THE ASTEROID IMPACT MISSION: CONSOLIDATED MISSION ANALYSIS AND SCIENTIFIC PAYLOAD OPERATIONS AT BINARY ASTEROID DIDYMOS

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Abstract: The Asteroid Impact Mission is an ESA mission, part of a joint collaboration with NASA in the AIDA (Asteroid Impact & Deflection Assessment) mission. The primary goal of AIDA is to assess the feasibility of deflecting the heliocentric path of a Near Earth Asteroid binary system, by impacting on the surface of the smaller asteroid of the couple. To this purpose, AIDA includes a kinetic impactor, DART by NASA and an observer, AIM by ESA. The consolidated mission analysis of AIM spacecraft is presented with a breakdown into the main mission phases. AIM is planned to be launched in late 2020 and to arrive at Didymos system in middle 2022. Suitable transfer solutions and launch window are presented; the approaching strategy to rendezvous with the binary system is discussed and close proximity operations at the asteroid are finally described. The results and analyses presented in the paper are currently performed by OHB System AG, Politecnico di Milano and Spin.Works under the European Space Agency study for phase A/B1 design of the AIM spacecraft. The project is currently ongoing and the mission analysis will be further iterated and refined through the design phase.

Keywords: AIM, AIDA, Binary Asteroid, Mission Analysis, Close-Proximity Operations.

1. Introduction

The Asteroid Impact Mission (AIM) [1] is an ESA mission whose goal is to explore and study the binary asteroid 65803 Didymos [2], which is expected to transit close to the Earth (less than 0.1 AU) in late 2022. AIM is part of a joint collaboration with NASA in the AIDA (Asteroid Impact & Deflection Assessment) [3, 4] mission. The primary goal of AIDA is to assess the feasibility of deflecting the heliocentric path of a Near Earth Asteroid (NEA) binary system, by impacting on the surface of the smaller (or secondary) asteroid of the couple. To this aim, AIDA includes the kinetic impactor, DART (Double Asteroid Redirection Test) [5] by NASA and the observer, AIM (Asteroid Impact Mission) by ESA.

The work here presented is part of the phase A study, currently performed by OHB System AG, Politecnico di Milano and Spin.Works under the European Space Agency study for phase A/B1. The paper shows updates on the AIM mission design work [6] and summarizes the consolidated mission analysis of AIM spacecraft during all mission phases and the scientific payload operations at Didymos. The paper critically discusses the choices made to design each mission phase trajectory, to support the platform design.
The AIM mission objectives are summarized first. The payloads on-board are then briefly presented. The interplanetary trajectory design is discussed and the available launch window to reach Didymos with correct timing is presented. Suitable transfer solutions are selected based on \( \Delta v \) constraints due requirements imposed by the launcher and by the spacecraft design. More in detail, AIM is planned to be launched in late 2020 and to arrive at Didymos system in middle 2022. As the spacecraft approaches the asteroid system, it will go through far- and close-approaching maneuvers. The far-approaching maneuver is discussed: the final \( \Delta v \) to stop AIM at Didymos is split into five smaller maneuvers, performed at one week distance between each other, to decrease the overall maneuver cost and to allow for precise tracking and rendezvous with the binary system. Close proximity operations at the asteroid are then described. During this phase, AIM mission analysis is driven mainly by observational requirements coming from scientific payload on board, to study the asteroid system before and after DART impact (expected for late 2022), such to accomplish mission objectives.

2. AIM Mission Objectives

As part of AIDA, AIM is planned to characterize the asteroid 65803 Didymos (1996 GT) and then to assess the consequences of an impact from a NASA-provided spacecraft named DART on the secondary asteroid in the binary Didymos asteroid system. Prior to the arrival of DART, AIM will rendezvous with the asteroid system, after being launched to a direct injection with a Soyuz Fregat 2-1b. On arrival, AIM would conduct observations that can be used to complement and prepare for the DART impact and perform technology demonstrations. During the proximity operations, a measurement phase shall provide this data for DART and deploy a lander (MASCOT-2) on the surface of the secondary asteroid. In addition, a demonstration of deep space optical communications is planned. If allowing, the AIM spacecraft should also analyze the consequences of the DART impact and release a number of cubesats (COPINS).

