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Hera CubeSats Operational Mission Analysis for Didymos binary asteroid characterization

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Abstract

The Asteroid Impact Deflection Assessment (AIDA) mission, a collaborative effort for Planetary Defense, involves the DART and Hera missions targeting the Didymos-Dimorphos binary asteroid system. Their objectives include assessing asteroid deflection, conducting close observations, and demonstrating future mission technologies. DART, launched by NASA, impacted Dimorphos in September 2022, while Hera, an ESA spacecraft, carrying Juventas and Milani CubeSats, is set to reach Didymos in December 2026 after a two-year Cruise phase. The French Space Agency (CNES) contributes to Hera mission through the CubeSats flight dynamics and mission planning operations. This paper discusses the CubeSats trajectory design, taking into account the platform and safety requirements and the mission payload needs. Both CubeSats will carry out operations including ejection and separation, commissioning, far range observation, close range observation, and landing/disposal phases. The focus of the present paper is on the observation phases of the CubeSats. It highlights the importance of considering dispersion in the trajectory design, and its effect on both nominal trajectories and programming strategies. The paper illustrates how these latter elements are also impacted by the safety management between the three satellites involved in the Hera mission.

Keywords: Hera, CubeSat, Asteroid, Trajectory, Dispersion, Safety

Acronyms/Abbreviations

CMOC	CubeSats Mission Operation Center
CRP	Close Range Phase
D_1 & D_2	Didymos & Dimorphos
FOCSE	French Operation Centre for Science and Exploration
FRP	Far Range Phase
HMOC	Hera Mission Operation Center
ISL	Inter-Satellite Link
OD	Orbit Determination
SRP	Solar Radiation Pressure
SSTO	Self-Stabilized Terminator Orbit

1. Introduction

The planetary defense and science objectives of the two missions, DART by NASA, and Hera by ESA, are to assess the deflection of Dimorphos, the smaller asteroid of the Didymos binary system, to perform close observations for asteroid characterization, and to demonstrate navigation bases and autonomous technologies for future deep space missions. DART first impacted successfully Dimorphos on September 26, 2022. Hera, a spacecraft carrying two European CubeSats (Juventas and Milani) was launched on October 7, 2024. Hera is currently on a 2-year cruise phase, under ESA/ESOC operations lead.

When starting its close proximity operations at the binary asteroid, by December 2026, Hera, the mothercraft, will first characterize the asteroids in terms of dynamics, shape, and gravity models, before the release of the two CubeSats: Milani and Juventas. The French Space Agency, CNES, was granted responsibility for close proximity flight dynamics and mission planning operations of these two CubeSats around the binary asteroid. These operations will be held in Toulouse at the FOCSE (French Operation Center for Science and Exploration), which is part of the CMOC (CubeSat Mission Operation Center, ESEC, Belgium) with direct exchanges with the HMOC (Hera Mission Operation Center, ESOC, Germany). As part of the preparation activities for proximity operations, CNES is in charge of the Operational Mission Analysis of both CubeSats at a system level. The present paper focuses on this aspect, while the CubeSats payloads operations concepts are presented in another paper ([1]). The operational mission analyses conducted by CNES follow the preliminary studies handled by GMV and Politecnico di Milano.

The asteroid close proximity operations will consist of a series of phases, for both CubeSats, with ejection and separation, commissioning, insertion on mission orbit, far range observation, close range observation, landing and disposal phases. Taking into account the mission payloads, platform, and safety constraints for each phase implies specific trajectories and dedicated manoeuvre strategies. The CubeSats trajectory dispersion or trajectory prediction uncertainties, which are significant in this unknown environment and dynamics, should be considered in the trajectory design to ensure safe trajectories and robust programming strategies.

The paper first provides a mission overview with key background elements relevant to the topic. Secondly, the method used to take into account dispersion in the trajectory design is presented, a process which will prove to be key for this type of mission. The approach for safety management between the three satellites of the Hera mission is also detailed in this second section. Finally, the paper focuses on the trajectory design of the observation phases of the two CubeSats, taking into account mission needs, safety and dispersion aspects. The studies related to the other phases (commissioning, insertion, landing) of the mission are not addressed in this article.

2. Mission overview

2.1 Didymos dynamics

Didymos 65803 system is composed of two asteroids: Didymos the primary and Dimorphos the secondary. Their main properties are described in Table 1 (derived from [2]). A spacecraft inserted into the Didymos system environment is subject to four main interactions: the gravitational attraction towards D1, D2 and the Sun, and the force due to solar radiation pressure (SRP). There are still many uncertainties linked to the dynamics of the system, particularly concerning the orbit and phasing of Dimorphos, requiring robust and adaptable trajectories.

Table 1 – Didymos system properties (following DART impact)

D1 properties	**D2 properties**
Diameter* 730 m	Diameter* 150 m
Gravitational parameter 40.0867 $m^3.s^{-2}$	Gravitational parameter 0.292671 $m^3.s^{-2}$
Rotation Period 2.26 h	Orbital Period 11.3685 h Rotation Period supposed equal to orbital period if tidally locked
Distance between the centre of primary and secondary 1.204 km	

*(*Diameter of the sphere with the same volume as the asteroid)*

2.2 Juventas payload and platform

Juventas is a 6U-XL CubeSat with a wet mass of 10.95 kg developed by GomSpace. Its primary payload (JuRa) is a low-frequency radar used for the geophysical characterization of Didymos asteroids. It also has a 3-axis gravimeter

(GRASS) and ISL antennas for Radio Science Experiment, as well as two opportunity payloads. Juventas is equipped with the ADCS & GNC sensors and actuators described in Table 2. For navigation purpose, Juventas should have a maximum distance of 88 km from Didymos and a maximum phase angle[1] of 90°. The communication with the Hera mothercraft is ensured through an Inter-Satellite Link (ISL). Juventas should remain within a 60 km range from Hera to ensure ISL communications.

Table 2 – Juventas ADCS & GNC

ADCS Sensors	7	Fine Sun Sensors
	1	IMU
	2	Star trackers
GNC Sensors	1	Navigation camera
	1	Laser altimeter
Actuators	4	Reaction wheels
	8	Cold gas thrusters *(F = 1 mN, Isp = 50 s)*

2.3 Milani payload and platform

Milani is a 6U-XL CubeSat with a wet mass of 12.05 kg developed by Tyvak International. Its main payload is a multispectral imager (ASPECT) used to perform mineralogical analysis of both asteroids and to image the DART impact site. It also has a dust analyser (VISTA), a navigation camera (used as opportunity payload in addition to its main purpose: navigation) and ISL antennas (like for Juventas). Milani is equipped with the ADCS & GNC sensors and actuators described in Table 3. For navigation purpose, Milani should remain at a distance from Didymos between 200 m and 30 km and have a maximum phase angle of 90°. As for Juventas, the communication with Hera is ensured through ISL and Milani should remain within a 60 km range from Hera to ensure operational communications.

