

SpaceOps-2025, ID # 523

## Hera CubeSats Mission Planning and Payloads Operations Concept 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, under ESA/ESOC operations lead. CNES, the French Space Agency, is in charge of the CubeSats close-proximity operations in terms of flight dynamics and mission planning, covering ejection and separation, commissioning, far range observation, close range observation, and landing/disposal phases. This responsibility begins with the Cubesats operations concept design elaborated with the different Payloads Teams requirements to fulfill the scientific objectives of close characterization of Didymos, Dimorphos and the DART impact.

This paper presents the CubeSats payloads operations concept with an overview on mission programming optimization and refinement definition from long term (cruise) to very short term (close proximity operations) planning in partnership with Milani and Juventas Payloads Teams and Hera ground segment European stakeholders.

**Keywords:** Hera, CubeSat, Asteroid, Trajectory, ConOps, Close Proximity Operations, Mission Planning Concept, Planetary Defense, DART

### Acronyms/Abbreviations

C-FDSOC	Cubesats Flight Dynamics and Science Operation Center
CMOC	Cubesats Mission Operation Center
CMCC	Cubesats Mission Control Center
FDS	Flight Dynamics System
FOCSE	French Operation Centre for Science and Exploration
HMOC	Hera Mission Operation Center
MPS	Mission Planning System
SSTO	Self-Stabilized Terminator Orbit
SRP	Solar Radiation Pressure
$D_1$ & $D_2$	Didymos & Dimorphos
ISL	Inter-Satellite Link

## 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 and has completed in March 2025 a Mars swing for gravity assist to complete its journey to Didymos and Dimorphos.

During Cruise, Hera mothercraft is carrying Juventas and Milani, two 6U-XL CubeSats. When arriving at the binary asteroid, by December 2026 with a rendez-vous manoeuvre, close proximity operations will begin with the first characterization of the asteroids in terms of dynamics, shape, and gravity models, before the release of the two CubeSats. The French Space Agency (CNES) contributes to Hera's mission through CubeSats preliminary trajectory design and close proximity operations for flight dynamics and payloads programming. From the mothercraft ejection to the realization of the scientific objectives of the different payloads (imager, radar, gravimeter, dust detection, radio-science experiment) to landing, the proximity operations will be held in 2027 within the C-FDSOC (Cubesats Flight Dynamics and Science Operation Center, France) in support of the CMOC (Cubesat Mission Operation Center, Belgium) with direct interface with the HMOC (Hera Mission Operation Center, Germany) as all uplinks and downlinks transit through the Hera mothership.

Taking into account the various constraints for each phase implies specific trajectories design with dedicated manoeuvre strategies and payloads acquisitions sequences through an adapted Concept of Operations shared with Hera ground segment European stakeholders and Payloads teams. As part of the preparation activities for proximity operations, CNES is in charge of the Operational Mission Analysis of both CubeSats which is presented in another paper ([1]). The present paper focuses on CubeSats payloads operations concepts and associated need for automation. The asteroid close proximity payloads operations consist in different mission planning strategies and optimizations, from far range to close range, during landing and surface operations. For Milani main payload, the hyperspectral imager ASPECT, optimized hyperbolic arcs and images acquisition planning are defined in order to map both asteroids and image DART impact site from different longitudes and illuminations conditions. For Juventas low frequency radar JuRa, optimized acquisitions sequences are planned from SSTOs (Sun Stabilized Terminator Orbit) at different altitudes for fulfill the tomographic coverage of the asteroids internal structure. These radar acquisitions are balanced with Radio Science Experiments sequences, considering the different resource constraints, to fulfill the objective of gravity field determination based on ISL range measurements. For Juventas final landing, the gravimeter GRASS and ADCS/GNC sensors will be programmed to ensure fine gravity field measurements during descent and on Dimorphos surface.

Considering the specific designed trajectories, the payloads operations concept considers from long term planning to very short term planning the different CubeSats constraints to refine the payloads acquisition programming sequence for each phase of the mission. This paper first provides an overview of Juventas and Milani mission timeline and trajectory design and then focuses on the CubeSats payloads operations concept with an overview on mission planning optimization and refinement definition from long term to very short term planning, as designed in partnership with Milani and Juventas Payloads Teams and Hera ground segment European stakeholders.

## 2. Mission overview

### 2.1 Hera mission

Hera is a planetary defense mission of firsts: rendez-vous with a binary asteroid and smallest asteroid ever visited, radar tomography of an asteroid, full-scale cratering physics experiment investigation, deep-space CubeSats for very close asteroid inspection. Hera, a 1.2 tons spacecraft, is carrying two Cubesats of less than 12 kg. The mothercraft will arrive close to the Didymos system by the end of 2026 for 6 months of science observation, whereas Cubesats operations shall last at least 3 months.

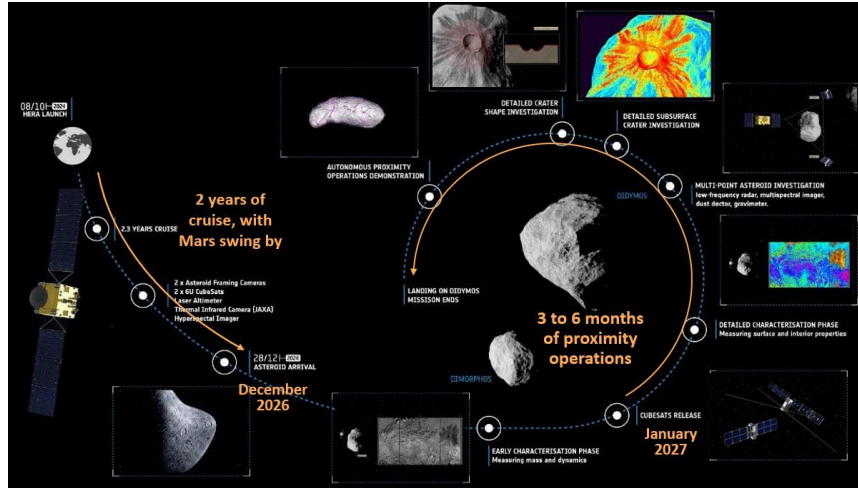


Figure 1: Hera timeline overview

## 2.2 Didymos dynamics

Didymos 65803 system is composed of two asteroids: Didymos the primary and Dimorphos the secondary. The main asteroid Didymos, or D1, was discovered by the University of Arizona Observatory in 1996. Its heliocentric orbit is eccentric with an apogee at 2.3 AU and perigee at 1 AU. Hence, its revolution around the Sun takes 770 days. Regarding the moon of the system, Dimorphos or D2, was not discovered before 2003. Indeed, due to the low Signal-to-Noise Ratio, the presence of D2 was hardly detectable. And thanks to the success of the DART mission, more precise data are available from the system and presented hereafter in Table 1. D1 and D2 properties are taken from the Didymos Reference Model [2] provided by ESA with estimated characteristics obtained through DART and LICIA Cubes probes images and from post-DART impact ground radar observation for estimation of the orbital period change after deflection. To mention just one of the outstanding results, the period of Dimorphos around Didymos has been reduced by  $33\text{min} \pm 1.0 (3\sigma)$  [3].

But there are still many uncertainties linked to the shapes and the dynamics of the system, particularly concerning the orbit and phasing and orientation of Dimorphos. Before DART impact, its rotation period was supposed equal to its orbital period with tidally locked hypothesis. After DART, Dimorphos rotation period may have been modified and the impact may have caused a tumbling effect.

Therefore, to fulfil science acquisitions needs, an adaptable mission planning concept is mandatory.

D1 properties	D2 properties
Diameter* 730 m	Diameter* 150 m
Rotation Period 2.26 h	Orbital Period 11.3685 h
Distance between the centre of primary and secondary 1.204 km	

Table 1: Didymos system properties (following DART impact)  
 (\*Diameter of the sphere with the same volume as the asteroid)

Note that the post-impact shape models are unknown. Preliminary models for a case of strong reshaping of Dimorphos are available but not taken as reference as the final Dimorphos model will be characterized once Hera reach the binary system.

