ESA'S ASTEROID IMPACT MISSION: MISSION ANALYSIS AND PAYLOAD OPERATIONS STATE OF THE ART

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ABSTRACT

The Asteroid Impact Mission (AIM) is an ESA mission whose goal is the exploration and study of binary asteroid 65803 Didymos. AIM is planned to be the first spacecraft to rendezvous with a binary asteroid: its mission objectives include the highly relevant scientific return of the exploration as well as innovative technological demonstrations. The paper presents some updates on the ongoing design of the mission. Each phase of the operative life of AIM spacecraft is detailed with information and results on the solutions adopted for Mission Analysis design and on the strategies to suitably operate payloads. The work presented in this paper has been performed by the authors under ESA contract within the phase A design of AIM mission.

Index Terms— AIM, asteroid, mission analysis, payload operations,

1. INTRODUCTION

Space missions to small bodies in the Solar Systems are the current hot spot in the space exploration field. The Asteroid Impact Mission (AIM) [1, 2, 3, 4] is an ESA mission whose goal is the exploration and study of binary asteroid 65803 Didymos, which is expected to transit close to the Earth (less than 0.1 AU) in late 2022. AIM is planned to be the first spacecraft to rendezvous with a binary asteroid: its mission objectives include the highly relevant scientific return of the exploration as well as innovative technological demonstrations. In addition, AIM is part of a joint collaboration with NASA in the AIDA (Asteroid Impact & Deflection Assessment) mission [5, 6, 7]. 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) by NASA [8, 9, 10] and the observer, AIM (Asteroid Impact Mission) by ESA. The work presented in this paper has been performed by the authors under ESA contract within the phase A design of AIM mission.

The paper presents some updates on the ongoing design of the mission [11, 12]. Each phase of the operative life of AIM spacecraft is detailed with information and results on the solutions adopted for Mission Analysis design and on the strategies to suitably operate payloads. The selected interplanetary trajectory is presented, including the available launch window to reach Didymos on time. Suitable transfer solutions are selected based on Δv constraints imposed by the launcher and further requirements imposed by 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 presented in detail: the final Δv 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. Observation stations are selected for AIM spacecraft to study Didymos by operating scientific payloads. As mentioned, Didymos is a binary system: its two components are informally called Didymain (the bigger of the couple) and Didymoon (the smaller one). Close proximity operations include the release of a lander on the surface of the smaller asteroid of the couple (secondary) and the release of a network of cubesat opportunity payloads (COPINS). The deployment strategies are described from the operational and maneuvering point of view. In addition, payload operations include technological demonstration of deep space laser communications, low frequency radar tomography of the smaller asteroid of Didymoon and high frequency radar subsurface investigation. The Earth-Spacecraft-Sun-Asteroid geometry is presented into detail during all mission phases. The paper includes the analysis of coverage and illumination conditions during all phases of the missions, 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. The results and analyses presented here are part of the phase A design of the AIM spacecraft. The project is currently ongoing and the mission analysis will be further iterated and refined through the design phase.

2. THE ASTEROID IMPACT MISSION

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. The AIM spacecraft will also analyze the consequences of the DART impact on the asteroid system 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. Scientific goals

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 Didymoon. The smaller asteroid of the couple 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. Technological demonstrations

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 down link 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 mission still to be defined. 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 it 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. MISSION ANALYSIS

This section discusses the interplanetary transfer opportunities from Earth escape to asteroid arrival. Ballistic transfer is initially investigated. The extended launch window, including one Deep Space Maneuver (DSM) is also studied and reported here.

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, foresees 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. More in detail, the constraints imposed by AIM mission requirements translates into a departure epoch not earlier than September 1st, 2020 and with arrival to the asteroid system not later than July 1st, 2022.

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. As additional degree of freedom, a DSM can be included. This solution is 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 (or seven if DSM is considered) maneuvers: the first one is provided by the launcher at departure, while the remaining are provided by the spacecraft at asteroid arrival.

Concerning requirements on maneuver costs, the maximum escape velocity to be provided by the launcher is constrained to 5.2 km/s, while the maximum deterministic Δv to be provided by the spacecraft is constrained to a value of 1.25 km/s, here assumed as an upper bound.

