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ASTEROID IMPACT MONITORING MISSION: MISSION ANALYSIS AND INNOVATIVE STRATEGIES FOR CLOSE PROXIMITY MANEUVERING

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ABSTRACT

To prevent from future Potentially Hazardous Asteroids (PHA), one of the most relevant techniques to be proved and tested is the deflection of the heliocentric path of the asteroid. Despite many theoretical studies on asteroid deflections are present in literature, this kind of solution has never been tested in a relevant environment before. ESA's Asteroid Impact Monitoring (AIM) mission is a joint mission with NASA's DART mission (AIM+DART=AIDA mission). AIDA represents the first space mission aimed to assessing the possibility of deflecting the heliocentric orbital path of an asteroid [1], [3]. The target of the study is the binary Near Earth Asteroid (NEA) (65803) Didymos, which will transit close to the Earth (less than 0.7 AU) in late 2022. Didymos is a binary asteroid system composed by a primary asteroid of 800 m diameter and a smaller asteroid of about 170 m diameter [2], [4], [5]. The goal of AIM mission is to characterize the binary couple before and after the orbital deflection of the asteroid system. The heliocentric deflection is obtained by means of a high velocity (about 6 km/s) kinetic impact, performed by DART spacecraft. The paper presents the preliminary study for the mission analysis of AIM spacecraft. The study covers all main phases of the mission, from the selection of the launch window and the design of the interplanetary transfer, to close proximity operations at the binary system. Innovative solutions are presented to lower Δv budget during close proximity operations, by exploiting the gravity of the smaller asteroid. The binary system is modeled as a Three-Body system, to better exploit its peculiar dynamic environment and better design the mission [6]. Even if the paper content focuses on the AIM mission scenario, the presented approach can be easily generalized to assess the feasibility and costs in terms of Δv budget and time constraints of a mission to a NEA.

INTRODUCTION

The paper presents the preliminary mission analysis of the AIM spacecraft. After this introductory chapter, suitable solutions for launch and interplanetary transfer phase are discussed. Afterwards, close-proximity maneuvers are presented to deal with the arrival of AIM at the Dydimos and its early operation phases. One of the peculiarities of AIM mission is the release of a lander (MASCOT-2) on the surface of the smaller asteroid of the binary couple (Dydimos' moon or Dydimoon in the followings): innovative solutions are proposed and discussed to land MASCOT-2 on the surface of Dydimoon. Concluding remarks are eventually summarized at the end of this paper.

LAUNCH AND INTERPLANETARY TRANSFER

The launch opportunities for AIM mission are discussed in this section. A direct transfer is considered with bi-impulsive maneuver at the beginning and at the end of a single interplanetary transfer arc.

Launch opportunities

Figure 1 shows the porkchop plot of launch and interplanetary transfer opportunities for the AIM mission. The upper part of the figure shows the departure velocity to be provided to inject AIM into the interplanetary trajectory. It is assumed that this Δv is provided by the launcher, up to the maximum value of 5.2 km/s. The lower plot shows the arrival Δv to be provided by AIM to break at Dydimos. Minima of the porkchop plot identify good transfer opportunities.