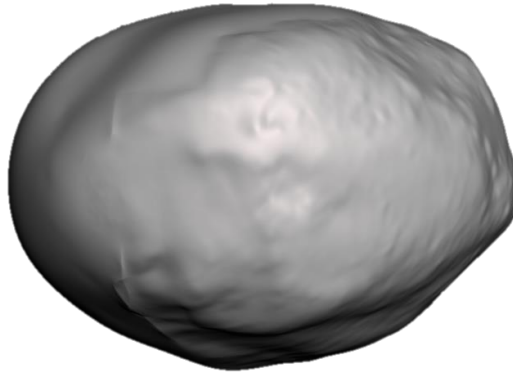


Figure 2: Didymos shape model (DART, DRACO images)

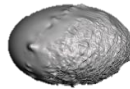


Figure 3: Dimorphos shape model before DART impact (DART, DRACO images)

### 2.3 Mission Timeline

Rendez-vous manoeuvre to get close to the binary asteroid is scheduled for October 2026 with the beginning of close proximity operations in December 2026. The two CubeSats will not be immediately released from the mothership. Hera will first perform an Early Characterization Phase to enhance our knowledge of the system in terms of dynamics. After 6 weeks, the first CubeSat, Juventas will be released in January 2027. If everything is nominal, fourteen days later, Milani will also be separated from the mothership to start its journey. Figure 4 below shows the preliminary timeline of each CubeSats, in relation with the mother craft timeline. These phases are summarized in Table 2 below and will be detailed in the next sections.

Juventas		
Preparation Phase	PREP	3 d
Commissioning Phase	COMP	4d
Insertion Phase	INSP	7d
Observation Phase 1	SSTO1	30d
Transfer Phase	TRFP	1 – 3d
Observation Phase 2	SSTO2	30d
Landing Phase	LAND	< 1d
Milani		
Ejection and Separation Phase	ESP	4 d
Commissioning Phase	COP	3d
Far Range Operation Phase	FRP	28d
Close Range Operation Phase	CRP	28d
Experimental Phase	EXP	17d
Disposal Phase	DIP	≈ 1d

Table 2: Juventas and Milani summarized Timeline Juventas and Milani summarized Timeline

The mission timelines of both CubeSats, from their release to their disposal, and the Hera one are put into perspective in Figure 4 below. Note that the Hera Close Observation Phase (COP) and Experimental Phase (EXP) durations are indicative only.

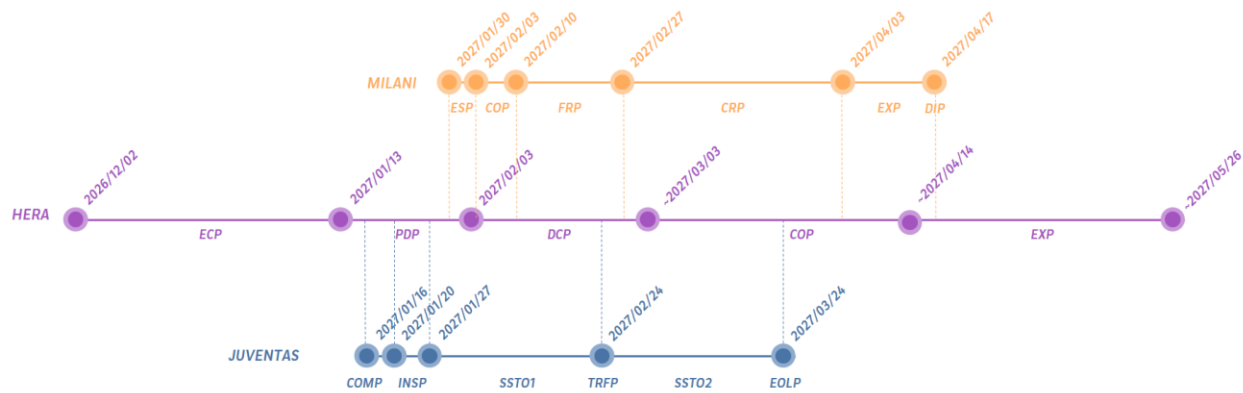


Figure 4: Hera timeline and CubeSats mission timeline (from release)

### 3. Juventas mission

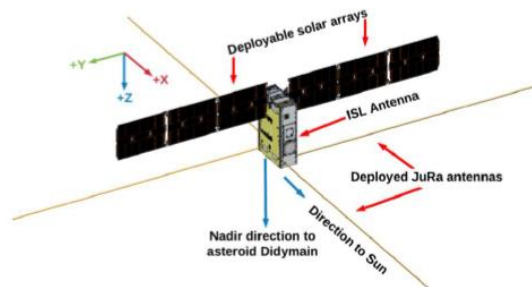
CNES is in charge of carrying on the preliminary studies handled by GMV on the Mission Analysis of Juventas until cubesat CDR. CNES is responsible of the Operational Mission Analysis taking into consideration both cubesats at a system level for proximity operations preparation and payloads requirements compliance.

#### 3.1 Payload & Platform

Juventas is a 6U-XL CubeSat with a wet mass of 10.95 kg developed by GomSpace and devoted to interior structure characterization and gravity field determination. Its primary payload (JuRa) is a low-frequency radar used for the interior structure characterization of Didymos asteroids. It also has a 3-axis gravimeter (GRASS) and ISL antennas for Radio Science Experiment. Juventas is equipped with the ADCS & GNC sensors and actuators described in Table 3. For navigation purpose, Juventas should have a maximum distance of 88 km from Didymos and a maximum phase angle<sup>1</sup> 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. Note that after deployment the solar arrays of Juventas are non-rotating.

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 (1mN, ISP=50s)

Table 3: Juventas ADCS & GNC



<sup>1</sup> Angle between the Asteroid-Sun direction and the Asteroid-CubeSat direction

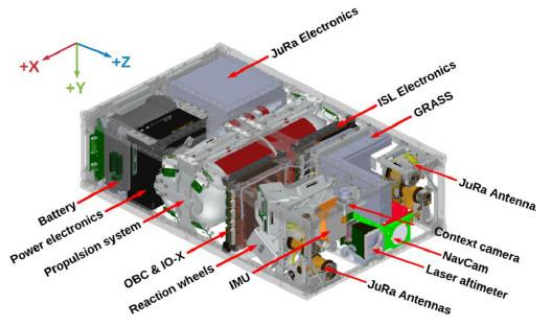


Figure 5: Juventas assembly (GomSpace)

### 3.2 Mission Objectives and Operational Constraints

Juventas main objectives are to determine the gravity field of Dimorphos, the interior structure of Dimorphos and the surface properties of Dimorphos. The main mission and operational constraints for Juventas are listed hereunder:

- The CubeSat shall map the surfaces of the asteroids with its navigation camera
- The Cubesat shall allow JuRa radar observation sequences and Radio Science Experiment measurements (ISL range measurements) with various relative geometries over close orbits
- The CubeSat shall allow GRASS gravimeter and landing IMU calibration sequences before the landing phase
- The mission shall end with the attempted landing of the CubeSat on the surface of Dimorphos
- The CubeSat shall remain within a 60km range from Hera to ensure ISL communications
- The Cubesats shall point toward D1 or D2 for optical navigation performances
- Trajectories arcs and manoeuvres shall have a duration compatible with operations timeline uplink and downlink pattern (4-3 days).
- Phase angle below 90 deg relative to both D1 and D2. This is a navigation constraint to ensure the visibility of D1 and D2 at any time, to enable optical navigation

### 3.3 Juventas Trajectory Design Overview

The proximity operations for Juventas mission are planned to start on January 2027 and are split into different phases listed below, for 3 months of operations that could be extended to 6 months.

Phase	Description
Preparation & Commissioning Phase – PREP & COMP -	The CubeSats will undergo checks in exposed phase then will be released on an hyperbolic arc with radar antennas deployment and S/C commissioning activities.
Insertion Phase - INSP	It represents the most critical part of Juventas mission. The CubeSat is inserted into its first observation orbit.
Observations Phase 1 - SSTO-3300	The spacecraft remains on a SSTO with a semi-major axis of 3300m. The purposes of the Observations Phase are to operate low-frequency radar (JuRa), and to perform radio science with the ISL.
Transfer Phase - TRFP	Juventas performs manoeuvres to reach a SSTO with a 2000m semi-major axis.
Observations Phase 2 - SSTO-2000	The spacecraft remains on this reduced SSTO.
Landing	Landing attempt on Dimorphos.
Bouncing and Surface	Surface operations with mainly GRASS measurements (JuRa measurements according to remaining power)

Table 4: Juventas Proximity Operations Phases

All Juventas manoeuvres associated to each phase are represented on the figure below (station keeping not included).

