

DOCUMENT

ASTEROID IMPACT MISSION: AIM₃P MISSION AND PAYLOAD OPERATIONS SCENARIO

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1 INTRODUCTION

This document describes a basic AIM mission operational scenario for the AIM spacecraft and its payload resulting from the AIM3P CDF study.

It highlights possible, design driving factors having an impact in the mission and system design trade-offs, in particular the relation between the spacecraft trajectory, pointing and configuration, as well as close-proximity operations dictated by the payload operations.

It shall serve as reference document for the system design during the AIM Phase A/B1 study. It is meant as a complement to the Phase A/B1 applicable documents (in particular the System Requirements Document and Payload Interface Document) and reference Mission Analysis Guidelines (MAG).

A discussion on AIM mission design drivers is presented in chapter 0. These are general aspects that are relevant for the AIM mission even beyond the scope of the AIM3P work.

Chapter 0 discusses the operations that are required for the AIM spacecraft to support the payload operation, and the payload operation concept in itself, as defined in the AIM3P CDF study.

For completeness, Annex A provides mission and system trade-offs, solutions and the results relevant to the AIM3P design baseline.

1.1 Reference Documents

Reference Documents (AD) are only applicable in the context of the Phase A/B1. Reference Documents (RD) are also defined in that context. The documents listed below are listed for information and as an aid for understanding.

- [AD2] AIM Payload Interface Document (PID)
- [AD3] Didymos Reference Model
- [RD1] AIM-3P CDF-149(A) Report
- [RD2] AIM-3P Mission and Payload Operations Scenario (this document)
- [RD3] AIDA mission rationale
- [RD4] AIM Mission Analysis Guidelines (will be made available at KO)

2 DRIVING FACTORS

The driving factors analysed in this document are a direct consequence of the mission schedule assumed upfront, and the chosen interplanetary cruise and nominal operation trajectories to satisfy payload operations constraints.

The mission phases are described in more detail in Table 2-1. The mission phases and key events shall be taken only as a guide pending consolidation during Phase A.

Mission Phase	Key Events	LPO Date (approx..)	LPC Date (approx..)
Launch	Launcher Integration	TBD	
	Launch	17/10/2020	06/11/2020
	Injection into interplanetary transfer orbit	17/10/2020	06/11/2020
	Spacecraft Commissioning	17/10/2020	06/11/2020
Cruise	1 st Cruise Phase	17/10/2020	06/11/2020
	Deep Space Manoeuvre (DSM): 225.0 m/s LPO and 547.0 LPC.	01/04/2021	01/04/2021
	2 nd Cruise Phase	01/04/2021	01/04/2021
Asteroid System Rendezvous	1 st Insertion Manoeuvre: 479.0 m/s	05/06/2022	TBD
	2 nd Insertion Manoeuvre: 435.0 m/s	12/06/2022	TBD
	3 rd Insertion Manoeuvre: 75.0 m/s	19/06/2022	TBD
	4 th Insertion Manoeuvre: 25.0 m/s	26/06/2022	TBD
	5 th Insertion Manoeuvre: 12.5 m/s	03/07/2022	TBD
Proximity Operations	Early Characterisation Phase	01/07/2022	
	Detailed Characterisation Phase 1	16/07/2022	
	MASCOT-2 deployment	16/08/2022	
	COPINS Release	10/08/2022 (TBC)	
	Detailed Characterisation Phase 2	01/09/2022	
	Retreat for DART Impact	01/10/2022	
	DART Impact (Earliest)	06/10/2022	
	Detailed Characterisation Phase 3	16/10/2022	
	Extension	TBD	
	End of Life	01/02/2023	

Table 2-1: Current Assumptions for Mission Phases and their key events (indicative only)

For reference, the following AIM3P milestones are used in the plots below:

- ☐ Launch: End October to early November 2020
- ☐ Arrival to asteroid system: Early July 2022
- ☐ Nominal End of Mission: Mid November 2022
- ☐ Extended End of Mission: Early February 2023

In the following sections the spacecraft distances to Sun and Earth, the relative positions spacecraft, Sun, Earth and asteroid, and the illumination conditions on the asteroids are presented through the mission timeline.

Furthermore the relevant facts brought forth by those factors are highlighted.

2.1 Distances to Sun and Earth

Distances to Sun and Earth widely change through the mission, as can be seen in Figure 1 (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission), but more important is to highlight the following facts:

- ☐ During the nominal asteroid operations phase, favouring the design, distance to Earth is at its minimum (below 0.5AU) and so is distance to Sun (below 1.5AU).
- ☐ Nevertheless these conditions degrade towards the end of the mission, which is relevant considering any delay or optional mission extension.
- ☐ During the interplanetary cruise phase, the spacecraft reaches the furthest distances to Earth (up to 3.2AU) at the same time as the furthest distances to Sun (up to 2.2AU).