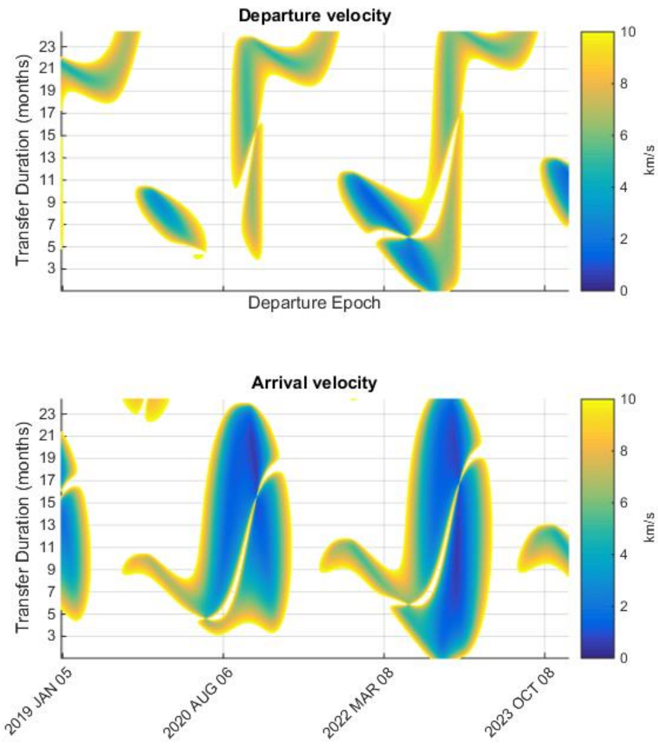

Figure 1: Porkchop plot. Departure and arrival velocity for interplanetary transfer. Departure (upper) and arrival (lower) Δv to be provided are shown

Some requirements have been extracted from the planned mission timeline. AIDA mission plans to take advantage of the close passage of the binary system Dydimos near the Earth in late 2022. To study the binary system before the arrival of NASA's DART, AIM spacecraft is required to arrive at the asteroid system not later than July,

2022. On the other hand, departure epoch is constrained not to be earlier than late 2020, to comply with the feasibility of the design process. Table 1 shows the opportunities for departure day, with corresponding arrival at asteroid, when mentioned constraints apply.

Table 1: Launch window

Launch window	2020 October 23rd – November 6th
Asteroid arrival	2022 April 5th – June 16th

Examples of launch opportunities, with corresponding time of flight, arrival day and cost are shown in Table 2. Among the many possible opportunities, LPO (Launch Period Opening), LPC (Launch Period Closing) and the best solution (minimum Δv) are reported.

Table 2: Launch opportunities

Launch date	**2020/10/23**	**2020/10/29**	**2020/10/31**	**2020/11/02**	**2020/11/06**
Escape velocity [km/s]	5.200	5.199	5.199	5.199	5.200
Asteroid arrival	2022/05/16	2022/06/14	2022/06/08	2022/05/27	2022/04/18
Duration [d]	570	593	584	571	528
Arrival maneuver [m/s]	**1106**	**974**	**969**	**987**	**1154**

Arrival maneuvers lower than 1 km/s can be achieved for departures between 2020/10/27 and 2020/11/02. The cheapest transfer is obtained when departing on 2020/10/31 (Δv=969 m/s), while the most expensive one corresponds to the Launch Period Closing (LPC) on 2020/11/06 (Δv=1154 m/s).