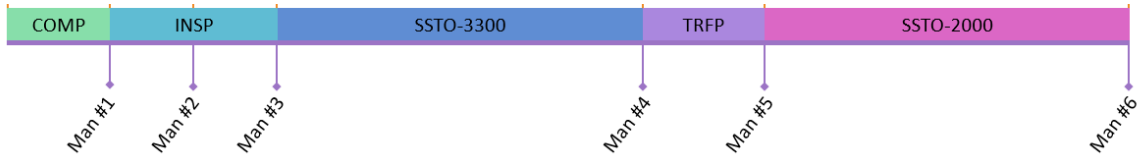


Figure 6: Juventas manoeuvres timeline

### 3.4 Insertion Phase (INSP)

The Insertion Phase of Juventas represents the first manoeuvres performed by the CubeSats in the Didymos dynamics. This phase follows the Commissioning Phase where the CubeSat was released by the mothership and left in free flight. After these 4 to 7 days of commissioning, the CubeSat is supposed to reach SSTO1 within 7 days. The design of this phase has been carried out with the idea of being robust to manoeuvring errors since calibration will not have been performed yet and given that the dynamics of the system will still be quite uncertain. The phase is designed such that the satellite is injected into a 7-day arc towards SSTO1 through a shooting method. This arc allows a possible manoeuver correction after 3 days if the first manoeuver was non-nominal.

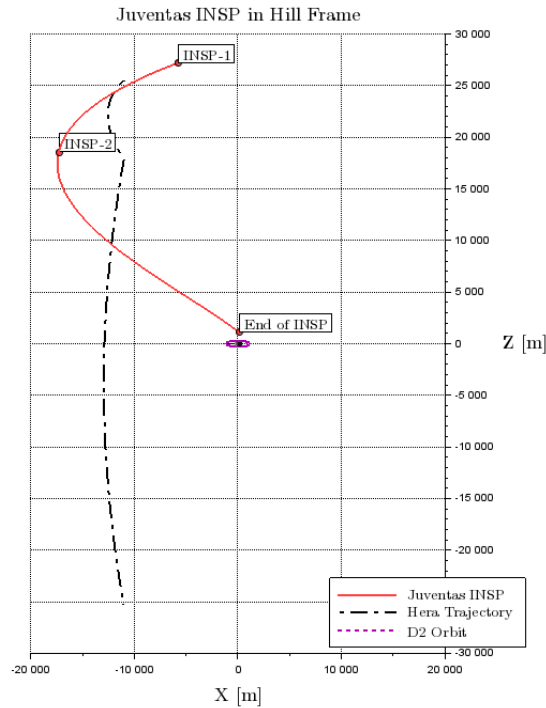


Figure 7: Insertion Phase in Hill Frame

### 3.5 Self-Stabilized Terminator Orbit (SSTO)

Juventas will pursue most of its scientific objectives during the observation phases where the spacecraft will evolve on a SSTO. This type of orbit was chosen for Juventas 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 from the barycenter of the system by ten to a hundred meters along the Sun direction. For JuRa radar acquisitions, it was decided that the satellite will evolve on two successive SSTO with a semi-major axis of 3300 m and 2000 m. Both of them are represented in the Hill frame in the figure below (where the Hill frame origin is at D1 mass center, X axis aligned with the Sun direction, Z axis aligned with the orbital momentum of D1 with respect to the Sun center, Y axis completes the right-handed system). The stability of these orbits implies that station-keeping manoeuvres are not mandatory. Though, dispersions studies are currently undergoing to assess the needs for station-keeping to answer mission

programming constraints. Note that the duration of each phase and the altitude considered during preliminary mission analysis could be modified depending on further mission programming optimization studies.

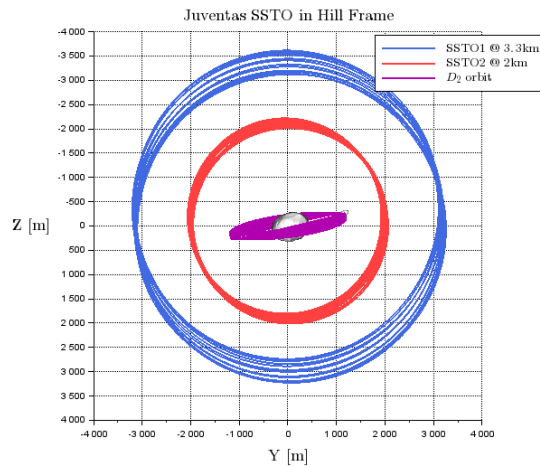


Figure 8: SSTO1 (3300 m) & SSTO2 (2000 m) in Hill Frame

### 3.6 Transfer Phase (TRFP)

The Transfer Phase consists of manoeuvring to leave the SSTO1 and reach the SSTO2 as in figure below. Current studies have revealed that a modification of the semi-major axis of SSTO1 induces an out-of-plan oscillation of the trajectory that will allow the satellite to intersect the plan of the second SSTO. The two manoeuvres are 180° apart and are initially computed using Keplerian hypothesis for semi-major axis modification then tangential correction is adjusted to match the final semi-major axis.

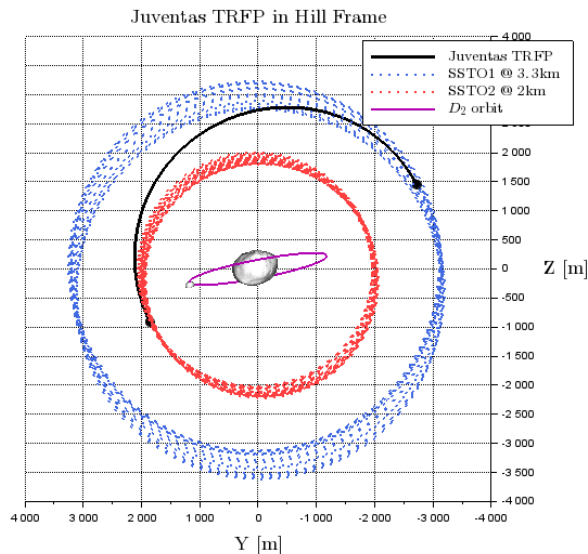


Figure 9: Transfer Phase in Hill Frame

### 3.7 Landing Phase (LAND)

Landing on an asteroid is quite critical operation, especially on a binary system such as Didymos. Considering a Circular Restricted Three Body Problem (CR3BP) expanded to take into account the ellipsoidal shape of Dimorphos, it is possible to determine the Guaranteed Return Speed (GRS) and an associated Time Of Flight (ToF) for a given Coefficient of Restitution (CoR) related to the surface properties of the asteroid. The GRS is a necessary condition,

from a purely energy perspective, that sets a maximum speed at the surface of D2 not to be exceeded on landing, at the risk of escaping from the body.

A preliminary study was carried out relying on a grid search on different landing parameters. Those were then converted into candidate trajectories departing from D2 surface, back-propagated to reach the SSTO using a variable time shooting method. However, this method failed due to high impact speeds exceeding GRS and CubeSat mechanical integrity ( $< 10 \text{ cm s}^{-1}$ ). To address this issue, a breaking manoeuvre was added, enhancing design flexibility. This method divides the landing into two phases: an approach arc bringing the spacecraft closer to D2 and a descent arc ensuring a safe landing.

