ASTEROID INVESTIGATION MISSION: THE EUROPEAN CONTRIBUTION TO THE AIDA EU-US COOPERATION

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Abstract: *The Asteroid Impact & Deflection Assessment (AIDA) is a cooperative mission of opportunity currently investigated by ESA, DLR and Observatoire Côte d'Azur (OCA) on one side and NASA and John Hopkins University Applied Physics Laboratory (JHU/APL) on the other. The US spacecraft, Double Asteroid Redirection Test (DART), would impact at high-velocity into the smaller asteroid of the target binary system 65803 Didymos on October 2022 with the purpose of modifying the relative orbit thus demonstrating asteroid deflection by means of kinetic impact. The European Asteroid Investigation Mission (AIM) spacecraft would rendezvous with Didymos a few months before to characterize the system, monitor the impact and ultimately allow for in-orbit validation of technologies including deep-space autonomous navigation and close proximity operations. This paper briefly presents the AIM mission scenario and some trade-offs currently under assessment.*

Keywords: *binary asteroid, deflection, mission*

1. Background

Near-Earth Objects or NEOs include both objects having a likely asteroidal origin, and extinct comets orbiting the Sun in the near Earth Space, crossing the region of the inner planets. Because of their close approach to the Earth, NEOs are the population of the smallest Solar System bodies that can be accessible to detailed physical investigations, but in the same time they represent also a potential threat to our planet. Although impacts of large objects with catastrophic consequences are extremely infrequent, size of few tens of meters in diameter can cause severe damage. Many conceptual studies have been carried out proposing different asteroid impact mitigation strategies [1] but no specific technological plan have been put in place.

In the last decade, ESA has supported work on space systems addressing the asteroid threat. Since 2002 and in the context of the Agency's General Studies Programme (GSP) mission studies have been conducted on the "Don Quijote" concept [2] [3] [4] and other asteroid probes, in close cooperation with international partners including NASA and JAXA. Since 2006, in the frame of the In-Orbit technology Demonstration project preparation, concepts such as PROBA-IP [5][6] have been evaluated, and activities such as NEOMEX (Near-Earth Object Micro EXplorer) pursued in basic technology programmes with developments relevant to that end [7]. Finally, since 2009 ESA's Space Situational Awareness (SSA) Programme has implemented one of its segments dedicated to asteroid detection and modeling, as well as assessing impact effects [8].

The awareness of ESA´s international partners of the asteroid impact hazard has increased due to the Chelyabinsk meteor event of February 2013; interest in asteroid activities is also demonstrated by current public and private investment initiatives for asteroid detection, redirection and resource exploitation. In this context a mission of opportunity has been identified by APL building on a much-simplified Don Quijote scenario. Such mission has been named the Asteroid Impact & Deflection Assessment, AIDA.

2. Asteroid Impact & Deflection Assessment (AIDA)

AIDA consists of two independent but mutually supporting mission concepts one of which is the asteroid kinetic impactor and the other is the characterization spacecraft. These two missions are, respectively, the Double Asteroid Redirection Test (DART) study [9] undertaken by the Johns Hopkins Applied Physics Laboratory with support from members of NASA centers including Goddard Space Flight Center, Johnson Space Center, and the Jet Propulsion Laboratory, and the European Space Agency's Asteroid Investigation Mission (AIM) mission study supported by Observatoire de la Côte d'Azur, CNES and DLR. DART will be the first ever space mission to demonstrate asteroid redirection. This will be done using the binary asteroid target 65803 Didymos. AIM is a rendezvous mission which focuses on the monitoring aspects i.e., the capability to determine in-situ the key physical properties of the binary system playing a role in the system's dynamic behavior. In order to demonstrate impact hazard mitigation, this mission must not only deflect the trajectory of an asteroid, but it must measure the deflection to within 1%.

The AIDA mission scenario offers a number of advantages with respect to the Don Quijote concept, as studied by European industry. These are summarized in Table 1 below.

