The Hera Milani CubeSat Mission

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Abstract

Hera is the European contribution to the Asteroid Impact & Deflection Assessment (AIDA) international collaboration. NASA is responsible for the DART (Double Asteroid Redirection Test) kinetic impactor spacecraft. The Hera spacecraft will be launched in October 2024 and will arrive at Didymos in January 2027. The Hera mothercraft will accommodate two 6U CubeSats, called Milani and Juventas. The Milani CubeSat is developed by Tyvak International leading a consortium of European Universities, Research Centers and industries from Italy, Czech Republic, and Finland. During the two-and-a-half-years cruise to its target asteroid Didymos the Milani CubeSat will be hosted inside the Hera mothercraft. Its battery will periodically be charged and the platform checked for health. At arrival it will be deployed and commissioned while Hera is performing the Didymos detailed characterization phase, at about 30 km distance from the asteroid. The mission objectives are defined as to add scientific value to the overall Hera mission: i) Map the global composition of the Didymos asteroids, ii) Characterize the surface of the Didymos asteroids, iii) Evaluate DART impacts effects on Didymos asteroids and support gravity field determination, iv) Characterize dust clouds around the Didymos asteroid, enhancing the scientific return of the whole Hera mission. The scientific payloads supporting the achievement of these objectives are the main Payload “ASPECT” (developed by VTT, Finland), a SWIR, NIR and VIS imaging spectrometer and the secondary Payload “VISTA” (developed by INAF, Italy), a thermogravimeter aiming at collecting and characterizing volatiles and dust particles below 10µm.

Among the project’s main challenges are the use of COTS components in the deep-space environment, the implementation of the optical navigation, and management of interfaces with the Hera mothercraft. Tyvak International work focuses on the development and integration of the Milani CubeSat platform, including mission specifics development enabling the mission.

Introduction

In 2027, the Hera spacecraft will rendezvous with the binary asteroid 65803 Didymos as the European contribution to the AIDA (Asteroid Impact and Deflection Assessment) international collaboration. NASA is responsible for the Double Asteroid Redirection Test (DART) kinetic impactor spacecraft. Hera and DART have been conceived to be mutually independent, however, their value is increased when combined. Indeed, Hera is a planetary defense mission aimed to investigate the effect of DART impact, with clear scientific objectives as a bonus. In proximity of the target, Hera will release two 6U CubeSats called Milani and Juventas. The two nanosatellites will be the first CubeSats to orbit in the close proximity of a small body and the first to perform scientific and technological operations around a binary asteroid.

Tyvak International is responsible for the system development and is leading (as Prime Contractor) a large consortium made by 10+ entities from Italy, Czech Republic and Finland. Milani will contribute to the scientific value of the Hera planetary defense mission, mainly through the visual inspection of the asteroid (main payload: ASPECT) and dust detection (secondary payload: VISTA).

Didymos properties

Didymos is a binary Near-Earth Asteroid (NEA) of S-type discovered in 1996 formed by Didymos, or D1 (the primary) and Dimorphos, or D2 (the secondary). Up-to-date data about Didymos and Dimorphos are reported in the following tables:

Table 1. Binary system parameters (semi-major axis, eccentricity, inclination, revolution period)

System parameters			
a 1.66446 AU	e 0.3839	i 3.4083 deg	T 770 days

Table 2. Didymos and Dimorphos mass and spin periods properties

System parameters			
M1 5.226×10^{11} kg	M2 4.860×10^{9} kg	T1 2.26h	T2 11.92h

The orbital properties are retrieved from the up-to-date kernels of the Hera mission. In the up-to date reference model, Dimorphos and Didymos are assumed to share the same equatorial plane on which their relative motion occurs and Dimorphos is assumed to be in a tidally locked configuration with Didymos. In this work, two reference frames are used. “DidymosEclipJ2000” is a quasi-inertial reference frame, centred in the system barycentre with the axis directed as the inertial EclipJ2000 reference frame. This frame can be considered inertial for intervals of time negligible with respect to Didymos heliocentric motion. “DidymosEquatorialSunSouth” is a non-inertial reference frame in which the trajectories are shown. It is centred in the system barycentre and has the xy plane on the asteroid equatorial plane. The x-axis is aligned with the projection of the Sun vector on the equatorial plane and the z-axis is aligned to the south pole of Didymos.