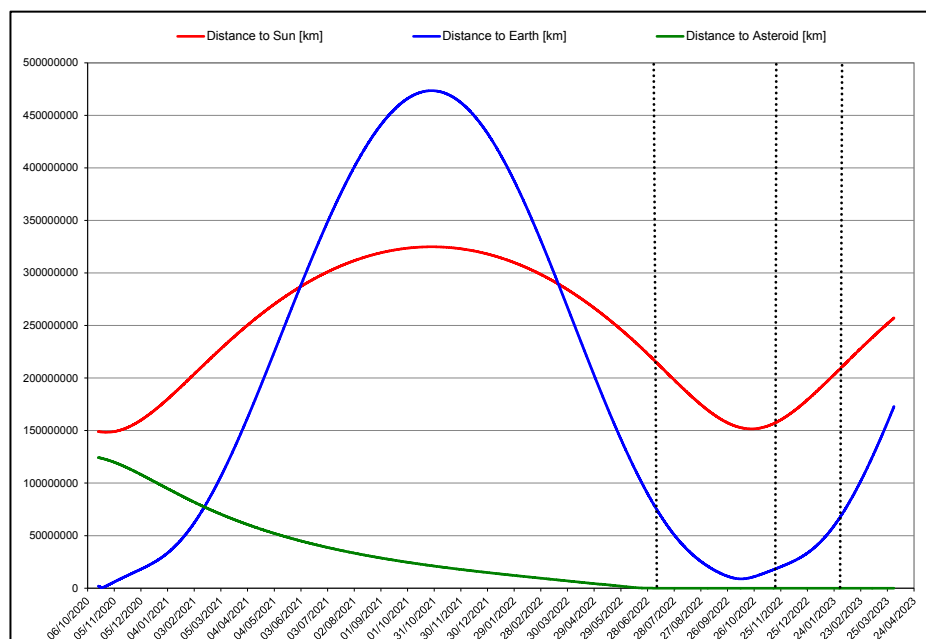


Figure 1 – Distances from Spacecraft

This extreme range of operation conditions, depending on power and communication needs at each phase, is likely to shift the driving case from one phase to another.

2.2 Earth Solar Elongation and Phase Angle

Similar to the spacecraft distances to Sun and Earth, also their positions relative to the spacecraft widely change through the mission.

This can be seen in Figure 2 (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission) by means of the Earth solar elongation (Sun-S/C-Earth angle, thick blue plot) and the Earth phase angle (Sun-Earth-S/C angle, thin blue plot).

In particular the following facts are relevant to highlight:

- During the interplanetary cruise phase, Sun and Earth tend to be aligned towards the period when the spacecraft is at its furthest distance from both (Earth solar elongation near to zero).
- During this period of alignment, Earth is behind the Sun as seen from the spacecraft (Earth phase angle near to zero) which prevents following the spacecraft or any possible communication with it.
- During the nominal operations phase, the angular distance between Sun and Earth as seen from the spacecraft changes from 20° up to 70° .

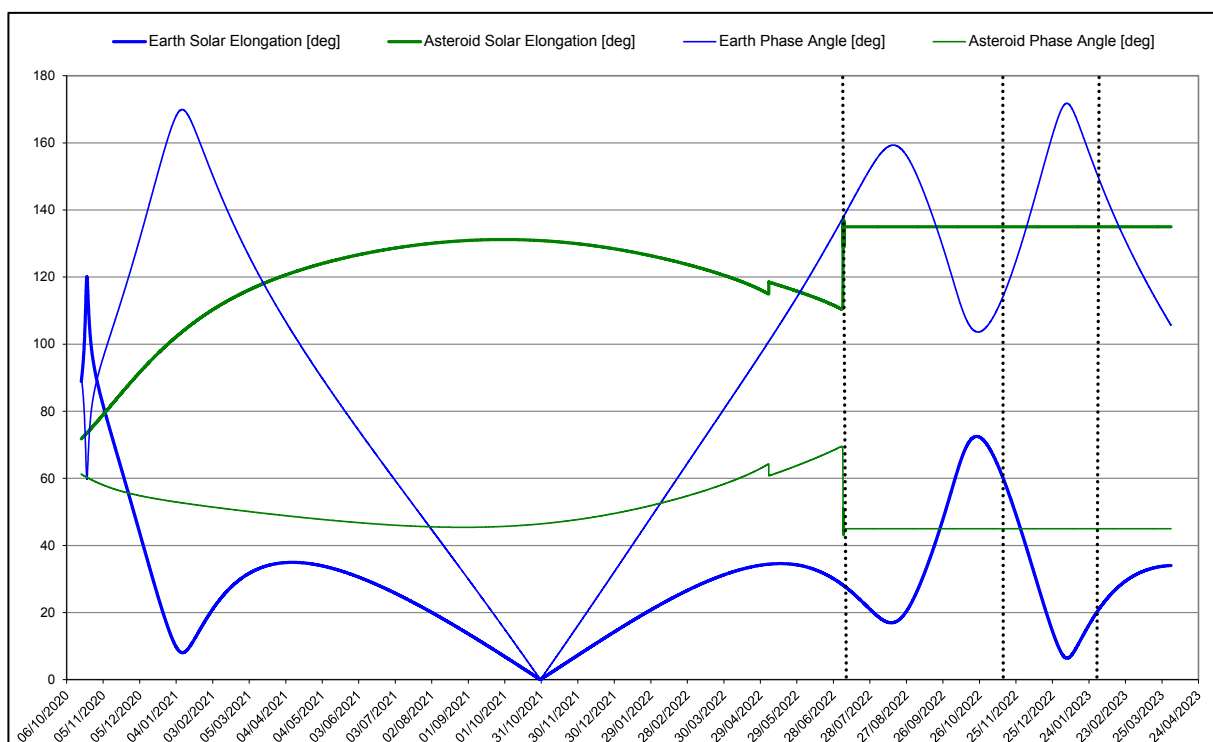


Figure 2 – Solar Elongations and Phase Angles

In order to cope with these differences, depending on power and communication needs at each phase, either a flexible spacecraft configuration or a pointing strategy is required. The chosen approach is likely to shift the driving case from one phase to another.