Interplanetary transfer

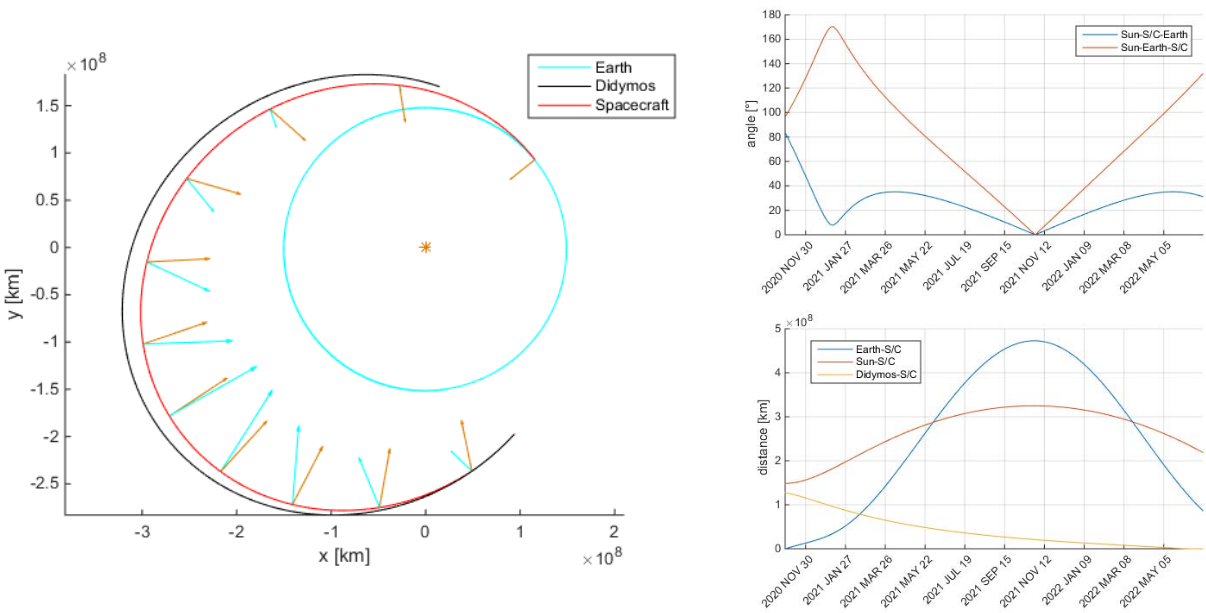

Figure 2: S/C-Sun and S/C-Earth directions, angles and distances during interplanetary transfer phase

Figure 2 shows the S/C-Earth and S/C-Sun directions during the interplanetary transfer. The top-right plot shows the Sun-S/C-Earth and Sun-Earth-S/C angles during cruise. Angles will range from a maximum of 170° (Sun-S/C-Earth) and 83° (Sun-Earth-S/C) to a minimum of 0°. The minima conditions happen simultaneously, hence the spacecraft, the Sun and the Earth are in conjunction. In this particular case, AIM is at aphelion (2021/10/30), and the S/C-Sun-Earth conjunction will interrupt communications with Earth.
During interplanetary transfer, the S/C will experience a maximum distance from Earth of 3.2 AU and a maximum distance from Sun of 2.2 AU.

CLOSE PROXIMITY OPERATIONS

Heliocentric trajectory

After arrival, the spacecraft will co-fly with the asteroid system. From the heliocentric point of view, its trajectory coincides with the asteroid path (Figure 3).

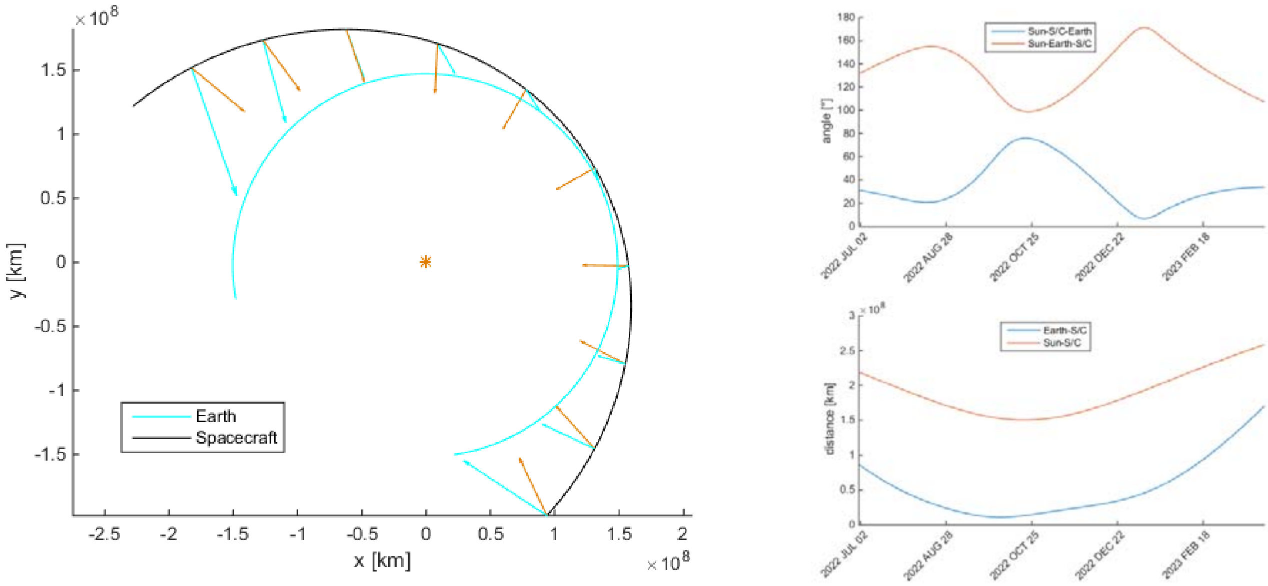

Figure 3: S/C-Sun and S/C-Earth directions, angles and distances during close proximity operations