Table 3 - Milani ADCS & GNC

ADCS Sensors	1	IMU
	1	Star trackers
GNC Sensors	2	Coarse sensor module
	1	Navigation camera
	1	Laser altimeter
Actuators	3	Nano Reaction Wheels
	8	Cold gas thrusters *(F = 7.5 mN, Isp = 40 s)*

2.4 Mission timeline

Table 4 and Table 5 describe the different operational phases of Juventas and Milani, and their durations. The latter are preliminary and may evolve to answer the different operational challenges of the mission. The baseline is a total duration of 90 days of operations for each CubeSat (from its release), plus one optional month of operations. The observation phases of the two CubeSats, the focus of the paper, are highlighted in yellow.

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[1] Angle between the Asteroid-Sun direction and the Asteroid-CubeSat direction

Table 4 - Juventas operational phases

Juventas			
Preparation phase	PREP	3 days	Perform checks on instruments and systems (incl. in exposed configuration) before release
Commissioning phase	COMP	3.5 days	Release Juventas onto a safe ballistic arc and perform additional checks
Insertion phase	INSP	7 days	Insert the CubeSat on its first observation orbit
Observation phase 1	SSTO1	28 days	Carry out mission (JuRa and ISL)
Transfer phase	TRFP	< 1 days	Transfer from one orbit to another
Observation phase 2	SSTO2	28 days	Carry out mission (JuRa and ISL)
Landing phase	LAND	< 1 days	Land on Dimorphos and perform surface operations (GRASS and JuRa)
Total mission duration		**71.5 days**	

Table 5 - Milani operational phases

Milani			
Preparation phase	PREP	3 days	Perform checks on instruments and systems (incl. in exposed configuration) before release
Ejection and separation phase	ESP	3.5 days	Release Milani onto a safe ballistic arc Perform instruments and systems checks
Commissioning phase	COP	7 days	Insert the CubeSat on its first observation orbit
Far Range Observation phase	FRP	17 days	Carry out mission (mapping of both asteroids and microstructures)
Close Range Observation phase	CRP	28 days	Carry out mission (mapping with higher resolution and high-resolution data of DART impact site)
Experimental phase	EXP	21 days	Insert into successive SSTOs to get closer to the Didymos system and prepare landing
Disposal phase	DIP	< 1 days	Land on Dimorphos or Didymos
Total mission duration		**80.5 days**	

The mission timelines of both CubeSats, from their release to their disposal, and the Hera one are put into perspective in Figure 1 below. Note that the Hera Close Observation Phase (COP) and Experimental Phase (EXP) durations are indicative only.

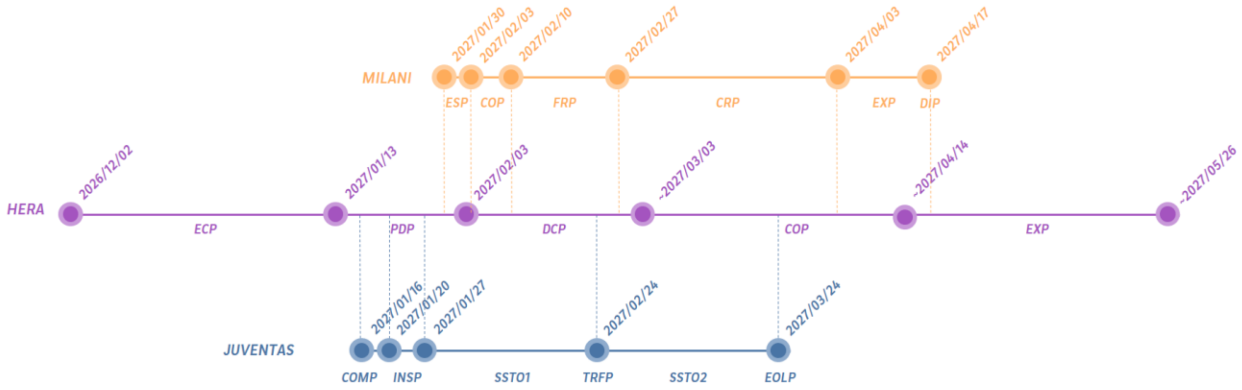

Figure 1 – Hera timeline and CubeSats mission timeline (from release)

3. Methods

3.1 Dispersion analysis method

Dispersion analyses are conducted in order to test the trajectory design robustness. Dispersion is defined as the deviation of the true spacecraft state with respect to the reference trajectory. Dispersion is linked to uncertainty sources like dynamical miss-modelling (mainly the gravity fields of the asteroids in the Didymos system), the spacecraft state knowledge (related to the precision of measures in particular) and manoeuvre execution errors. Dispersion analyses are performed over each phase of the CubeSat mission. It is anticipated that the dispersions will decrease over time as the understanding of the Didymos system improves and the confidence in the CubeSat propulsion system grows. The operational timeline for manoeuvre computation and command (outlined in section 3.1.1) has a significant impact on the result of the dispersion analysis.

3.1.1 Operational timeline for manoeuvre computation and command

The manoeuvres of the CubeSats are determined on ground in accordance with the trajectory design and the mission objectives. The manoeuvres are every 3-4 days to align with the Hera uplink / downlink schedule. Prior to the last (nominal) uplink before the manoeuvre execution, the manoeuvre is updated using the most recent result of the Orbit Determination (OD). The measures available for the orbit determination are about 50 hours old at the time of the manoeuvre execution. The manoeuvre is commanded via an uplink approximately one day prior to its execution (allowing for a back-up uplink). The nominal and back-up programming plans are commanded simultaneously with the manoeuvre. A programming plan starts with the manoeuvre execution and ends with the following manoeuvre opportunity. The operational timeline including orbit determination, manoeuvre computation based on the most recent OD, the manoeuvre and programming plans uplink and the manoeuvre execution is illustrated in Figure 2.