2.3 Illumination Conditions at Asteroid System

Multiple factors, most of which are still uncertain, affect the illumination conditions on the surface of the primary and secondary asteroids so, in order to perform an initial analysis, the following assumptions have been taken:

- ☐ The binary asteroid orbit is circular¹
- ☐ Primary asteroid rotation axis orientation and period are known (see [AD3]).
- ☐ Secondary asteroid orbit radius and period are known (see [AD3]).
- ☐ Secondary asteroid orbit plane in the equatorial plane of the primary asteroid¹.
- ☐ Secondary asteroid rotation axis orientation same as the primary².
- ☐ Secondary asteroid rotation period same as its orbit period³.

This implies that illumination conditions on the secondary asteroid can be assumed to be the same as for the primary just adding the effect of any possible eclipse caused by the primary on the secondary.

The first factor presented is the eclipse conditions on the secondary asteroid. And the second factor is the latitude zones for permanent illumination/darkness and those in between with a cyclic day/night variation for each rotation period.

Because of the assumptions given above, both factors depend only on the orientation of the asteroid system with respect to the Sun which can be seen in Figure 3 (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission).

¹ This is consistent with current theories on the Didymos binary system formation. For a detailed explanation see

² This is also a likely consequence of the secondary formation process and its synchronous orbital rotation.

³ Due to the synchronous rotation of the secondary

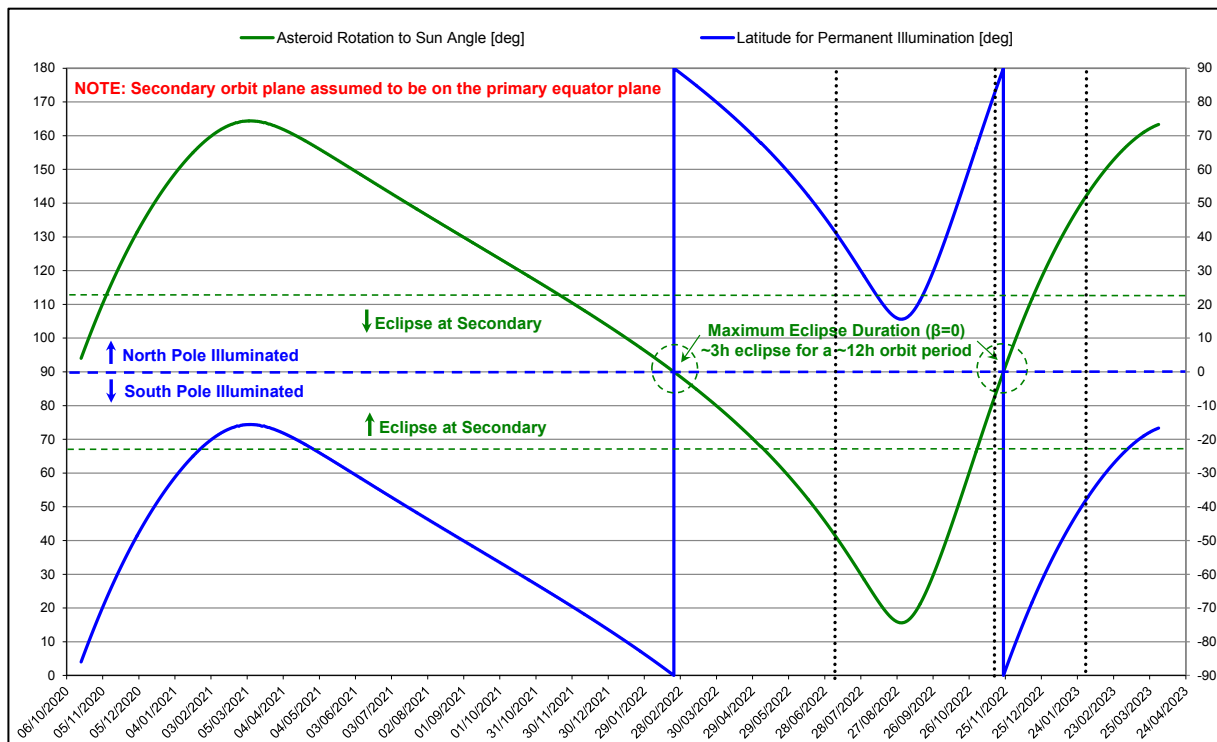


Figure 3 – Illumination Conditions on the Asteroids' Surface

Due to the radius of the secondary orbit, there is a band (represented by the green dashed lines) for the asteroid rotation axis to Sun direction angle (green plot, left scale) that causes the secondary to cross the shadow cast by the primary during part of its orbit.

In particular the secondary would be affected by eclipses only towards the end of the nominal operations phase becoming maximum (around one fourth of the orbit period) at the nominal end of mission (when the angle becomes 90° , zero orbit beta angle). And only towards the end of the potential extended mission it gets again out of the eclipse zone.

