Design, Development, Validation and Verification of the HERA GNC subsystem

Ángel Palomino Aguado[1], Andrea Pellacani[1], Francisco Da Silva Pais Cabral[2], Aída Alcalde Barahona[1], Francesco Pace[1], Alessio Cortesse[1], Rafael Contreras Fernandez[1], Félix de Arribas Antonio[1], Florin-Adrian Stancu[3], and Pablo Colmenarejo Matellano [1]

(1) GMV, Isaac Newton 11, 28760 Tres Cantos, Madrid, Spain, +34 91 807 21 00, {apalomino, apellacani, francisco.cabral, aalcalde, fpace, alessio.cortese, rafael.contreras.fernandez, felix.arribas.deantonio, fstancu,pcolmena}@gmv.com
(2) GMV, Alameda dos Oceanos 115, 1990-392 Lisbon, Portugal, +351 21 382 93 66, francisco.cabral@gmv.com
(3) GMV Innovating Solutions, SkyTower, 246C Calea Floreasca, 32nd Floor, District 1, 014476 Bucarest, Romania, +40 318 242 800, fstancu@gmv.com

ABSTRACT

Hera is a planetary defence mission currently being developed by the European Space Agency (ESA). Its main aims are to fully characterize the Didymos binary asteroid and to measure in-depth detail the aftereffect of the impact of NASA's DART (Double Asteroid Redirection Test) mission.

One of the key aspects of the Hera mission is the increasing autonomy required to meet the mission objectives. Autonomy is achieved through the Guidance Navigation and Control (GNC) Subsystem which is under development by GMV and is the main topic of this article. The designed solution is a vision based GNC that using images taken by the Asteroid Framing Camera, can reconstruct the spacecraft state and will allow to get closer to the binary system in safety conditions.

This paper will include an overview of the whole Hera mission and the design of the Hera GNC subsystem to overcome the present challenges. The Design, Development, Validation and Verification (DDVP) process be also briefly described. Hera is currently in its phase D and the GNC baseline is well consolidated.

1 INTRODUCTION

Hera is an ESA mission that will rendezvous with and explore the Didymos binary asteroid system approximately two years after the impact of DART, studying both Didymos and Dimorphos (the moon of the system) in detail and examining the visible after-effects of the impact. Hera was approved at the ministerial council Space 19+ and it will be launched in 2024 as one of the missions of the new Space Safety Program (S2P).

GMV leads an international consortium composed by Spain, Romania and Portugal that is responsible for designing the intelligence that drives the HERA spacecraft. The HERA Guidance, Navigation and Control (GNC) subsystem is based on a robust solution that will allow the spacecraft to be operated manually during the interplanetary phase and during the first part of the proximity operations, with the main purpose of safely study the low gravity environment around the binary asteroid. During the proximity operations, it is intended that the autonomous GNC system will undergo systematic in-flight testing, leading to the gradual increase of spacecraft autonomy.

To guarantee a high level of autonomy, the first step is to provide to the Spacecraft enough on-board information to estimate its state relative to the asteroids and, based on that estimation, to react accordingly following a preloaded sequence of commands or objectives. To achieve this requirement, a vision based GNC has been designed, which includes image processing algorithms and a navigation filter capable of processing the visual information and to get the required estimation. The HERA GNC subsystem is capable of using not only a visual camera but also other payloads like the laser altimeter (PALT). This additional instrument will be able to give observability on the radial direction, which is poorly estimated in a monocular configuration of a vision based GNC, especially if the selected trajectories are not closed orbits.

This paper will include an overview of the whole HERA mission and will present the design of the HERA GNC subsystem to overcome the present challenges. This includes the GNC architecture and modes design and the GNC Failure Detection and Isolation Recovery (FDIR) system. The paper will also present the consolidated strategies of the vision based GNC designed for the HERA mission, together with the analysis campaign results. Finally, the DDVP procedure will be briefly described.

2 MISSION OVERVIEW

A comprehensive description of the mission can be found in Figure 3-1. The launch of the DART spacecraft was scheduled for the year 2021, and it finally impacted on Dimorphos in September 2022. The Hera spacecraft, on the other hand, is planned to be launched in October 2024, with its arrival at Didymos expected in January 2027.