This section describes the mission and payload objectives on the highest level. Put in a single sentence, the Asteroid Impact Mission may be summarized by the following mission statement:

**AIM shall characterize the secondary component of the binary near-Earth asteroid (65803) Didymos (1996 GT) from a dynamical and geophysical point of view while demonstrating spacecraft technologies and operations to advance future small and medium missions.**

The following paragraphs discuss into more detail the main science and technology objectives.

2.1. **Science**

Even more importantly than the demonstration of planetary defense technology by monitoring the DART impact, AIM will characterize the Didymos system for the sake of fundamental planetary science. This being the primary objective, (partial) mission success can be achieved even if DART would fail or was canceled. In this sense, AIM can be considered a mission in its own right to a significant extent.

The primary science goal is to determine the geophysical properties of Didymoön (being it the
satellite of the more massive Didymain). Didymoon is the primary subject matter because DART is planned to impact it, rather than Didymain. The geophysical characterization will include shape, mass, (sub-) surface and interior structure, the mechanical and thermal properties, as well as its dynamical state (its own rotation and its revolution around Didymain). Determining the momentum transfer of DART is the second most important goal. Additional objectives of slightly less importance are to characterize Didymain, and to characterize the system as a whole to constrain different proposed formation scenarios (such as breakup due to fast rotation). Characterizing the system and achieving these goals in this manner will help answering a number of overarching science questions. These include the rotational states of asteroid systems, the formation of asteroids and asteroid systems, and the evolution of the solar system with particular regard to collisional evolution of asteroids or proto-planets among others.

2.2. Technology demonstration

As mentioned in the mission statement, AIM shall also demonstrate spacecraft technologies and operations to advance future small and medium missions. There are three key objectives:

- To carry out a Telecommunication Engineering eXperiment (TEX) based on the OPTEL-D optical terminal. This will demonstrate deep-space operations of a laser-based optical telecommunication system. It is intended to increase the downlink rates for transmitting science data products greatly.
- To perform the Moonlet Engineering eXperiment (MEX) based on the MASCOT-2 asteroid lander. This will demonstrate the ballistic landing and operations of a miniaturized asteroid lander. The system will demonstrate operations of the lander-spacecraft relay system and acquire in-situ measurements from the asteroid surface, thus supporting the science goals.
- To release the Cubesat Opportunity Payload Independent Nano-Sensors (COPINS). The COPINS are made up of two or more cubesats of up to three units, with a TBD mission. They will demonstrate an inter-satellite link deep-space network.

Next to these primary tech-demo payloads, other technologies could be flown and demonstrated on AIM. However, especially given the rigid schedule, these would have to be selected carefully. This is subject to the spacecraft design and beyond the scope of this technical note.

2.3. Payloads on board

This section gives a short summary of the payloads on-board the AIM spacecraft and their main objectives.

- **VIS**: The Visual Imaging System (VIS) is a camera that is used for Guidance, Navigation, and Control (GNC) and science purposes. Strictly speaking, it is considered part of the spacecraft bus. It will acquire images of the Didymos system to provide information on its dynamics and physical characteristics.
- **TIRI**: The Thermal Infra-Red Imager (TIRI) is an imaging instrument that operates in the infrared part of the spectrum. Its main goal is to determine the surface properties of Didymoon, for example, whether areas are bare rock or granular surfaces. Several secondary goals are related to thermal properties and the DART impact. Further the TIRI will be used to demonstrate the use of an IR instrument to support the asteroid rendezvous phase.
• **HFR**: The High-Frequency Radar (HFR) will deliver research data for the surface and shallow sub-surface of Didymoon. It will operate in the 300 MHz to 800 MHz range and assist in several other ways, for example by contributing to the shape-model construction.

• **LFR**: The bi-static Low-Frequency Radar (LFR) is used to determine the deep interior structure of Didymoon. As the instrument is made up of segments on MASCOT-2 and AIM, it will also be used to track MASCOT-2 during its descent.

• **OPTEL-D**: The OPTEL-D Laser Communication Terminals (LCT) main purpose is to demonstrate high data-rate deep-space communications. However, being based on laser technology, it can also be used as a scientific instrument in a lidar-like fashion.

• **MASCOT-2**: MASCOT-2 will be a small lander that performs in-situ measurements after its deployment to Didymoon’s surface.

• **COPINS**: The COPINS cubesat opportunity payloads will establish an inter-satellite link (ISL) network and carry a number of payloads.

The payload operations will be planned to address the payload objectives directly. While some objectives may need dedicated or specific observations (such as tracking MASCOT-2), others may actually be covered by a single generic asteroid observation. For example, most VIS payload objectives can be achieved by deriving information from images that have been obtained in a single observation campaign.