Regarding the illumination/darkness cycle on the surface of the asteroids, the latitude for permanent illumination (blue plot, right scale) has been derived from the rotation axis to Sun direction angle, in order to ease the interpretation:

- ☐ For positive values, any latitude above the plot latitude value up to the north pole are permanently illuminated.
- ☐ For negative values, any latitude below the plot latitude value down to the south pole are permanently illuminated.
- ☐ In both cases the opposite latitudes become of course permanently in darkness.
- ☐ Any latitude in between opposite latitude values has a day/night cycle variation for each rotation period.

This cycle is represented in Figure 4 (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission) for some

representative latitudes. In particular the percentage of the rotation period that the surface is in darkness (night) for each given latitude is provided.

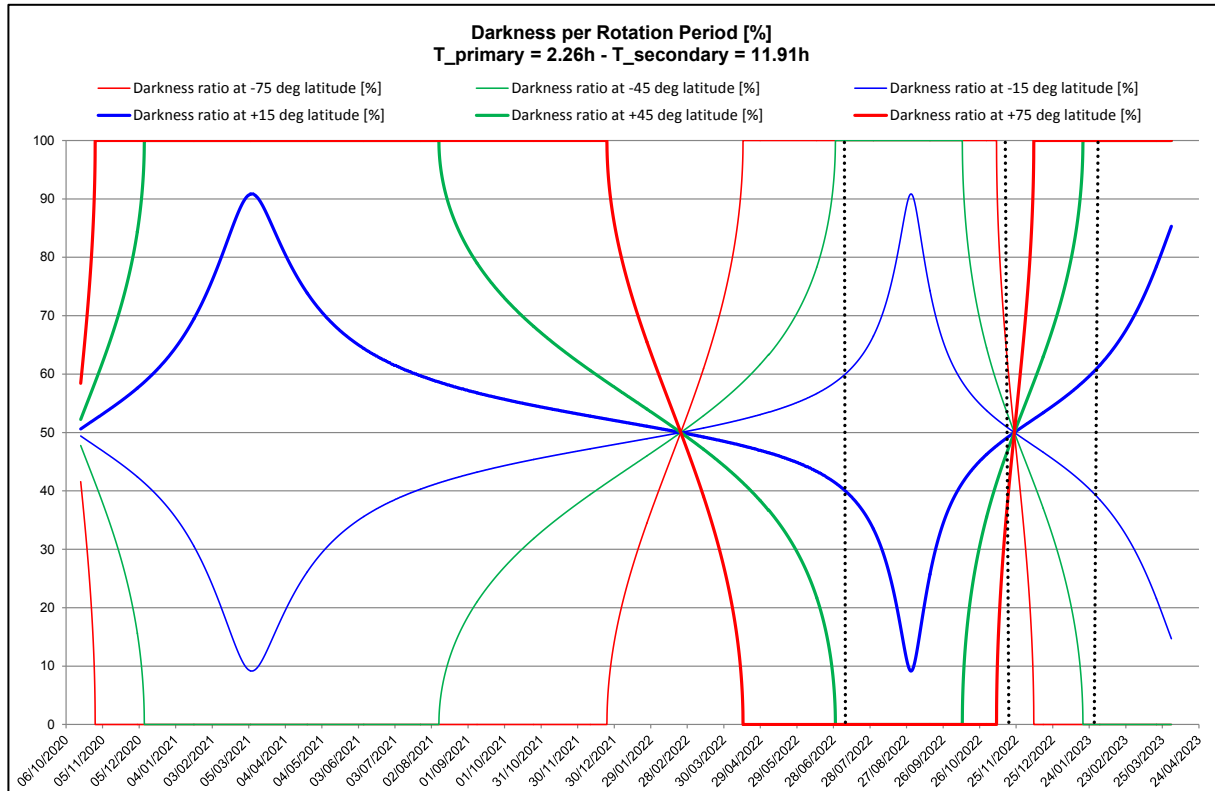


Figure 4 – Illumination/Darkness Cycle at Asteroids' Surface

Both figures show that the only latitudes that have such day/night cycle for the whole duration of the nominal operations phase are those between $\pm 15^\circ$.

Latitudes below -15° will be dark for the whole nominal operations phase becoming illuminated only early after the nominal end of mission and for the rest of the extended mission.

As mentioned before, these two effects, latitude and eclipses, get combined for the secondary asteroid; meaning that some longitude bands (irrespectively of the latitude) could have an additional period of darkness due to the eclipse which can be used to artificially extend the duration of these periods if required.

These factors are likely to drive, due to remote sensing needs, the required position of the spacecraft relative to the Asteroid and Sun and, due to power and thermal needs, the landing latitude for the MASCOT-2 lander.

3 PAYLOAD OPERATION DRIVING FACTORS

To achieve the necessary observation conditions on the asteroids' surfaces and instruments resolution for remote sensing during the nominal asteroid operations phase, the spacecraft is assumed to be co-flying with the asteroid system.

3.1 Operations in the characterisation phases

Different instruments have different observation goals and constraints. These are described in the [AD2].

During the characterisation phases the spacecraft operations should support two main types of remote sensing observations:

- Supporting observations aimed at the characterisation of features on the asteroids (for the Secondary as a must, and for the Primary as a goal). This will be necessary both to study local conditions with the required resolution (related to range) and viewing geometry (and hence angles), and also to extract information for the development of global models i.e. shape model, thermal model, and tomographic model.
- Operations supporting an accurately measurement the orbital and dynamical parameters.

The first type or measurement requires specific s/c operations to support the payload use. These operations depend on asteroid-spacecraft range, Sun-asteroid-spacecraft angle (Solar phase angle), and latitude coverage.