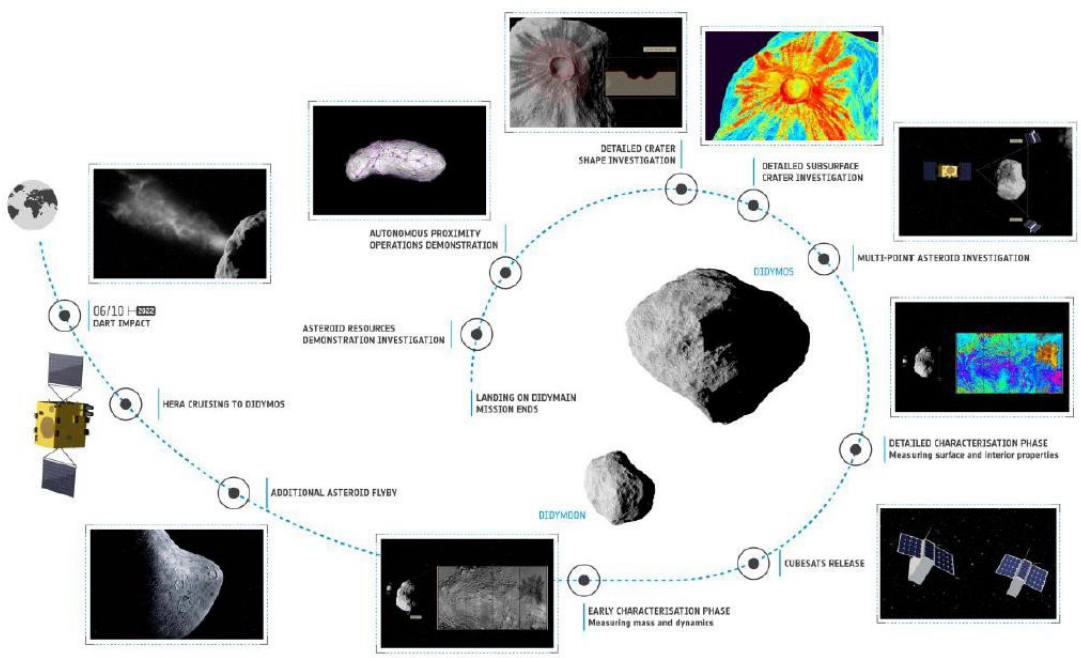


Figure 2-1 Scheme of the mission overview

A summary of the mission timeline is presented here, divided into the main phases.

Launch and Early Operations

There are two launch opportunity windows, each in a different year: 2024 and 2026. The launch strategy for the 2024 launch window can be Ariane 62 with ASTRIS kick-stage (baseline), Ariane 64 (backup 1) and Falcon 9-6500, expendable (backup 2). For the 2026 launch window, the strategy is Ariane 64 (baseline) and Falcon Heavy, fully re-usable (backup). After launch the first weeks will be dedicated to, first, perform the essential LEOP deployments and critical system initialisations followed by the commissioning of all the required systems.

Interplanetary Transfer

Depending on launch opportunity and date (launch period opening, LPO, or launch period closure, LPC), the transfer to Didymos can have different durations and typologies. Durations can range anywhere from 2.4 to 5.3 years. Moreover, the number and order of Swing-by's and DSMs can also vary considerably.

Rendezvous

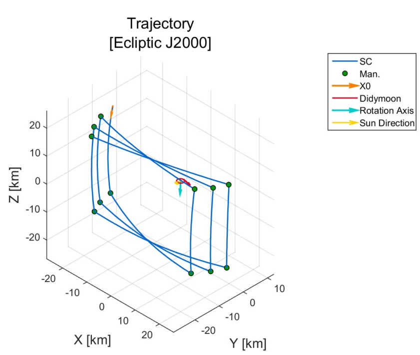
Depending on the transfer opportunity the arrival velocity can vary between very different values, namely, 234 and 688 m/s. This means that a conservative approach must be assumed, to account for the possible values and a 2-month window is kept to bring the probe to Didymos' final velocity. To achieve this, and be robust to manoeuvre errors, the braking manoeuvre is split into a set of 5 manoeuvres, split by a minimum of two weeks to allow for opportunities to brake with little to no ΔV penalty in case of a manoeuvre misfiring.