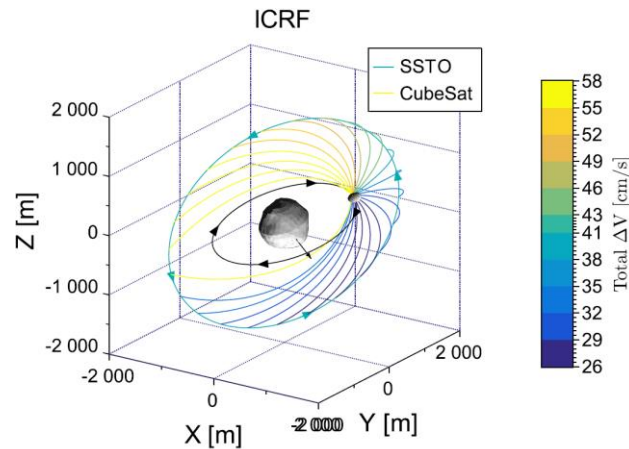


Figure 10: SSTO phasing study for landing and total DV assumption

- This strategy produces trajectories with sufficiently low impact speeds. The landing strategy involves five key parameters: landing epoch  $t_{land}$ , SSTO departure anomaly  $\theta_{SSTO}$ , approach and descent times of flight  $\Delta t_{approach}$  and  $\Delta t_{descent}$ , and landing velocity  $v_{land}$  taken normal to the surface. An optimizer was implemented with a selection of different minimization objectives. The initial guess for this optimization algorithm is determined as follows:
  - $t_{land}$ : characterization of the position of D2 is set by the user and the illumination conditions
  - $\theta_{SSTO}$  and  $\Delta t_{approach}$ : rely on preliminary phasing studies and on illumination condition throughout the landing
  - $\Delta t_{descent}$  and  $v_{land}$ : determined using the three body problem characterization.

### 3.8 JuRa payload operations on Juventas

JuRa is a low-frequency radar connected to two dipole antennas. JuRa observation sequence will typically last for 45 minutes and consists of a repetition of soundings composed of two bursts each with different polarizations. Each burst is composed of a repetition of thousands of pulses, while Juventas is pointing toward Didymos. During the radar measurements, the motion of Juventas w.r.t. the surface of the asteroids allows for 2D assessments. The accumulation of multiple observation sequences with varying conditions yields the third dimension, hopefully enabling full 3D tomography of D2, and approximately 150 m depth probing of D1. One of the challenges of the scheduling of JuRa sequences to increase the final performance (resolution and sensitivity) is to maximize the coverage of the entire surface of the asteroids with a wide variety of geometries while meeting and mitigating all applicable constraints.

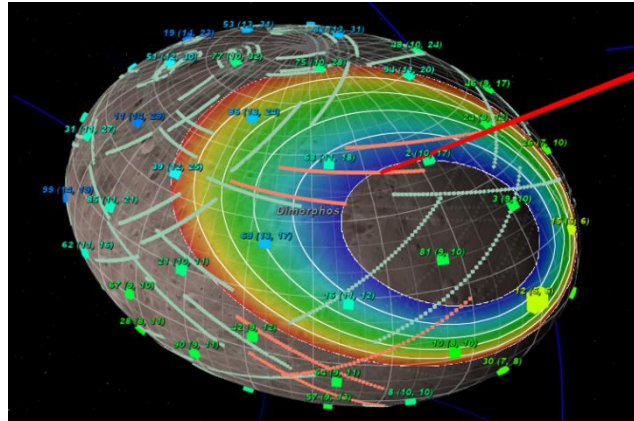


Figure 11: D2 surface sampling and ground tracks of all acquisitions. Example of JuRa instant acquisition contributing for point 12 (satellite direction in red) and areas with incidence angles within  $[25^\circ, 45^\circ]$  at this time

Regarding the latter, most stringent ones are the uncertainty of Juventas position prediction on SSTO (implying superabundant acquisitions and margins in JuRa sequence tuning both resulting in larger data volume) and energy consumption limits. Note that JuRa also offers the capability to prioritize measurements for their future download to Earth. So, the scheduling principles of JuRa acquisitions encompass the management of altitude and position prediction uncertainties on SSTO, the optimized revisit with varying geometrical conditions, the coverage through an Ewald sphere model and surface discretization (see Figure 11 and paper [4]), the energy balance modelling, the use of the download prioritization and also the possible activations for surface operations after landing on Dimorphos.

#### 4. Milani mission

CNES is in charge of carrying on the preliminary studies handled by Politecnico di Milano on the Mission Analysis of Milani until CDR. CNES is responsible of the Operational Mission Analysis taking into consideration both cubesats at a system level for proximity operations preparation and payloads requirements compliance.

##### 4.1 Payload & Platform

Milani is a 6U-XL CubeSat with a wet mass of 12.05 kg developed by Tyvak International and devoted to the visual inspection and dust detection of Didymos asteroid following DART impact. 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 5. For navigation purpose, Milani should remain at a distance from Didymos between 200 m and 30 km and have a maximum phase angle of  $90^\circ$ . 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. Note that the solar arrays of Milani are non-rotating.

ADCS Sensors	1	IMU
	1	Star trackers
GNC Sensors (including NavCam and LIDAR)	2	Coarse sensor module
Actuators	3	Nano Reaction Wheels
	8	Cold Gas Thrusters (7.5 mN, ISP=40s)

Table 5: Milani ADCS & GNC

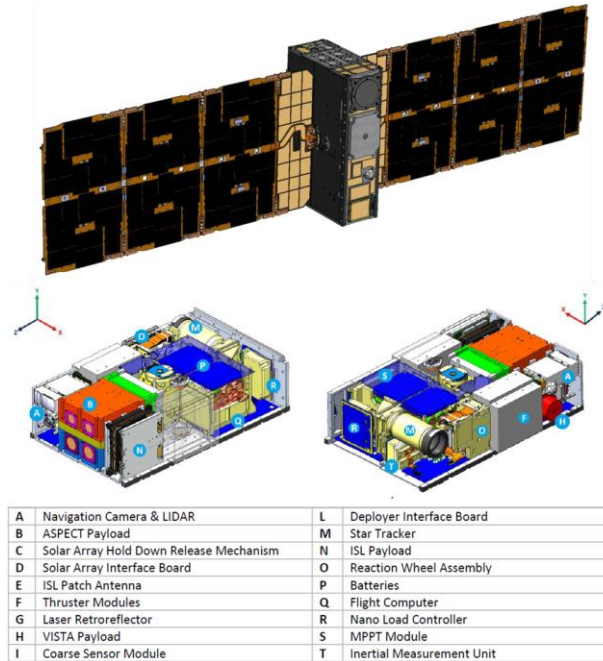


Figure 12: Milani assembly (Tyvak)

#### 4.2 Mission Objectives and Operational Constraints

Milani main scientific objectives are to:

- Map the global surface of the Didymos/Dimorphos asteroids
- Support gravity field determination
- Evaluate DART impact effects on Dimorphos
- Characterize dust clouds around the Didymos asteroids

The mission and operational constraints for Milani are derived from the mission requirements and the constraints due to ASPECT properties and operations (range, phase angle, relative velocity), optical navigation (range, phase angle), and data budgets.

The main mission and operational constraints for Milani are listed hereunder:

- The spatial resolution for Didymos bodies imaging shall be better than 2 m/pixel
- The spatial resolution for Didymos and Dimorphos imaging shall be better than 1 m/pixel
- The mission shall image the DART impact site with a spatial resolution better than 0.5m/pixel
- The CubeSat shall capture at least 5 images equally distributed over the longitude of D1 in both VIS and NIR wavelengths
- The CubeSat shall capture at least 5 images equally distributed over the longitude of D2 in both VIS and NIR wavelengths
- The mission shall image a selected area of Didymos bodies surface for phase curve measurement (surface microstructure) with ASPECT observations at various phase angles in the range of [0; 60] deg
- Phase angle below 90 deg relative to both D1 and D2. This is a navigation constraint to ensure the visibility of D1 and D2 at any time, to enable optical navigation
- Transversal component of the relative velocity between Milani spacecraft and the D2 surface during the observation of the crater shall be less than 2 m/s
- The CubeSat shall remain as close as possible to Didymos bodies during VISTA dust accumulation phases
- The CubeSat shall remain within a 60km range from Hera to ensure ISL communications
- The CubeSat shall remain on hyperbolic arcs to ensure the integrity of the system in case of missed manoeuvres
- The Cubesats shall point toward D1 or D2 for optical navigation performances

- Trajectories arcs and manoeuvres shall have a duration compatible with operations timeline uplink and downlink pattern (4-3 days).

#### 4.3 Milani Trajectory Design Overview

The mission of Milani begins after ejection from the mothercraft Hera. Its mission is split into five phases that are listed in table below.