3.1.1 *Range*

The spacecraft-asteroid range during the characterisation phases depends on the payload specifications and ranges. The VIS should achieve a 0.5 m pixel size resolution (IFOV 50 μ rad) while for TIRI 20 m surface resolution (IFOV 1 milirad) is required. With the AIM3P model payload assumptions this were achievable from a 10 km distance.

The minimum range for the radar operation is 10 km. For this reason, 10 km was chosen in AiM3P as the nominal operational range in the characterisation phases.

3.1.2 *Solar phase angle*

For the VIS nominal surface observations and to obtain constant illumination conditions on the asteroids' surfaces a constant e.g. 45° solar phase angle position is considered as the most appropriate during VIS operation as an instrument.

During nominal operations, any position at 45° phase angle (any on the surface of a 45° semi-angle cone around the asteroid to Sun direction) would be equivalent in terms of illumination conditions.

Illumination conditions and the related operations are also relevant to TIRI, though this instrument can also be operated on the asteroid dark side. For TIRI, in order to measure day-night (or eclipse-induced) thermal variations and hence thermal inertia, access to the terminator region would be necessary at regular intervals during the characterisation phase.

Illumination conditions are not directly relevant to the HFR or LFR, though the detailed operational cycles of LFR will depend on the MASCOT-2 operations and power availability.

3.1.3 *Latitude coverage*

Moving the spacecraft up and down off the asteroid orbital plane would in principle improve pole coverage. If it turned out the asteroids' poles are not oriented perpendicular to the asteroid system orbital plane, which is unlikely, the coverage of the poles might not necessarily be improved in that way and an alternative angular motion of the spacecraft with respect to the poles would be needed.

At least one of the two possible pole solution specified in [AD3] would make the asteroid orbital plane almost perpendicular to the ecliptic. In that case, the access to the poles would be possible without abandoning the ecliptic plane.

In terms of surface coverage, for the VIS, TIRI and HFR the spacecraft operations required to obtain a global coverage could be similar. For the TIRI, and due to its push-broom operation principle, the swath should be enabled either by the rotation of the asteroids, the slewing of the spacecraft, or a combination of both.

The geometry for the LFR is chose according to different considerations. The principle of the transmission radar is, like in Rosetta's CONSERT, that the radar signal will propagate from the transmitter through the asteroid(s) to the transmitter. For this reason the lander and the spacecraft should be positions in opposite side with respect to the asteroid centre. The coverage could be achieved by positioning the spacecraft within the -30° elevation cone with respect to the local MASCOT-2 horizon.

3.1.4 *Characterisation s/c station points*

The combination of all the factors described above led to the definition of a number of discrete characterisation points where the spacecraft is positioned to operate remote sensing payload instruments. The spacecraft would have to move between these station



point to change the viewing geometry and meet the constraints imposed by the different payloads.

An alternative not analysed in detail in the course of the AIM3P study could be the use of flybys, like Rosetta does. This might make the planning of operations more complicated for a short mission, but has also advantages e.g. possibility to probe the gravity field, relevant to the mission goals (mass determination).

The station points are stationary with respect to Didymos orbit. For this reason these points are also used for the determination of the asteroid relative orbit period and the dynamical properties of the system by operation of the VIS (baseline is 480 times each 12 h).

3.2 Operations during MASCOT-2 and COPINS deployment

During deployment of MASCOT-2 the spacecraft position and orientation with respect to the secondary asteroid will be determined by the landing conditions, and in particular the landing speed relative to the ground and the landing latitude and longitude, driven by MASCOT-2 power and thermal operation and by the DART impact direction, respectively.

3.3 Operations during impact observation

During the impact observation phase the spacecraft would be positioned in a safe point 100km away from the asteroid, and lies in a plane perpendicular to the direction of the incoming DART spacecraft at asteroid impact (which is the likely direction of the resulting ejecta plume). This is expected to mitigate risks of the spacecraft being hit by the ejecta.

A solar phase angle that is optimal for the observation of the ejecta shall be considered to support the VIS, TIRI and HFR observation shortly after the impact (within the instrument integration time or sampling frequency).

3.4 Overview of payload operations plan

This section describes in more detail the temporal sequence that was assumed for the payload operations in the AIM3P study.

During the interplanetary cruise phase, only an early check-up and commissioning of the instruments is foreseen. The possibility of performing a long-range test with the Optel-D has been identified but not analysed in detail. The actual payload operations start two weeks prior to the arrival at the asteroid the AIM S/C would undergo a final approach phase in which the functionality of the payload will be checked again and final preparations for the measurement phases are performed. According to the mission timeline the



scheduled arrival at the asteroid is between 22th May and 1st July. After the approach the following phases would be executed:

- Early Characterisation Phase (ECP) / 2-6 weeks, depending on early or late arrival date: A *minimum* of one single VIS measurement set is acquired from 36 km distance from the asteroid and transmitted via the Optel-D data downlink system as a technology test. As a backup and for test validation purposes, the data is transmitted with the RF system. A measurement set consists in...It is also in this period and through the VIS operation, plus possible the operation of TIRI. When the landing site selection starts.
- Detailed Characterisation Phase Period 1. (1. DCP) / 4 weeks: The S/C will move to a position 10 km from the asteroid and conducts a *minimum* of one measurement set with the VIS, one set with the TIRI and one with the HFR. The generated data is transmitted to the GS via the RF link and possibly also by the OPTEL-D. The daily data volume downlink is maximised but always below the constraints set by the link performance and the DHS storage capacity (i.e. 16 Gbits).
- Lander phase / 2 weeks: The MASCOT-2 lander is deployed on the secondary asteroid in a point of the surface within a +/- 15 deg latitude band (TBC) that can guarantee power and thermal conditioning and safe MASCOT-2 operation for 3 months. In the same period the Cubesat Opportunity Payloads (COPINS) are also deployed and start operating for at least 1 month (this is just an initial assumption, as deployment timing and exact mission duration will depend on t exact mission that they should perform).
- Detailed Characterisation Phase Period 2. (2. DCP) / 4 weeks: A *minimum* of two measurement sets is conducted with the TIR and VIS. The HFR and LFR will both be operated. This will also be the case for any other payloads carried by MASCOT-2 in addition to the LFR. This data is transmitted to GS during this time period. Detailed instrument operation plan is defined by the daily datalink and mass memory storage Both the RF and Optel-D are used to maximise daily data downlink.
- Impact phase: The S/C retreats to a safe position one week prior to the DART impact (100 km from asteroid and in a plane 90 deg from the impact direction). The VIS, TIRI and possibly HFR and LFR are used to observe the ejecta resulting from the impact without putting at risk the spacecraft (the COPINS might be supporting this phase if operational).
- Detailed Characterisation Phase Period 3. (3. DCP): Following the DART impact the S/C will move to an observation point at 10 km distance from the asteroid. It will then conduct *at least* two VIS measurement sets and three TIRI measurement sets. The HFR and LFR will both be operated. The data is transmitted to the GS within the measurement phase.
- Possible extension: The mission may be extended for 3-4 weeks until 1st February.



Table 3-1 provides an illustration of the basic payload operation timeline. Temporal constraints for the operation of the LFR have not been defined within the AIM3P study. Any payload operations during DART impact have also not been specified.

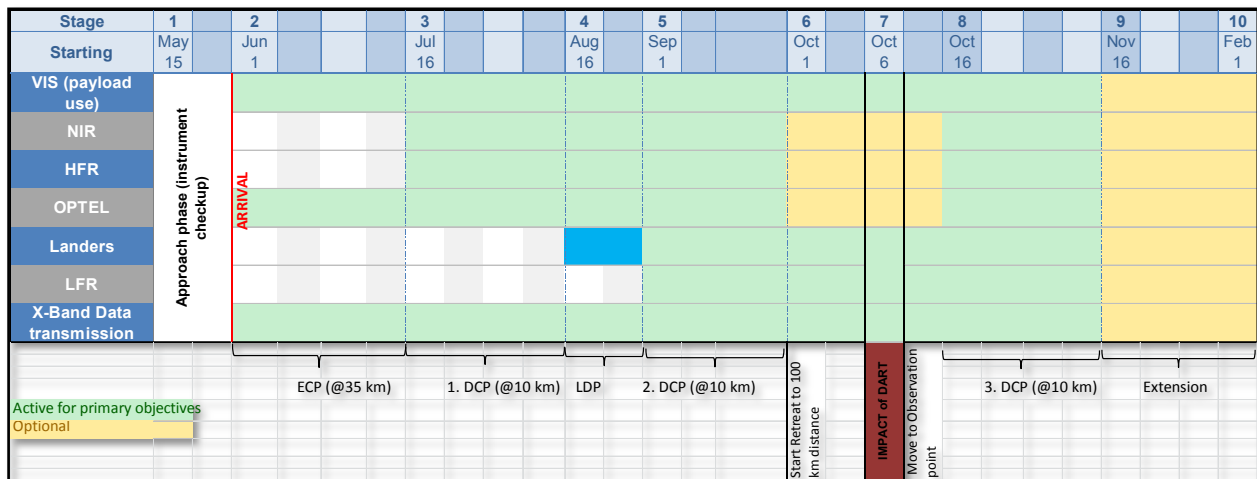


Table 3-1 AIM observation timeline

Table 3-2 presents a summary on the *minimum* data volume that would need to be produced during the mission to meet the asteroid observation goals.

Full use of downlink capacity by daily contacts compatible with the baseline ground stations i.e. ESA DSN and OGS, and the efficient use of on-board data storage, together with a suitable payload operation plan, are assumed to maximise data return.

Observation phase	Data volume [Mbit]	Measurements
Early Characterisation Phase	1258.	1 measurement set of VIS
Detailed Characterisation Phase Period 1.	11261	1 measurement sets of VIS + 1 measurement sets from TIR + HFR
MASCOT-2 Deployment Phase	TBD	
Detailed Characterisation Phase Period 2.	2523	2 measurement sets of VIS + 2 measurement sets from TIR
Impact Phase	TBD	
Detailed Characterisation Phase Period 3.	3784	2 measurement sets of VIS + 3 measurement sets from TIR
TBD	3690	Minimum data volume (MASCOT-2 inc. LF) + COPINS
Total	21260	

Table 3-2 Generated data volume by AM payloads

ANNEX. ANALYSIS OF SYSTEM IMPACTS ON AIM₃P CDF DESIGN

Due to driving factors such as those discussed in chapter 2, which are inherent to the baseline AIM mission design ([RD4]) a number of impacts on design trade-off can be derived for a given a set of system requirements.