In analogy with Figure 2, Figure 3 represents directions from the spacecraft to Earth and Sun during close proximity operations. Sun-S/C-Earth and Sun-Earth-S/C angles are also represented, together with distance of spacecraft from Earth and Sun. During this mission phase, Sun-S/C-Earth angle ranges from a minimum value of 6° to a maximum value of 76°, while Sun-Earth-S/C angle ranges from a minimum of 99° to a maximum of 172°.

Asteroid illumination

Illumination conditions on the surface of the primary asteroid during close proximity operations depend on the relative angle between the asteroid rotation axis and the Sun-Didymos direction. According to data currently available on Dydimos, two possibilities exist for the pole orientation of the binary system [2], [4], [5]. The rotation axis of the primary is assumed to be oriented as the rotation axis of the secondary about the primary (angular momentum of the orbit of the secondary). The ecliptic coordinates of the north pole of the primary asteroid of Didymos system are reported in Table 3.

Table 3: Dydimos pole solutions

Solution #	Ecliptic coordinates (λ, β)
1	157°, 19°
2	329°, -70°

Figure 4 shows the angle between the north pole direction and the Sun direction on the primary asteroid. When the angle is below 90°, the north pole is illuminated (below yellow dotted line); otherwise, the south pole of the asteroid is illuminated (above yellow dotted line). Since the rotation axis of the smaller asteroid is assumed to be aligned with its revolution axis, illumination conditions can be equivalently applied to the surface of the secondary asteroid.

