead, smaller 100m-class size NEOs are still largely unknown. UN COPUOS, among many other international committees, recognizes the “kinetic impactor” deflection technique as the most technically mature, and recommendations are put forward for a precursor demonstration mission to reduce the uncertainties, especially for high impact velocities and highly porous bodies where these are largest. NEOs are of special interest also because they can be physically explored with lower energy requirements than even the Moon, due to their combination of low ΔV with respect to Earth and weak gravity. This allows designing for small and fast missions based on simple spacecraft architectures (e.g. NASA’s NEAR, JAXA’s Hayabusa, CNSA’s Chang’e 2). Such low-gravity regimes and slow-dynamics represent an ideal testbed for new technologies, spacecraft can be in constant contact with ground, several rehearsals can be planned for close-proximity operations, and they represent the perfect stepping stone to more complex science and exploration missions. Asteroids represent as well a potentially economical source of extra-terrestrial materials for human exploitation. Several private initiatives are emerging both in US and Europe with the long-term objective of extracting valuable minerals (mainly platinum-group metals) as well as O2 and H2 for propellants. Business models are based on the commercial value of the enabling technologies under development that can be sold for other applications in LEO as well as spacecraft capabilities and services (e.g. environmental monitoring based on hyperspectral observations).

AIM: TECHNOLOGY FOR THE FUTURE

There is an increasing interest in ESA Member States on frequent small and medium science and exploration spacecraft, and opportunity payloads on a variety of platforms, including CubeSats. The use of alternative technical solutions in certain domains will help ensure feasibility and enhance the science return while keeping the system budgets and technical and programmatic risks under control. Thus, in this framework, AIM intends to demonstrate the following technologies and technical concepts for spacecraft technology miniaturisation, small spacecraft advanced capabilities and enhanced payload resources allocation:

- Adaptive network inter-satellite link with ranging capabilities in deep space (with data re-routing capabilities and meter-level ranging accuracy)
- Spacecraft-relayed CubeSats operations
- Advanced GNC for close-proximity operations including on-board image processing and landmark tracking navigation for semi-autonomous lander delivery
- Sensor data-fusion for fault detection, isolation and recovery (FDIR)
- Infrared/hyperspectral close-proximity navigation
- Deep-space optical communications
- Metasurface high-gain X-band antenna with double beam
- Miniaturized X-band transponder
- Multifunctional payload operations (ranging lidar capabilities of the optical communication terminal in support of the GNC, infrared imaging, high-frequency radar altimetry, back-up communication system with low-frequency radar).
- Optical metrology experiment for lander position determination

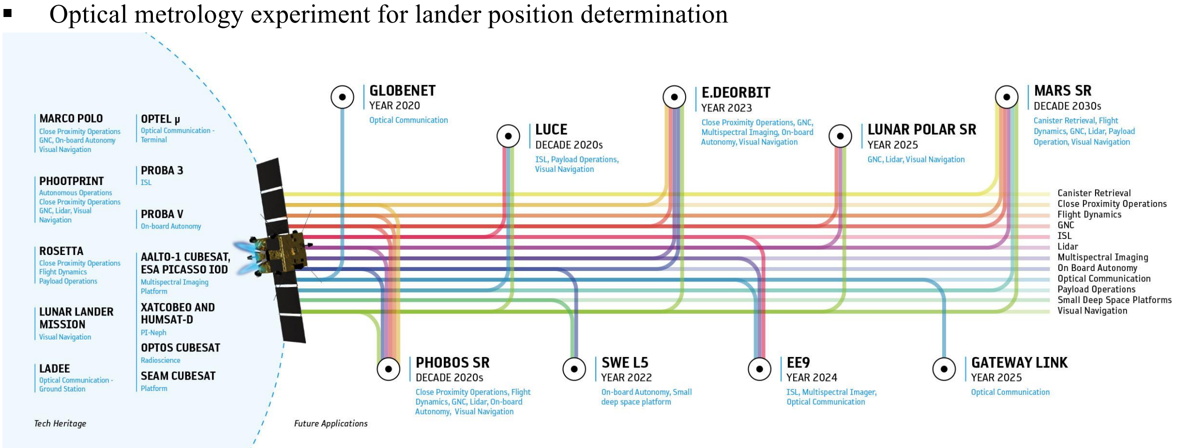

Fig. 2. AIM technology heritage and technology demonstration applications to future missions