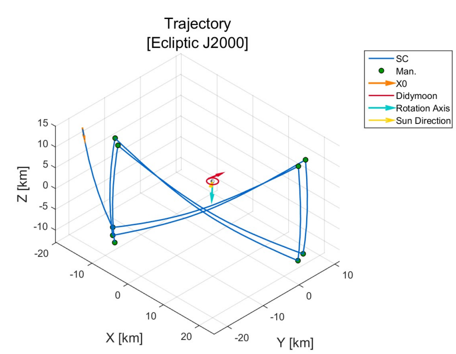
Proximity Operations

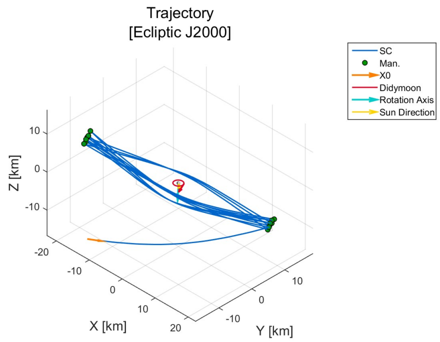
The proximity operations are, perhaps, the most challenging phase due to the proximity to the target. This phase is divided in smaller phases, all with different durations and operational tasks that are driven by the distance to the asteroid and level of autonomy required to meet the phase objectives.

Phase	Tasks	Duration
Early Characterisation Phase (ECP)	• Perform first estimation on the dynamical parameters: target's gravitational parameter, target's translational and rotational ephemerides, target's shape model, scale factor error, target's centre-of-mass, comet gas drag (if applicable), other bodies ephemerides (if applicable). • Safe navigation of ECP trajectories. • Keep target on camera's Field of View (FoV). • System and procedures performance in-flight validation. • AOCS operations as needed (e.g.: RW off-loading, SADM commanding, etc)	8 weeks
Payload Deployment Phase (PDP)	• Payload Delivery Rehearsals (including system and procedures performance in-flight validation). • Accurate payload delivery (according to cubesat requirements). • Safe navigation of ECP-style release trajectories. • Keep target on camera's FoV. • AOCS operations as needed (e.g.: RW off-loading, SADM commanding, etc)	Included in ECP

Detailed Characterisation Phase (DCP)	• Improve the knowledge on the parameters first estimated on ECP • Safe navigation of closer DCP trajectories. • Keep target on camera's FoV. • System and procedures performance in-flight validation. • AOCS operations as needed (e.g.: RW off-loading, SADM commanding, etc) • Scientific Operations & Downlink of Science Data	4 weeks
Close Observation Phase (COP)	• Improve the knowledge on the parameters first estimated on ECP. • Safe navigation of closer COP trajectories. • Keep target on camera's FoV. • System and procedures performance in-flight validation. • AOCS operations as needed (e.g.: RW off-loading, SADM commanding, etc) • Scientific Operations & Downlink of Science Data • Fulfilment, as far as possible, of the SRD requirements SY-OBJ-10, 11 and 12	6 weeks
Experimental Phase (EXP)	• Fly-by rehearsals to validate the autonomous GNC system. • Technology demonstration of the autonomous GNC system. • Safe navigation of closer fly-by trajectories. • Keep target on camera's FoV. • System and procedures performance in-flight validation. • AOCS operations as needed (e.g.: RW off-loading, SADM commanding, etc) • Scientific Operations & Downlink of Science Data	5 weeks
Extended Operations Phase (EOP)	• Mission operations extended based on remaining deltaV and extended objectives • End of life landing on Didymos' pole	Based on remaining mission capabilities







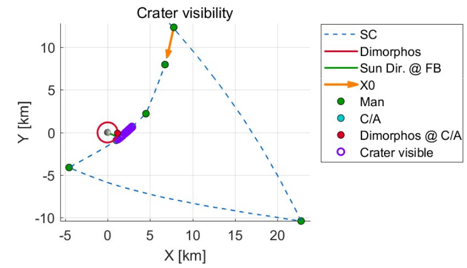


Figure 2-2 Trajectories of ECP, DCP, COP and VCFB.

