Hera Cubesats Trajectory Design and ConOps 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 spacecrafts 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 6U-XL CubeSats, will be launch in October 2024 to reach the binary asteroid system after a two-year Cruise. Hera will arrive in December 2026 in order to characterize afterwards the result of the DART impact in terms of reshaping and deflection of Dimorphos. 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, 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 maneuver strategies and payloads acquisitions sequences through an adapted Concept of Operations shared with Hera ground segment European stakeholders and Payloads teams. This paper will therefore present the different types of trajectories and the preliminary ConOps and necessary ground segment automation elaborated to fulfill mission programming and flight dynamics objectives for the two Hera CubeSats, Milani and Juventas.

INTRODUCTION

The scientific objectives of the two missions DART and HERA 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. The first NASA mission, DART, has impacted successfully Dimorphos on September 26, 2022. The second, Hera, is an ESA spacecraft carrying two European CubeSats (Juventas and Milani) to be launched in October 2024 (from the 7th to the 27th). Hera will have a 2-year cruise phase, under ESA/ESOC operations lead, with a Mars fly by in Spring 2025.

When arriving close to the binary asteroid, by December 2026, Hera, the mothercraft, will first characterize the asteroids in terms of dynamics, shape, and gravity models, before the ejection, separation and 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. This responsibility begins from the ejection of the mothercraft and extends up to the fulfillment of the scientific objectives of the different CubeSats' payloads, with a final landing on the Asteroids. 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).

The asteroid close proximity observation will consist of a series of phases, for both CubeSats, with ejection and separation, deployment, insertion, far range, transfer, close range, landing and disposal phases. Taking into account the mission payloads, navigation, and safety constraints for each phase implies specific trajectories and dedicated maneuver strategies. For instance, ASPECT (hyperspectral imager), Milani's main payload, aims to map both asteroids and image DART impact site with specific resolutions and phase angles (Sun-Asteroid center-Satellite). For JuRa (low-frequency radar), Juventas main payload, the mission constraints lead to the choice of Sun-Stabilized Terminator Orbits (SSTO) at different altitudes for global coverage of sounding acquisitions, with a dedicated station-keeping strategy in low gravity environment.

This paper will first introduce the Mission overview, then it will present each CubeSat trajectory design, and finally it will detail the ConOps for manoeuvres and payloads ground programming.

MISSION OVERVIEW

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 will be launched in October 2024 for a 2-year cruise including a Mars flyby. Hera will arrive close to the Didymos system by the end of 2026 for 6 months of science observation.

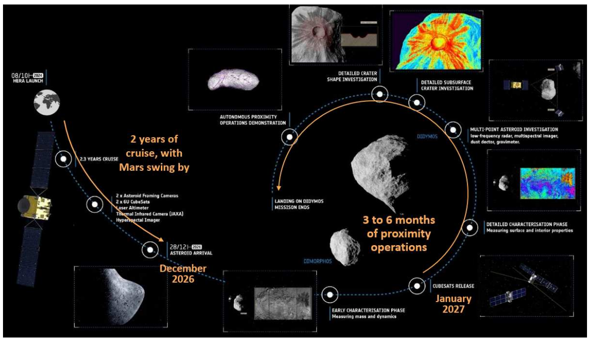


Figure 1: Hera timeline overview

Didymos Dynamics

Didymos 65803 system is composed of two asteroids of different sizes and shapes. 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 [1] provided by ESA with estimated characteristics obtained through DART and LICIACubes 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 33min ± 1.0 (3σ) [2].

D1 properties	D2 properties
Diameter* 730 m	Diameter* 150 m
Extents along principal axes 819 × 801 × 607 m	Extents along principal axes 179 × 169 × 115 m
Bulk density 2950 kg m^{-3}	Bulk density Unknown
Rotation Period 2.26 h	Orbital Period 11.3685 h Rotation Period supposed equal to orbital period if tidally locked
	Orbital eccentricity 0.031
Distance between the centre of primary and secondary 1.204 km	

Table 1: Asteroid properties after 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 by the end of 2026.