Don Quijote	AIM/DART	Comment
Two spacecraft launched separately	Two spacecraft developed and launched separately	AIM and DART C/D phase remain independent
Asteroid variation of heliocentric semi-major axis (Δa) shall be greater than 100m	Binary system variation of the relative orbital period greater than 1%, no requirement on Δa	Can be measured both in-space and on-ground (photometry), mission scenario more robust
Impactor launched after Orbiter rendezvous	AIM launched to rendezvous before DART hits its target	AIM and DART still fully meaningful in absence of the other spacecraft
An orbiter performing radio-science experiment is required	Co-flying, orbiting or precise tracking not required	Simple telecom subsystem and operations possible
In-situ experiment only at end of mission	In-situ remains only an option	Secondary payload depends of mass, operations cost, PI contribution
Autonomous optical navigation 2 days before impact	Autonomous optical Autonav as an optional test for AIM, not mandatory	Technology experiment for rendezvous spacecraft

Table 1 AIM/DART simplifications of the Don Quijote concept

2.1 Asteroid (65803) Didymos (1996 GT)

The target is the secondary of the binary asteroid 65803 (1996 GT) Didymos (Figure 1), an Apollo asteroid (perihelion distance smaller than 1.017 AU, semi-major axis greater than 1 AU) discovered on April 11, 1996 by Spacewatch at Kitt Peak. It has a satellite orbiting it with a period of 11.9 hours. Known parameters of Didymos are:

Semi-major axis:	1.644 AU
Orbital (heliocentric) period:	770.14 days
Eccentricity:	0.384
Inclination:	3.4 deg.
Geometric albedo:	0.147
Primary rotation period:	2.26 hr
Diameter of the primary:	800 m
Diameter of the secondary:	150 m
Orbital period of the secondary:	11.91 h (almost circular orbit).
Separation:	1100 m
Binary orbit semi-major axis:	1050 m
Pole Solutions (lambda, beta)	(157 deg., 19 deg.) or (329 deg., -70 deg.)

Thanks to a close approach of the asteroid to the Earth in November 2003 (0.048 AU on Nov. 12, 2003), radar observations were performed by Goldstone and Arecibo. Radar data could provide a model of the secondary as the signal-to-noise ratio is was too weak and echoes were not sufficiently resolved. The dimensions, mass and density of the secondary are thus not well constrained. Secondary bandwidths and visible extents were consistent with synchronous rotation. The radar albedo was consistent with silicates and inconsistent with pure metal. Near-surface roughness can therefore assumed to be lower than the NEA average and somewhat less than on Eros, Itokawa, and Toutatis.

