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Hera cubesats operations design around a binary asteroid for small bodies characterization and planetary defense

Annat.P[1], Felin.A[2], Vernière.J[3], Pinede.R[4], Beauvalet.L[5], Moussi.A[6] and Verheyden.A[7]

[1] *CNES, C-FDSOC System Engineer, France, pamini.annat@cnes.fr*
[2] *CNES, GNC Engineer, France, aurelien.felin@cnes.fr*
[3] *CNES, GNC Engineer, France, julie.verniere@cnes.fr*
[4] *CNES, Mission Analysis Engineer, France, romain.pinede@cnes.fr*
[5] *CS Group, Mission Analysis Engineer, France, laurene.beauvalet@csgroup.eu*
[6] *CNES, Hera C-FDSOC Project Manager, France, aurelie.moussi@cnes.fr*
[7] *SPACEBEL, Hera CMOC Project Manager, Belgium, alain.verheyden@spacebel.be*

Abstract

After DART impact, the mothercraft Hera, carrying two cubesats Milani and Juventas, is planned to be launched at the end of 2024 and aims at observing the Didymos/Dimorphos binary asteroid system, in particular the crater from the impact and the deflection of Dimorphos. The CNES contribution is twofold. First, the operational mission analysis studies for the two 6U-XL cubesats, from the mothercraft ejection to the realization of the scientific objectives of the different payloads (imager, radar, gravimeter). Then, the proximity operations in 2027 within the C-FDSOC (Cubesats Flight Dynamics and Science Operation Center: Flight Dynamics and Mission Programming) in support of the CMOC (Cubesat Mission Operation Center, Belgium) in direct interface with the HMOC (Hera Mission Operation Center, Germany) as all uplinks and downlinks transit through the Hera mothership. Taking into account the mission constraints for each phase implies specific trajectories and dedicated maneuver strategies.

Keywords: HERA, Operations, Didymos, Juventas, Milani

Acronyms/Abbreviations

AIDA	Asteroid Impact Deflection Assessment
DART	Double Asteroid Redirection Test
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 HERA mission originates from AIDA which is an international collaboration program for planetary defense to test full-scale asteroid deflection. The overall program is split into two missions that will head to the Didymos 65803 binary system. The first mission, led by NASA and named DART, was launched on 2021-10-24 and successfully impacted the moon of the system - Dimorphos - the 2022-09-26. The overall mission was designed to evaluate the change in orbital speed resulting from the impact of the spacecraft on the moon. This collision was expected to change the orbital period of the moon by $\approx$73 seconds while it has changed it by 32 minutes $\pm$2, enough to be measured from Earth. However, owing to the large range between Earth and the binary system, the information that would be measured from Earth would have an uncertainty of 10%. Moreover, information on the crater, the internal and external properties of the asteroids, and other data can only be measured with close-range measurements. This is where the second mission led by ESA and named HERA originates [1]. Its launch is scheduled for October 2024. HERA will have the mission to assess in-situ the effects of the impact but also to perform precise analyses of the dynamics perturbations generated. For this purpose, Hera will deploy two 6U CubeSats, Milani and Juventas, which will orbit near the system to collect precise scientific data for the surface and the interior of the binary system. Thus, HERA will provide valuable information for scientific small bodies' characterization, leading to a better understanding of asteroid geophysics as well as solar system formation and evolutionary processes. This mission gathers 16 European countries to cover every aspect of each satellite [2]. France is part of this international collaboration through the support of French laboratories and the French Space Agency, CNES. The CNES was granted the responsibility of the Operational Mission Analysis and the Proximity Operations in 2027 within the C-FDSOC as a support to the CMOC. The CMOC, in Belgium, directly interfaces with the HMOC, in Germany, acting as a bent pipe as all cubesats in/out data are embedded in Hera down/uplinks.

2 Cubesats Operational Mission Analysis

Hera mothercraft houses the two cubesats, Milani and Juventas, as payload instruments. After a cruising phase of 2.3 years, the spacecraft will arrive at the Didymos binary system and starts its Early Characterization Phase (ECP) to analyze the mass and dynamics of the system. This phase aims at refining the models of the dynamics before releasing the cubesats during the Payload Deployment Phase (PDP). The deployment of the cubesats is performed with the Deep Space Deployer, where each cubesat will first undergo an exposure to deep space while still being electrically connected to Hera. Then, after a radio frequency and ISL check, the cubesats will be released with a Δv of a few cm/s from the mothership. There starts the cubesats journey.