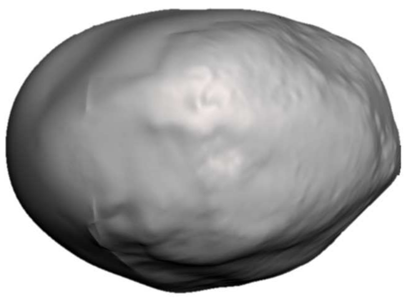


Figure 2: Didymos shape model (DART, DRACO images)

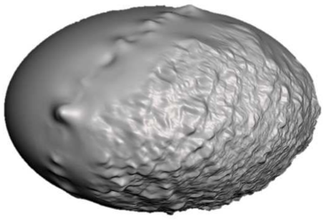


Figure 3: Dimorphos shape model before DART impact (DART, DRACO images)

A spacecraft inserted into the Didymos system environment is subjected to four main interactions that, depending on its distance from the barycenter of the system, will have an impact on the dynamics of the spacecraft. The main forces that will act on the CubeSats around the Didymos system are : the gravitational attraction towards D1, D2 and the Sun ; the force due to the Solar Radiation Pressure (SRP).

Preliminary Timeline

Launch is scheduled for October 2024 with an arrival in the Didymos system on 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. Fourteen days later, Milani will also be separated from the mothership to start its journey. Figure 2 below shows the preliminary timeline of each CubeSats, in relation with the mother craft timeline. These phases are summarized in Table 3 below and will be detailed in the next sections.

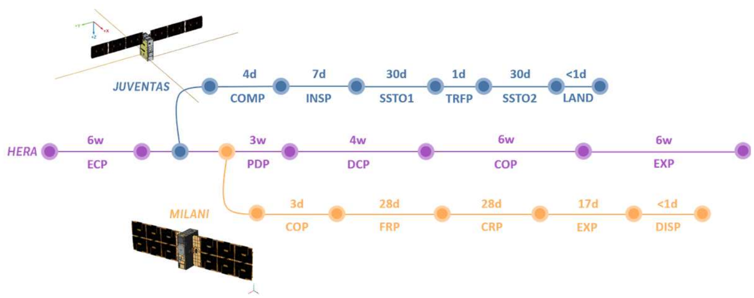


Figure 4: Preliminary Timeline of the HERA spacecrafts ('w' corresponds to week and 'd' to day, not to scale)

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 MISSION ANALYSIS

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 requirements.

Payload & Platform

Juventas is a 6U-XL spacecraft with a wet mass of 12kg developed by GomSpace devoted to the geophysical characterization of Dimorphos. Juventas mission analysis study has been entrusted to GMV. It is equipped with a low-frequency radar (JuRa), 3-axis gravimeter (GRASS), radio inter-satellite link (ISL), visible light camera plus Inertial Measurement Unit (IMU). Regarding the ADCS and GNC, the cubesat is equipped with the hardware exposed in Table 1 below. 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

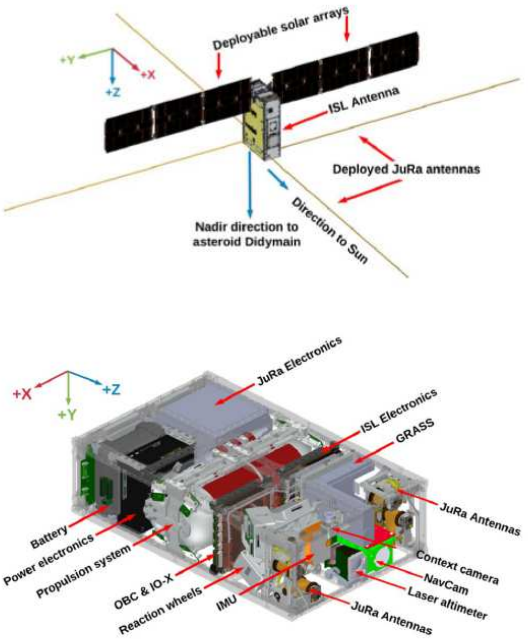


Figure 5: Juventas ADCS & GNC *(GomSpace)*

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).