### 3. Interplanetary transfer

This section discusses the interplanetary transfer opportunities for a pure ballistic transfer and a bi-impulsive maneuver from Earth escape to the beginning of the asteroid rendezvous maneuver.

The purpose is to rendezvous with the asteroid system during the close passage of Didymos near the Earth in late 2022. This will allow to couple in-situ measurements with ground observation and to facilitates communication issues between the spacecraft and ground segment on the Earth. On the other hand, the AIM design time line, foresee the spacecraft not to be ready to depart before late 2020. These facts impose very strict and demanding constraints on the transfer time, which shall take place between the spacecraft design and the asteroid’s close passage near the Earth. In order to guarantee such time line, a bi-impulsive maneuver with direct ballistic transfer appears as the only valid strategy to design the transfer. This solution is then used as baseline to design the rendezvous phase which entails a sequence of five maneuvers. Summarizing, the overall interplanetary Mission Analysis, from launch to asteroid rendezvous, foresee a total number of six maneuvers (one provided by the launcher at departure, five provided by the spacecraft at asteroid arrival), plus corrections maneuvers needed for navigation.

#### 3.1. Ballistic transfer

The transfer is designed with a bi-impulsive maneuver: the first maneuver is provided by the launcher, which brings the spacecraft on its interplanetary path, while the second maneuver is provided by the spacecraft to stop at Didymos binary system. Figure 1(a) shows the pork-chop plot associated to AIM spacecraft interplanetary cruise. The figure shows the costs of departure and arrival maneuvers, as function of departure date and transfer duration. After the application of the
time constraints on departure and arrival dates, the regions near suitable local minima are identified as possible launch windows.

More in detail, the upper bound for the total cost of the maneuver to be provided by the launcher at departure is constrained to a maximum of 5.2 km/s, while the maneuver to be provided by the spacecraft at arrival is constrained not to exceed 1.25 km/s. Given those constraints, the applicable launch window extends from 2020 October 23rd to 2020 November 6th. Depending on the launch day, arrival at asteroid will occur between 2022 April 5th and 2022 June 16th. Note that an earlier departure does not imply an earlier arrival and latest departures does not correspond to latest arrivals. The arrival date here indicated are not referring to the actual arrival at asteroid (which will be given after the rendezvous approach), but represent the arrival point of the ballistic transfer. More in detail, Fig. 1(b) shows a simple and schematic projection of the pork-chop plot in Fig. 1(a), with the representation of $\Delta v$ and arrival date trend with respect to departure date. It is shown that a minimum $\Delta v$ of 969 m/s is found for a departure on 2020 October 31st and it corresponds to a late arrival at the asteroid. However, an earlier arrival might be beneficial for the scientific and payload operations point of view: as shown in Fig. 1(b) an earlier arrival is possible when departing earlier or later in the launch window, at a cost of a higher maneuver $\Delta v$. The minimum $\Delta v$ solution, with departure on 2020 October 31st, is hereafter referenced as nominal solution.

With reference to the nominal case, Fig. 2(a) shows the interplanetary trajectory of AIM spacecraft during the cruise, together with the orbital path of the Earth and Didymos. Figure 2(b) shows the geometry of the Sun-S/C-Earth constellation, with the time profile of Sun-S/C-Earth and Sun-Earth-S/C angles as well as the distances of the spacecraft from Earth, Sun and Didymos, as relevant to the design process.
Figure 2. (a) Earth, AIM and Didymos trajectory during interplanetary cruise, Earth-Solar elongation is highlighted (b) Sun-S/C-Earth and Sun-Earth-S/C angles, with Earth, Sun and Didymos distances from the spacecraft during interplanetary transfer.

3.2. Rendezvous with asteroid

The approaching sequence to rendezvous with the asteroid can be tuned according to mission design and operations needs. The total number of maneuvers, the time span between each maneuver, the overall amount of $\Delta v$ to be provided after the whole sequence and how to distribute it among the different burns are some of the design parameters that can be tuned to design the approach sequence. Also, an important role is played by the launch day, which influence the ballistic trajectory to the asteroid, and then the starting point of the far-approach.