Phase	Description
Commissioning Phase - COP	This phase starts at the separation from Hera. The required instruments and spacecraft systems will undergo some checks
Far Range Phase - FRP	Global mapping of both asteroids is performed at a range of 9-11 km from the system.
Close Range Phase - CRP	A Close-up Observation is done at a range of 2-6 km from the system to better map Didymos and Dimorphos and acquire high-resolution data from DART crater.
Experimental Phase - EXP	Milani starts a progressive descent of its altitude to inject itself on a SSTO at 3 km to wait for a phasing with Dimorphos allowing a landing
Disposal Phase - DISP	The spacecraft begins a descent to land on one of the Asteroids

Table 6: Milani Proximity Operations Phases

All Milani manoeuvres associated to each phases are represented on the figure below.

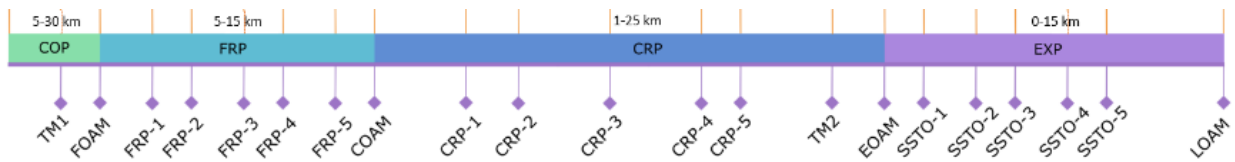


Figure 13: Milani manoeuvres timeline

#### 4.4 Far Range Phase (FRP)

The FRP phase aims at observing the system from a distance about 10 km ensuring the safety of the probe and carrying out a complete mapping of D1 and the first images of D2. Its trajectory consists of a succession of hyperbolic arcs on the illuminated side of the two bodies. The manoeuvres of this phase are designed to follow the pattern of the Hera mothercraft manoeuvres patterns, synchronized with the ground segment uplink operations cycles which are a succession of 4 and 3 days duration arcs. From the scientific requirements, one can define Waypoints which correspond to manoeuvre points in the figure below. Once these points are defined, a shooting method is used to generate the arcs between the waypoints.

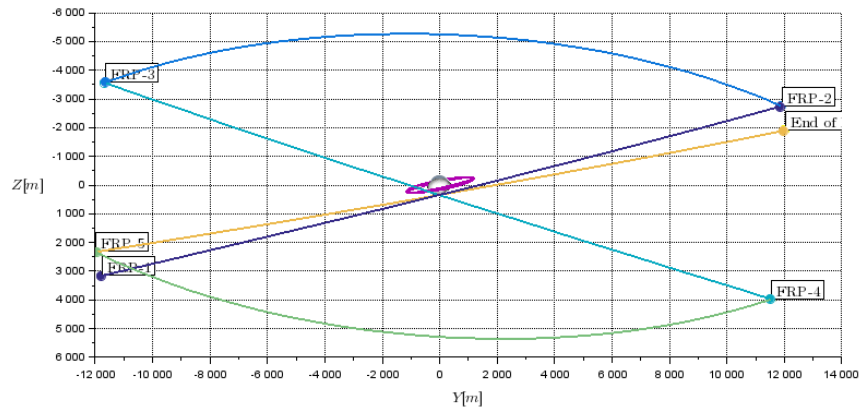


Figure 14: Far Range manoeuvres in Hill Frame

#### 4.5 Close Range Phase (CRP)

The Close Range Operation Phase goal is to provide a detailed mapping of D2, as well as detailed images of the DART crater. The DART impact site is set on D2 surface with a longitude of  $264.30^\circ$  and a latitude of  $-8.84^\circ$  [2]. Two images of the crater at different phase angles have to be acquired. To do so, the phase alternates between three types of arcs: Waypoint, Escape, Re-catch.

**Waypoint arcs:** These arcs are dedicated to the observations of the crater at specific points of the orbit, called Key points. These points are set to respect crater imaging requirements mentioned previously. Placing them at such a distance from D2 is critical and represents a safety risk for Milani which is why they are located around the end of the observation arcs 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. To determine which direction ensures the safety of the spacecraft, a dispersion analysis is performed for fixed  $\Delta v$  and escape velocity norm. 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 through a shooting method.

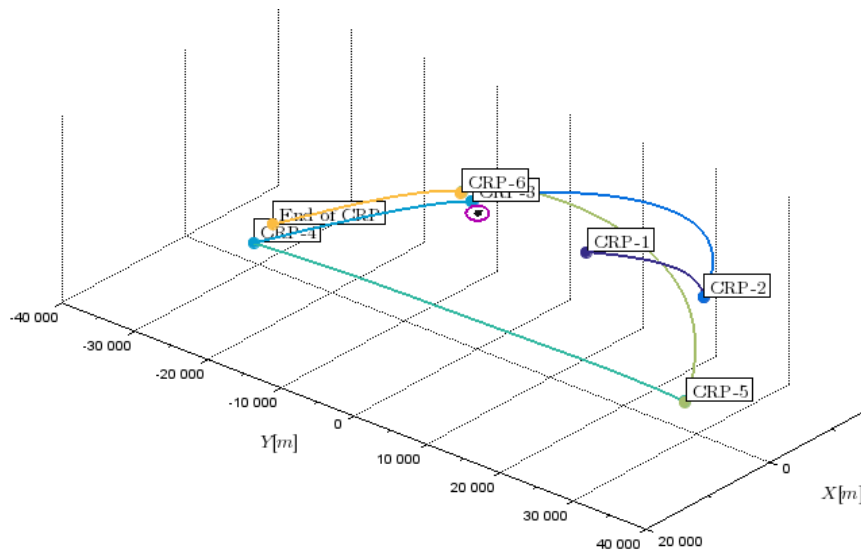


Figure 15: Close Range manoeuvres in Hill Frame

#### 4.6 Experimental Phase (EXP)

At the end of the CRP, Milani performs a final manoeuvre to reach the initial position of a 6 km SSTO. There begins the Experimental Phase. The trajectory design is intended to reduce progressively the distance to D1 to insert

Milani into a 3 km SSTO. The method implemented here consists in performing an initial manoeuvre that will inject the spacecraft into an initial 6 km semi-major axis SSTO (Man1 of Fig-16). This is followed by eight manoeuvres spaced 180° apart, gradually reducing the SSTO from 6 km to the desired 3 km.

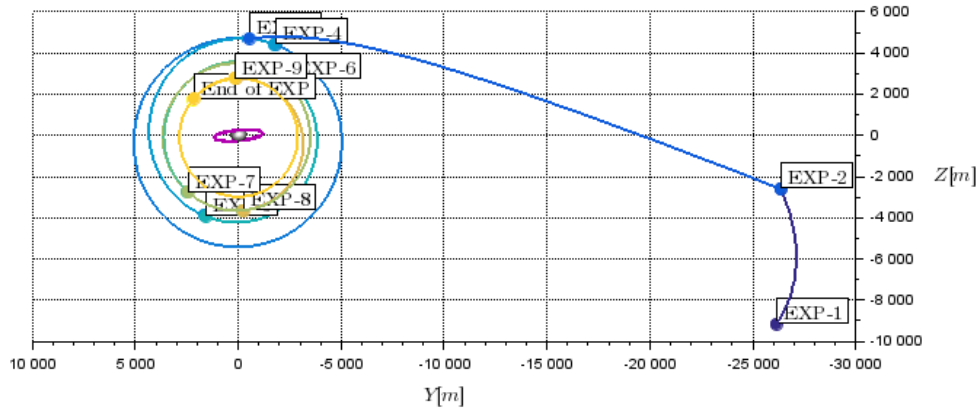


Figure 16: Experimental Phase manoeuvres in Hill Frame

Note that for Disposal phase (DISP) of Milani, current studies are ongoing for analysing different options for designing a trajectory approach and controlled descent for landing on D1 or D2. Actually, DART images taken from DRACO camera have shown regions of interest on D1 that would be interesting in terms of science for eventual landing.