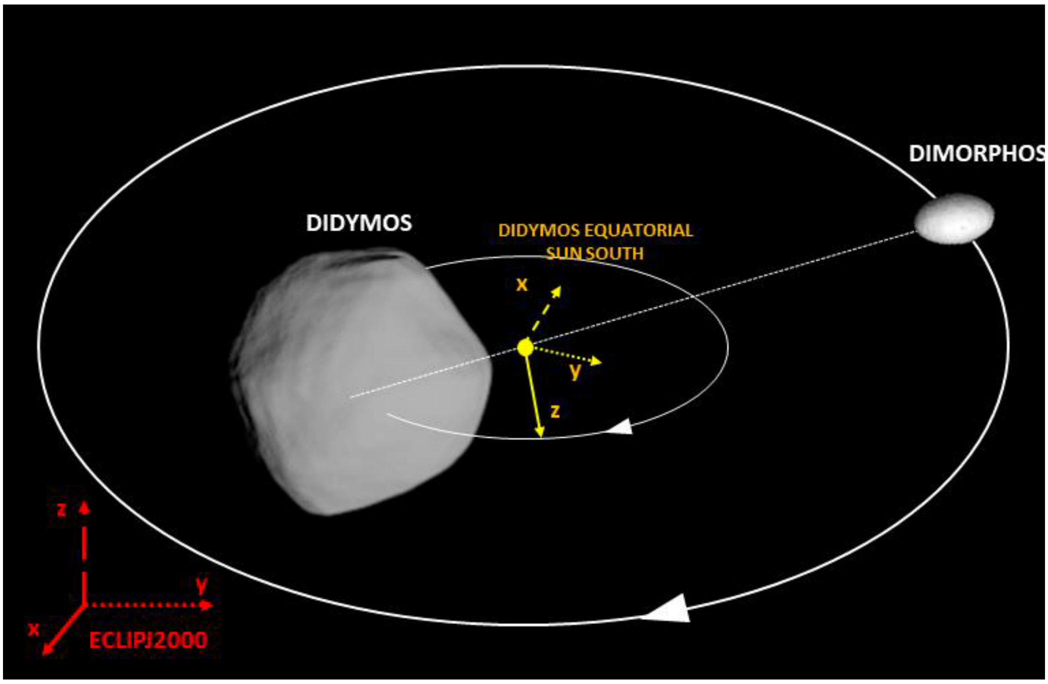

Figure 1. Didymos geometry. The reference frames are highlighted. The red frame is the inertial Eclip2000 which corresponds to the quasi-inertial DidymosEclipJ2000 when centred in the system barycentre. The yellow frame is the Didymos Equatorial Sun South (*Courtesy: Politecnico di Milano*)