3.1. Launch window

The results presented here correspond to local minima of the ballistic transfer problem and they are used to identify the launch opportunities at a first design phase. Suitable solutions are taken as baseline during the subsequent design phase, when trajectory refinements to perform orbital corrections and asteroid approaching maneuver are computed.

The transfer is designed with a bi-impulsive maneuver: the first maneuver is provided by the launcher, which brings

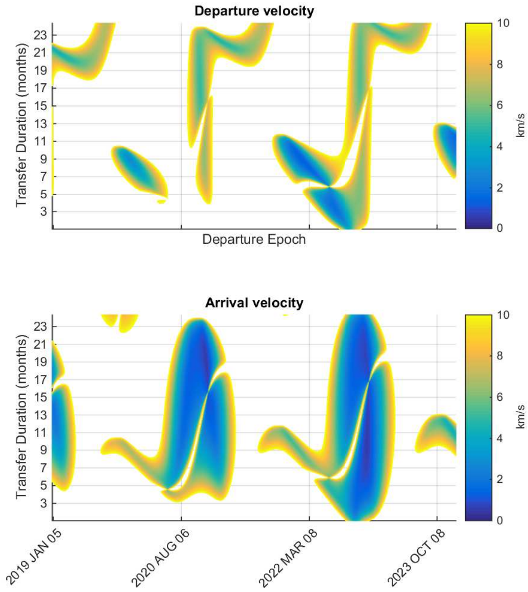

Fig. 1. Pork-chop plot associated to AIM interplanetary transfer through bi-impulsive maneuver.

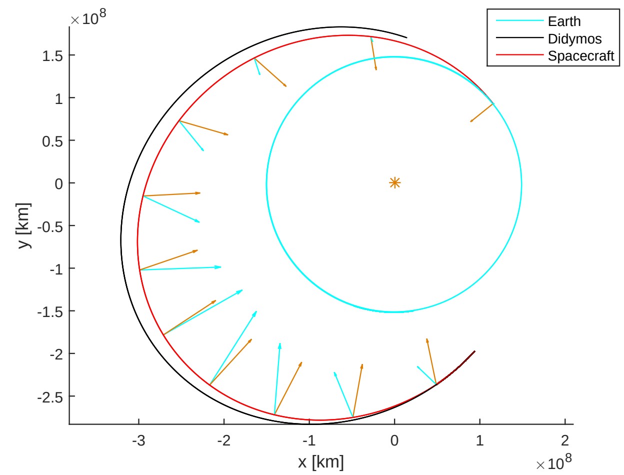

Fig. 2. Earth, AIM and Didymos trajectory during interplanetary cruise, Earth-Solar elongation is highlighted.

the spacecraft on its interplanetary path, while the second maneuver is provided by the spacecraft to stop at Didymos binary system. Figure 3.1 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.

Given the aforementioned constraints on the maximum allowable Δv, the applicable launch window extends from 2020 October 23$^{\text{rd}}$ to 2020 November 6$^{\text{th}}$. Depending on the launch day, arrival at asteroid will occur between 2022 April 5$^{\text{th}}$ and 2022 June 16$^{\text{th}}$. 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. A minimum Δv of 969 m/s is found for a departure on 2020 October 31$^{\text{st}}$ 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: an earlier arrival is possible when departing earlier or later in the launch window, at a cost of a higher maneuver Δv. The minimum Δv solution, with departure on 2020 October 31$^{\text{st}}$, is hereafter referenced as *nominal* solution.

With reference to the nominal case, Figure 3.1 shows the interplanetary trajectory of AIM spacecraft during the cruise, together with the orbital path of the Earth and Didymos. Figure 3.1 shows the geometry of the Sun-S/C-Earth constella-