For each of the phases, a specific GNC strategy has been identified and the autonomy level required has been determined to achieve the phase objectives. The ECSS autonomy levels are defined below:

- E1: Mission execution under ground control; Limited on-board capability for safety issues.
- E2: Execution of pre-planned, ground-defined, mission operations on-board.
- E3: Execution of adaptive mission operations on-board.
- E4: Execution of goal-oriented mission operations on-board.

Table 2-1: HERA mission scenarios and autonomy levels

Mission Phase	Description	Autonomy level	GNC Sensor
LEOP	First operations after SC separations and commissioning	E2	IMU Sun Sensors
Interplanetary and Rendezvous	Interplanetary cruise, Deep Space Manoeuvres and Approach phase	E2	IMU Star Trackers Sun Sensors
ECP	Early Characterization Phase at a distance beyond the gravitational sphere of influence (around 30 km distance, TBC) with the objective of conducting a physical and dynamical characterization of Didymos.	E2	IMU Star Trackers Sun Sensors (AFC)
PDP	During this phase the CubeSats are released and commissioned until they reach fully operational capabilities	E2	IMU Star Trackers Sun Sensors
DCP	It involves closer proximity operations at about 10 km from the system barycentre, enabling the accurate characterisation of Dimorphos's mass. Different viewing angles will be used as in the ECP to access different latitudes and longitudes from different local times by means of (intrinsically safe) hyperbolic arc flyby trajectories	E3 (Autonomous attitude pointing)	IMU Star Trackers Sun Sensors AFC

Mission Phase	Description	Autonomy level	GNC Sensor
COP	HERA will progressively approach Dimorphos to fully characterize DART´s impact. Approach is assumed to go down up to ~4 km for full payload operation. Higher resolution images of the crater will be taken with close flyby trajectories.	E3 (Autonomous attitude pointing)	IMU Star Trackers Sun Sensors AFC
EXP	During higher-risk autonomy demonstration experiment very close fly-by will be performed with autonomous re-targeting manoeuvres	E3 For the entire GNC subsystem	IMU Star Trackers Sun Sensors AFC PALT (necessary for this experimental phase)
ELP	Disposal by landing on the surface of "Didymain".	E2	IMU Star Trackers Sun Sensors AFC PALT (necessary for this phase)

Table 2-1 reports the different scenarios and their relative autonomy level. Furthermore, the sensors and actuators used in the GNC loop are listed. The modes and sub-modes architecture of the GNC subsystem has been designed to respond to the needs expressed in the table.

3 GNC SUBSYSTEM ARCHITECTURE AND MODES DESIGN

3.1 GNC Subsystem high level architecture

In the following section a GNC high level architecture is provided. Figure 3-1 shows the main components of the GNC S/S together with their high-level interfaces:

- GNC Application Software (GNC ASW)
- GNC units (GNC sensors and Reaction Wheels)
- GNC payload: the Image Processing Unit (IPU)
- Image Processing algorithms (inside the IPU and inside the 2nd core of the OBC)