Advanced GNC, image processing and close-proximity operations are necessary to operate the spacecraft at very close distances to the asteroid. Once demonstrated by AIM, more ambitious missions like asteroid resources utilisation, Phobos, Mars, and Lunar polar sample return will directly benefit. In addition, deploying a μ-lander and two CubeSats in deep-space for the first time ever, will not only enhance the mission return but prove unique capabilities to operate distributed systems through a novel multi-nodal inter-satellite link with embedded accurate ranging capabilities. This is a core technology required not only in deep-space to retrieve sample canisters but also in LEO for new swarm architectures of micro-satellites being conceived for near-real time environmental monitoring. In order to operate in complex illumination conditions, a multispectral/infrared camera will be used to demonstrate relative navigation. AIM will also demonstrate for the first time deep-space optical communication which is an enabling technology for future human exploration and mission with increasingly higher data return needs (observatories, gateway satellites). Finally, AIM will inaugurate a new approach to small and fast missions by demonstrating the integration of multiple teams removing strict barriers in the interfaces between platform, payload and operations definition. Such an approach can be reused to reduce the cost of future missions like L1/L5 space weather observatories or constellation of mini-satellites in LEO.

MISSION PROFILE

To achieve its mission objectives, AIM will be launched on-board the maiden flight of Ariane 6.2 or Soyuz within a launch window of 21 days opening on 17 October 2020. For the purpose of mission feasibility analysis, launcher trajectories and performance with Soyuz 2.1b-Fregat MT from Kourou (the launch on the maiden flight of Ariane 6 is being investigated) have been analysed and validated with Arianespace. The spacecraft has been designed against the lowest launcher performance within the launch window adding extra robustness to the mission design.

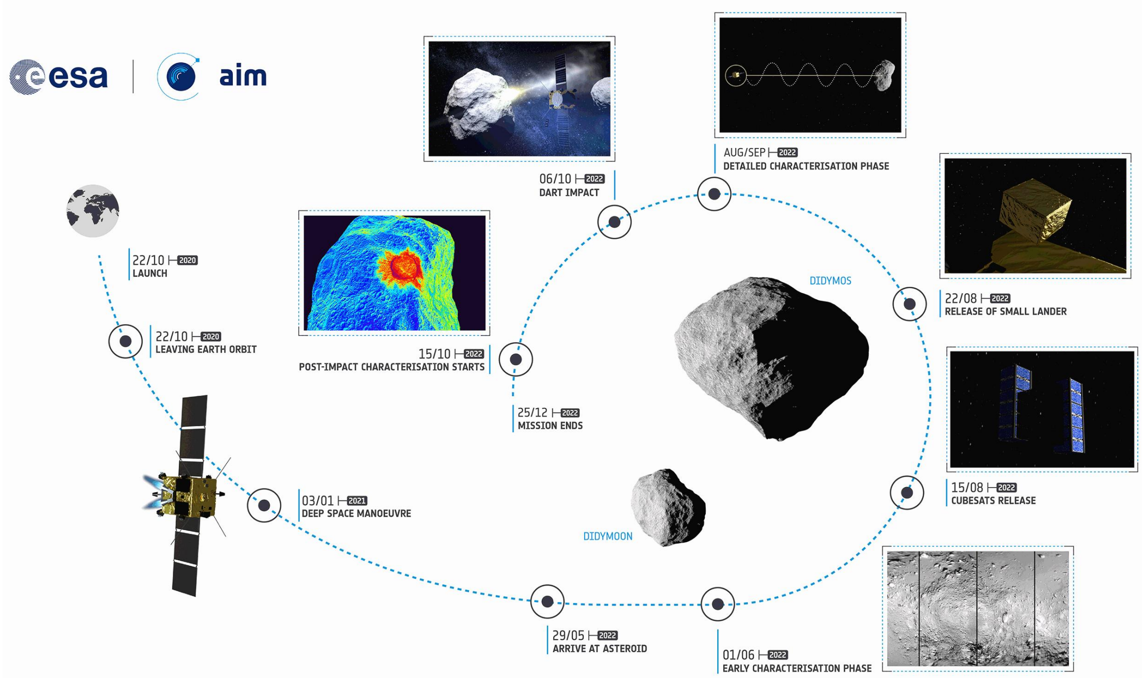

Fig. 3. AIM mission timeline

Following the injection into a direct escape trajectory and commissioning phase, a deep-space manoeuvre is foreseen in the second half of December 2020. The rendezvous phase will start in April 2022 and last about one month, based on a strategy similar to Rosetta. Once in situ, the mission is divided in the following main phases:

1. **Early Characterization Phase (ECP)** 6 weeks (01/06/22-15/07/22)
   This phase takes place beyond the gravitational sphere of influence at about 30 km distance and only optical remote sensing instruments will be operated with the objective of conducting a physical and dynamical characterization of Didymos (notably: size by imaging, mass by determining the ¨wobble¨ period around the barycentre, density by the combination of the two, dynamical characterization -including orbital and rotation periods- by imaging).
2. **Detailed Characterization Phase 1 (DCP1)** 3 weeks (16/07/22-07/08/22)
   It involves a closer proximity at about 10km still beyond the gravitational influence of the asteroid but enabling medium-resolution imaging and the operation of the HFR. Different viewing angles will be used as in the ECP to access different latitudes and longitudes form different local times by means of flyby “pyramid” (intrinsically safe) trajectories.
3. **Payload Deployment Phase (PDP)** 3 weeks (08/08/22-31/08/22)
   The spacecraft will first rehearse and then execute flyby trajectories ranging from 1km to 200m from leading to the payload deployment operations. First the release of COPINS (rehearsing and better characterizing the

gravity field), then move closer to release MASCOT-2, and then return to about 10km in order to support MASCOT localization and relocation operations with VIS, LFR and LEDs. Once MASCOT-2 has reached its operating station (within a 1-2 days and e.g. 2-3 controlled hops supported by ground-based modelling) the LFR radar operation can start together with the rest of the instruments.

4. **Detailed Characterisation Phase 2 (DCP2)** 2 weeks (o1/09/22-14/09/22)
   Equivalent to DCP1 but involves also operations of MASCOT-2, LFR and COPINS, high data volume phase but Earth range close to its minimum.
5. **Impact Phase (IP)** 3 weeks (15/09/22-5/10/22)
   In the AIDA scenario, AIM will move to a safe distance at about 100 km and carry out detailed observation of the impact directly and through the COPINS CubeSats. The ejecta and debris fields in vicinity of the asteroid will be characterized
6. **Detailed Characterisation Phase 3 (DCP3)** 4 weeks (6/10/22-7/11/22)
   AIM will progressively approach Didymoon to fully re-characterize Didymoon after DART´s impact. Approach is assumed to up 10km for full payload operation including MASCOT-2 and COPINS, until the end of the nominal mission in mid-November 2022.
7. **Post-Impact Phase (PIP)** 6 weeks (08/11/22-25/12/22)
   A close-range phase to precisely assess mass variations and image the location of the lander after the impact (with MASCOT-2 and LFR operations also in extended mission, baseline is only for 3 months). Higher resolution images of the crater to be taken with close flyby trajectories to 2km distance. This phase also involves higher-risk autonomy demonstration experiment close to the surface and, finally, spacecraft disposal by landing on the surface of Didymain.

OPTICAL COMMUNICATION DEMONSTRATION

Laser communications at near-infrared wavelengths may be the way of the future when it comes to downloading massive amounts of data from spacecraft orbiting Earth, Mars or even more distant planets. These units can be lighter, smaller and need less power than today's radio systems for certain applications, promising to cut mission costs and provide opportunities for new science payloads. AIM will need to operate much further than the two-way contact established by ESA's OGS with NASA's LADEE lunar orbiter (across 400 000 km) in 2013. The maximum span being targeted is of 75 million km, or half the distance between Earth and the Sun. Operating around Mars one day will involve much further distances still. To meet the challenge, AIM will tackle key issues including telescope design, detector electronics and coarse and fine-pointing systems.

AIM's laser system will be one of the single largest payload items, and will also serve scientific purposes, in particular, as an altimeter to chart the asteroid. The system design is building on its existing family of Optel laser communication terminals, the latest of which is tailored for direct-to-Earth downlinks from mini-satellites. The Optel-D optical downlink system will be an in-orbit demonstration of its capability to transmit data from large distances in deep space. Provided that it will be used as an altimeter, it will additionally contribute to asteroid science. The primary Optel-D altimeter asteroid research objectives are to provide the accurate three-dimensional shape of Didymoon. The measured accuracy will be equal to or less than 50 cm, with a precision of less than or equal to 20 cm. Optel-D will support the determination of the mass by measuring the wobble of Didymain with an accuracy equal to or less than 1 m. In addition, it will determine Didymoon surface topography i.e. highlands, lowlands, ponds, and measure fine-scale features (regolith, bedrock, boulders) with a precision of 20 cm and a sampling of the surface between footprints of 30 cm by a footprint no bigger than 30 cm in diameter. The secondary AIM Optel-D altimeter research objectives are to provide the accurate 3D shape of Didymoon after DART impact and to determine any changes in the mass and surface topography.