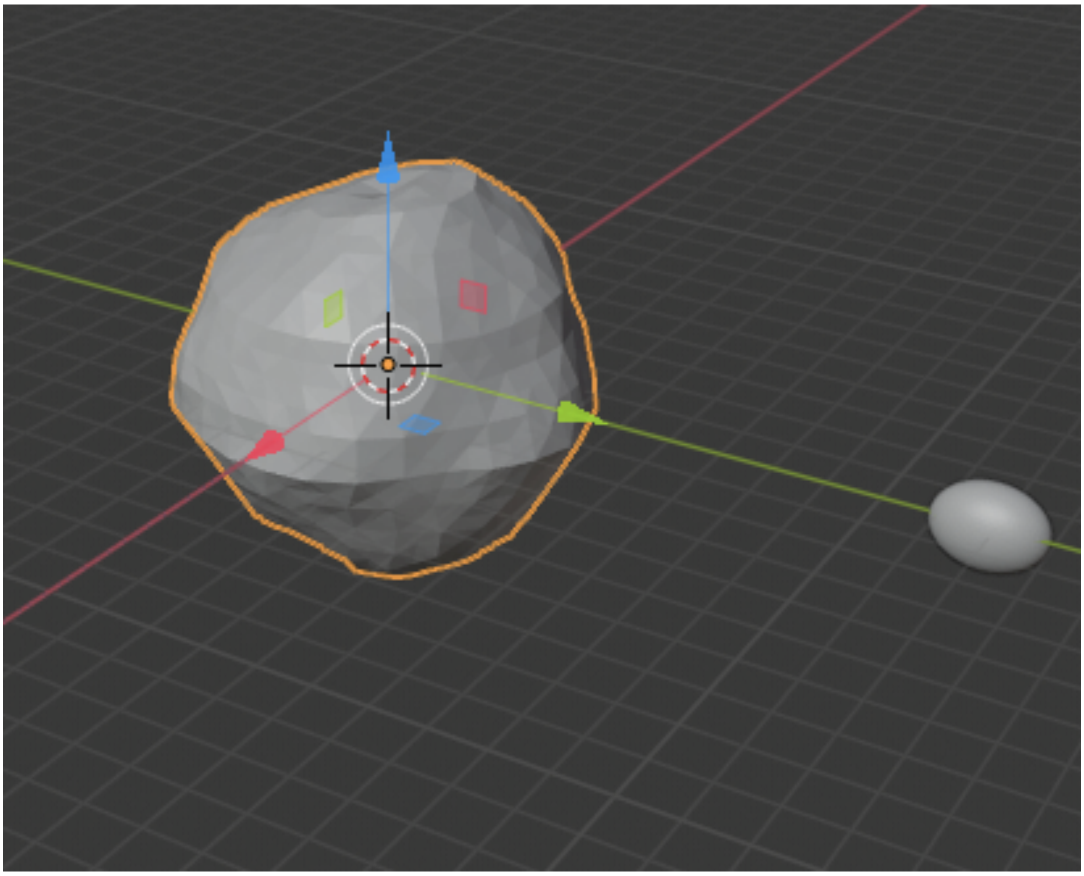

Figure 2 Didymos system geometry: polyhedral radar shape model of D1 and triaxial ellipsoidal model of D2 in D1_Body reference frame. (*Courtesy: Politecnico di Milano*)

Scientific goals and operational constraints

Milani scientific phases design has been mostly driven by its main payload, ASPECT. ASPECT is a passive payload, equipped with a visible to near-infrared hyperspectral imager and will be used on Milani to perform global mapping of the asteroids with detailed observation of the DART crater on Dimorphos. ASPECT main scientific goals can be summarized in three actions:

1. Imaging both the asteroids with a spatial resolution better than 2 m/pixel
2. Imaging the secondary asteroid with a spatial resolution better than 1 m/pixel
3. Imaging the DART crater with a spatial resolution better than 0.5 m/pixel at phase angle (Sun-asteroid-Milani angle) in the range [0-10] deg and [30-60] deg.

In terms of trajectory design, spatial resolution requirements drive the maximum range at which scientific observations can be performed.

From an operational point of view, Milani's communication with ground will be performed via Inter-Satellite Link (ISL) using Hera as data relay. For this reason, data downlink and uplink must be performed within the same communication windows used by Hera. Operations will be scheduled considering:

- Hera mission operations requirements
- Milani CubeSat mission operations requirements
- Mission Data downlink (Milani-to-Hera)
- Communication window (Hera-to-Earth)

In order to avoid open-loop manoeuvres, Milani needs to select the manoeuvring frequency to be as close as possible to Hera's pattern (4-3 days). This is not mandatory, however, it ensures the compatibility of the strategy with the requirement on the Turn-Around time (TAT)[1] of 48 h.

Scientific goals and operational constraints are the results of an initial phase of requirements definition and consolidations, led by Politecnico di Torino team and have been the main driver for the detailed design of the main phases of Milani's mission: Far Range Phase (FRP) and Close Range Phase (CRP). The scientific goals that mostly drove the mission design of Milani have been derived from its main payload, ASPECT, presented in the following sections.

Milani Mission Profile and Concept of Operations (ConOps)

The Milani Mission is designed by Politecnico di Milano (PoliMI). Milani trajectory design has been mainly driven by the main scientific goals of the mission, but it has also been influenced by both technical and operational constraints. Due to the low gravity environment around the asteroids, selecting Keplerian orbits as nominal trajectories would require a demanding station keeping strategy to counteract the SRP effect. For this reason, a patched-arc manoeuvring strategy that leverage the SRP acceleration to target pre-selected waypoints has been implemented. This strategy has flight heritage in small-body environment. It is the one currently envisaged by the Hera spacecraft during its operational phases and previously performed by the Rosetta spacecraft during its initial scientific phase, after rendezvous with comet 67-P/Churyumov-Gerasimenko. The waypoints selection has been mostly influenced by the passive nature of Milani's payload as well by the on-board navigation strategy, which force the CubeSat to avoid the night-side. The resulting trajectories are loop orbits with manoeuvres points placed as far away from each other as possible to maximize the time spent in proximity to the system.