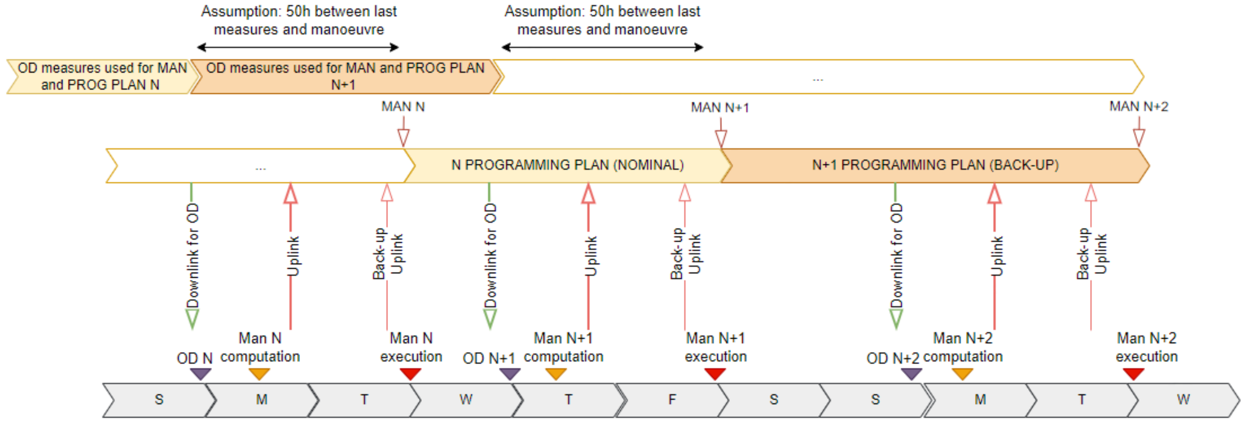

Figure 2 – Operational timeline for manoeuvre computation and command

3.1.2 Monte-Carlo simulations

The dispersion analyses are performed thanks to Monte-Carlo simulations. Between 500 and 1000 draws are usually done for the different studies. The following process is applied to each trajectory arc from the Nth Orbit Determination to the (N+1)th manoeuvre execution (see Figure 3): at OD N, knowledge uncertainties are applied to the initial spacecraft state (position-velocity) and then a propagation is done from OD N to manoeuvre execution N+1 taking into account uncertainties on Didymos gravitational parameters and gravity fields (modelled by Spherical Harmonics Expansion coefficients), the Solar Radiation Pressure and the manoeuvre N execution.

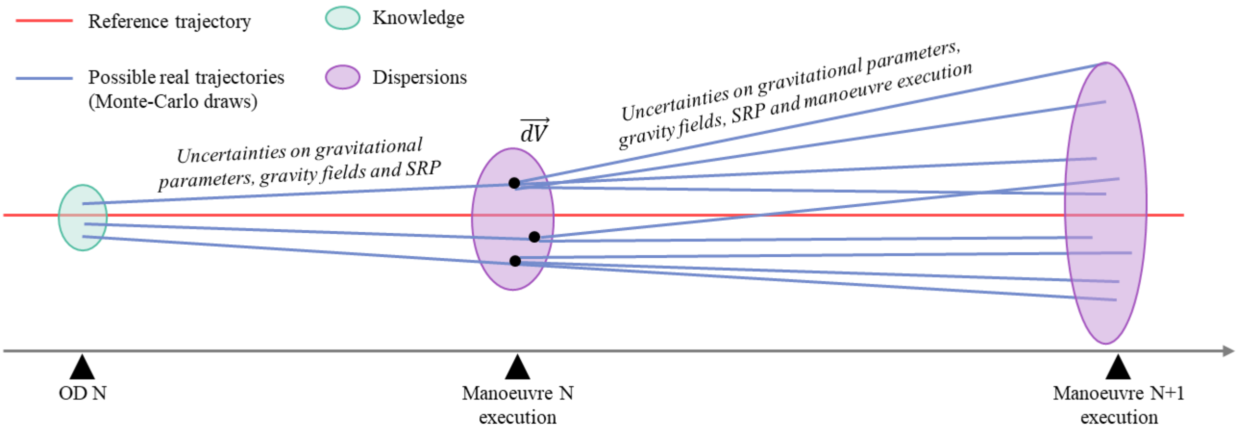

Figure 3 – Monte-Carlo simulations for dispersion analyses

The fact that the manoeuvre execution is around 50 hours after the last measures used for the manoeuvre computation (as explained in section 3.1.1) has a significant impact on the resulting dispersion envelop.

3.2 Safety management method

The collision risks between the CubeSats, and between each CubeSat and Hera, must be analysed throughout their respective missions. One of the objectives of the CubeSats operational mission analysis is to define CubeSats trajectories, collision-free by design, using worst-case dispersions (maximum 3σ values) for Hera and the CubeSats. This is an iterative process during which the nominal trajectories are analysed and updated if risks are identified. To analyse collision risk, the dispersions in position of each object is modelled by an ellipsoid (as illustrated in Figure 4), whose centre is on the object and whose axis are the maximum 3σ dispersions (over the phase) of the object defined in a Local Orbit Frame (Tangential, Along-track, Cross-track).

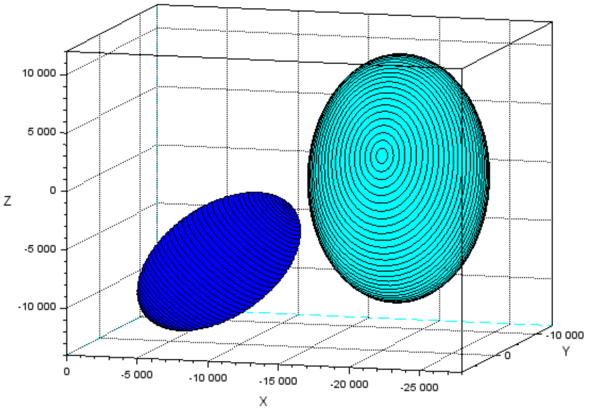

Figure 4 – Illustration of the dispersion ellipsoids of 2 objects in inertial frame

The trajectory is considered safe by design, if there is no intersection between the 2 ellipsoids at any point throughout the phase. The method used to detect intersections is based on [3].

4. Observation phases

The observation phases of Juventas and Milani are the phases during which the CubeSats will pursue most of their scientific missions. The trajectories have been designed to meet the requirements of the payloads used during these phases (JuRa for Juventas, ASPECT for Milani), while respecting all applicable constraints such as safety, platform or planning.