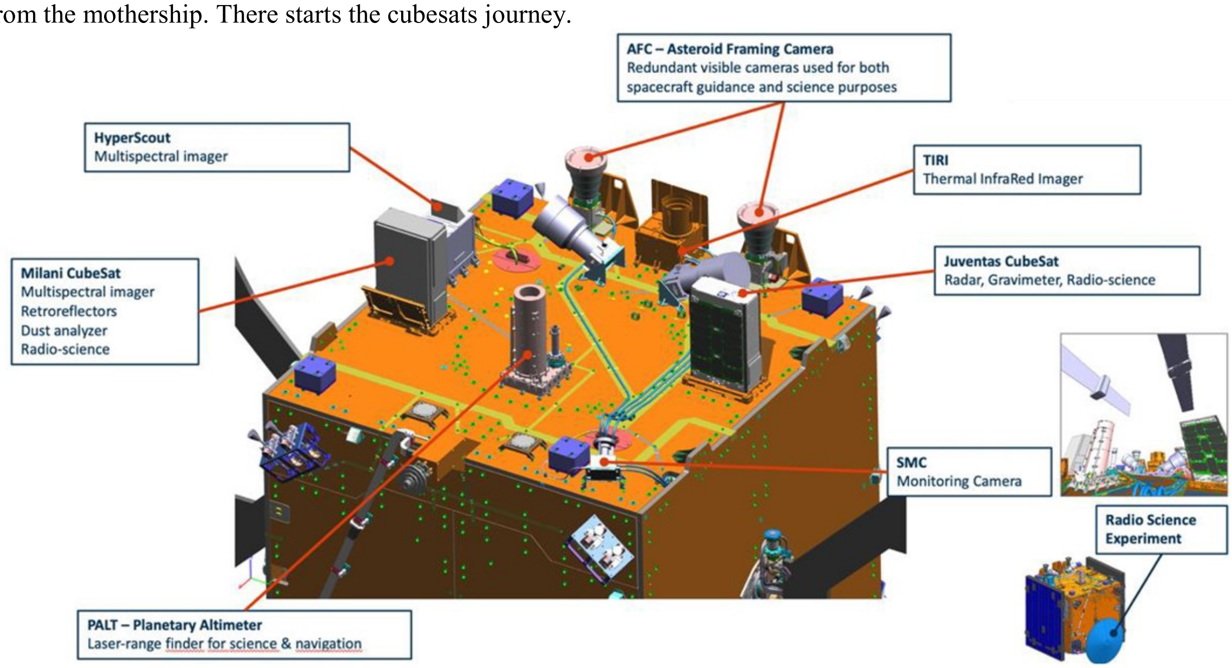


Figure 1: Hera Payloads *(ESA)*

2.1 Juventas

CNES is in charge of carrying on the preliminary studies handled by GMV on the Mission Analysis of Juventas until cubesat CDR [3]. CNES is responsible of Operational Mission Analysis taking into consideration both cubesats at a system level for proximity operations requirements.

2.1.1 Cubesat Payload & Platform

Juventas is a 6U 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 the solar arrays of Juventas are non-rotating.

ADCS & GNC	3-axis stabilized		
	ADCS Sensors	6	Fine Sun Sensors
		1	IMU
		2	Star trackers
	GNC Sensors	1	Navigation Camera
		1	Laser altimeter
	Actuators	4	Reaction Wheels
		8	▪ Cold Gas Thrusters ▪ $\Delta v_{total} = 6$ [m/s] ▪ $ISP = 50\ [s]$ ▪ $1\ mN$

Table 1: Juventas ADCS & GNC

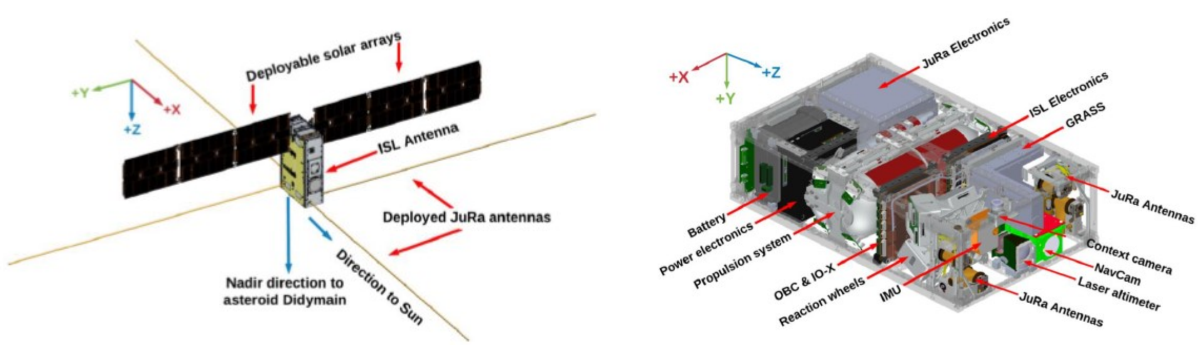


Figure 2: Juventas ADCS & GNC *(GomSpace)*

2.1.2 Mission & 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 in Table 2 & Table 3.

Mission Constraints	The system shall support a nominal operational mission life of 3 months, with possible extension up to 6 months in total.
	The CubeSat shall attempt to image the DART crater with its navigation camera if visible.
	During the Payload Observations Phase, the CubeSat shall operate between 1-10km from the target asteroid surface.
	The mission shall end with the attempted landing of the CubeSat on the surface of Dimorphos or Didymos.

Table 2: Juventas Mission Constraints

Operational Constraints	Remain within a 60km range from Hera to ensure ISL communications
	Trajectories shall have a duration compatible with operations teams shifts (4-3 day pattern).

Table 3: Juventas Operational Constraints

2.1.3 Proximity Operations Phases

The mission of Juventas is planned to start on 2027-03-26 and is split into seven phases that are listed in Table 4 below.

Phase	Description	Duration [days]
Preparation Phase - PREP -	Hera will be following an ECP trajectory during which the CubeSat operations will start. The required instruments and spacecraft systems will undergo some checks.	3
Commissioning Phase - COMP -	It is composed of a single arc with the possibility of performing four more arcs.	4
Insertion Phase - INSP -	It represents the most critical part of Juventas mission. The Cubesat is inserted into its first observation orbit.	6
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.	30
Transfer Phase - TRFP -	Juventas performs maneuvers to reach a SSTO with a 2000m semi-major axis.	1-3
Observations Phase 2 - SSTO-2000 -	The spacecraft remains on this reduced SSTO.	30
End Of Life Phase - EOLP -	Landing attempt on Dimorphos.	<1

Table 4 : Juventas Proximity Operations Phases

All manoeuvers associated to each phases are listed in Figure 3. To this day, studies have been conducted on the observations and transfer phases are presented in the following sub-sections.