Main Milani mission phases are hereafter presented:

[1] Time between the download of navigation information and the upload of the instruction.

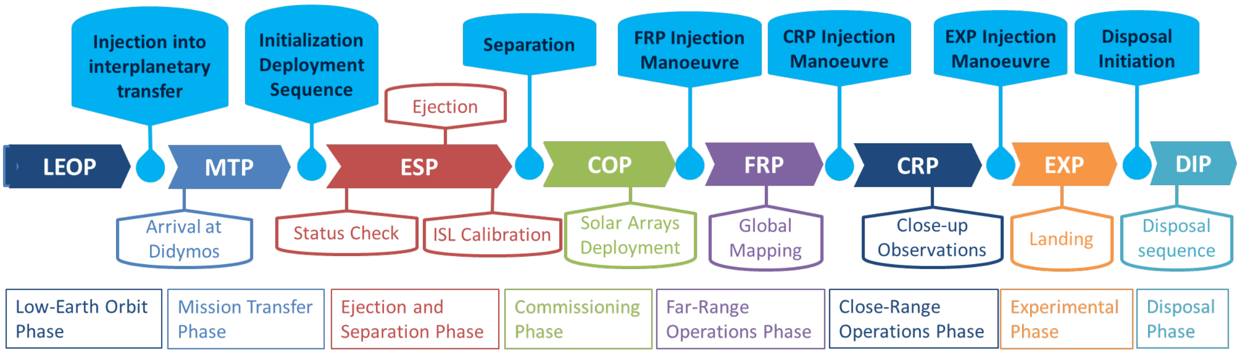

Figure 3. Milani mission phases

- **Low Earth Orbit Commissioning Phase (LEOP)**, ~2-3 months, will be done on Hera spacecraft upon launch; a specific list of checkout tests will be executed also on Milani CubeSat to verify the basic functionalities that can be verified in stowed and integrated configurations
- **Mission Transfer Phase (MTP)**, or interplanetary cruise, ~2,5 years, will be characterized by regular checkout tests to be executed on Milani CubeSat to verify the basic functionalities
- **Ejection and separation phase (ESP)**, ~2-3 weeks (TBC), will start upon arrival to the asteroids and will be characterized by checkout test in stowed configuration, ejection of Milani CubeSat outside Hera, pre-deployment checkout in exposed configuration, Milani CubeSat separation from Hera
- **Commissioning Phase (COP)**, ~1-2 weeks (TBC), checkout, stabilization, and calibrations
- **Far Range Operations Phase (FRP)**, ~3-4 weeks (TBC), transfer to the operative orbits, first global mapping, and technologies demonstration
- **Close Range Operations Phase (CRP)**, ~3-4 weeks (TBC), transfer to the operative orbits closer to the asteroids, Close-up observation of Didymos bodies, additional technology demonstration, observation of the DART impact crater
- **Experimental Phase (EXP)**, foreseeing the landing on the asteroids or transfer on a heliocentric graveyard orbit, currently under evaluation
- **Disposal Phase (DIP)**, ~2 weeks (TBC), Passivation