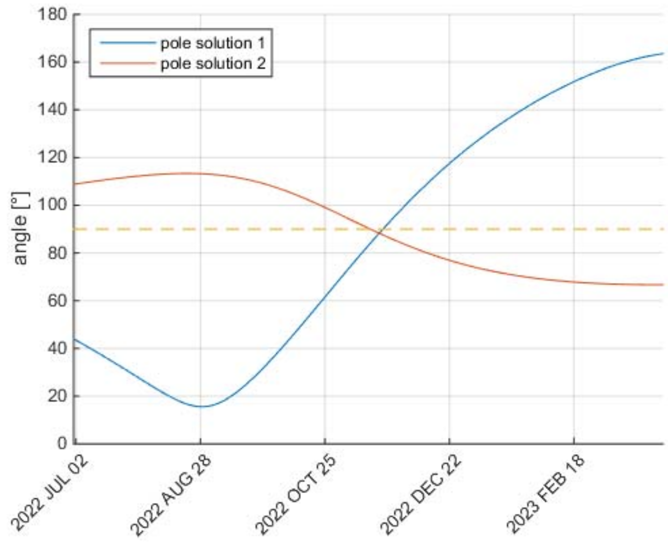

Figure 4: Angle between north pole and Sun direction

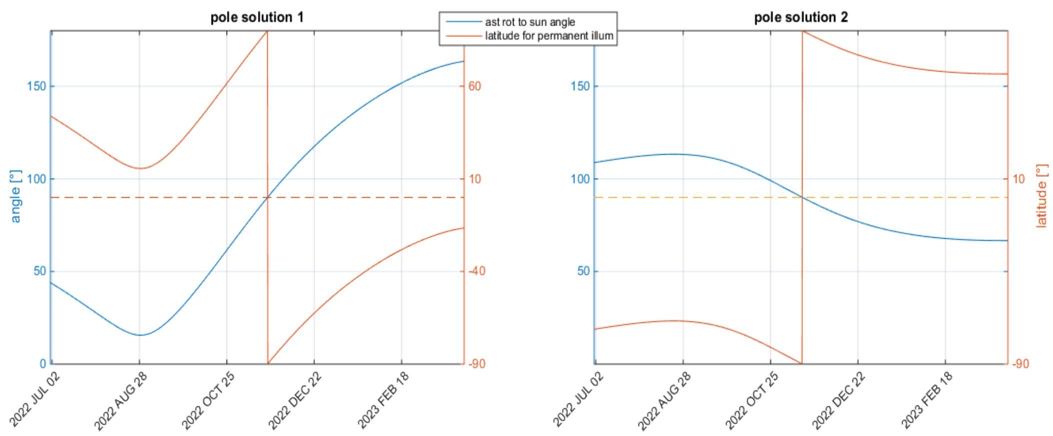

Figure 5: Illumination conditions on the asteroid surface

Figure 5 shows latitude of permanent illuminations on the primary surface depending on epoch. Figure 4 and Figure 5 show that in mid-November the Sun-Didymos direction lies in the orbital plane of the smaller asteroid about the primary (angles equals 90°). In this condition, eclipses of the secondary asteroid can happen. In particular, eclipse will last for about 1.4 hours, and it will occur on 2022/11/21 (pole solution #1) or on 2022/11/15 (pole solution #2).

MASCOT-2 LANDING

A strategy to design MASCOT-2 landing on the surface of the secondary asteroid is here presented. The dynamical properties intrinsic into a distributed mass system, as the binary is, are exploited. This approach reveals to succeed in lowering the powered Δv demand and in limiting the more the risks associated to the landing maneuver. Since the target is a binary system, the couple of asteroids is naturally modelled as a restricted three-body system. The proposed approach provides a more accurate estimate of the trajectory with respect to a simple two-body model and allows for the full exploitation of convenient dynamical properties of this peculiar system. More in details, the system is modelled by means of a Circular Restricted Three-Body Problem (CR3BP) [6].

The landing maneuver starts with AIM+MASCOT-2 at 10 km distance from the barycenter of the binary. The spacecraft descent to a distance of about 5 km where MASCOT-2 is released. The overall maneuver ends with AIM flying back to a distance of 10 km and MASCOT-2 on the surface of Dydimoon.

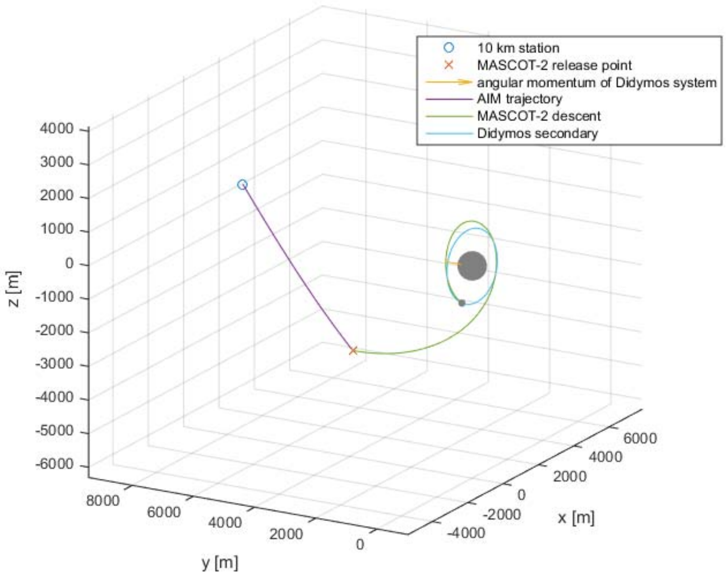

Figure 6: MASCOT-2 landing maneuver

Figure 6 shows the complete AIM/MASCOT-2 landing maneuver, when pole solution #1 (Table 3) is considered. The timeline and cost of the maneuver is schematically reported in Table 4.

Figure 7 shows MASCOT-2 landing trajectory in a Didymos-centered frame, from AIM release to surface of the smaller asteroid. The right-side plot represents the trajectory as seen from an observer which is co-rotating with Didymos secondary: in this rotating system the position of both asteroids is fixed on the x axis. The landing trajectory has been selected among a family of stable invariant manifolds of Didymos three-body system. Suitable landing solutions are depicted in Figure 8.