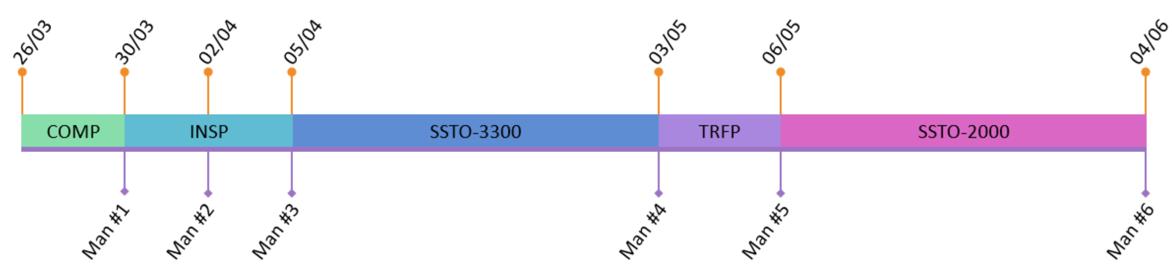


Figure 3: Juventas Manoeuvres Timeline (2027)

2.1.4 Observation Phases

As it can be seen in Table 4, Juventas will pursue most of its scientific missions during the observation phases where the spacecraft will evolve on a SSTO. This type of orbit was chosen for Juventas because of 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 or even a hundred meters along the Sun direction. Initial conditions for stable orbit can be generated based on the theory developed in [4] [5]. Regarding Juventas, it was decided that the satellite will evolve on two successive SSTO with a semi-major axis of 3300m and, afterward, 2000m. Both of them are represented in the Hill frame* in Figure 4. The stability of these orbits implies that no station-keeping maneuver is necessary during the observation phase. This is also the case if the satellite is inserted in an SSTO with a navigation error in position of 100m and velocity of 2.0×10^{-3}m/s. These navigation errors are extracted from the Mission Analysis study conducted by GMV on Juventas. Note that, for mission programming purpose, the duration of each phase and the altitude considered for preliminary mission analysis could be modified depending on further mission programming optimisation studies.

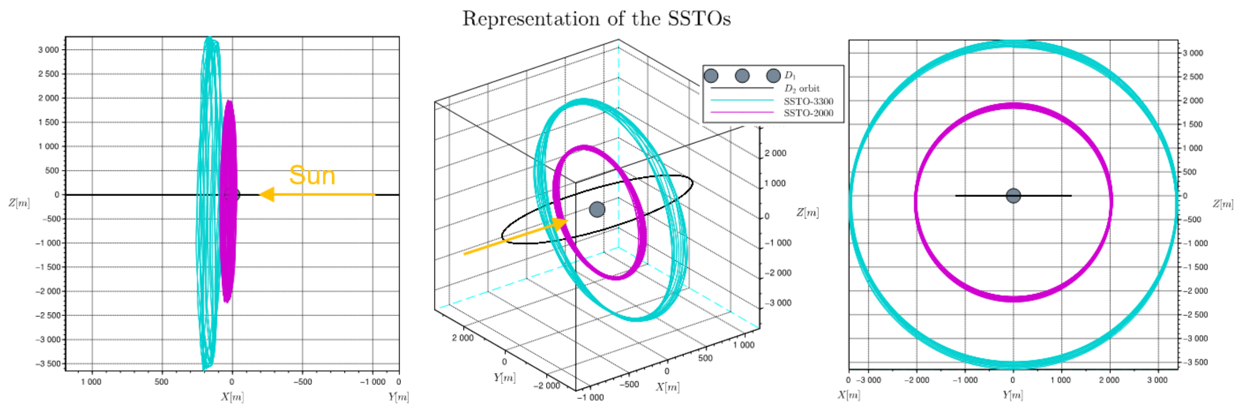


Figure 4: SSTO-3300 & SSTO-2000 in the Hill Frame

2.1.5 Transfer Phase

The Transfer Phase consists of manoeuvring to leave the SSTO-3300 and reach the SSTO-2000 as exposed in Figure 5. To do so, we take advantage of a trajectory change induced by a perturbation. Indeed, a modification of the semi-major axis of a SSTO induces an out-of-plan oscillation of the trajectory that will allow the satellite to intercept the plan of the second SSTO. The cost of this transfer is between 3 and 4 cm/s, depending on the geometry chosen for the transfer trajectory.

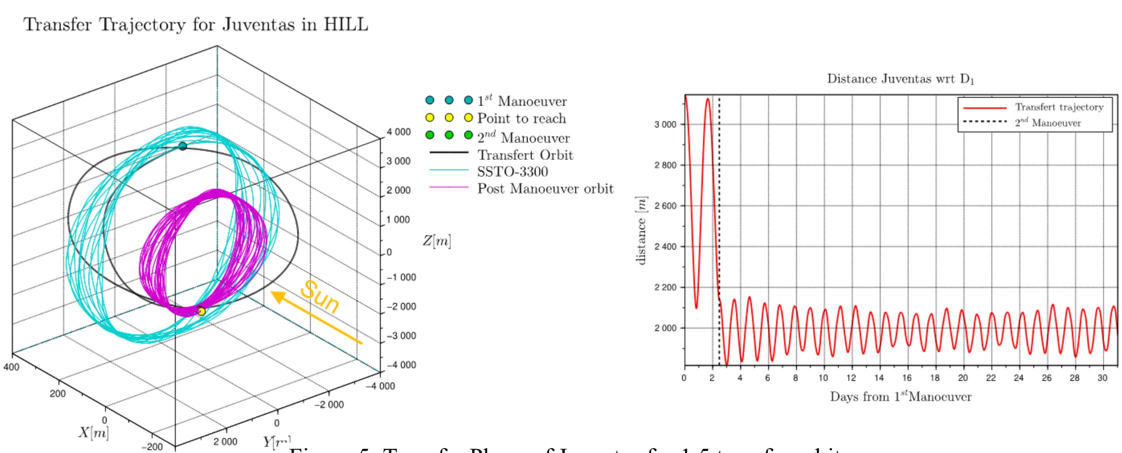


Figure 5: Transfer Phase of Juventas for 1.5 transfer orbit

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

This Δv is shared between two maneuvers, at departure of the first SSTO and at arrival to the final one. During the transfer phase, a corrected Hohmann transfer is performed. In addition to these results, errors in magnitude ($\pm 5\%$) and direction (5°) were added at both maneuvers to ensure that the transfer is robust to possible maneuvering errors.