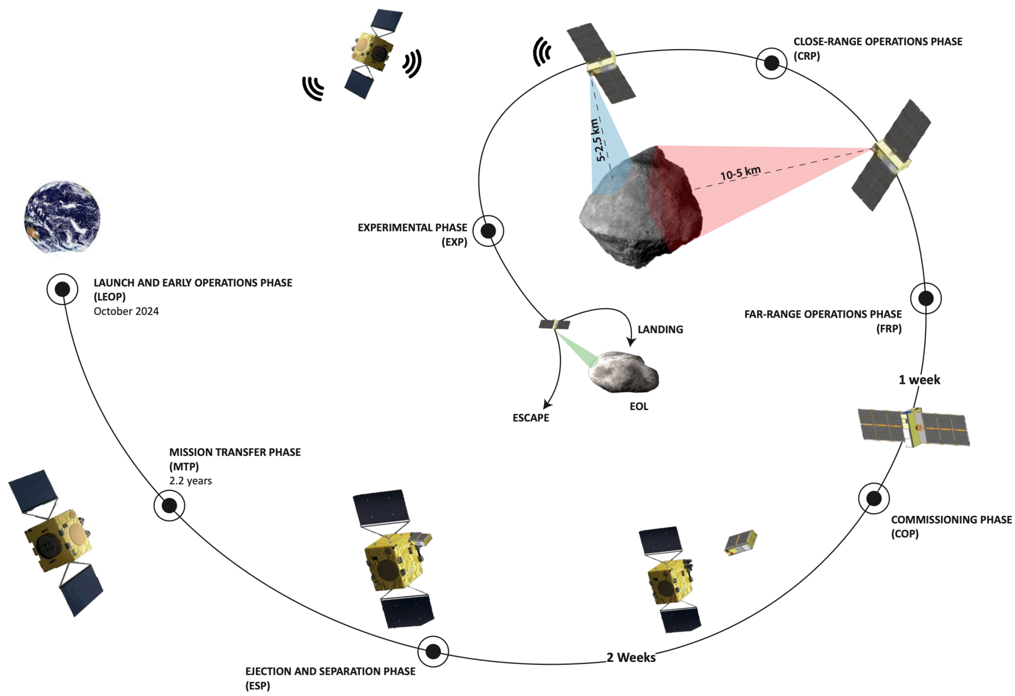

Figure 4. Hera Milani Reference Mission

As previously said, main phases of Milani's mission related to the achievement of the scientific mission objectives, are the Far Range Phase (FRP) and Close Range Phase (CRP).

Far Range Phase (FRP)

The complete mapping of the bodies with a resolution better than 2 m/pixel with ASPECT can be achieved with observations at a distance lower than 11 km from the surface. This is accomplished during the Far Range Phase in which Milani hoovers over the bodies in a repetition of loop orbits quasi-symmetric with respect to the Sun direction. Figure 4 shows the trajectory as a 6-points hyperbolic loop with a manoeuvring pattern of 4-3 days repeated three times.

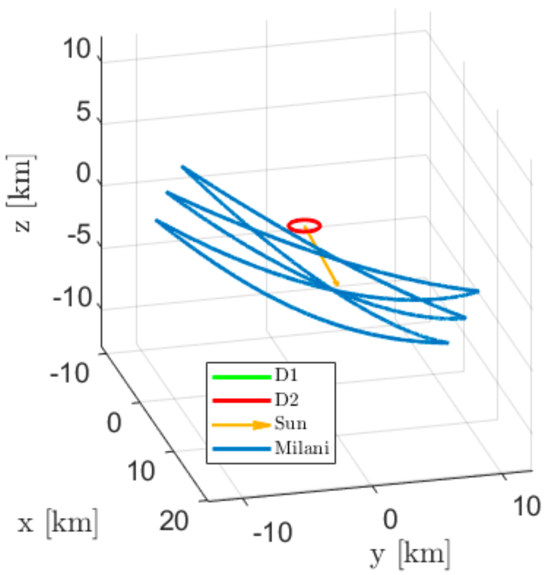

Figure 5 FRP trajectory in DidymosEquatorialSunSouth (*Courtesy: Politecnico di Milano*)

Close Range Phase (CRP)

The complete mapping of the bodies with a resolution better than 1 m/pixel and the DART crater observations are achieved during Close Range Phase. The latter being the most challenging goal of the phase, with a maximum distance requirement of 2.78 km from D2, the CRP design has been focused on the crater observation. Instead, the complete mapping is a by-product of this phase. Due to the tidally locked nature of the system, the observation of a feature fully illuminated and visible is possible only in specific configurations of the two bodies. In this case, since the DART crater will be on the leading side of D2, the crater can be visible and illuminated only around the D2 dawn at each revolution of D2 around D1. Fulfilling both the resolution and phase angle constraints, when D2 is in that configuration, while respecting the operational constraints on the manoeuvring frequency and the permanence into the dayside, makes it impossible to adopt the same trajectory design strategy as in the FRP. Consequently, a slightly modified waypoints strategy has been used for the CRP design. Indeed, CRP design is based on the selection of KeyPoints. A KeyPoint is the position at which the satellite can perform the desired scientific observation fulfilling all the requirements. Thus, while the relative position of the KeyPoints ensures the fulfilling of the scientific requirements, the manoeuvring points position serves to comply with the constraints and to ensure the flyability of the trajectory. Indeed, CRP design has been performed in an iterative fashion considering the navigation assessments results to make it robust to uncertainty and increase its flyability. In fact, many CRP arcs last 7 days, to allow for a correction manoeuvre execution in the middle of a nominal ballistic arc. Furthermore, at the end of CRP, Milani will be injected into a Sun Synchronous Terminator Orbit (SSTO) and to facilitate this plane change, during CRP, Milani slightly increases its declination with respect to the equatorial plane.