Table 4: AIM/MASCOT-2 landing maneuver

Phase	Distance from Dydimos barycenter [km]	Δv [m/s]	Time
Maneuver is initiated	10	0.149	T0
MASCOT-2 release	5.4	0.104	T0 + 12 h
Arrival at Dydimoon (MASCOT-2)	1.1	-	T0 + 35 h
Departure from release point (AIM)	5.4	0.248	T0 + 12 h
Back to initial point (AIM)	10	0.149	T0 + 24 h

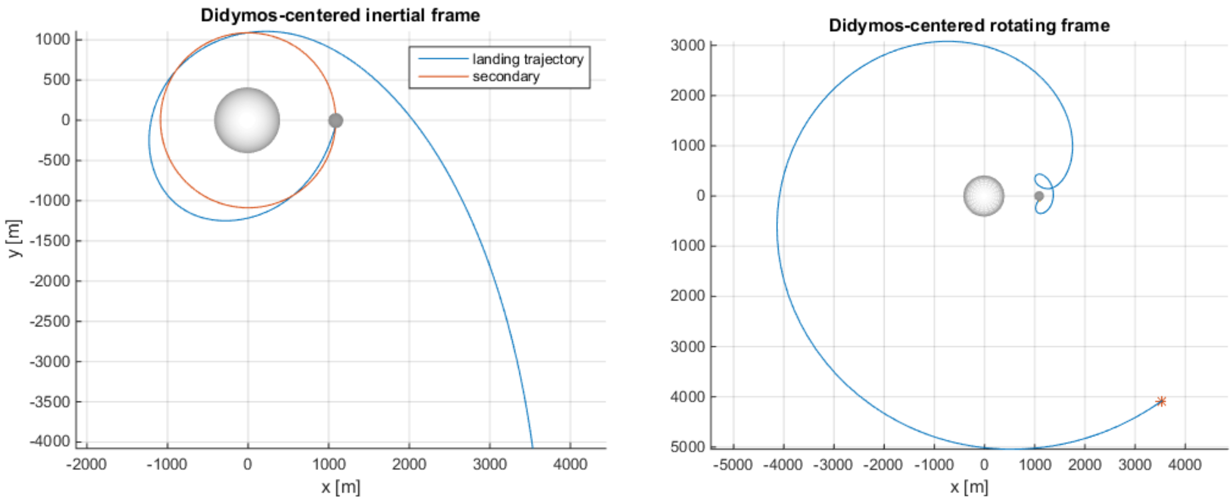

Figure 7: MASCOT-2 landing trajectory in inertial (left) and rotating (right) frame

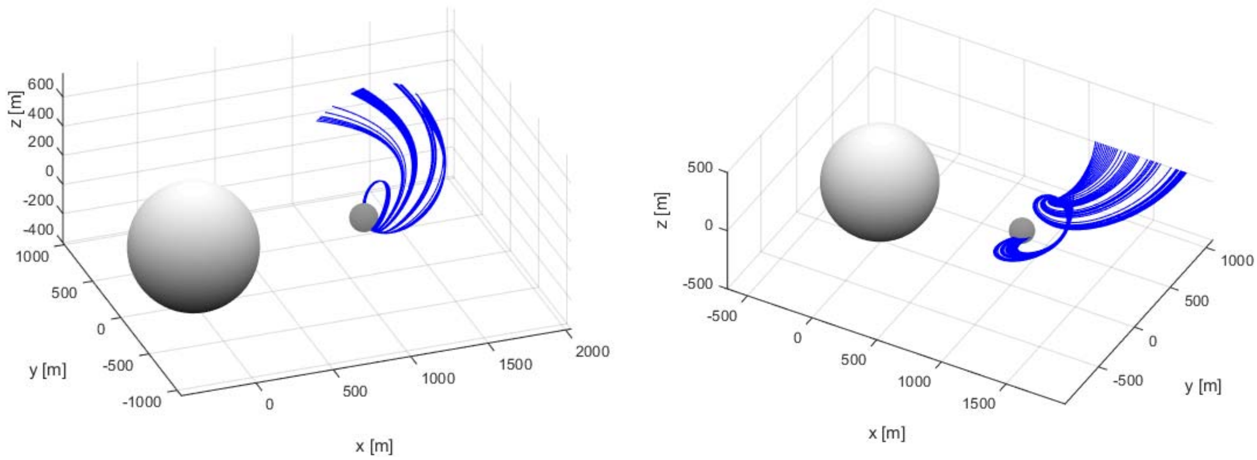

Figure 8: Famillies of invariant manifolds in the Dydimos CR3BP. Suitable out-of-plane and in-plane landing solutions