4.1 Juventas

4.1.1 Trajectory design

During this phase, Juventas will evolve on Self-Stabilized Terminator Orbits (SSTO). This type of orbit was chosen for its stability. Indeed, in an environment where the SRP is comparable to the attraction forces of asteroids, this choice enables to obtain quasi-periodic orbits. Those orbits have particular characteristics: they belong to a plan normal to the Sun direction and this plan is offset by ten to hundred meters along the Sun direction. Initial conditions for stable orbit can be generated based on the theory developed in [4] and [5]. The current baseline is two successive SSTOs with a semi-major axis of 3300 m and 2000 m. Both of them are represented in the Hill frame[2] in Figure 5. This baseline may evolve to optimize JuRa programming plan. In particular, an alternative of more successive SSTOs (and thus shorter durations) with decreasing altitude is under consideration (see 4.1.2).

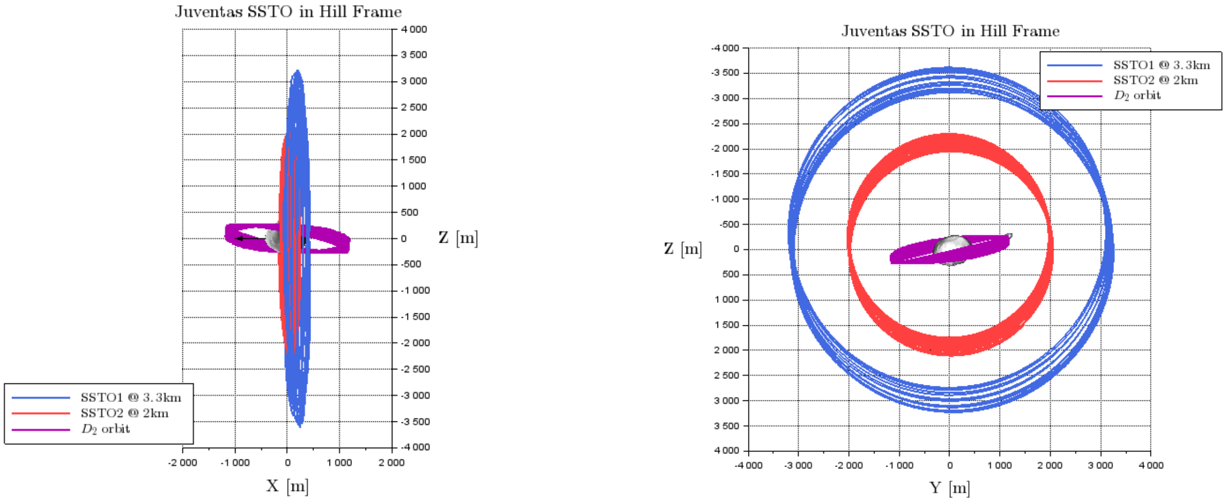

Figure 5 - Juventas SSTO-3300m & SSTO-2000m in Hill Frame

The stability of these orbits implies that station-keeping manoeuvres to stay in orbit around Didymos are not necessary. However, a station-keeping strategy to optimize mission programming could be envisaged in specific cases, as detailed in the next sub-section 4.1.2.

4.1.2 Mission programming & manoeuvre strategy

One of the challenges of JuRa scheduling is to maximize the coverage of the entire surface of the asteroids with a wide variety of geometries in order to increase the final performance. Several strategies have been considered for JuRa programming and Juventas associated manoeuvre strategy. A first one consists of using a reference trajectory, on which the CubeSat is asserted to. The mission programming plan is built and optimized based on this reference trajectory (long-term predicted trajectory). Station-keeping manoeuvres are performed to ensure the CubeSat remains close to this reference trajectory / to correct the dispersions. An analysis has been performed to assess if this kind of strategy was realistic considering the levels of uncertainties and dispersions on the CubeSat trajectory. For the study, the main operational parameter chosen (i.e. the parameter to maintain close to the reference) was the angular position of the spacecraft in the (yOz) Hill plane (referred to as "Argument of Latitude" (AoL)). The results of one simulated scenario is presented. The errors considered for the scenario are listed in Table 6. A station-keeping manoeuvre is computed to correct the initial dispersion on AoL of around 70° in 3 days. As demonstrated in Figure 6, it is not possible to predict whether the manoeuvre will improve or degrade the delta in AoL with the reference (left plot). In addition, there is a risk to obtain degraded SSTO, as illustrated in Figure 6 (right plot) where the semi-major axis of several cases have changed significantly. An improved solution would be to alternate AoL manoeuvres (manoeuvres to reach a given position) with SSTO stabilizing manoeuvres (manoeuvres to reach a given velocity). However, given the dispersions and the limited number of manoeuvres opportunities (only every 3-4 days, or accepting that manoeuvres are performed without orbit determination in between), this solution has not been considered viable either.

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[2] X-axis: Anti-sun direction | Z-axis: Parallel to the heliocentric orbital momentum of Didymos |Y-axis: completes the triad

Table 6 – Errors for Juventas SSTO station-keeping scenario

Errors	**Values**
Knowledge on Position-Velocity (diagonal matrices)	[10 10 10] m 1σ [1 1 1] mm/s 1σ
Didymos Gravitational Parameter	0.5% 1σ
Dimorphos Gravitational Parameter	1% 1σ
Didymos Spherical Harmonics Expansion	10% 1σ
Dimorphos Spherical Harmonics Expansion	10% 1σ
Solar Radiation Pressure (SRP) constant	8% as ECRV (Exponentially Correlated Random Variable)
Thrust amplitude	5% 3σ
Thrust direction	5° 3σ