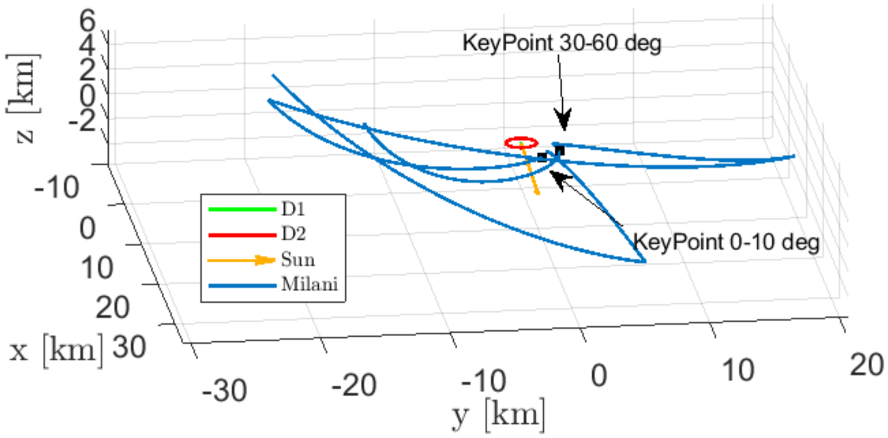

Figure 6 CRP trajectory in DidymosEquatorialSunSouth (*Courtesy: Politecnico di Milano*)

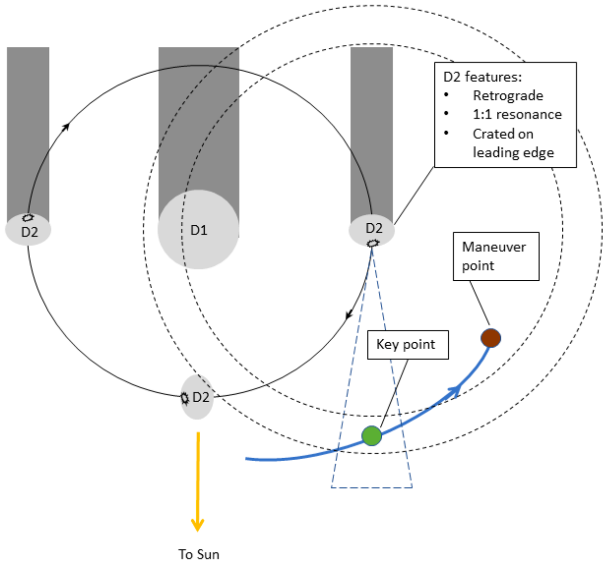

Figure 7. The choice of the "Key Point" where the CubeSat can image the crater on Dimorphos at optimal illumination conditions, at required distance and phase angle. The manoeuvre points of the observation arcs are chosen to avoid going into the night-side (*Courtesy: Politecnico di Milano*)

The complexity of orbiting in a highly perturbed low-gravity environment is increased using miniaturized components and considering the relative operational constraints. The solutions elaborated and presented by PoliMI team show how the design gets more complex when the CubeSat needs to get closer to the system. During the Close Range Phase the spacecraft must get very close to Dimorphos Thus, it requires a complex asymmetric design with the definition of KeyPoints at which Milani can perform science and a concurrent phasing with the motion of Dimorphos and the manoeuvring schedule of Hera. Milani navigation and guidance also get more complex during CRP.

System Overview

The CubeSat leverages on Tyvak Trestles platform architecture, avionics technology Mark II. The Trestles platform is a standard platform, however, some customizations were made specifically for Milani mission. In Figure 7 a view of the vehicle configuration is shown.

Figure 8. MILANI CubeSat – Deployed configuration

The CubeSat system is composed of the following elements:

- Avionics (Tyvak Mark II technology), including Flight Computer, Electrical Power System, ADCS
- Primary Payload (ASPECT)
- Secondary Payload (VISTA)
- Cold-gas propulsion system, enabling technology
- External Inter-satellite link (ISL) radio + antennas
- Navigation Camera
- COTS components
- Mission Specific Interfaces (such as Payload Interface Board, PIB)

A radiation-related analysis to mitigate risks associated to the execution of the mission in deep space environment. The radiation analysis effort is led by Politecnico di Torino team and includes both fault injection approaches and dedicated radiation testing on a subset of components identified as critical.