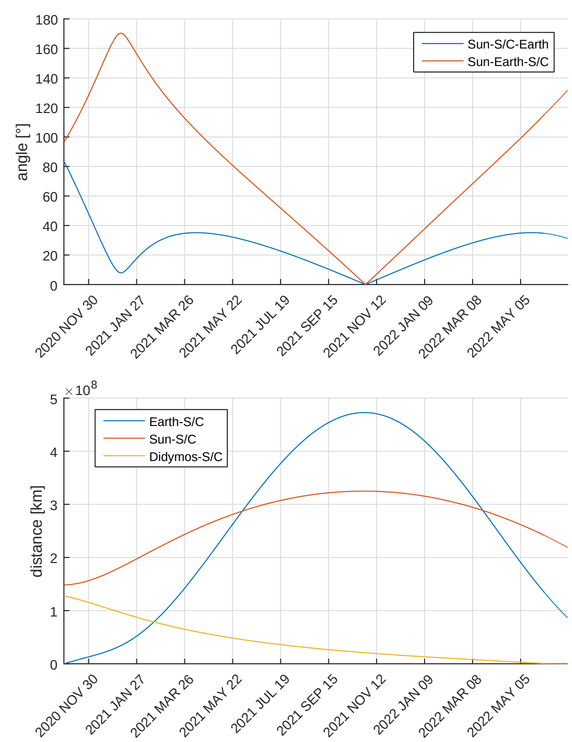

Fig. 3. Sun-S/C-Earth and Sun-Earth-S/C angles, with Earth, Sun and Didymos distances from the spacecraft during interplanetary transfer.

tion, 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.

Table 1. Launch window (ballistic transfer) and extended launch window (including DSM). Launch Period Opening (LPO) and Launch Period Closing (LPC) are reported.

	LPO	LPC
ballistic	2020/10/23	2020/11/06
with DSM	2020/10/17	2020/11/09

A deep space maneuver can be included to extend the launch window. Table 1 shows the extension of the launch window when a single mid-term maneuver is included in the ballistic arc, while keeping the same constraint described in the previous paragraph. More in detail, the LPO is anticipated of six days, to the 2020/10/17 and the LPC is postponed of three days, to the 2020/11/09.

3.2. Rendezvous with the asteroid system

The interplanetary transfer concludes with the rendezvous with the asteroid system. This section discusses a possible solution in terms of a multiple-breaking maneuver. More in detail, the arrival maneuver has been split into five smaller maneuvers performed with intervals of seven days. In general, 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 Δv 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. The time between two consecutive maneuvers allows for detailed navigation estimate, to correctly rendezvous with the asteroid, and for a complete re-scheduling of the maneuvering sequence if needed. In addition, 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.

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. 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.

Figure 4 shows the relative distance and relative velocity with respect to the target asteroid during the rendezvous phase.

Table 2. Rendezvous maneuvering sequence

Date	$\Delta v[m/s]$	Distance from Didymos [km]
2022/06/03	496.6	4.21e5
2022/06/10	378.5	1.21e5
2022/06/17	75.0	4.16e4
2022/06/24	25.0	1.05e4
2022/07/01	12.5	35
TOT	**960.6**	

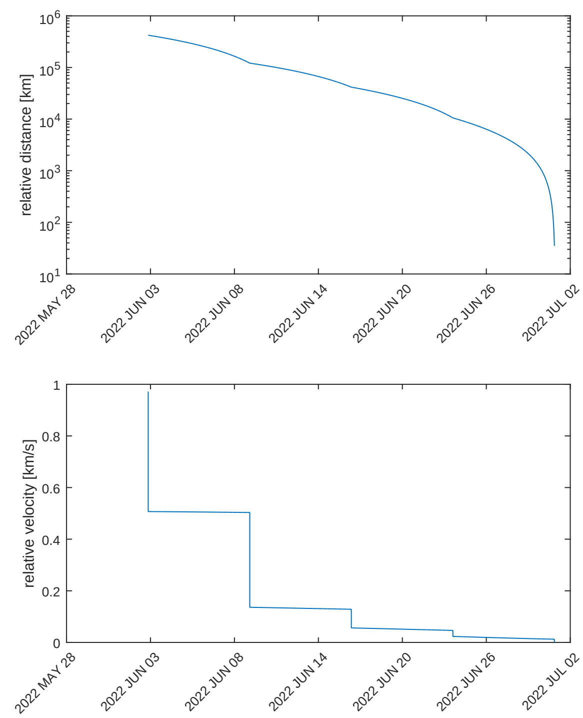

Fig. 4. Rendezvous sequence.