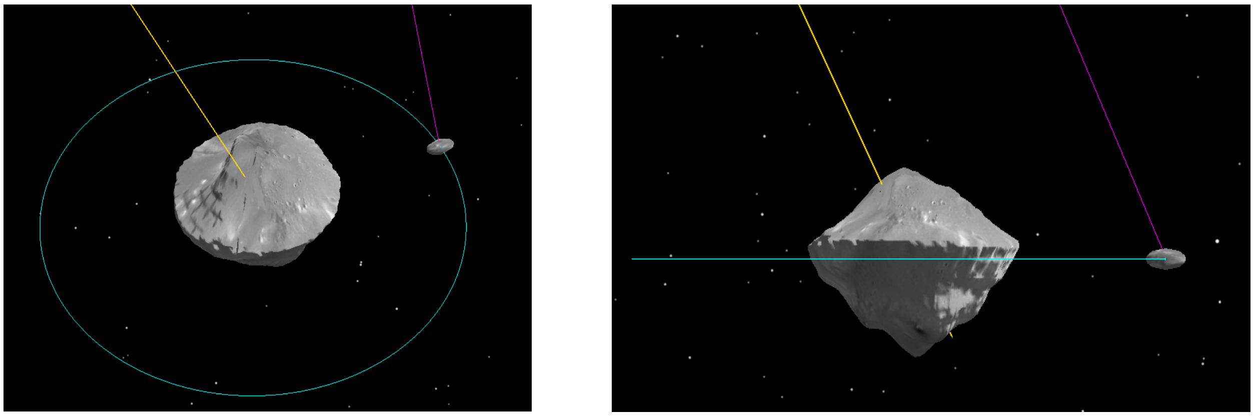


Figure 1 The Didymos binary asteroid

2.2 DART

The DART mission will use a single spacecraft to impact the smaller member of the binary near-Earth asteroid Didymos in October 2022. The impact of the >300 kg DART spacecraft at 6.1 km/s will change the mutual orbit of these two objects. By targeting the smaller, 150 m diameter member of a binary system, the DART mission produces an orbital deflection which is both larger and easier to measure than would be the case if DART targeted a typical, single near-Earth asteroid so as to change its heliocentric orbit. It is important to note that the target Didymos is not an Earth-crossing asteroid, and there is no possibility that the DART deflection experiment would create an impact hazard. The DART asteroid deflection demonstration targets the binary asteroid Didymos in Oct 2022, during a close approach to Earth. The DART impact will be observable by ground-based radar and optical telescopes around the world, providing exciting opportunities for international participation in the mission, and generating tremendous international public interest, in the first asteroid deflection experiment.

The DART mission will use ground-based observations to make the required measurements of the orbital deflection, by measuring the orbital period change of the binary asteroid. The DART impact will change the period by 0.5% - 1%, and this change can be determined to 10% accuracy within months of observations. The DART target is specifically chosen because it is an eclipsing binary, which enables accurate determination of small period changes by ground-based optical light curve measurements. In an eclipsing binary, the two objects pass in front of each other (occultations), or one object creates solar eclipses seen by the other, so there are sharp features in the lightcurves which can be timed accurately. The DART mission additionally returns vital data needed to determine the momentum transfer efficiency from the DART impact. DART will carry a high resolution visible imager, based on the LORRI instrument from the New Horizons mission, in order to return detailed images of the target object as well as its binary companion. DART will autonomously guide itself to impact using this imager. The DART mission uses a simple, high-technology-readiness, and low-cost spacecraft to intercept Didymos. DART hosts no scientific payload other than an imager for targeting and data acquisition as described above.

The spacecraft is single string, and most of the components are either rebuilds of previous APL designs or commercial off-the-shelf equipment. Terminal guidance to the target asteroid is accomplished using the LORRI telescope for optical navigation and using autonomous guidance algorithms based on APL experience in development of the Standard Missile. A monopropellant propulsion system is used for all delta-V burns. Three-axis attitude control is performed using thrusters as on New Horizons. The spacecraft wet mass is estimated to be 235 kg with 30% dry mass margin and with delta-V capability of 100 m/s. Ballast mass would be added to reach the launch capability of 330 kg. Power is estimated at 202 W. The spacecraft has a fixed 1-meter high gain antenna with X-band telemetry. The mechanical layout of the spacecraft is optimized for the terminal navigation phase, with fixed geometries for the imager, high gain antenna, and solar arrays. The spacecraft has no gimbals or deployables.

2.3 AIM objectives

The mission goal for ESA's Asteroid Investigation Mission (AIM) study is to characterize the components of a binary asteroid, especially from the dynamical point of view. The mission concept focuses on the monitoring aspects i.e., the capability to determine, in-situ, the key physical properties of a binary asteroid playing a role in the system's dynamic behavior. For this purpose, even if not a must, choosing a target whose dynamics have already been well characterized from the ground (e.g., by means of radar and photometry observations) such as Didymos, is beneficial to address the goals, especially as the target is the subject of an independent impact experiment i.e. DART. The main objectives of the AIM rendezvous spacecraft are:

- Determine binary asteroid orbital and rotation state
- Analyze size, mass and shape of both binary asteroid components
- Analyze geology and surface properties
- Characterize the asteroid density and interior
- Observe the impact crater and derive collision and impact properties (requires the DART mission)
- Provide opportunities for technology tests relevant to cost reduction in future ESA interplanetary missions

It is to be noted that the full AIDA concept serves all NEO exploration stakeholders (see figure 1). With the exception of the deflection demonstration, the same applies to AIM as a stand-alone mission.