#### 4.7 ASPECT payload operations on Milani

ASPECT payload is a hyperspectral imager operating in the visible (VIS) and infrared (NIR, SWIR) part of the electromagnetic spectrum. The main scientific goals and requirements for Didymos/Dimorphos stated in section 4.2 are recalled hereafter :

- Global mappings in various wavelengths with resolution of 2m/pixel for D1/D2 and 1m/pixel for D2 (and D1 potentially), phase angle between [5°, 25°].
- Imaging of the DART impact site in various wave-lengths with resolution of 0.5m/pixel, phase angle between [0°, 10°] and [30°, 60°].
- Analysis of surface microstructure from phase curve measurements on one selected area on each D1 and D2, with 5 different phase angles, one in [0°, 5°] range, one in [5°, 10°] range and three distributed in [10°, 60°] range.

Phase angle, geometric resolution and viewing incidence (maximum 45°) requirements shall be satisfied during the full imaging period, at the center of the area of interest (or the center of the image for mappings). In addition, no occultation nor eclipse of the imaged body (for mappings) or imaged area shall occur during acquisitions. And finally, a minimum 3-hour delay shall be respected between any ASPECT acquisition and the arc manoeuvres as per power-related constraint.

FRP and CRP trajectories presented previously are constructed to offer observation slots that satisfy the science requirements in terms of distance to the asteroids and phase angles. In order to ease and optimize the planning and scheduling of all these acquisitions, a dedicated process has been implemented (see paper [4]) for optimizing the acquisitions positioning and possible factorizations to comply with several requirements at a time.

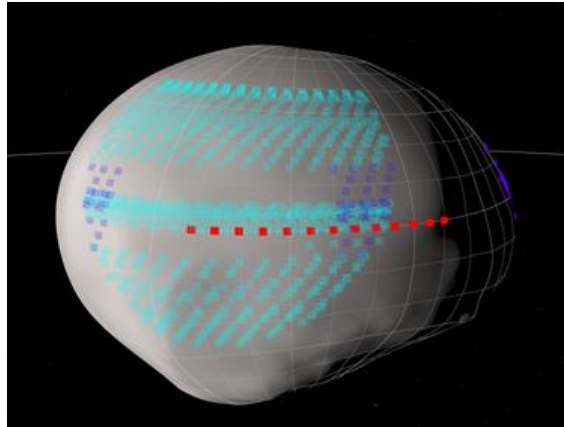


Figure 17: Discretization problem : sub-satellite points for D1 mapping at 2m/pix and D1 microstructures (candidate sites in red)

The main objective of the optimization is to maximize the minimum delay between the closest consecutive observations in order to reduce the risk of infeasibility due to power constraints and to keep enough flexibility and robustness for the trajectory design in case of a different phasing of D2 with respect to the current assumption. A secondary objective is to spread mapping observations in longitude as equally as possible. The figure below identifies the optimization results with the candidate observation points on FRP and CRP trajectories, which satisfy simultaneously the science requirements of ASPECT imaging.

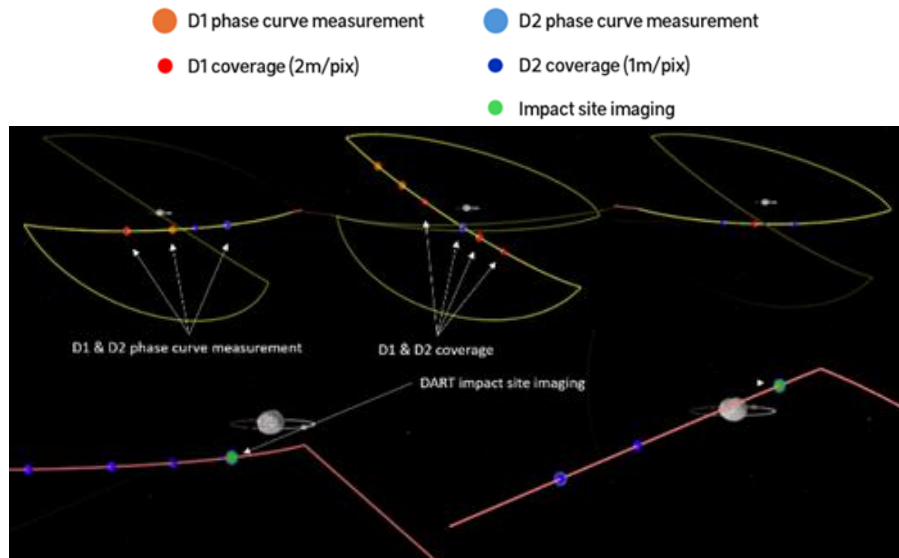


Figure 18: Optimized positioning of the 20 ASPECT acquisitions along FRP/CRP trajectories

## 5. Hera CubeSats Mission Planning Concept

### 5.1 Hera Operational Phases

Hera operations are divided into the following successive phases as defined in the Hera Mission Operations Concept Document [1] and the dates are based on a SpaceX Falcon 9 launch in October 2024:

**LEOP** (Launch and Early Orbit Phase): up to 3 days with the launcher dispersion trajectory correction, acquisition of safe attitude and nominal communication with ground.

**NECP** (Near Earth Commissioning Phase): begins in October 2024 for a duration of 4 to 6 weeks for spacecraft platform and instruments commissioning.

**Cruise**: 23.5 months from end of NECP in December 2024 to start of Rendez-Vous Manoeuvres for asteroid arrival in December 2026, consisting in Deep Space Manoeuvres (DSM), A Mars swing by.

**RDV&SYNC** (Asteroid Rendez-Vous and Synchronisation): up to 2 months with the execution of the RDV manoeuvres and the synchronization of Proximity Operations manoeuvres with the Mission Operation Center weekly schedule.

**PROX-OPS** (Proximity Operations): up to 4.5 months from arrival at the asteroid in December 2026 to the end of the experimental phase in July 2027.

**EoM** (End of Mission): up to 1 month from the end of experimental phase to end of mission.

The CubeSats operational phases are synchronized with the Hera timeline, with dedicated operations according to each phase, as shown in the figure below.



Figure 19: CubeSats operational phases and Hera timeline

### 5.2 Hera Ground Segment Overview

The Hera System is composed of the different following parts.

The Hera Space Segment including:

- Hera (mothercraft)
- MILANI and JUVENTAS CubeSats (sisters’ crafts)

The Hera Ground Segment including:

- Deep Space Ground Stations Network,
- Hera Mission Operation Center (**HMOC**), located at ESOC in Darmstadt (Germany), in charge of Hera mothercraft Operations, Management of the TC uplink and TM downlink for the mothercraft and the two CubeSats, Data dissemination
- CubeSat Mission Operation Center (**CMOC**) including the **C-FDSOC** (CubeSats Flight Dynamics and Science Operation Center) and the **CMCC** (CubeSats Mission Control Center)
- CubeSats **Payload Teams**, in charge of the Payloads Data management

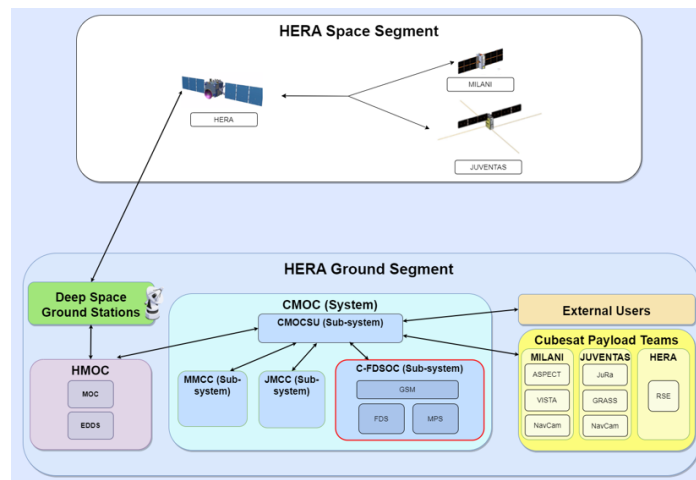


Figure 20: Hera space and ground segment overview

### 5.3 CubeSats Sequence of Operations Baseline

In order to command the trajectories and associated manoeuvres detailed in the previous sections, a dedicated baseline sequence of operations has been designed to comply with the science objectives for close proximity operations covered by SSTO phases on Juventas and FRP, CRP on Milani.

Note that other operational sequences will be defined later (Commissioning, Payload Calibration, Landing, Contingencies scenarios as 'Safe Mode Return' or 'Collision Avoidance' for example).