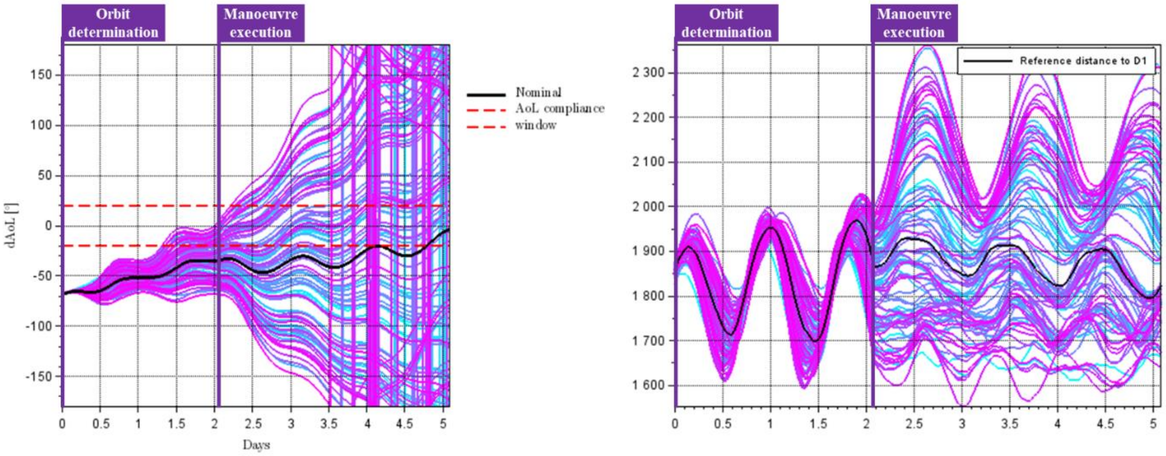

Figure 6 – Station-keeping manoeuvre impact on the operational parameter (left) and the distance to Didymos (right)

As conclusion of this study, it was decided as current baseline that JuRa nominal programming strategy should not rely on a reference trajectory, and especially not on a long-term predicted reference trajectory. Mission programming plan should be adjusted based on the short-term predicted trajectory or built with regular acquisitions (regardless of the trajectory prediction). The latter has the drawback of requiring superabundant acquisitions and margins in JuRa sequence tuning, resulting in larger data volumes and power limits. The manoeuvre strategy could consist of on-request / ad-hoc manoeuvres executed to create new geometric conditions for JuRa acquisitions, following JuRa data analysis (e.g. exit phasing conditions, target identified missing area…). In pursuit of the aforementioned objective, which is to enhance the diversity of orbital configurations, an alternative trajectory design, with successive SSTOs at different altitudes, is under consideration. The trajectory illustrated in Figure 7 includes 5 successive SSTOs between 2 km and 3.3 km and varying durations (1 week to 4 weeks).

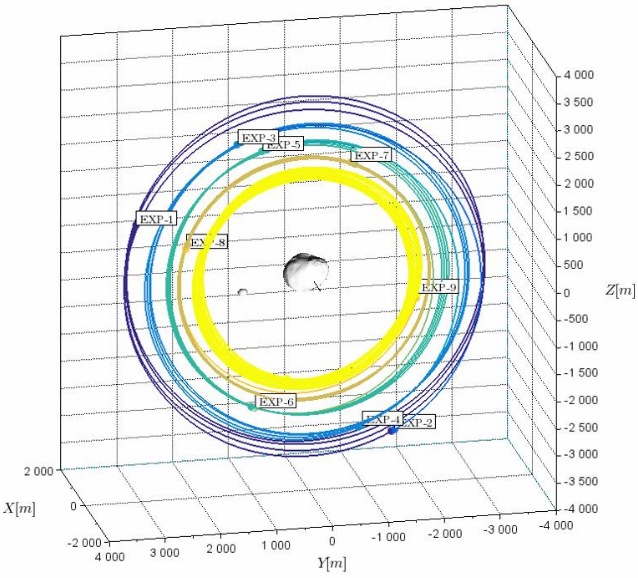

Figure 7 – Juventas successive SSTOs in Hill frame

4.2 Milani

4.2.1 Far-Range Phase (FRP)

Milani observation phase starts with a Far Range Phase whose main objective is the mapping of Didymos asteroids at different resolutions.

4.2.1.1 Trajectory design

The trajectory is designed with keypoints which meet the mapping acquisitions constraints, i.e. conditions in distance to the asteroid and phase angle. The trajectory is a succession of arcs on the day-side of Didymos. Some of the arcs are observation arcs (also called mission arcs) passing through keypoints, and some of them are "link arcs" which do not enable acquisitions (but are necessary for the feasibility of the constrained trajectory design). All arcs start / end with a manoeuvre. An illustration of this kind of trajectory is given in the Hill frame in Figure 8. Manoeuvres are planned to follow the pattern of the Hera probe manoeuvres, which leads to a succession of 4 and 3-day arcs. Several patterns have been envisaged for this phase and are illustrated in 2D in a plane perpendicular to the Sun direction in Figure 9. The first pattern (top left plot) consists of observation arcs only. The second pattern (top right plot) consists of a succession of observation arcs and link arcs with high phase angle. The third pattern (bottom plot) also consists of a succession of observation arcs and link arcs, but the link arcs have even higher phase angle which lead to less optimized programming plan. Nevertheless, the baseline is the third pattern, as it ensures greater safety with regard to Hera (as explained in section 4.2.1.3). The phase design may evolve to include different patterns with different durations (in accordance with ASPECT programming needs and safety).

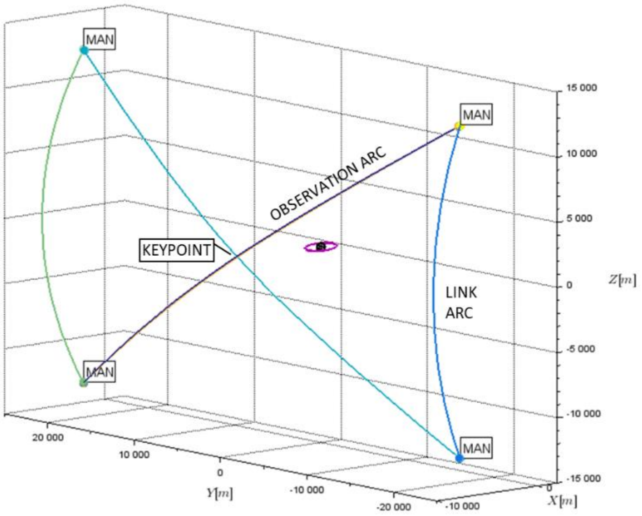

Figure 8 – Milani FRP trajectory design in D1-equatorial Sun frame[3]