As an example, in the context of the AIM₃P CDF study [RD1], the baseline configuration design aimed for a demonstration of the feasibility of a solution involving no mechanisms, hence fixed solar arrays, high gain antenna and payloads (with the exception of Optel-D) where analysed and all the factors presented in the previous chapter where taken into consideration. The resulting solutions are briefly described below to illustrate the system impact of the mission design driving factors.

A.1 Power and HGA Pointing

The fixed solar panels have been placed such that their normal direction is +X in the spacecraft body-fixed frame, and deployed along the $\pm Y$ axis (minimum inertia around these axes) following a conventional configuration.

To maximise power generation while pointing the high gain antenna to Earth, a fixed pointing offset with respect to the solar panels' normal was chosen. In Figure 2, the angular distance between Sun and Earth (Earth solar elongation) covers the range 0° to 70° having the maximum range variation during the nominal operations phase.

If a steerable antenna had been considered the pointing range to be covered during the nominal operations phase would have been -60° to 0° azimuth (in the XY plane measured from +X positive towards +Y) and -10° to $+60^\circ$ elevation (out of the XY plane positive towards +Z).

A first estimation of the power needs for communications moves the driving case to the interplanetary cruise phase when the spacecraft is at its furthest distance from Sun and Earth. In particular, a solar aspect angle of maximum 20° is required to ensure continuous communication with Earth.

Additionally there is an exclusion zone of 5° around the Sun, when the Earth is behind the Sun (see **Error! Reference source not found.**), preventing any communication. So this period can be excluded from the solar aspect angle constraint, due to the lower power needs if just in receiving mode or because, alternatively, power optimised attitude could be used.

Based on previous constraints, the high gain antenna was placed on the +X panel with a fixed pointing offset of 25° with respect to +X on the +X to +Z quadrant (to keep, as much as possible, pointing manoeuvres around the minimum inertia axis).

Comparing now the Earth Communications (antenna towards the Earth, +X aligned with the Sun direction) pointing mode to the other pointing modes in terms of power generation (Solar Aspect Angle) in **Error! Reference source not found.**

- During the interplanetary cruise phase, the solar aspect angle remains below 20° except for the exclusion period when it is not applicable.
- During the nominal operations phase, the solar aspect angle can go up to $\sim 45^\circ$ but still well below the limits for this phase due to the closer distance to Sun and general lower power consumption needs.

This last aspect can be better understood in Figure 5 (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission).

In this figure all effects, solar array orientation for each pointing mode and distance to Sun, are combined to provide the actual effective solar flux available per square meter through the mission.

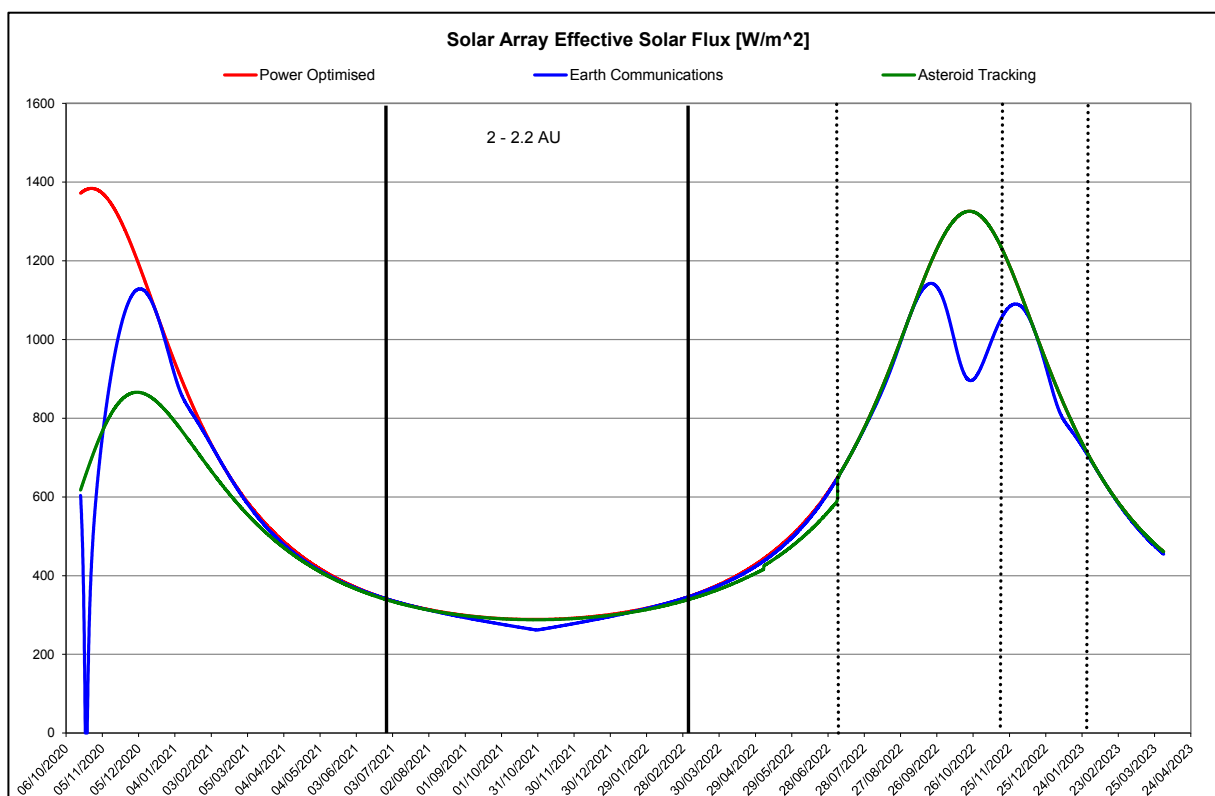


Figure 5 – Solar Array Effective Solar Flux

In particular how the power generation has been optimised for any pointing mode during the period the spacecraft is at its furthest distance from the Sun and Earth (between bold black lines) but minimising the impact while pointing to Earth for communications during the nominal operations phase when the spacecraft proximity to the Sun compensates the bigger solar aspect angles.