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 maneuvers 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 *(no trajectory design)*	Surface operations with mainly GRASS measurements (JuRa measurements according to remaining power)

Table 4: Juventas Proximity Operations Phases

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

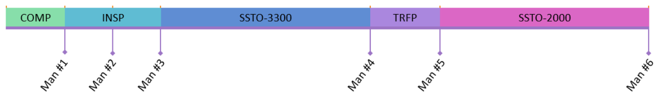


Figure 6: Juventas manoeuvres timeline

Insertion Phase (INSP)

The Insertion Phase of Juventas represents the first maneuvers 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 maneuvering 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 maneuver correction after 3 days if the first maneuver was non-nominal.

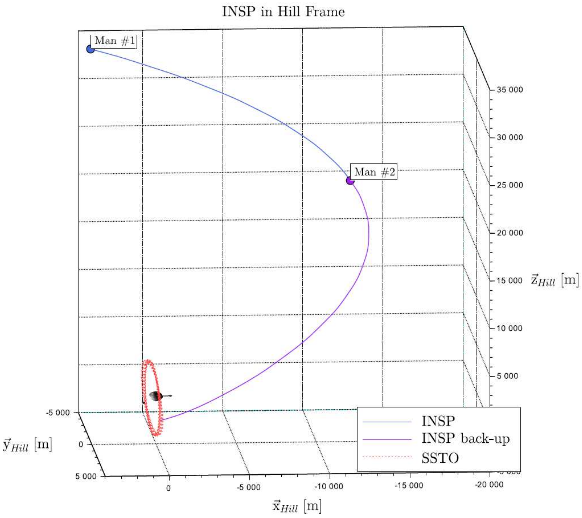


Figure 7: Insertion Phase in Hill Frame

Sun-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. The stability of these orbits implies that station-keeping maneuvers 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.

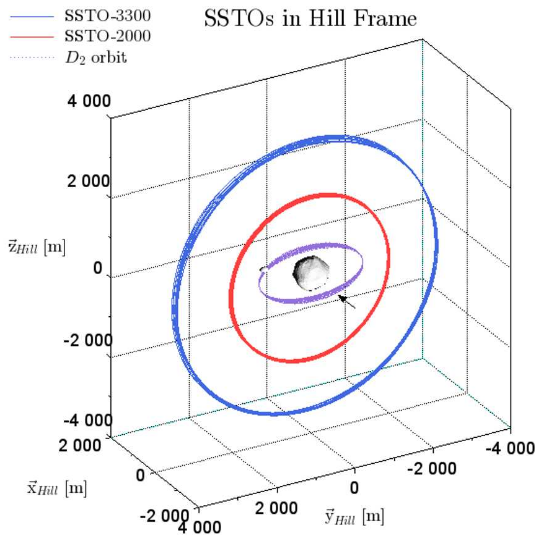


Figure 8: SSTO1 (3300 m) & SSTO2 (2000 m) in Hill Frame (black arrow represents the Sun direction)

Transfer Phase (TRFP)

The Transfer Phase consists of maneuvering 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 maneuvers 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.

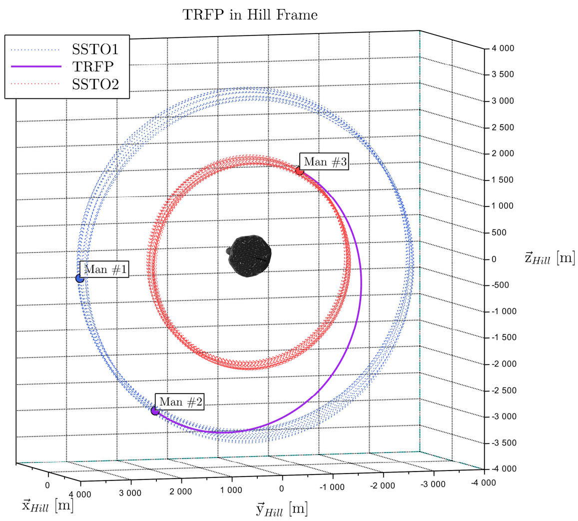


Figure 9: Transfer Phase in Hill Frame

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 cm s−1). To address this issue, a breaking maneuver 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.