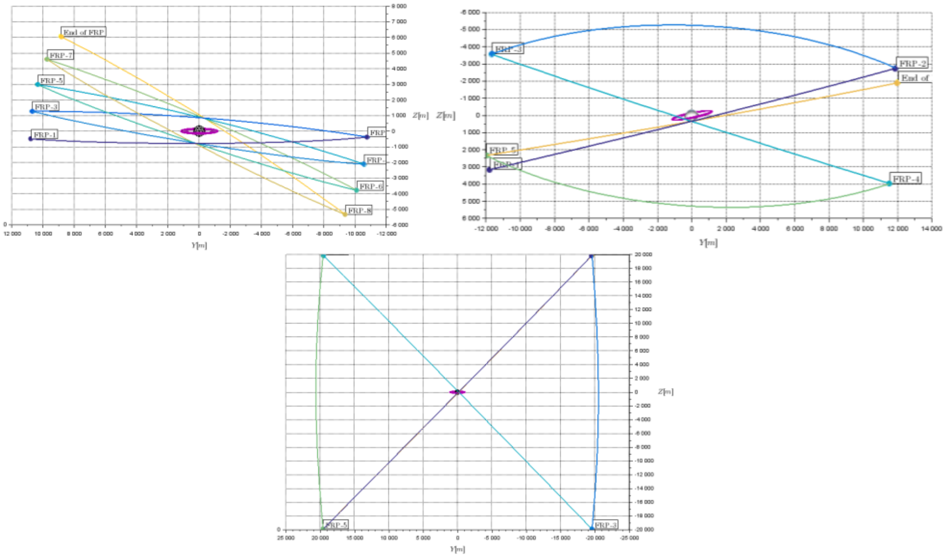

Figure 9 – Milani FRP patterns (2D illustration in a plane perpendicular to Sun direction)

4.2.1.2 Mission programming & manoeuvre strategy

During this phase, Milani follows the reference trajectory. Each manoeuvre at the start of an observation arc is adjusted to ensure the CubeSat meets the conditions required for ASPECT acquisitions (as long as other requirements related to the platform and the safety are respected), given the initial dispersions on the CubeSat position and velocity at the beginning of the arc. The programming plan is uplinked together with the manoeuvre and computed based on the predicted short-term trajectory including this manoeuvre. It is assumed that no adjustment of ASPECT acquisition times is performed on-board to take advantage of the better on-board position knowledge. A manoeuvre at the beginning of a link arc is computed to go back to the reference trajectory at the end of the same arc, or if the deviation is too high (and the arc would not meet platform and safety requirements), the reference trajectory is adjusted. Margins must be defined on conditions to be met for acquisitions to take into account for dispersions and anticipate trajectory prediction uncertainties. Figure 10 illustrates the dispersed positions of Milani at the time of one acquisition for one FRP arc, simulating the errors listed in Table 7. Figure 11 shows the effect on the phase angle and raw resolution. With the given assumptions for trajectories prediction accuracy, it is found that up to 27% of cases violate the targeted

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[3] X-axis: Anti-sun direction | Z-axis: Projection of the spin axis of D1 on the plane normal to X |Y-axis: completes the triad

maximum phase angle (25°). As illustrated in Figure 12, the margins to ensure that conditions for acquisition are respected for this scenario would be approximately 1.25 km in distance and 15° in phase angle (which exceeds the phase angle window specification). The margins increase in proportion to the duration between the last orbit determination used for programming and the acquisition.

Table 7 – Errors for Milani FRP dispersions scenario

Errors	**Values**
Knowledge on Position-Velocity (diagonal matrices)	[10 10 10] m 3σ [1 1 1] mm/s 3σ
Didymos Gravitational Parameter	0.5% 1σ
Dimorphos Gravitational Parameter	1% 1σ
Didymos Spherical Harmonics Expansion	0.5% 1σ
Dimorphos Spherical Harmonics Expansion	1% 1σ
Solar Radiation Pressure (SRP) constant	1% as ECRV (Exponentially Correlated Random Variable)
Thrust amplitude	2% 3σ
Thrust direction	2° 3σ

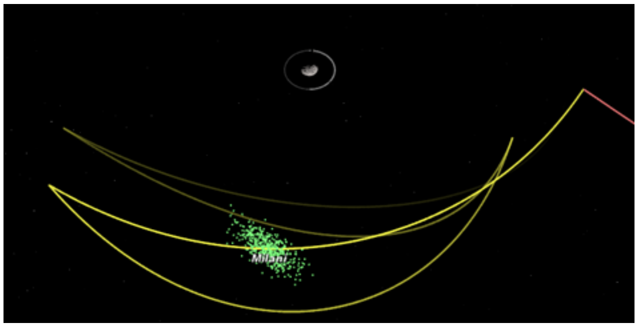

Figure 10 – Milani dispersed positions at the time of one acquisition during FRP (the green dots represent the dispersed positions, the yellow line the reference trajectory)

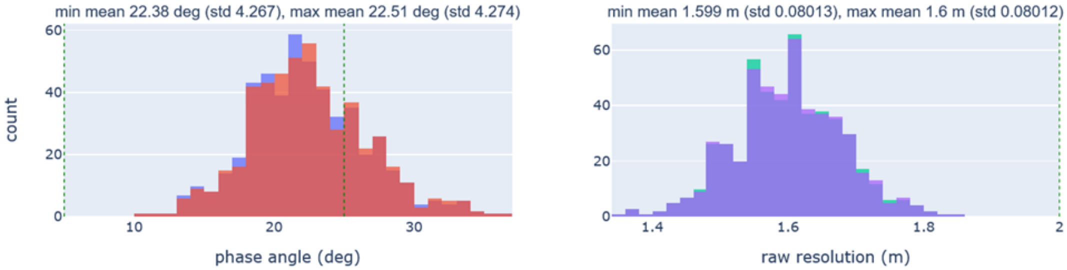

Figure 11 - Impacts on phase angle and raw resolution (min/max values)