Interfaces with the Hera mothercraft:

- The CubeSat System is integrated into the Deep Space Deployer (DSD) developed by ISIS, providing also a specific CubeSat Interface Board to interface the Milani CubeSat with the DSD
- The main interface with the assembly constituted by the DSD and Milani CubeSat with the Hera mothercraft is the Life Support Interface Board (LSIB), developed by KUVA Space and allowing the exchange of power and data between the two spacecraft and so the execution of the checkout tests during the stowed and exposed configuration.

The Ground Segment of Milani CubeSat is the Milani Mission Control Center (MMCC), part of the CubeSat Mission Operations Center (CMOC) which development will be launched in Q2 2022.

Main Payload overview: ASPECT

ASPECT payload is a hyperspectral imager operating in the visible and infrared part of the electromagnetic spectrum.

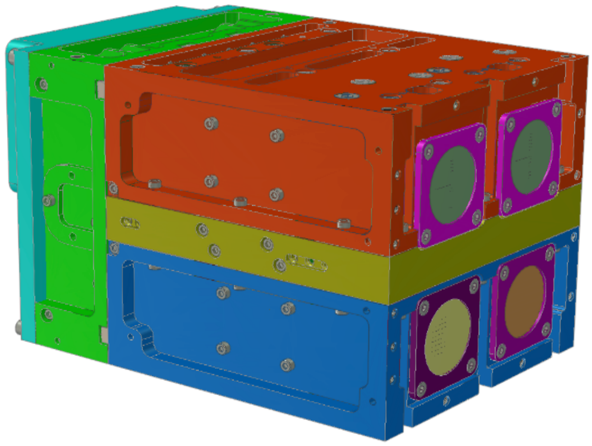

Figure 9. ASPECT Payload overview

The scientific goals of ASPECT are hereafter reported:

- ASP SG1 - To map the global composition of the Didymos asteroids
- ASP SG2 - To characterize the surface of the Didymos asteroids
- ASP SG3 - To evaluate space weathering and global shock effects on Didymos asteroids
- ASP SG4 - To identify local shock effects on Dimorphos caused by DART impact

To fulfil the scientific objectives, ASPECT imager covers the wavelength range of 500 - 2500 nm, and has imaging capability between 500 and 1650 nm. Indeed, the imager is split into four channels:

- VIS (500-900 nm)
- NIR1 (850 - 1250 nm)
- NIR2 (1200 - 1650 nm)
- SWIR (1600 - 2500 nm)

The VIS and NIR channels have imaging capability, while the SWIR channel is non imaging (single pixel). All channels are independent (i.e. redundant) and can be powered on and operated separately if needed. By covering this wavelength range, ASPECT can identify the silicate minerals that make up S-type asteroids. Covering this wavelength range is important, as it allows the study of space weathering effects on the asteroid surfaces. ASPECT can also provide information about shock effects on asteroid surfaces, as it can image the DART impact crater.

Main instrument parameters, characteristics and performances are hereafter presented:

Table 3. ASPECT Main parameters

Parameter	VIS channel	NIR1 channel	NIR2 channel	SWIR channel
Field of View [deg]	10 x 10	6.7 x 5.4	6.7 x 5.4	ca 5.85 circular
Spectral range [nm]	500 - 900	850 - 1250	1200 - 1600	1650 - 2500
Image size [px]	1024 x 1024	640 x 512	640 x 512	1 x 1
Pixel size	5.5 x 5.5 um	15 x 15 um	15 x 15 um	1 x 1 mm
No. spectral bands	Ca. 14	Ca. 14	Ca. 14	Ca. 30
Spectral resolution [nm]	< 20	< 40	< 40	< 40