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 [13, 14]. 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 schedule

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 Didymoons 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. Constellation 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

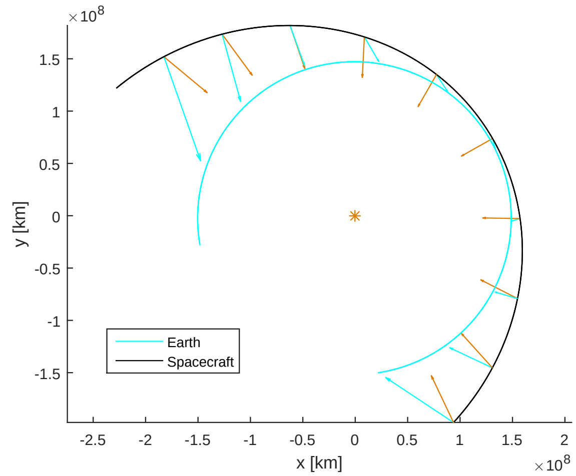

Fig. 5. Earth, AIM and Didymos trajectory during close proximity operations at Didymos, Earth-Solar elongation is highlighted.

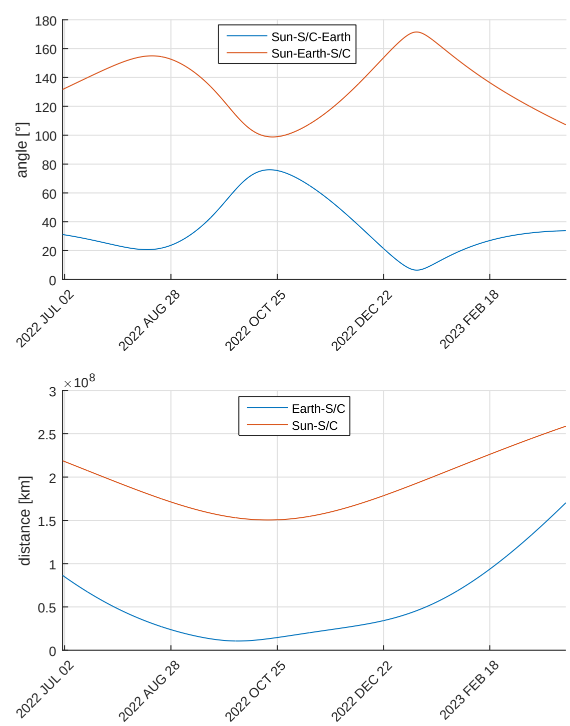

Fig. 6. Sun-S/C-Earth and Sun-Earth-S/C angles, with Earth and Sun distances from the spacecraft during close proximity operations at Didymos.

operate its scientific instruments from observation stations located close to Didymos.

With analogy to Figure 3.1, Figure 4.2 shows the orbital path of the S/C (at Didymos) and of the Earth during close proximity operations, while Figure 4.2 shows the geometry between the spacecraft, the Sun and the Earth, in terms of relevant angles and distances, with analogy to Figure 3.1. These data are very important for the design of AIM platform, to correctly operate all payloads during this crucial phase of the mission.

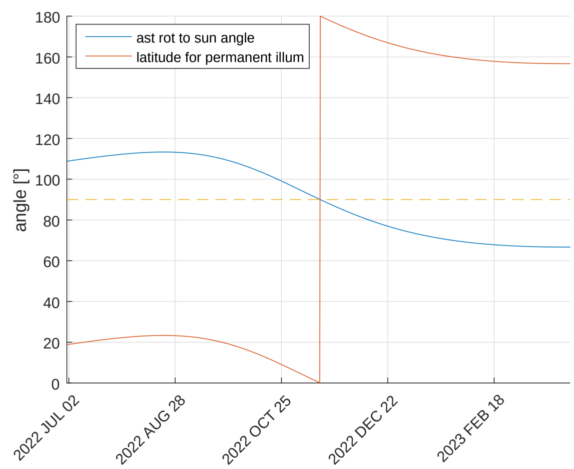

Fig. 7. Angle between Didymos north pole and Sun direction and illumination conditions on the asteroids' surface (latitude for permanent illumination).

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 7 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 7, 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

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