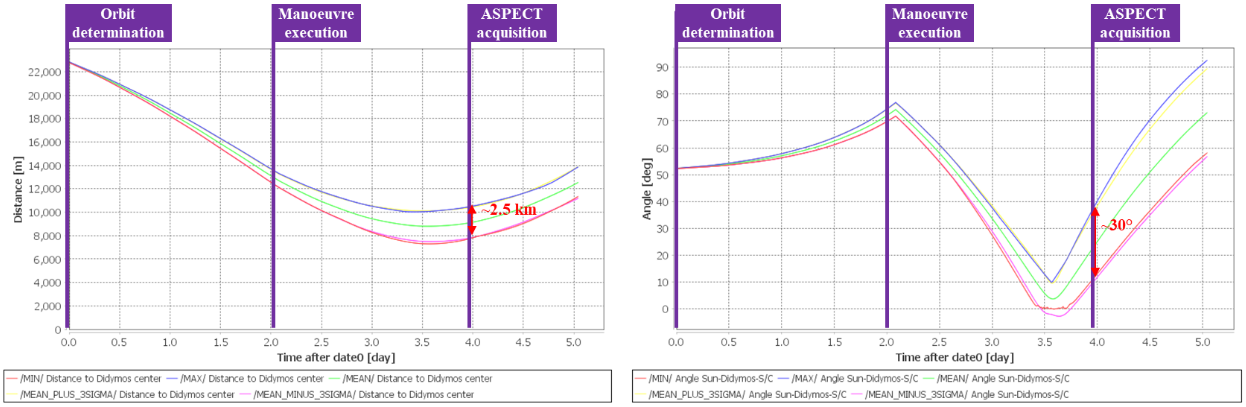

Figure 12 – Dispersions in distance to Didymos (left) and phase angle (right) on FRP observation arc

4.2.1.3 Safety management between Hera and Milani

During Milani FRP, Hera is executing hyperbolic arcs on the day side of Didymos and is passing through the sub-solar point of Didymos for images acquisition, just as Milani (but Milani is a little closer to Didymos). The analysis of the nominal trajectories led to the discard of the FRP initial design, which included mission arcs only, but for which the distance between Hera and Milani (on reference trajectories) around the sub-solar point of Diydmos was very low (below 2 km). Milani trajectory design was updated to include "link arcs" (see section 4.2.1.1) between two mission arcs and thus avoid being at the sub-solar point of Diydmos at the same time than Hera. As a result of this update, the minimum distance between Milani and Hera during the FRP was doubled (around 4 km). However, when applying the safety management method described in 3.2, considering the dispersions given in Table 8, collision risks were detected and a new design update was required (illustrated in Figure 13). This last design is safe by design but has other drawbacks. In particular, it is more expensive (Δv around 50% to 70% higher than in the previous design) and the ASPECT programming plan is more constrained (less acquisitions possible in one mission arc, thus requiring a potential extension of the FRP to fully answer the mission requirements).

Table 8 – Maximum 3σ dispersions of Milani and Hera during Milani FRP

Maximum 3σ dispersions (km)	**Hera**	**Milani**
Radial	6.12	5.5
Along-track	10.5	9.45
Cross-track	10.23	9.2

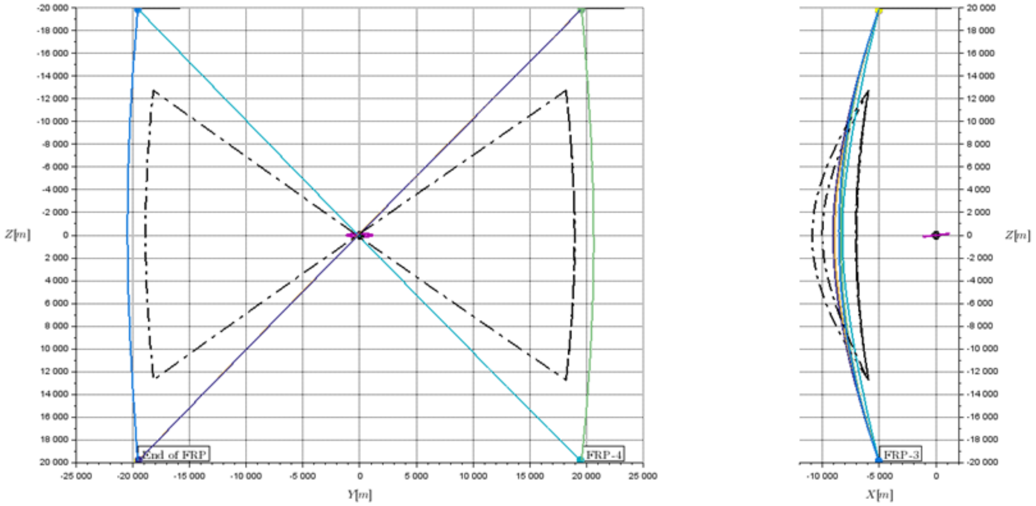

Figure 13 – Milani (coloured line) and Hera (black dotted line) during Milani FRP in D1-equatorial Sun frame

4.2.2 Close-Range Phase (CRP)

Milani observation phase continues with a Close Range Phase, whose goal is to provide a detailed mapping of D2, as well as detailed images of the DART impact site. The DART impact site is set on D2 surface with a longitude of 264.30° and a latitude of -8.84° [2]. Two images of the DART impact site at different phase angles shall be acquired.

4.2.2.1 Trajectory design

The phase alternates between three types of arcs: Waypoint, Escape, Re-catch. The design is similar to the FRP with succession of arcs in the day-side of Didymos and manoeuvres planned at the beginning / end of each arc.

Waypoint arcs: These arcs are dedicated to the observations of the DART impact site at specific points of the orbit, called Keypoints. Just as for FRP, these points are set to respect the imaging requirements. Placing them at such a low distance from Dimorphos is critical and represents a safety risk for Milani, which is why they are located around the end of the observation arcs (i.e. just before a manoeuvre opportunity) to ensure a minimum time spent at such low distance.

Escape arcs: These arcs are placed right after the waypoint arcs and are designed such that Milani goes quickly and safely away from the system. It is worth pointing out that these manoeuvres are the most expensive of the Milani mission analysis due to their close proximity to the system.

Re-catch arc: These arcs are conceived to reach the initial state of the next waypoint arc. This initial point is set to fulfil safety criteria for the forthcoming waypoint arc and to ensure that Dimorphos mapping acquisitions can be carried out over this same arc.

The current baseline for the CRP trajectory includes two full patterns (re-catch arc - waypoint arc - escape arc), as illustrated in Figure 14.