2.2 Milani

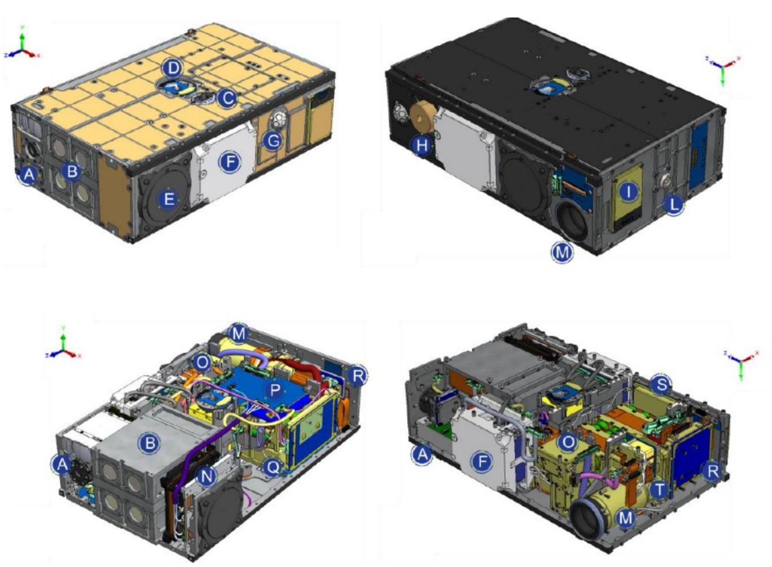
CNES is in charge of carrying on the preliminary studies handled by Politecnico di Milano on the Mission Analysis of Milani until CDR [6] [7]. CNES is responsible of the Operational Mission Analysis taking into consideration both cubesats at a system level for proximity operations requirements.

2.2.1 Cubesat Payload & platform

Milani is a 6U 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 Table 5 below. Note that the solar arrays of Milani are non-rotating.

ADCS & GNC	3-axis stabilized		
	ADCS Sensors	1	IMU
		1	Star trackers
	GNC Sensors	1	Coarse sensor module
	Actuators	3	Nano Reaction Wheels
		4	▪ Cold Gas Thrusters ▪ $\Delta v_{total} = 10$ [m/s] ▪ $ISP = 40$ [s] ▪ 7.5 mN

Table 5: Milani ADCS & GNC



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

Figure 6: Milani ADCS & GNC *(Tyvak)*

2.2.2 *Mission & Operational Constraints*

Milani main scientific objectives are:

- 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 based 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. In Table 6 below, the list of the mission constraints for Milani :

Mission Constraints	The spatial resolution for Didymos bodies imaging shall be better than 2 m/pixel for surface points acquired at 0° viewing incidence angles
	The spatial resolution for Dimorphos imaging shall be better than 1 m/pixel for surface points acquired at 0° viewing incidence angles
	The mission shall image the DART impact crater with a spatial resolution better than 0.5m/pixel
	Phase angle between 5 deg and 25 deg relative to both D1 and D2 for ASPECT global mapping of the surface of D1 and D2
	Phase angle between 0 deg and 60 deg relative to both D1 and D2. This is a scientific constraint related to ASPECT instrument, for the surface microstructure of D1 and D2
	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
Operational Constraints	Remain within a 60 km range from Hera to ensure ISL communications
	Remain on hyperbolic arcs to ensure the integrity of the system in case of missed manoeuvres
	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
	Trajectories shall have a duration compatible with operation team shifts (4-3 day pattern)

Table 6: Milani Mission and Operations Constraints

2.2.3 *Proximity Operations Phases*

The mission of Milani begins after ejection from the mothercraft Hera. Its mission is split into five phases that are listed in Table 7 below:

Phase	Description	Duration [days]
Commissioning Phase - COP -	This phase starts at the separation from Hera. The required instruments and spacecraft systems will undergo some checks	7
Far Range Phase - FRP -	Global mapping of both asteroids is performed at a range of 9-11 km from the system.	25
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.	31

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	21
Disposal Phase - DIP -	The spacecraft begins a descent to land on Dimorphos	~1

Table 7: Milani Proximity Operations Phases

All manoeuvers associated to each phases are listed in Figure 7.To this day, we conducted studies on the FRP and EXP phases detailed in the next section.

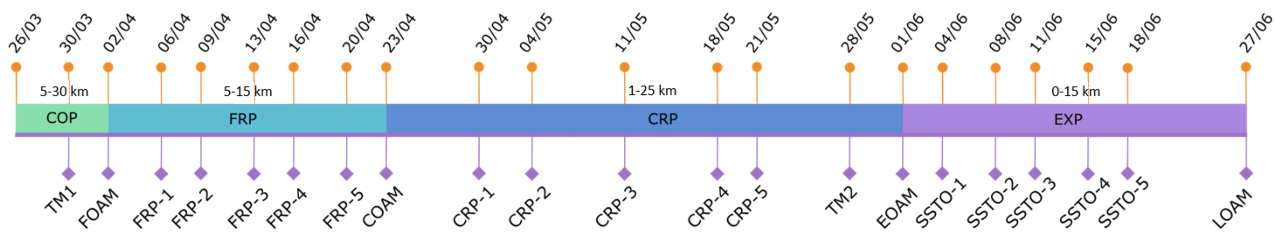


Figure 7: Milani Manoeuvres Timeline (2027)

2.2.4 *Far Range Phase - FRP -*

The FRP phase aims at observing the system from a distance ensuring the safety of the probe and carrying out a complete mapping of D_1 and the first images of D_2. As its name indicates, during this phase, the cubesat always remains at a relatively far distance from D_1 and D_2. Its trajectory consists of a succession of hyperbolic arcs on the side of the illuminated hemispheres of the two bodies. Each arc is interrupted by a maneuver that places the cubesat on the trajectory of the following arc. This phase consists of 6 arcs, whose inclination increases each time by 5°. The maneuver pattern of this phase is currently designed to follow the pattern of the HERA probe maneuvers, that is a succession of 4 and 3 days duration arcs.