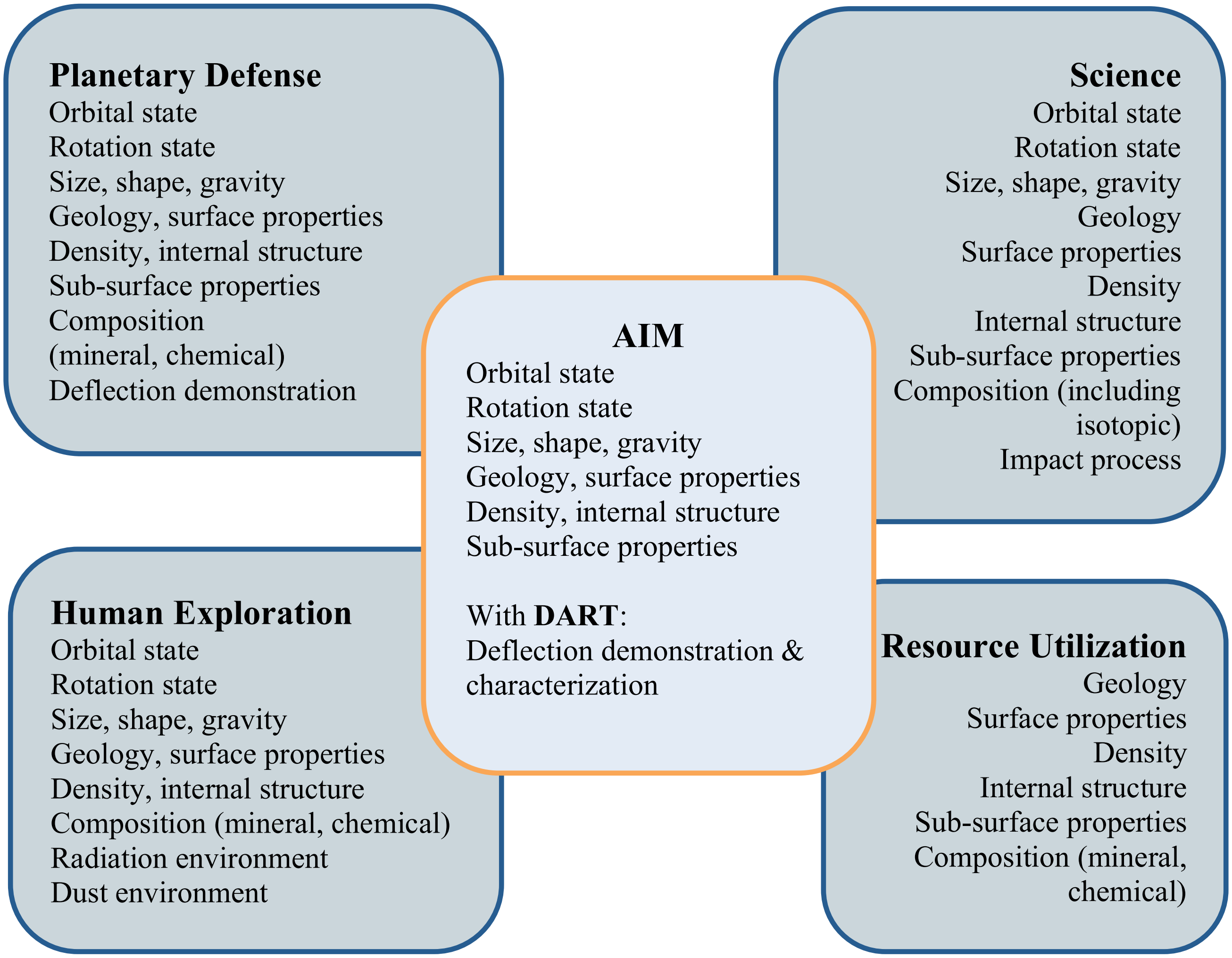


Figure 2 The full AIDA concept serves all NEO exploration stakeholders. The same applies to AIM as a stand-alone mission except for the deflection demonstration.