A.2 Consequences on the Remote Sensing Instrument accommodation and pointing

To achieve the necessary illumination conditions on the asteroids' surfaces and instruments resolution for remote sensing during the nominal asteroid operations phase, the spacecraft was assumed to be co-flying with the asteroid system such that the spacecraft lies between 10km and 100km away from the asteroid.

To obtain suitable illumination conditions on the asteroids' surfaces for the VIS a 45° phase angle position ahead of the asteroid on its orbit plane is assumed.

In order to allow pointing the instruments towards the asteroid while being power optimised (+X towards the Sun), the instruments must be placed on any spacecraft panel but +X (+Z was chosen) with their boresights pointing towards a direction 45° away from -X (-X to +Z quadrant was chosen).

The configuration defined in such way provides the results that can be seen in Figure 6 **Error! Reference source not found.** (where vertical dotted lines represent arrival to asteroid system, nominal end of mission and foreseen extended end of mission).

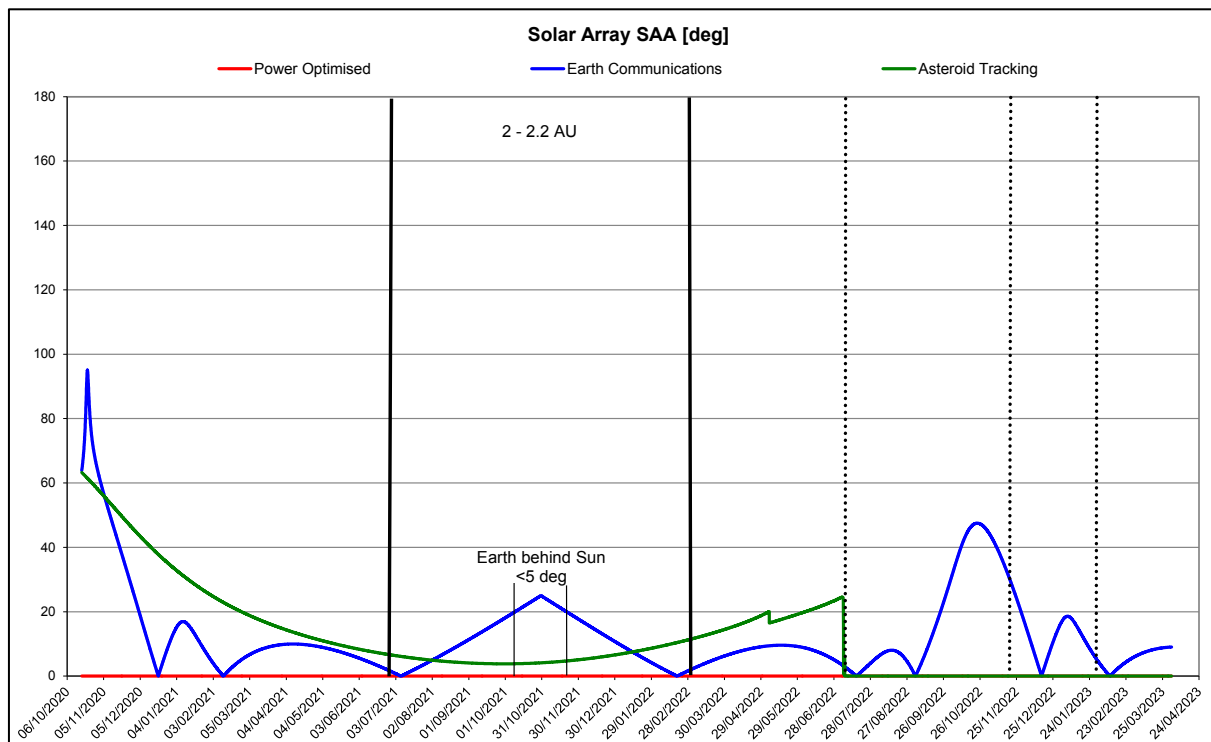


Figure 6 – Solar Aspect Angles per Pointing Mode



Comparing the Power Optimised (+X towards the Sun, instrument align with asteroid direction) and Asteroid Tracking (instrument towards the asteroid, +X aligned with the Sun direction) pointing modes in terms of power generation (Solar Aspect Angle).

- During the final approach at the end of the interplanetary cruise phase, observing the asteroid requires operating with solar aspect angles below 25° towards the asteroid arrival. The solar aspect angle is much bigger (up to 65°) at the beginning of the cruise phase, though the asteroid will be too dim to be observable by the VIS for most of this phase.
- During the nominal operations phase, by design, both pointing modes result in the same attitude and provide optimal power optimisation (zero solar aspect angle).