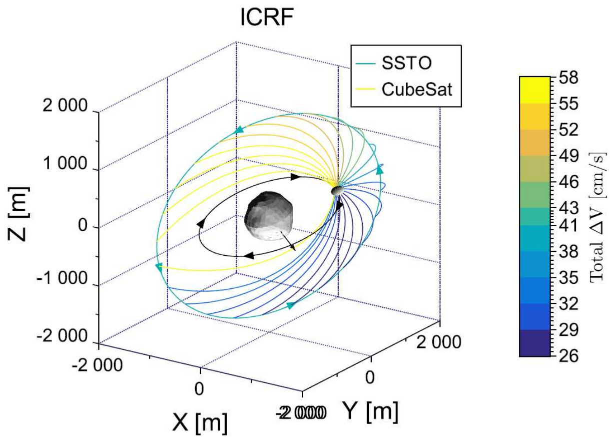


Figure 10: SSTO phasing study for landing and total DV assumption

- This strategy produces trajectories with sufficiently low impact speeds. The landing strategy involves five key parameters: landing epoch t_{land}, SSTO departure anomaly θ_{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
- θ_{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.

The figure below represents a possible landing trajectory designed using the method described.

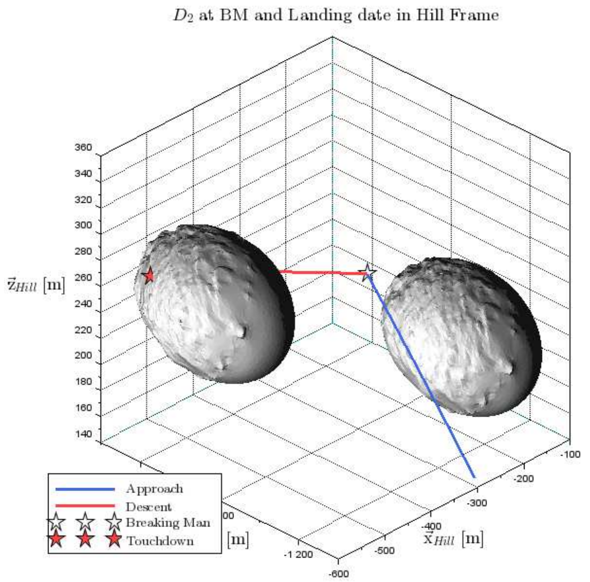


Figure 11: Juventas Landing (D2 represented at breaking manoeuvre (right) and at landing (left))

MILANI MISSION ANALAYSIS

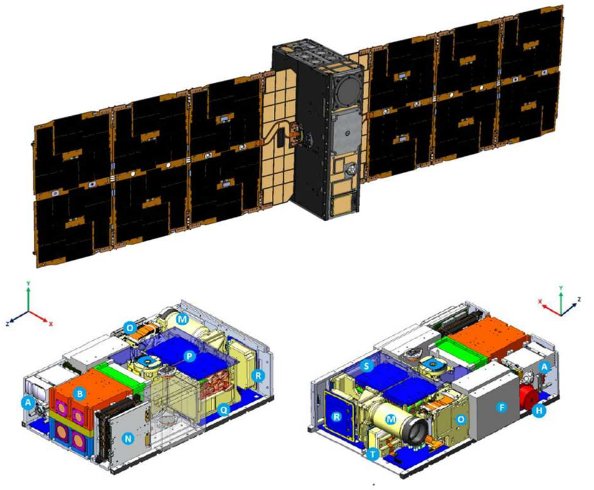
CNES is in charge of carrying on the preliminary studies handled by Politecnico di Milano on the Mission Analysis of Milani until CDR. CNES is responsible of the Operational Mission Analysis taking into consideration both cubesats at a system level for proximity operations requirements.