Table 4. ASPECT Main characteristics

Parameter	Value
Total Mass	1,5 kg
Power consumption during acquisition	13-14W

Total amount data	4.7 Gbit

Table 5. ASPECT Performances

Parameter	VIS channel	NIR1/2 channel	SWIR channel
Image size (km x km) @ 10 km	1750 m x 1750 m	1170 m x 940 m	1022 m (spot diameter)
Ground resolution @ 10 km	1.7 m	1.8 m	1022 m (spot diameter)
Image size (km x km) @ 5 km	875 m x 875 m	585 m x 469 m	511 m (spot diameter)
Ground resolution @ 5 km	0.85 m	0.9 m	511 m (spot diameter)
Image size (km x km) @ 1 km	175 m x 175 m	117 m x 94 m	102 m (spot diameter)
Ground resolution @ 1 km	0.17 m	0.18 m	102 m (spot diameter)
Spectral resolution	10-20 nm (TBC)	20-30 nm (TBC)	30-40 nm (TBC)
Spectral range	500-900 nm	850-1650 nm	1600-2500 nm
Mean SNR @ 1 AU	ca. 60-70	ca. 60-70	high
Mean SNR @ 1.75 AU	ca. 50-60	ca. 50-60	high
Mean SNR @ 2.5 AU	ca. 40-60	ca. 40-60	ca. 60

The interface with the Milani vehicle is ensured through a mission specific Payload Interface Board.

The ASPECT Payload development is led by VTT, leveraging on the support of other entities covering specific areas: Brno University of Technology, responsible for the design of the ASPECT Payload data processing algorithms and workflow design, Institute of Geology of the Czech Academy of Sciences (GLI), responsible for the Didymos asteroid 3D shape reconstruction and hyperspectral data processing, University of Helsinki developing novel algorithms to determine asteroid composition through hyperspectral data, Kuva Space, managing the development of the ASPECT Payload DPU, HULD, managing the ASPECT Payload Controller.

Secondary Payload overview: VISTA

In the framework of Hera Mission for MILANI CubeSat scenario, Volatile In-Situ Thermogravimetry Analyser (VISTA) Payload, in synergy with ASPECT scientific objectives, will accomplish the following scientific goals:

- VIS SG1 – Detect the presence of dust particles smaller than 10µm (residual dust particles from the impact and suspended dust in the binary system or coming from dust levitation process);
- VIS SG2 – Characterization of volatiles (e.g., water) and light organics (e.g., low carbon chain compounds) by using TGA cycles, i.e. heating controlled thermal cycles. The desorption rates at specific temperatures are used to characterize volatiles and organics desorbed by the sensor surface;
- VIS SG3 – Molecular contamination monitoring in support to other CubeSat instruments and ASPECT Spectrometer, coming from outgassing processes on-board the spacecraft/CubeSat hardware components.

Figure 10. EQM VISTA Payload overview.

VISTA sensor head is the instrument core and is composed of three separate sub-units packaged in a shielded enclosure which includes:

- The first sub-unit includes two quartz crystals mounted in a sandwich-like configuration. The top one is the sensing crystal, which is exposed to the external environment and collects the outgassing material. The bottom one is the reference crystal. The output signal is the beating frequency i.e., the frequency difference between sensing and reference crystal. Since the two crystals work in thermal equilibrium, their difference is in principle not affected by temperature effects
- The second sub-unit is the Thermal Control System (TCS), which drives and regulates the temperature of the crystals. It is composed by the built-in resistors on the crystals (i.e., the two heaters and the two temperature sensors) and one Thermoelectric Cooler. The TCS temperatures will be controlled by FCM and managed by OBS. In particular, the TCS is useful to guide the crystals at temperature +30K (heaters) or more and -5K (TEC) or less with respect to the temperature of the external environment in the range from 253K to 313K (temperature range of MILANI).
- The third sub-unit is the Proximity Electronics (PE), including an Oscillator and a Beating module.

Main instrument characteristics are hereafter presented:

Table 6 VISTA Main characteristics

Parameter	Value
Mass budget	0,09 kg
Power consumption during heating/calibration	< 1,5W
Total Data volume	1,6 Mbit

The interface with the Milani vehicle is ensured through a mission specific Payload Interface Board.

The VISTA Payload development is led by INAF, leveraging on the support of other entities covering specific areas: Institute on Atmospheric Pollution Research of the CNR (CNR-IIA), responsible for the piezoelectric crystals and Proximity Electronics development, integration and testing, Politecnico di Milano (PoliMI), covering the thermo-mechanical design, payload integration and testing.

Conclusions

To date, the Milani project is in Critical Design Review and the vehicle is set according to the Hera development plan. Upon successful vehicle qualification, a System Validation Testing (SVT) Phase will be foreseen aiming at testing the end-to-end communication with the Hera mothercraft at OHB facilities. A risk mitigation approach is implemented through the reduced EM development and delivery. Although it will be used along the development for SW interface testing, the final SVT phase will be crucial for the final validation prior to final integration.

Acknowledgement

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