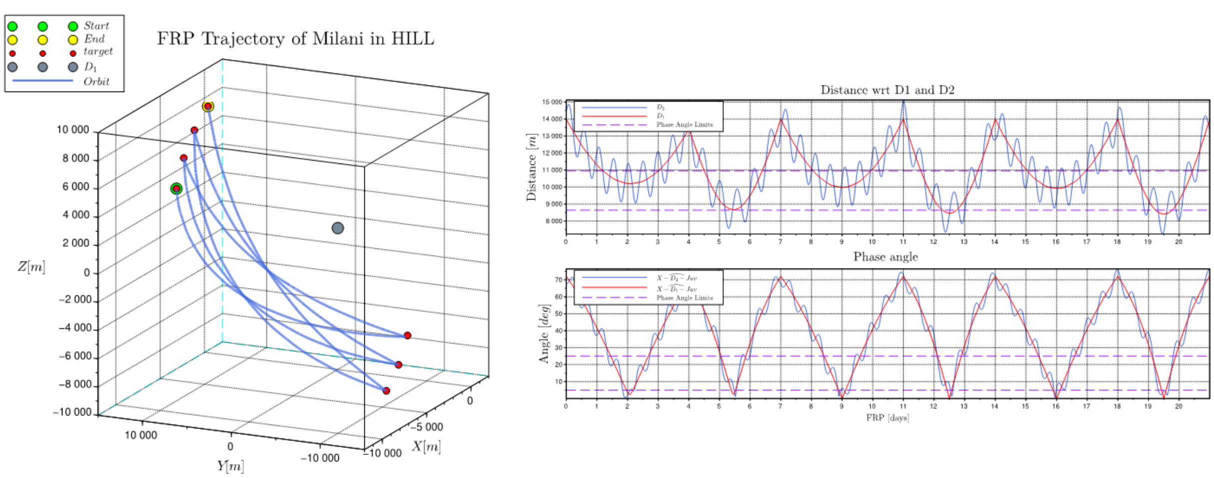


Figure 8: Far Range Phase of Milani

2.2.5 Close Range Phase - CRP -

As mentioned in Table 7, the CRP is similar to the FRP analysis except that scientific requirements are much more challenging (distance from the system and phase angle) making it the most critical phase for Milani. This phase is designed to acquire a high resolution global mapping of D_2 (1m/px) and image its crater. As the spacecraft will get close to the surface of D_2, several options are considered regarding the analysis of dispersions and collisions risks (relaxed requirements vs. higher risk).

2.2.6 Experimental Phase - EXP -

The EXP phase aims at approaching the system and inserting the spacecraft in a SSTO at 3 km to wait for a perfect phasing with D_2 before attempting a potential landing on it. We divided this phase into two strategies. The first, at long distance from the system, arcs will be performed with a Lambert-like transfer to get close enough to the system to reach the stability zone for SSTO. When Milani is close enough for the SSTO to be stable, several maneuvers are performed in order to place Milain in the Y-Z Hill plane and reduce its semi-major axis to 3 km. In the planned timeline, Juventas will have already made its landing, removing any risks of collisions between the two cubesats.

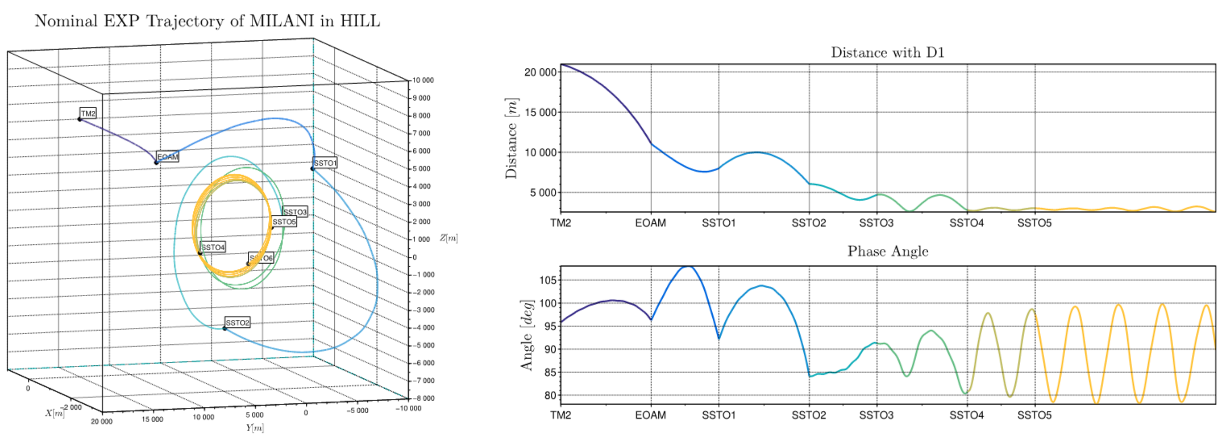


Figure 9: Experimental Phase of Milani

3 Cubesats Operations in CNES

3.1 C-FDSOC in Cubesats Ground Segment

The Cubesats ground segment is distributed over two main control centers located in Belgium and France as presented in Figure 10. The Cubesats data are uploaded and downloaded through Hera uplinks and downlinks, during ground communication slots between Deep Space Earth Stations and the mothercraft. Therefore, every data provided or awaited by the Cubesats ground segment (CMOC, CMCC, C-FDSOC, Payload teams) pass through the Hera ground segment (HMOC).

The operations led by CNES in C-FDSOC will cover Flight Dynamics operations and Payloads Mission Planning for both Cubesats. The Flight Dynamics team will be in charge of GNC activities, collision risk analysis, and Flight Dynamics products (trajectory, maneuvers, events). The Mission Planning team will be responsible for the mission and payload planning as well as the mission timeline preparation of both cubesats, taking into account the different constraints (Hera mission, Cubesats platform and payload constraints). For these activities the C-FDSOC interacts with HMOC for Flight Dynamics data exchange through CMOC supervision, Payload teams for Science Requests and products, CMCC for operational constraints, post-proecessed TM and TC parameters. The CMOC Supervision is responsible for overall constraints check before sending TC to HMOC, cubesats monitoring (health and GNC), data flow interface scheduling and archiving. It interacts with every CMOC sub-components for data distribution and archiving. The CMCC is responsible for the Cubesats platform and payload TC generation, the TM processing, platform and payload monitoring and maintenance.