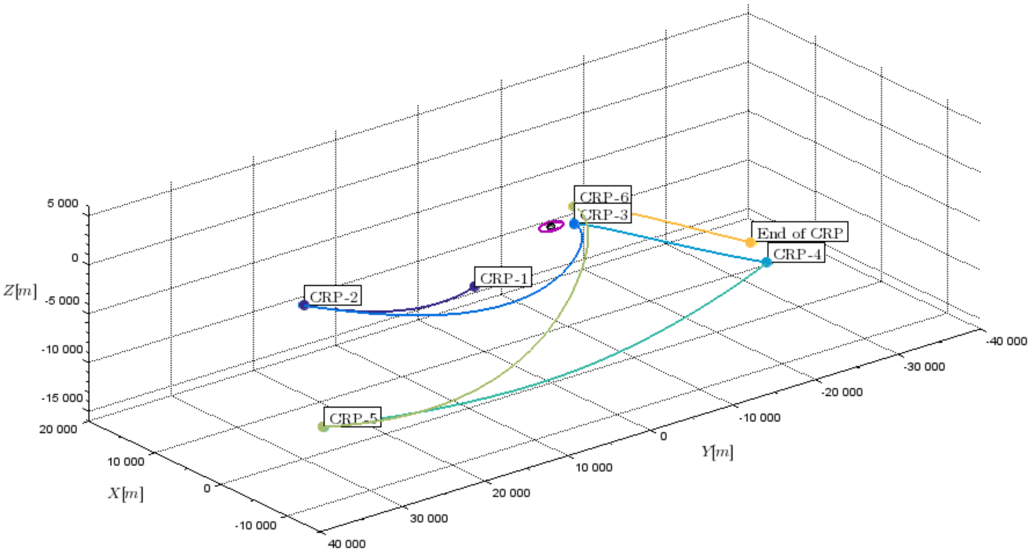

Figure 14 – Milani CRP in Hill frame

4.2.2.2 Mission programming & manoeuvre strategy

The manoeuvre strategy for waypoint and re-catch arcs is similar to the FRP one, where the waypoint arc consists of computing the associated arc from an observation point, and the re-catch arc allows the link to be made to the new observation arc. The strategy differs slightly from the FRP for the manoeuvre at the beginning of an escape arc, since this manoeuvre is not used to return to the reference trajectory. It is rather used to safely move away from the system, while respecting several constraints related to the platform (maximum ΔV, maximum phase angle) and the safety. Additional constraints, related to the DART impact site imaging, exist for the waypoint arc, leading to a specific operational timeline. First, the impact site should be imaged with optimal illumination conditions (low angle between the Impact site-Sun direction and the normal to the impact site). As a consequence, the position of Dimorphos on its orbit at the time of acquisition is constrained, and therefore so is the date of the keypoint / acquisition. The right time for the acquisition will have to be determined in operations using the short-term predicted trajectory. This date will impact the date of the manoeuvre post-keypoint, given that a certain delay should be respected between an acquisition and a manoeuvre (Δt_{min} in Figure 15). On the contrary, for safety reasons, the manoeuvre should be executed as soon as possible after the keypoint (Δt_{max} in Figure 15). In addition, due to the close proximity to the system at the end of the waypoint arc and the resulting safety risk, the waypoint arc duration was set to about seven days to allow for a corrective manoeuvre after 3 days. This corrective manoeuvre is used to correct dispersions caused by the manoeuvre execution errors at the beginning of the waypoint arc and the trajectory prediction errors, or even to abort the system approach (and thus the impact site imaging) if the situation is deemed too risky. The final programming plan for the DART impact site imaging is uplinked together with this corrective manoeuvre. Figure 15 illustrates the detailed timeline and key events of a waypoint arc. Figure 16 illustrates the advantage of the corrective manoeuvre on a waypoint arc after 3 days, considering dispersions limited to the manoeuvre execution error (equivalent to 5% (3σ) in magnitude and 5° (3σ) in direction) at the beginning of the waypoint arc. Although the corrective manoeuvre allows to reduce the dispersion envelop at the end of the waypoint arc, the close proximity observed in Figure 16 at the end of this arc (about 1.5 km for the closest case) suggests that, taking into account all dispersions (in particular including those in position-velocity), the resolution for the impact site imaging may need to be relaxed to ensure safety.

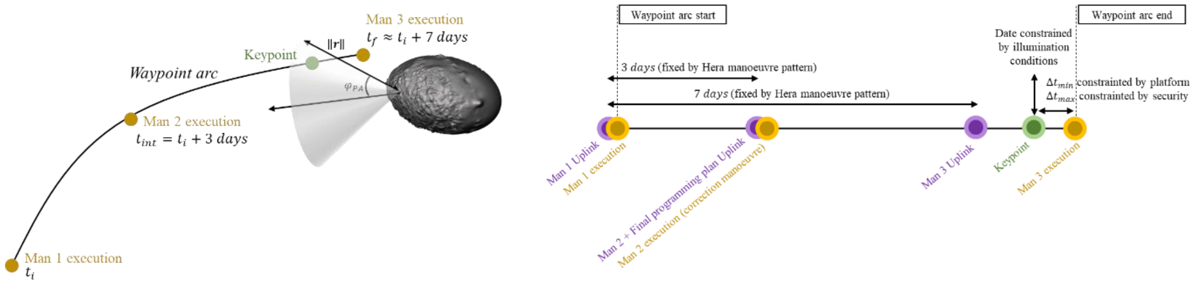

Figure 15 – CRP waypoint arc detailed timeline

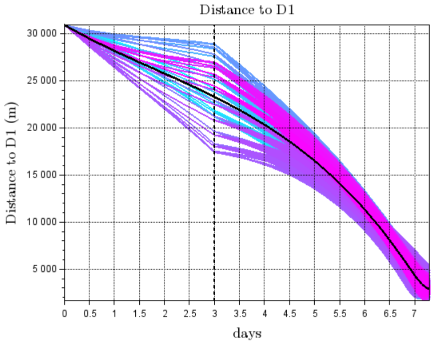

Figure 16 – Dispersion linked to manoeuvre on CRP waypoint arc

5. Conclusions

This paper presented some of the trajectory design studies conducted by CNES in the frame of the CubeSats Operational Mission Analysis. It emphasised the importance of considering dispersion in the trajectory design of the observation phases of Juventas and Milani. For Juventas, the expected level of dispersion makes it unrealistic to rely on a reference trajectory and requires reactive programming strategies and trajectory design adjustment during operations. For Milani, the introduction of margins and redundancies in the planning of payload activities are necessary to address these same uncertainties. This paper also pointed out that the safety management has a significant impact on the trajectory design (timelines, nominal trajectories…) and the programming plans. It highlighted that trade-offs between mission requirements and safety have already been necessary and are likely to be required again during operations. On top of that, considering that dynamical models will be updated when Hera will arrive nearby the binary system, it is important to consider additional possible adjustments on the mission timelines and trajectories designs due to model updates, as well as to eventual new opportunity science objectives and operational constraints arising from the asteroid environment.

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