The implementation of the full AIDA mission will lead to critical information regarding the concept of the kinetic impactor as a deflection tool and the impact process itself. In addition to the knowledge gains resulting from the AIM mission as a stand-alone mission, if DART produces an impact on the secondary of Didymos, AIM will allow:

- to interpret the resulting deflection in a way that is impossible if only ground observations measure the deflection;
- to observe for the first time the outcome of an impact on a small asteroid (e.g. the crater's size and morphology, the amount of ejecta), at a scale that is largely above what can be done in the laboratory.

Regarding the first item, AIM will contribute to access the initial conditions of the impact, e.g. the impact angle, and will relate the position of the impact point on the target measured by DART (within 1 meter accuracy) to the detailed properties of the whole object. This knowledge is crucial for the correct interpretation of the momentum transfer efficiency measurement. Moreover, although the deflection can be observed from the ground, AIM would allow measuring it with greater accuracy and provide additional information about the binary system behavior after the impact.

Regarding the second item, AIM can provide unique knowledge on the impact process in the very conditions of an asteroid environment at a scale that is unreachable in the laboratory. For the first time, AIM would allow testing hypervelocity impact modeling and scaling laws at appropriate scale, and provide real data regarding the outcome, in terms of crater's size, morphology, as well as ejecta production and properties. This information allows checking or refining impact modeling tools and scaling laws that can then be used with higher reliability to design other similar concepts in the future. It will also have a wide range of implications in planetary science, as the understanding of the impact response of a small body as a function of impact conditions and physical properties is crucial to estimate its collisional lifetime, the collisional evolution of asteroid populations (when this knowledge is extrapolated to other bodies), and the role of collisions in various phases of our Solar System history.

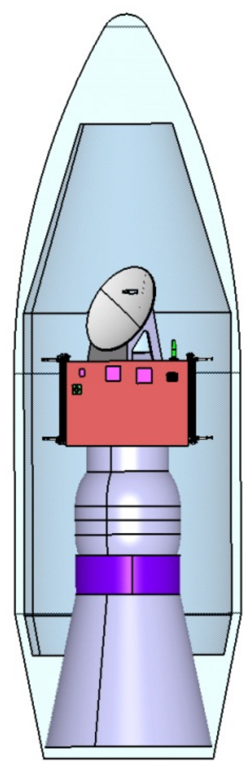
3. AIM mission scenarios

Two main mission scenarios are currently being considered, namely:

AIM UltraLight:	based on a European VEGA launch vehicle and a solid rocket motor upper stage for the interplanetary orbit insertion (e.g. STAR 37/48).
AIM -S:	(¨Spartan¨) based on a Soyuz launch vehicle

3.1 AIM UltraLight (UL)

This is the most demanding scenario in terms of spacecraft design. Assuming an onboard chemical propulsion system to minimize mission costs, two trajectories have been considered (summarized in Table 2 hereunder). Given the robust project plan enabled by a launch in November 2020 this option has been selected. The shorter duration, the absence of an Earth swing-by and thus simplified operation (and reduced cost) also make the 2020 launch more attractive.



AIM UltraLight maxium dry mass is 192 kg that are broken down as follows: 173 kg for the spacecraft bus, 15 kg for the payload and 10 % system margin. In order to minimize the spacecraft resources requirements, the operations are constrained at around 1 AU and modest Earth-Asteroid range (impact event at 0.11 AU) only. In the remaining orbital period, the spacecraft is put in a hibernation mode. Operations have been considered for only 2-3 months before and after DART's impact. The spacecraft is based on a simple X- and S-band communication system and fixed high-gain antenna and solar arrays, which minimize mass, development risks and costs.