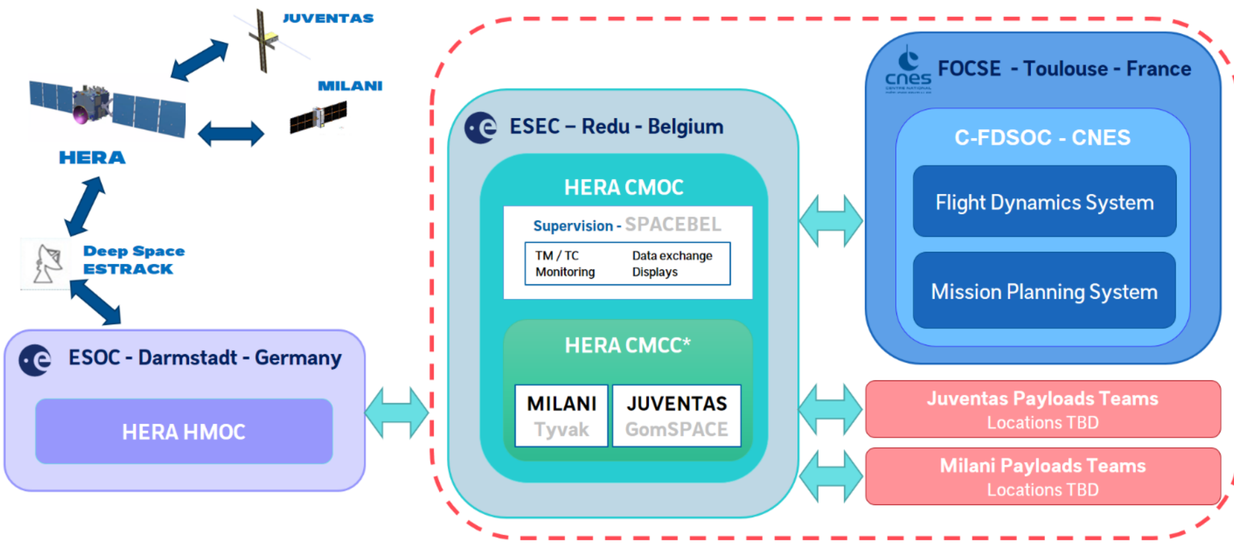


Figure 10: Cubesats Ground Segment

The operations led by the C-FDSOC team will be held in the Small Bodies Operations Facilities in FOCSE within the CNES Toulouse. These facilities were designed following CNES experience and lessons learned during past small bodies missions like Rosetta/Philae and Hayabusa2/Mascot. Before HERA mission, FOCSE will also host the operations of the missions MMX, DORN and, potentially DROID too, thus positioning itself as the Solar System exploration control center of CNES. The dedicated organization for Hera Cubesats operations is detailed in §4.3.

3.2 C-FDSOC Data Exchanges

For Flight Dynamics and Mission Programming activities, the C-FDSOC needs to exchange data with HMOC, CMOC/CMCC, and Payload teams. According to the different functionalities involved in CNES operational activities, interfaces exchanges can be resumed in the following categories: Trajectories data (past and predicted), Maneuvers data (calibrated and predicted), post-processed TM (for monitoring), TC parameters (for platform and payload commands through CMCC), Operational constraints (for mission planning), Scientific requests (for payload programming), Mission programming plan (for final mission timelines). A simplified overview of this different data transfer is represented below in Figure 11. All data send and received from the Cubesats ground segment are transmitted through the mothercraft Hera and its mission operation center HMOC. It is important to note that the science operations scheduling process is iterative and several loops have still to be defined with the different entities (such as payload teams) and are not described in this preliminary interfaces schematic view.
During the different operational phases, from critical to nominal, the data exchange files are distributed among Hera ground segment according to two main sequences: after data downlink from the mothercraft and before data uplink to the mothercraft. In order to reduce operations complexity, fixed time pattern will be considered for operational sequences and products deliveries between the different control centers.