In this section, some alternatives are presented. Two ballistic transfers are considered as baseline: the first one is the nominal transfer, the second one is referred as the latest departure transfer and it refers to a departure on the last day of the launch window (2020 November 6th). Table 1 summarizes the results in terms of actual arrival date at Didymos and total $\Delta v$ cost after the five-maneuver burning sequence. Feasible arrival range of dates is chosen as it corresponds to solutions with overall cost less or equal than 1250 m/s. The validity of Tab. 1 is confined within the cases investigated: it is possible that different solutions, obtained with different choice of design parameters exceed the ranges identified in Tab. 1. All solutions refer to a five-maneuver sequence with one week interval between each maneuver. In agreement with Fig. 1(b), results show that solutions with latest departure correspond to earlier arrival at asteroid and to more expensive arrival maneuvers.

Table 1. Nominal departure (2020 OCT 31) and latest departure (2020 NOV 6): asteroid arrival after approaching maneuver sequence.

<table>
<thead>
<tr>
<th></th>
<th>2020 OCT 31</th>
<th>2020 NOV 6</th>
</tr>
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<tbody>
<tr>
<td>Asteroid arrival</td>
<td>2022 JUN 23 - JUL 3</td>
<td>2022 MAY 7 - 14</td>
</tr>
<tr>
<td>Total arrival maneuver [m/s]</td>
<td>960 - 1250</td>
<td>1147 - 1250</td>
</tr>
</tbody>
</table>
Table 2 shows an example of a maneuvering sequence associated to the nominal ballistic transfer and the corresponding cost and date of each maneuver to be performed by the spacecraft. Maneuvers are provided with a time interval of one week between two consecutive maneuvers. This time allows for detailed navigation estimate, to correctly rendezvous with the asteroid, and for a complete re-scheduling of the maneuvering sequence if needed. The cruise and first part of the rendezvous is navigated through ground tracking. The last part of the rendezvous sequence foresee to be relatively navigated with respect to the asteroid system, using the on-board visual camera, to ultimately estimate the actual orbital path of the asteroid and to correctly rendezvous with it. According to the accuracy of visual camera, correction maneuvers due to navigation errors in the rendezvous phase are estimated to be on the order of few m/s.

<table>
<thead>
<tr>
<th>Date</th>
<th>Δv [m/s]</th>
<th>Distance from Didymos [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022/06/03</td>
<td>496.6</td>
<td>4.21e5</td>
</tr>
<tr>
<td>2022/06/10</td>
<td>378.5</td>
<td>1.21e5</td>
</tr>
<tr>
<td>2022/06/17</td>
<td>75.0</td>
<td>4.16e4</td>
</tr>
<tr>
<td>2022/06/24</td>
<td>25.0</td>
<td>1.05e4</td>
</tr>
<tr>
<td>2022/07/01</td>
<td>12.5</td>
<td>35</td>
</tr>
<tr>
<td><strong>TOT</strong></td>
<td><strong>960.6</strong></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 shows the relative distance and relative velocity with respect to the target asteroid during the rendezvous phase.

Figure 3. Rendezvous sequence.
3.3. Ground station coverage

The European ESTRACK network will be employed to communicate with the spacecraft during all phases of the mission. Figure 4 shows the ground coverage for ESTRACK network. Small non-visibility (white) regions are shown to exist during the first and last few months; at these dates, the spacecraft will not be visible for a couple of hours. A S/C-Sun-Earth conjunction will occur at spacecraft’s aphelion (2021/10/30, Fig. 2(b)), one year after AIM’s departure. This will interrupt communication (vertical white line in Fig. 4).

![Figure 4. ESTRACK ground station coverage of AIM spacecraft.](image)

4. Close Proximity Operations

This section describes briefly the main outline of the mission analysis and scientific operations during close proximity phase at the Didymos system. Some observation stations are selected for AIM spacecraft to study Didymos by operating scientific payloads. As mentioned earlier, close proximity operations include the release of a lander on Didymoon and the release of a network of cubesat opportunity payloads. A more detailed description of MASCOT-2 release strategy and landing trajectory design can be found in [7, 8]. In addition, payload operations include technological demonstration of deep space laser communications, low frequency radar tomography of Didymoon and high frequency radar subsurface investigation.

The Earth-Spacecraft-Sun-Asteroid geometry is also presented in this section. The chapter includes the analysis of coverage and illumination conditions, to provide inputs to the planning of scientific payload operations and ground segment operations. Both AIM ground and asteroid coverage is analyzed. Constraints imposed by natural illumination of the asteroids are highlighted, to identify poles visibility and to assess visible latitude bands, during the mission time line and payload operations at asteroid.
4.1. Scientific operations at Didymos

This paragraph provides a global overview and summary of the proximity operations. After evaluating all payload objectives and defining the required observations, each observation has been assigned to an observation phase. Each phase is briefly highlighted next.