	Earth-Asteroid (baseline)	**Earth-Earth-Asteroid (not selected)**
Launch date	02/11/2020	18/09/2019
Escape velocity [km/s]	5.1	1.97
Declination [deg.]	23.5	12.3
Escape mass [kg]	286	471
Earth swing-by	-	09/11/2020
Arrival	03/04/2022	30/06/2022
Deep space maneuver 1 [km/s]	0	1.38
Deep space maneuver 2 [km/s]	-	0
Arrival delta-v [km/s]	1.26	0.8
Total delta-v [km/s]	1.26	2.18
Arrival mass [kg]	**192**	**235**

Table 2 AIM UL mission scenario based on chemical propulsion

The payload allocation considers a 10 kg asteroid lander based on MASCOT [10] heritage and 5 kg for remote sensing instruments. A strawman payload could include for instance optical camera and miniaturized Thermal IR or Near IR instruments; other possible contributions by the research community fitting the mass allocation are under consideration [11].

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An option based of solar electric propulsion has also been assessed (see Table 4). This is based on the use of a PPS-1350 thruster and a VEGA launcher. However this option has been discarded for the reasons mentioned above.

Launch date	**19/08/2019**
Escape velocity [km/s]	1.0
Declination [deg.]	-14.46
Escape mass [kg]	400
Earth swing-by	**07/11/2020**
Arrival	**01/08/2022**
Final mass [kg]	**324**
SEP delta-v [km/s]	2.9
Xenon consumption [kg]:	73
Thruster on time [d]:	213
Total Impulse [10^6kg m/s]:	1.05

Table 4 AIM UL mission scenario based on electric propulsion

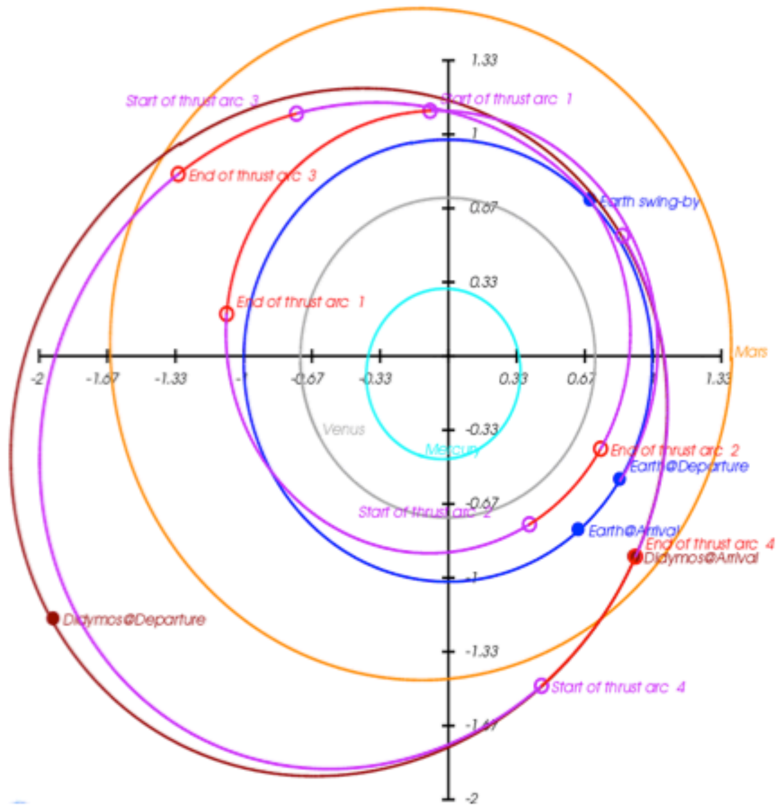

Figure 3 AIM UL trajectory based on electric propulsion (PPS-1350)