Payload & Platform

Milani is a 6U-XL Cubesat developed by Tyvak International devoted to the visual inspection and dust detection of Didymos asteroid following DART impact. It is equipped with VISTA a dust analyzer, and ASPECT a multispectral imager to perform mineralogical analysis. In addition to these two main payloads, the NAVCAM, a payload mainly used for navigation, and the ISL as well as Juventas. Regarding the ADCS and GNC, the cubesat is equipped with the hardware exposed in the table below. Note that the solar arrays of Milani are non-rotating.

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

Table 5: Milani ADCS & GNC



A	Navigation Camera & LIDAR	L	Deployer Interface Board
B	ASPECT Payload	M	Star Tracker
C	Solar Array Hold Down Release Mechanism	N	ISL Payload
D	Solar Array Interface Board	O	Reaction Wheel Assembly
E	ISL Patch Antenna	P	Batteries
F	Thruster Modules	Q	Flight Computer
G	Laser Retroreflector	R	Nano Load Controller
H	VISTA Payload	S	MPPT Module
I	Coarse Sensor Module	T	Inertial Measurement Unit

Figure 12: Milani assembly (Tyvak)

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 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).

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 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 Dimorphos

Table 6: Milani Proximity Operations Phases

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

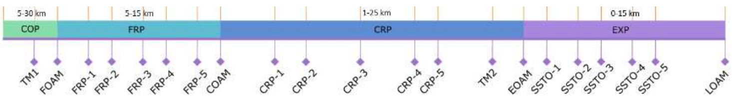


Figure 13: Milani manoeuvres timeline

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 maneuvers of this phase are designed to follow the pattern of the Hera mothercraft maneuvers 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 maneuver points in the figure below. Once these points are defined, a shooting method is used to generate the arcs between the waypoints.

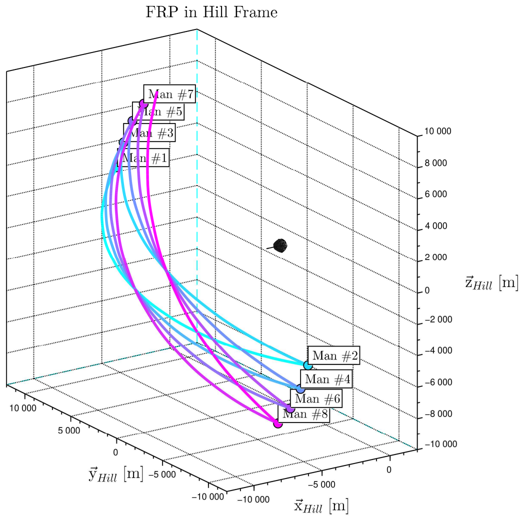


Figure 14: Far Range manoeuvres in Hill Frame

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° and a latitude of -8.84° [1]. 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 Δv 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.

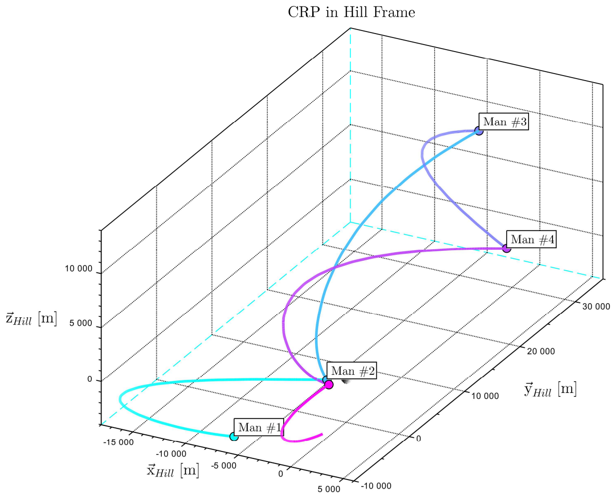


Figure 15: Close Range manoeuvres in Hill Frame

Experimental Phase (EXP)

At the end of the CRP, Milani performs a final maneuver 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 maneuver that will inject the spacecraft into an initial 6 km semi-major axis SSTO (Man1 of Fig-13). This is followed by eight maneuvers spaced 180◦ apart, gradually reducing the SSTO from 6 km to the desired 3 km.