It is to be noted that this preliminary operational sequence dedicated to science is defined as a preliminary baseline. This baseline will be updated during Cruise and Early Characterization Phase, considering the better knowledge of the binary Asteroid system (reshaping, tumbling, boulders) and the CubeSats performances after commissioning.

The sequence of operations is prepared during Cruise with Pre-Long Term Planning (**PLTP**) definition and Long-Term Planning (**LTP**) definition in order to refine with Payloads Teams the science needs with regard to the CubeSats on-board constraints.

Then, during proximity operation, these preliminary sequences are refined in Short Term Planning (**STP**) and Very Short Term Planning (**VSTP**) which are operational sequences involving a reduced number of actors. These steps are represented in the figure below.

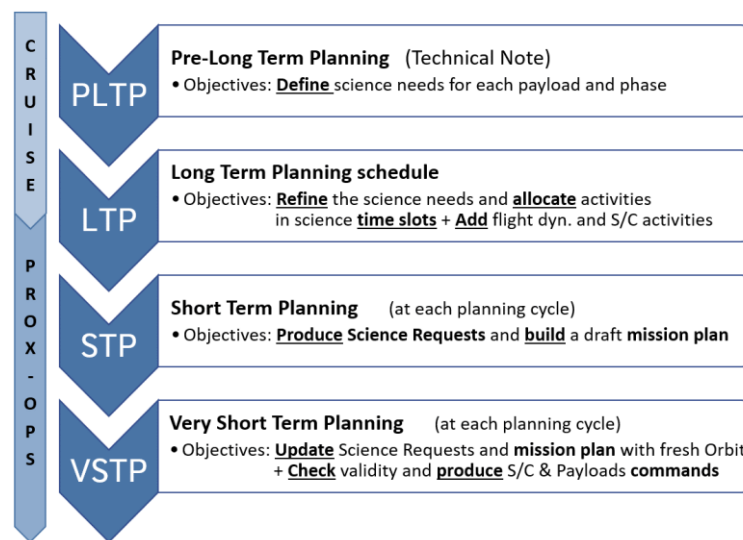


Figure 21:CubeSats Mission Planning ConOps for Proximity Operations

#### 5.4 Long Term Planning

For PLTP and LTP, the preliminary sequence of acquisitions of the different payloads are defined with the long term predicted trajectories as designed in the previous sections from Mission Analysis and Trajectory Design preliminary activities. This definition is summarized with the sequence diagram below, involving Flight Dynamics System (FDS) and Mission Planning System (MPS) computations within the C-FDSOC (Flight Dynamics and Science Operations Center).

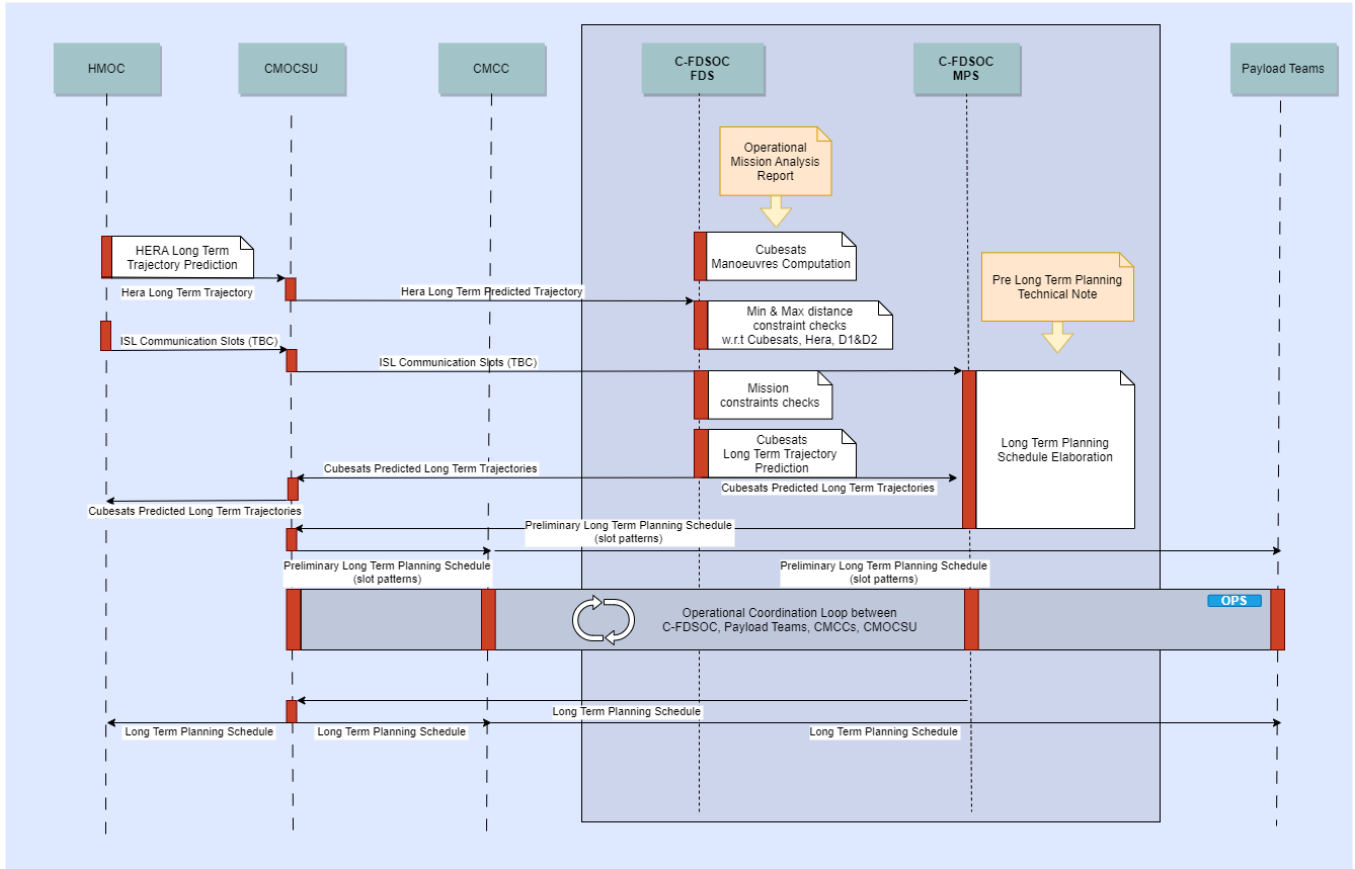


Figure 22: Long Term Planning (LTP) Schedule

### 5.5 Short and Very Short Term Planning

During close observation operations, once the CubeSats have been inserted on their ‘mission trajectories’ which are respectively SSTO for Juventas and FRP/CRP for Milani, the sequence of manoeuvres and payloads acquisitions defined on the previous Long Term Planning steps are refined in what are so called the Short Term Planning (STP) and the Very Short Term Planning (VSTP).

The main steps of the STP are the following:

- On-board state refresh in ground components FDS and MPS with the daily Telemetry and downlink
- Computation of the CubeSat Predicted Trajectory and manoeuvre computation on the next Programming Period
- MPS ingestion of manoeuvre programming from FDS
- MPS ingestion of JuRa Science Requests, consistent with the LTP Schedule
- Science Requests preparation and refinement on the basis of the LTP Schedule for the other payloads (ASPECT, GRASS, VISTA, RSE, NavCam)
- Preparation of draft Mission Plan taking into account manoeuvre plan and programming plan for the next Programming Period.

This preliminary Mission Plan is distributed to CMCC (Cubesats Mission Control Center) for validation.

A Mission Plan would nominally cover 2 Programming Periods (nominal and backup period extended to 14 days to be resilient to contact loss with Hera mothercraft or the Ground Stations).

Then, for final Mission Plan submission based on the latest orbit determination, the VSTP steps are performed in order to prepare the final telecommands to be sent from Deep Space Ground Stations to Hera mothercraft and transmitted to the CubeSats through Inter Satellite Link (ISL).

The main objectives of the VSTP operational sequences are the following:

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- Computation of the final Mission Plan including the selected list of Science Requests compliant with the different constraints
- Prediction of the most accurate CubeSats trajectories, based on latest orbit determination
- Final check of collision risks for each CubeSat (mitigated in advance on Long Term Trajectory definition) and eventual risk mitigation in case of last minute alarm.