3.1 AIM-S

As mentioned above, this scenario is based on a Soyuz launch from Kourou and a spacecraft equipped with (monopropellant) chemical propulsion system. A reference mission is summarized in Table 4:

Launch date	**2020/10**
Escape velocity [km/s]	5.1759
Escape mass (inc. adaptor) (kg)	900
Asteroid arrival (approx.)	2022/6
Time to DART impact [month]	5
Deep-space maneuver [m/s]	40
Arrival maneuver [m/s]	1160
Total Delta-v [m/s]	**1200**
Final s/c mass [kg]	500

Table 4 AIM-S mission scenario based on chemical propulsion

A Soyuz from Kourou requires a LEO intermediate phase and clearance for Fregat upper stage drop in the north Atlantic. For the required escape velocity i.e. 5.2 km/s, 900 kg can be inserted into the escape trajectory (including adaptor) leading to a final spacecraft mass that is currently estimated in 500 kg. Up to 50 kg could finally be available for payload. The payload allocation currently considers a 10 kg asteroid lander and 40 kg for onboard payloads. In this scenario, the possibility to carry out a deep-space optical communication experiment is considered.

4. AIM operations

After Earth departure, spacecraft operations will be minimized. Only a limited number of contacts is foreseen in case the interplanetary phases requires a deep space correction maneuver and before the arrival to the target. Other than that the spacecraft will be maintained in hibernation state, especially in the phases with larger heliocentric distances. The nominal operations will be constrained to geocentric distances below 1 AU and heliocentric distances close to 1 AU in order to simplify operations and the spacecraft design.

Upon arrival, the spacecraft will perform continuous observations from a series of fixed "station points" relative to the asteroid inertial frame and at a safe distance, out of the sphere of influence of both Didymos components. In order to be able to image the two bodies for precise measurements of the orbital state, distances of 13.5 to 17 km were considered for the first characterization point. The impact of DART will be observed from a second characterization point at 100 km distance, and with a DART-asteroid-AIM angle close to 90º to the direction of prevent damage by debris generated from the impact ejecta, and to provide adequate viewing and illumination conditions. The requirement is for DART to impact with a solar phase angle $\alpha<60º$ The attitude will be with sun-pointing solar arrays, which will result in a compromise between close to back-illuminated observation of ejecta and the lowest effective spacecraft cross section with respect to any potential debris impingement. The camera –and other remote sensing-pointing will be determined by such geometry. For routine observations the position of the spacecraft vantage point will be determined by these same factors.

The operations will also include the passive release of an asteroid lander. Communications with the lander will last for some weeks to up to 3 months. This parameter will depend on the choices made for the lander´s power subsystem and its ability to maintain operations during such period of time.

Depending on the selected AIM mission scenario and payload configuration, the operations of the mission could include a space to ground optical communication link at a distance of 0.11 AU, involving ESA´s Optical Ground Station in Tenerife, Spain, and an onboard optical terminal currently under assessment. The requirement is for the primary AIM mission to conclude in February 2023, three months after DART impact.

5. Conclusions

The mission goal for ESA's Asteroid Investigation Mission study was to characterise the components of a binary asteroid, especially from the dynamical point of view. The mission concept focuses on the monitoring aspects, that is the capability to determine in-situ the key physical properties of a binary asteroid playing a role in the system's dynamic behaviour. A low-cost small-class spacecraft design was identified that would increase Europe's competitiveness through the qualification of technologies and operations also relevant to other missions, in particular in the area of autonomous guidance, navigation and control, and spacecraft TT&C. When coupled to the DART impactor mission, and assuming both spacecraft are targeting the same object (Didymos) around its 2022 close Earth encounter, the mission objectives can be addressed in full: object characterisation, impact test, and momentum transfer assessment.

6. Acknowledgements

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