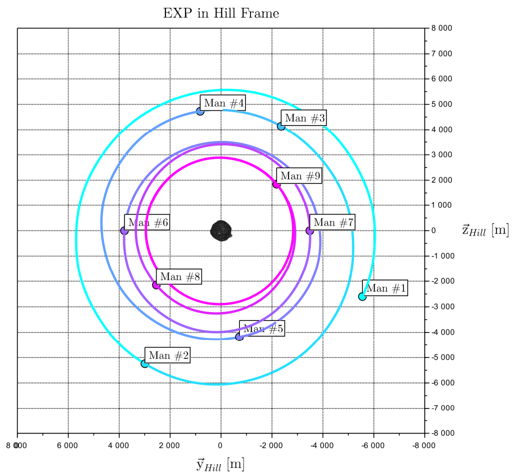


Figure 16: Experimental Phase manoeuvres in Hill Frame

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.

HERA CUBESATS CONCEPT OF OPERATIONS

Hera Operational Phases

The operations of the Hera mission are divided into the following successive phases ([HERA-MOCD]) 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.

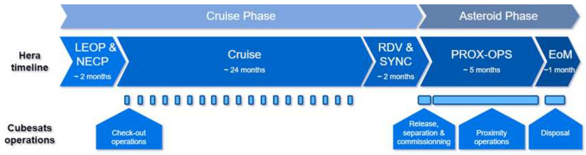


Figure 17: CubeSats operational phases and Hera timeline

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

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

For MILANI CubeSat

- ASPECT Visual and near-IR imaging spectrometer
- VISTA thermo-gravimeter

For JUVENTAS CubeSat

- JURA Low Frequency Radar
- GRASS Gravimeter

For both CubeSats, RSE and the Navigation Cameras (opportunity payloads)

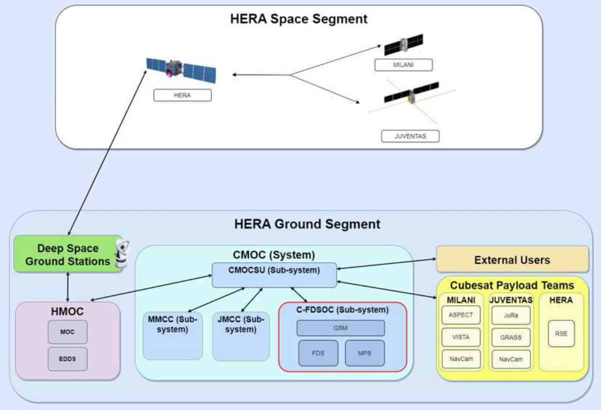


Figure 19: Hera space and ground segment overview

CubeSats Sequence of Operations Baseline

In order to command the trajectories and associated manoeuvers detailed in the previous sections, a dedicated sequence of ground operations is necessary to fulfill the trajectory design and the mission objectives. For this, a preliminary baseline sequence of operation 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.

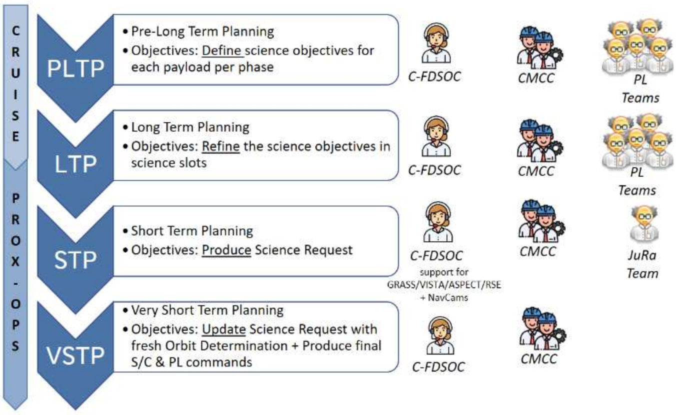


Figure 20: CubeSats Mission Planning ConOps for Proximity Operations

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)