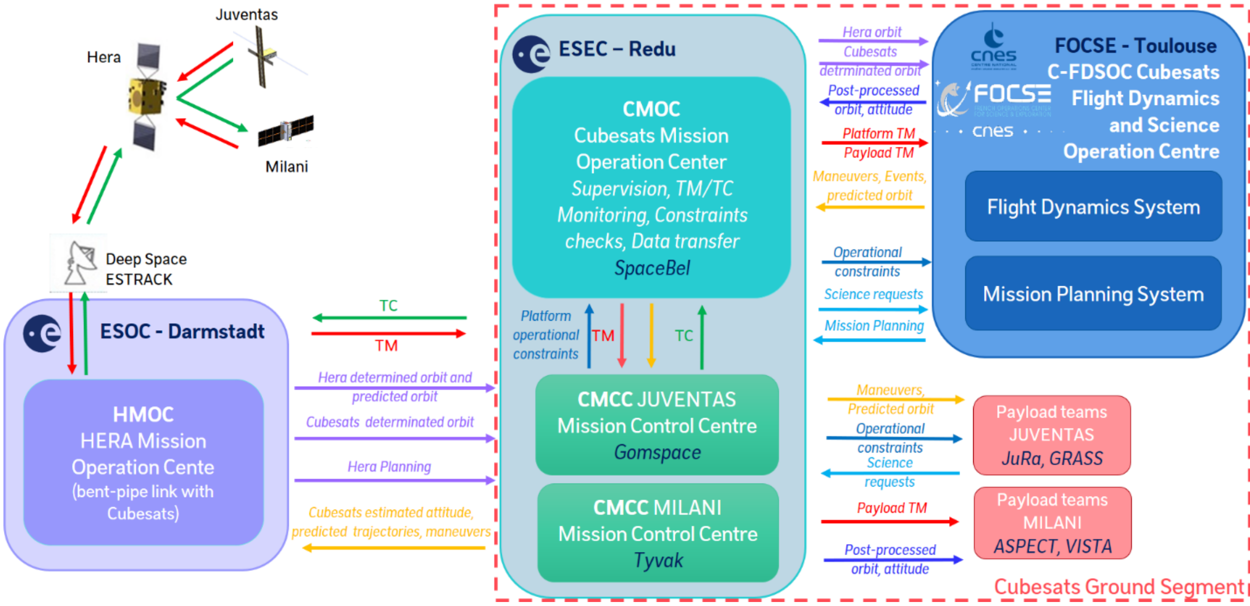


Figure 11: Simplified overview of C-FDSOC interfaces

3.3 C-FDSOC Functional Architecture

As exposed previously, CNES is responsible for the Flight Dynamics and the Mission Planning of both cubesats in C-FDSOC and interacts with CMOC and HMOC. In terms of Flight Dynamics, HMOC is responsible for Hera and Cubesats orbit determination, Didymos and Dimorphos dynamical models and trajectories updates, Hera orbit prediction, and provide this data to C-FDSOC for trajectory prediction. C-FDSOC operations will be performed thanks to the following operational tools FDS and MPS that are detailed here under.

The FDS component in C-FDSOC is responsible for both Cubesats of:

- GNC and autonomous functions monitoring
- Collision risk monitoring and mitigation
- Maneuvers calibration
- Maneuvers computation according to the Operational Mission Analysis (insertion, transfer, station keeping, wheel off-loading)
- Attitude determination based on telemetry
- Attitude profile prediction
- Cubesats orbit determination and asteroids models determination (shape/gravity/orientation) (as experimental functions for operational objectives and orbit prediction accuracy)
- Trajectory prediction
- Events computation

The MPS component of the C-FDSOC is responsible for Mission Planning of each payloads of both Cubesats with:

- Mission timeline preparation and programming considering Payloads Scientific Request and Hera, P/F and P/L constraints (instruments activities, downloading plan, predicted attitude, constraints checks)
- Instruments and on-board Ressource Management (data volume, power, thermal …)
- Mission plan scheduling and visualisation

These main functions presented in Figure 12 are currently under design and will be developed according to two main phases, before and after the Near Earth Commissioning Phase (NECP). Agile development process will be set up for expert tools in order to adjust the needs to the late knowledge of the operational inputs that will be updated during cruise and when arriving at asteroid phase. The detailed interfaces between FDS and MPS shown after are under progress.

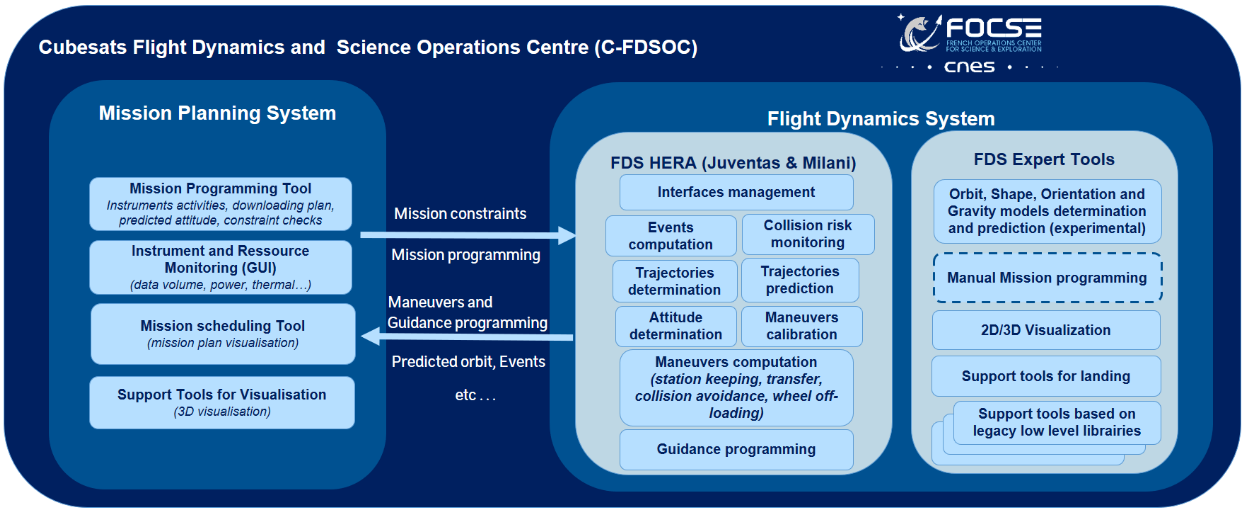


Figure 12: Simplified view of C-FDSOC operational tools

4 Mission Analysis and Operations Concepts

4.1 Mission Operations Concept

Considering the nominal launch scheduled in October 2024, after more than two years of cruise, the HERA spacecraft will arrive nearby the binary asteroid system by the end of 2026. For the Asteroid Phase, the global mission operations concept for the mothercraft Hera and its Cubesats Juventas and Milani is:

- First, at a far distance, a global characterization of the binary system, for the first gravity model refinement and for the identification of the eventual remaining elements of the DART impact in September 2022
- Secondly a far observation phase for the global mapping of Didymos and Dimorphos
- Followed by close-up observations phases for Dimorphos and DART crater characterization
- Then attempted Landing on Dimorphos
- Finally Disposal.

The operational phases of Juventas and Milani are synchronized with the main operational phases of Hera presented hereafter in Figure 13, considering that the Cubesats will be released to get closer to Didymos and Dimorphos. For instance, when Hera will characterize the binary system during the first far range observation phases ECP (Early Characterization Phase), PDP (Payload Deployment Phase) and DCP (Detailed Characterization Phase) at an average distance of 20 km, Milani will perform arcs trajectories at a closest distance of 8km in FRP (Far Range Phase) whereas Juventas will perform radar measurements at less than 4km in SSTO. After first phases of payload and autonomous on-board function calibrations, Hera will get closer during COP (Close Observation Phase) and EXP (Experimental Phase) to collect data from the crater. According to the same close-up operations concept, Milani and Juventas will get more and more closer for the asteroid surface characterization, with high resolution images and with a final attempt to touch the surface of Dimorphos.