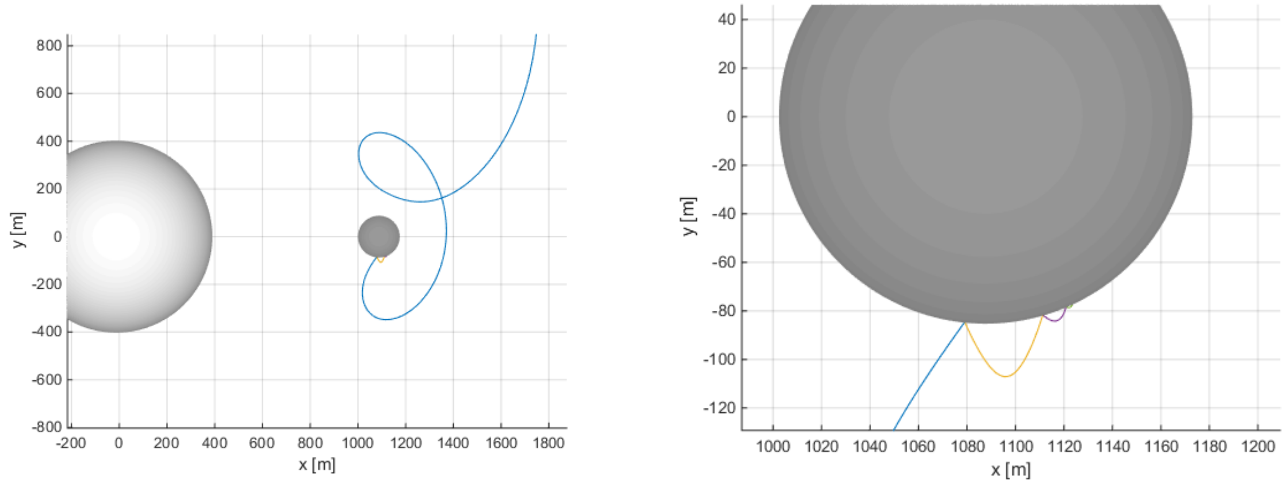

Figure 9: MASCOT-2 landing trajectory: touchdown

An equatorial landing site is chosen for MASCOT-2. Figure 9 shows an enlargement of Figure 7 (right). MASCOT-2 arrives at the secondary surface with a relative velocity of 7 cm/s (escape velocity at surface is estimated to 7.7 cm/s). The numerical simulation proved that MASCOT-2 remains on the surface, after a couple of rebounds. It is assumed that after rebounding, the velocity component tangent to the asteroid surface remains unchanged, while the normal component is halved, according to an elastic collision hypothesis, which is conservative.
To assess the cost and duration of this whole phase simulated sensitivity analysis run with respect to different initial conditions and durations of the different phases. In addition, both Didymos system poles solutions have been considered (Table 3).
The analysis shows that the overall Δv does never exceed 2 m/s for a total duration of about 35 hours (12 h descending from 10 km station to release point, 23 h for MASCOT-2 descent from AIM release to asteroid surface). The Δv has to be provided from AIM, to reach the release point and then to go back to 10 km station, while MASCOT-2 descent is a pure ballistic trajectory (Table 4). When longer transfer times are considered, Δv cost decreases and vice versa. The proposed design provides a simple and low-risk landing, since no further hovering or hyperbolic fly-by maneuver are required: only one maneuver has to be done and AIM spacecraft does not need to get too close to the binary system, since MASCOT-2 release occurs at about 5 km from the asteroids.

CONCLUSION

The preliminary mission analysis of AIM mission is presented, broken down in all mission phases. Innovative solutions are discussed to land MASCOT-2 on the surface of the smaller asteroid of the binary system, exploiting three-body dynamics. Low-cost and low-risk landing solutions are found.
This work can be generalized as an indicative example on possible costs and duration for a mission aimed to the exploration of a NEA.

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