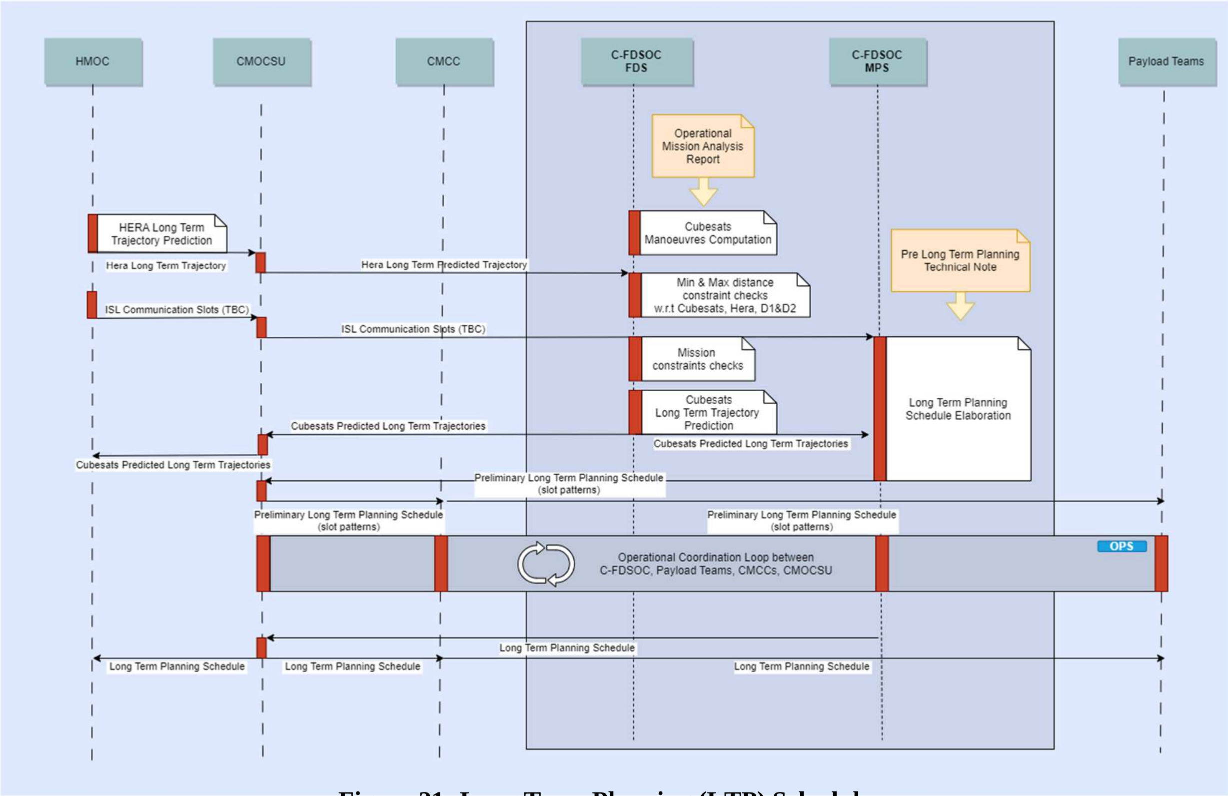


Figure 21: Long Term Planning (LTP) Schedule

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 manoeuver computation on the next Programming Period
- MPS ingestion of manoeuver 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 manoeuver 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 10 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:

- 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
- Detection of collision risks for each CubeSat (and eventual risk mitigation in case of lately raised alarm).

The STP and VTSP operational sequences, synchronized with Hera ground segment downlinks and uplinks, are summarized in the figure below.

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 centers 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 models updates but also to eventual new opportunity science objectives and operational constraints from the asteroid environment.