- **Early Characterization Phase (ECP):** initial characterization of the Didymos system, as preparation for the following phases.
- **Detailed Characterization Phase 1 (DCP1):** refine models acquired in ECP in preparation for the deployment phase. This especially means to investigate the equatorial area of Didymoon to prepare the MASCOT-2 landing.
- **Lander Deployment Phase (LDP):** deploy MASCOT-2 to Didymoon’s surface and release the COPINS.
- **Detailed Characterization Phase 2 (DCP2):** first primary science phase, global mapping campaign of Didymoon and optionally Didymain.
- **Impact Phase (IMP):** observe DART impact and the plume evolution afterwards.
- **Detailed Characterization Phase 3 (DCP3):** investigate how the DART impact has affected the Didymos asteroid system, second primary science phase with global mapping campaign.

In conclusion, each phase has a dedicated goal and not all phases will have the same importance in terms of science return. However, it is pointed out that any data that is acquired for purposes that are not directly of scientific nature can be used as such opportunistically.

4.2. AIM-Sun-Earth-Didymos geometry

The spacecraft is foreseen to perform scientific operations during its stay near Didymos binary system. In particular, the spacecraft will co-fly with the asteroid system and it will operate its scientific instruments from observation stations located close to Didymos.
With analogy to Fig. 2, Fig. 5(a) shows the orbital path of the S/C (at Didymos) and of the Earth during close proximity operations, while Fig. 5(b) shows the geometry between the spacecraft, the Sun and the Earth, in terms of relevant angles and distances. These data are crucial for the design of AIM platform, to correctly operate all payloads during this crucial phase of the mission.

4.3. Didymos coverage

Figure 6. (a) Coverage percentage associated to one of the observation stations (b) angle between Didymos-S/C vector and Didymos north pole.

Figure 7. Optical Ground Station (OGS) coverage during AIM operations at asteroid.

The observation stations have been selected such to guarantee a full coverage of Didymos system, and the correct operation of the scientific payload. An example of coverage percentage as function of epoch is shown for one of the observation stations in Fig. 6(a). Also, the angle between the Didymos-S/C vector and the Didymos north pole is shown (Fig. 6(b)). The information on the angle is important to assess the north/south pole visibility given a specific observation station and a specific date. An iterative and concurrent design process has been performed, between mission
analysis, platform design and payload operations to find a suitable configuration in terms of location of observation stations and scheduling of scientific operations, in order to fulfill mission objectives.

During operations at asteroids, due to the close passage of the asteroid near the Earth, the telescope of ESA’s Optical Ground Station (OGS) will be operated to support the scientific observations. Figure 7 shows the coverage of OGS during close proximity operations.

4.4. Didymos illumination

![Graph showing angles](image.png)

Figure 8. Angle between Didymos north pole and Sun direction and illumination conditions on the asteroids’ surface (latitude for permanent illumination).

Navigation in the proximity of the two asteroids will be performed using the visual camera. For this reason, to correctly navigate and observe the two asteroids, it is of great importance to know how Didymain and Didymoon are illuminated during close proximity operations. To the currently best known model, Didymoon is assumed to be tidally locked with the primary, meaning that its revolution period around Didymos barycenter is equal to its rotation period. Also, the orbital motion of Didymoon occurs on the equatorial plane of Didymain, such that the orbital angular momentum of Didymoon is aligned with the rotation axis of Didymos. This implies that north pole of both asteroids is directed towards the same direction. Figure 8 shows the illumination conditions of both asteroids. In particular, it shows the angle between the north pole and the Sun directions (same for both asteroids), and it highlights the illumination conditions on the surface of the asteroids, showing the latitudes where the surface has permanent illumination after one asteroid rotation. With reference to Figure 8, the yellow dotted line represents the limiting region for illumination of south or north pole: when the north-pole to Sun angle is greater than 90°, the south pole is illuminated (left part of the graph), while if the north-pole to Sun angle is lower than 90° the north pole is illuminated (right part of the graph).
5. Acknowledgment

The work here presented has been performed under ESA contract during the A/B1 design phase of AIM, by the consortium of Politecnico di Milano, OHB System AG and Spin.Works.

6. References