The Optel-D is a modular optical downlink system that is an evolution of the Optel-μ equipment designed for Earth orbit applications. The downlink system shall be capable of transmitting data to a ground stations using a modulated (16-PPM) laser beam (1550 nm, TBC). The footprint of the laser beam is kept on the GS during communication by a fine pointing mechanism (FPM) and a coarse pointing assembly (CPA) included in the Optel-D system. A robust pointing of the laser beam during transmission is achieved by detecting a beacon signal, emitted by the ground station, and using this as an optical reference for the space terminal steering. The Optel-D system includes active closed loop correction of S/C jitter. The Optel-D terminal provides the functionality to buffer on-board data of the AIM spacecraft. Furthermore, the following assumptions are made for the OPTEL-D operations:

- The ground segment is based on terminals with a 1 m aperture (ESA´s OGS)
- Data will be transmitted by the OPTEL-D for a maximum of 1 hour (TBC)

- An experiment representative of a Mars mission scenario could be envisaged if a larger (10m) aperture telescope is available

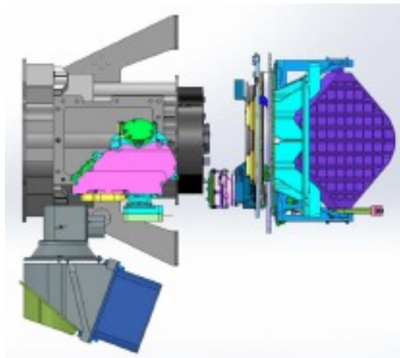

Fig. 3. Optel-D reference design

OPTEL-D system is composed of the Electronic Unit (EU), the Optical Head Unit (OH), the Laser Unit (LU) and its harness. The function of the OH is to provide the beam steering capabilities, while the LU generates the laser beam and the EU provides the signal modulation, reference beam detection and other functions. The figure shows the configuration of the Optel-D system within the AIM spacecraft.

AIM SPACECRAFT

The AIM spacecraft is 950 x 1440 x 1500 mm³ (stowed), 950 x 4125 x 1500 mm³ (deployed). Its dry mass is 437 kg carrying 306 kg of MON-hydrazine thus making a launch mass of 743kg. The current accommodation ensures that all payloads, antennae and thrusters have unobstructed FoV to function correctly and avoid any plume impingement. Given its small size, the AIM platform within the launcher fairing has more than 900 mm clearance in any lateral direction and more than 5000mm clearance in the launch direction. The spacecraft structure is made of aluminium honeycomb panels and frame with an aluminium milled bottom board. It is a three-axis attitude stabilized spacecraft with 4 reactions wheels (1.1Nms), twelve 1N thrusters and 2 redundant 22N thrusters for the deep-space trajectory correction manoeuvers and rendezvous phase (total ΔV is 1450 m/s). Two star trackers, a sun sensor and two IMUs ensure the necessary pointing requirements (AKE 10 arcsec, APE 70 arcsec, RPE 0.6 arcsec over 1s). The navigation camera is considered part of the platform and not an instrument, several options have been identified including the available DAWN framing cameras mentioned above. Power is ensured by two deployable solar panels with SADMs, with 56 strings and 18 cells per string. Power distribution at 28V is MPPT regulated. The core avionics is the same as in the ESA Proba missions based on LEON2-FT and an RTU interfacing with all subsystems. Thermal control is passive in general with the exception of thermal control of the batteries, the propulsion and payloads. To operate the Optel-D, louvers based on the Rosetta heritage and undergoing production for JUICE are necessary. The software heritage implemented in accordance to ECSS/PUS standard is designed for maximum on-board autonomy, including system mode management, payload operations and FDIR. Data downlink in X-band using a novel MoMeTA HGA ensures up to 1kbps telemetry download and supports ΔDOR.

CONCLUSIONS

AIM will be a fascinating mission capable of achieving a number of technological demonstrations in deep-space within only two years from launch. It will serve as a stepping stone to a number of future missions spanning from novel LEO constellations and swarms for terrestrial commercial and monitoring applications, to debris removal and to future robotic explorations missions including sample return from remote planetary bodies. AIM leverages on numerous past system and technology investments in an innovative and interdisciplinary manner to achieve a fast implementation demonstrating a new integrated design and implementation approach between industrial, engineering, operations and scientific teams. AIM is a highly inspiring mission, in cooperation with NASA it will demonstrate for the first the capabilities of humankind to protect its own planet from an asteroid impact. At the same time, it will witness and study in great detail a one of a kind cosmic experiment unveiling the mechanisms of the formation of the solar system. Ultimately, AIM will also contribute to answering fundamental questions related to our own origins. AIM will pave the way to the utilisation of space resources as well as unique technologies enabling future more ambitious human exploration or our solar system.