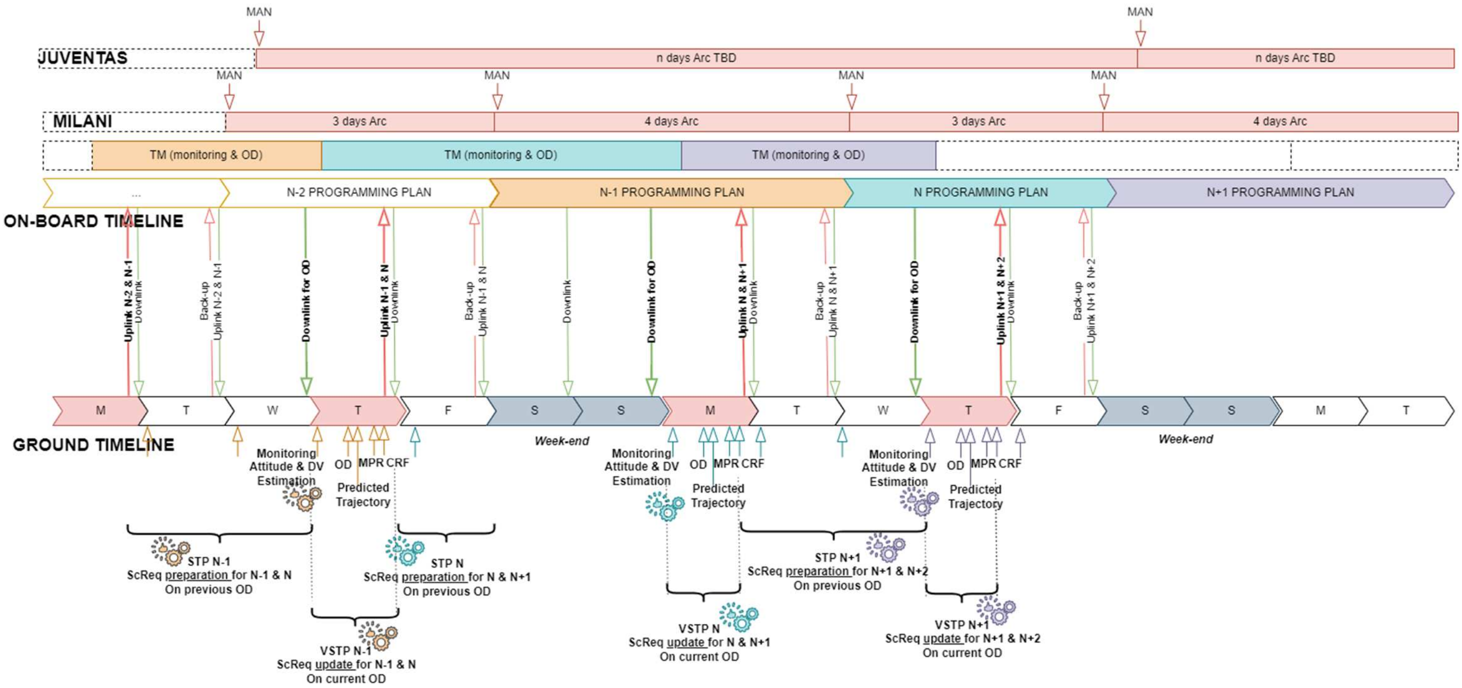


Figure 22: STP and VSTP Operational Cycles

Acronyms

AIDA Asteroid Impact Deflection Assessment.

C-FDSOC Cubesats Flight Dynamics and Science Operation Center

CMCC Cubesats Mission Control Center

CMOC Cubesats Mission Operation Center

CNES French Space Agency

D1 & D2 Didymos & Dimorphos

DART Double Asteroid Redirection Test

ESA European Space Agency

FDS Flight Dynamics System

FOCSE French Operation Center for Science and Exploration

HMOC Hera Mission Operation Center

ISL Inter-Satellite Link

MPS Mission Planning System

NavCam Navigation Camera for autonomous optical navigation

RSE Radio Science Experiment

SRP Solar Radiation Pressure

SSTO Sun-Stabilized Terminator Orbit

References

1. European Space Agency, Hera Didymos Reference Model, 24/09/2023, Issue 6, Rev. 0, ESA-TECSP-AD-017258
2. Cristina A Thomas, Shantanu P Naidu, Peter Scheirich, Nicholas A Moskovitz, Petr Pravec, Steven R Chesley, Andrew S Rivkin, David J Osip, Tim A Lister, Lance AM Benner, et al. Orbital period change of Dimorphos due to the DART kinetic impact. Nature, 616(7957):448–451, 2023.