The STP and VSTP operational cycles are based on Hera mothercraft ground operation cycle, with the nominal hypothesis of a programming plan, for mothercraft and Cubesats uplinked twice a week, out of weekends and during working hours.

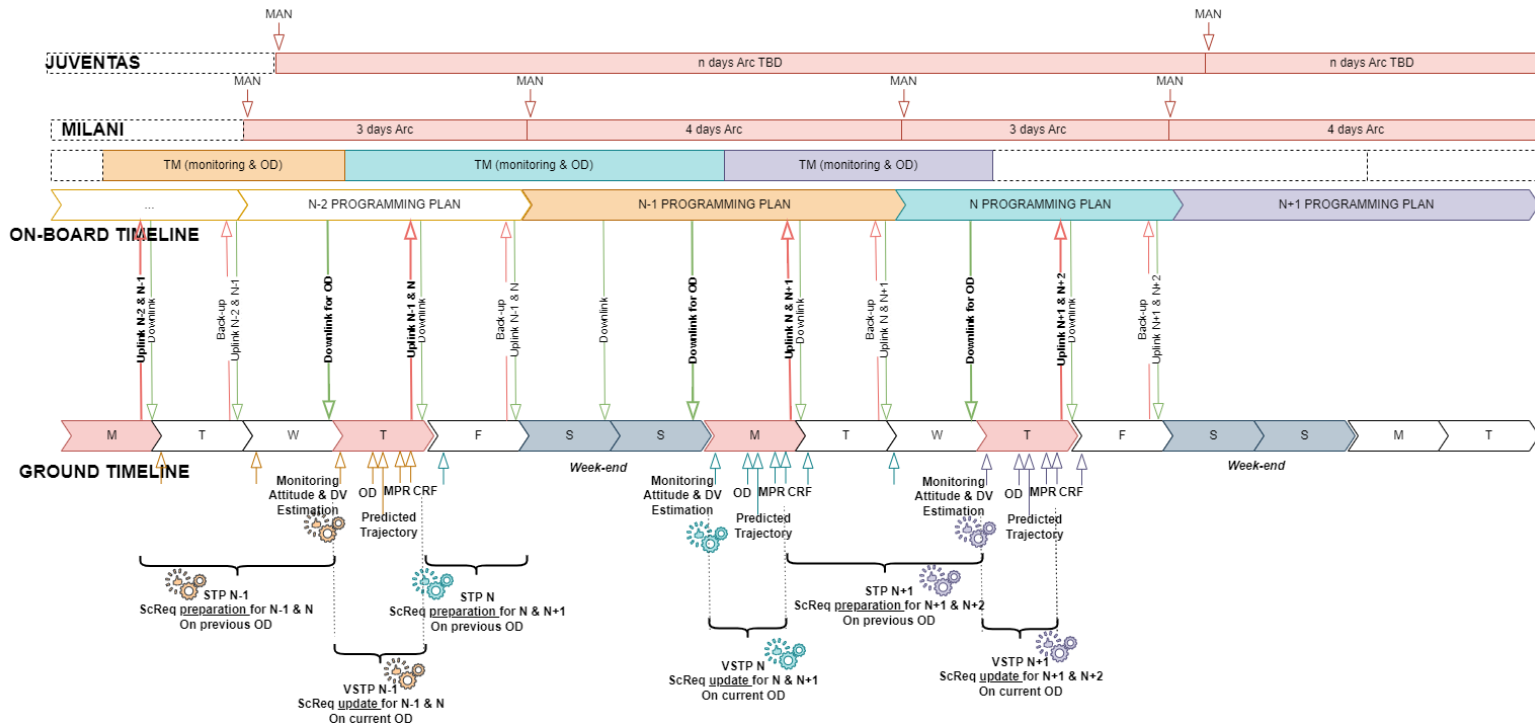


Figure 23: STP and VSTP Operational Cycles

The Mission Planning Concept, from LTP to STP and VTSP operational sequences, synchronized with Hera ground segment downlinks and uplinks, are finally summarized in the figure below (Juventas example).

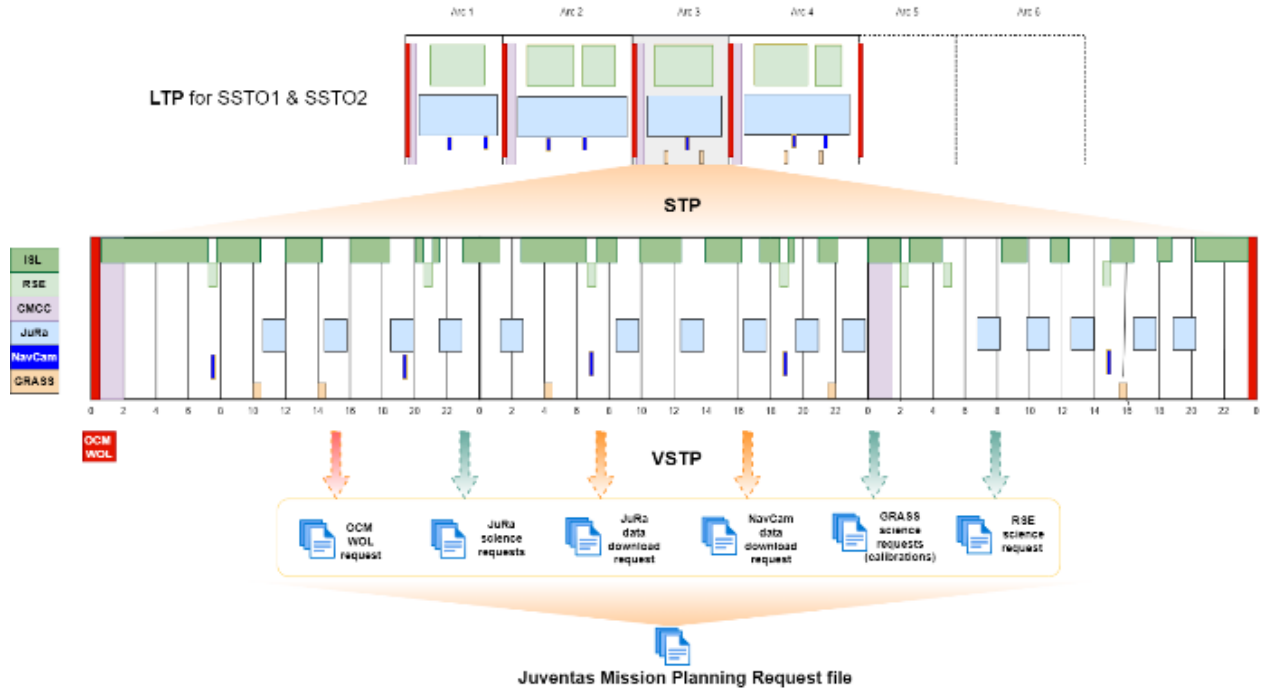


Figure 24: From LTP to STP and VSTP Operational Cycles (Juventas example)

## 6. Conclusion

This paper presented the preliminaries trajectory design studies under CNES responsibility for the overall Operational Mission Analysis considering both Juventas and Milani mission timelines. The payload acquisitions based on these trajectories will be commanded from ground and will involve different ground segment components and subcomponents for short time operations requirements. These operational activities will be performed in the different control centres through automated sequences of operations but they will also involve Flight Dynamics and Payload Programming experts’ operators for adapted manoeuvres computation and contingency mitigation, considering the low gravity environment and the unknown asteroids models. These two missions reveal challenging studies while orbiting around low gravity small bodies, especially when both CubeSats need to get closer for Dimorphos crater observation and for landing. Considering that dynamical models will be updated when Hera will arrive nearby the binary system, it is important to consider possible adjustments on the mission timelines and trajectories designs due to dynamical models updates, operational constraints from the asteroid environment, operational contingencies from the Cubesats, but also to eventual new opportunity science objectives.

## Acknowledgement

Many thanks to CNES Mission Analysis and Mission Planning teams, ESOC and SpaceBel partnership and Payloads teams from IPAG, ROB, Helsinki University, UniBo, PoliMi and INAF.

## References

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- [2] European Space Agency, Hera Didymos Reference Model, ESA-TECSP-AD-017258 6.0, 2023.
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