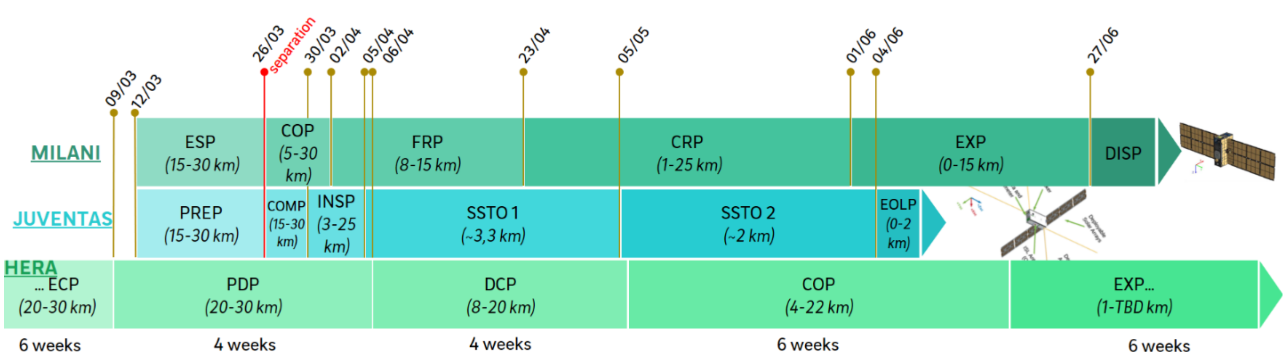


Figure 13: Synthesis of Hera, Juventas and Milani operational phases

4.2 Operational Mission Analysis updates

The Operational Mission Analysis studies led before arriving at the binary system, are based on dynamical models established with ground observations and data collected with the DART and LiciaCube missions. As seen before, the operational inputs will be adjusted during cruise and will lead to Operational Mission Analysis updates, eventually for operational phases durations and target distances to the asteroids. When arriving at asteroid phase, during Early Characterization Phase, we can expect new data on the binary system environment and we will be able to update shape models, orientation and rotation models, gravity models thanks to the preliminary RSE results (Radio Science Experiment) that are crucial for Flight Dynamics expert computations tools for trajectories prediction and maneuvers computations. The validity of the trajectories and maneuvers computed for the previous mission analysis versions will then need to be checked with the adequate tools to make sure the mission objectives can be reached as planned, to ensure the Cubesats safety and to take into account possible new constraints. Some phases strategies may be updated depending on new data from the binary system and Hera trajectory design. In any case, the Flight Dynamics Software reliability and adaptability will be decisive to successfully comply with the mission analysis updates.

4.3 Operational organization

For each operational phase a specific organisation will be detailed: tasks, operational actors, working groups and responsibilities will be described in the mission operations concept document. The lessons learned on other small bodies exploration missions (Rosetta/Philae and Hayabusa2/Mascot) show that a rehearsed ground loop, including operational meetings, is crucial for the mission success.
The organization of the workspace chosen for the operations is presented hereafter in Figure 14.

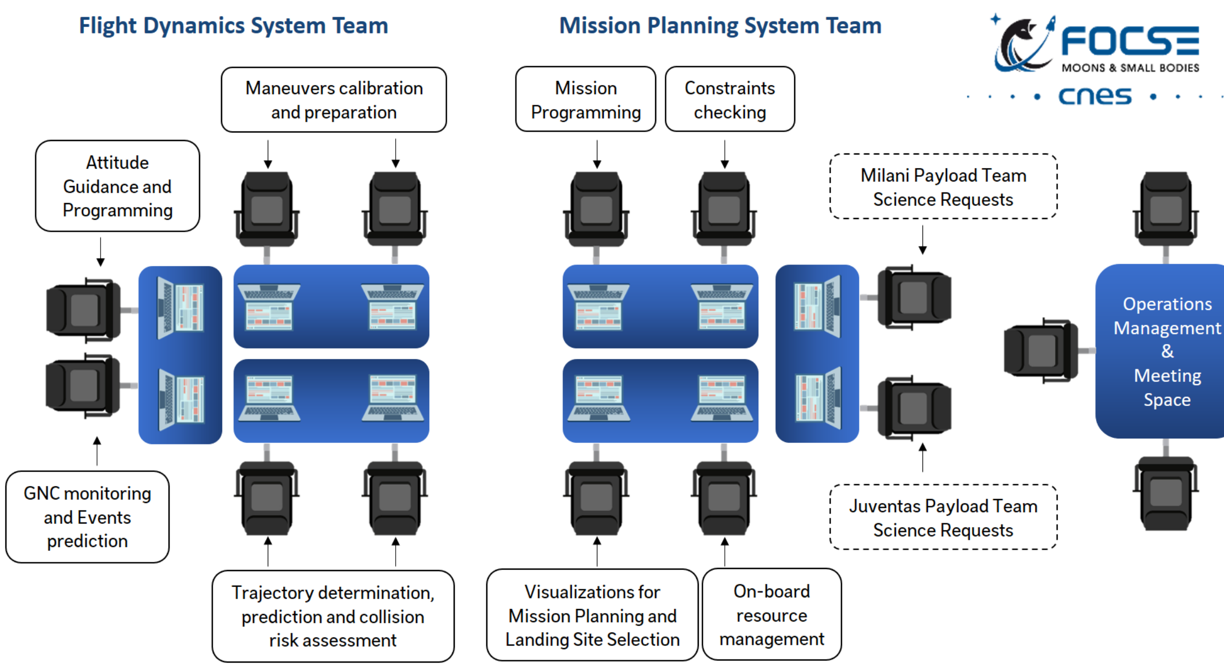


Figure 14: C-FDSOC in FOCSE

5 Conclusions

This paper presented the first phases studied under CNES responsibility for the overall Operational Mission Analysis considering both Juventas and Milani mission timelines. These two missions reveal challenging studies while orbiting around low gravity small bodies, especially when both Cubestas 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 of the mission timelines due to updated models but also to eventual new operational constraints from the asteroid environment and the global surface characterization for mission programming and adapted trajectories design.

6 Références

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