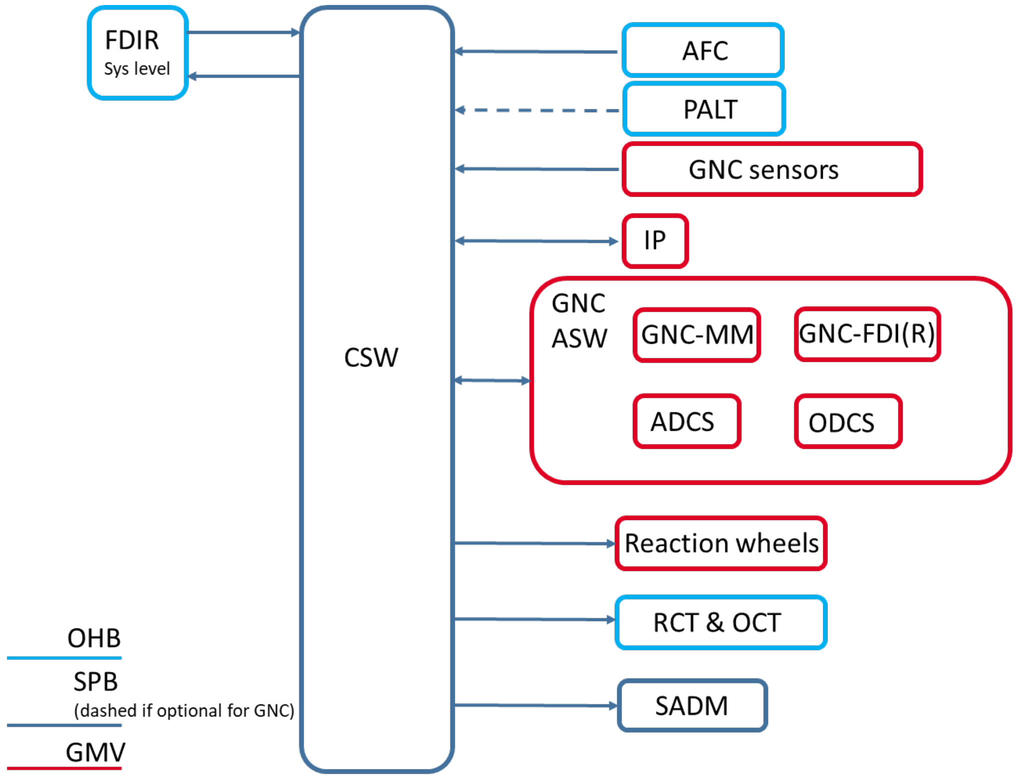


Figure 3-1: HERA GNC S/S high level architecture (main functions only)

The GNC ASW will include a GNC-FDIR. This means that, at GNC level, there will be a FDI with a possible recovery suggestion (e.g. executing a Collision Avoidance Manoeuvre). However, the final decision will be made by the FDIR at system level, since it is at system level that there will be full visibility of all the S/C status. This will automatically allow an override of the GNC-FDI at system level (and from ground if needed) because the GNC-FDI(R) will not have the authority to directly impose any reconfiguration/recovery action. More details are provided to describe the architecture of the GNC ASW in Figure 3-2.

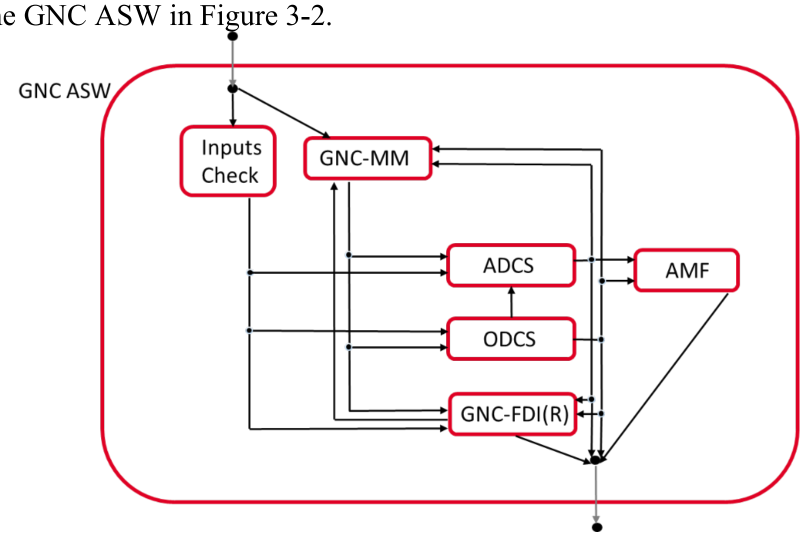


Figure 3-2: GNC ASW high level architecture

During previous phases several iterations have been done to harmonize the functions in the GNC

ASW and maximize performance/robustness. The result of these iterations was to split the GNC ASW into two group of functions:

- HP (High Priority): this group of functions includes at least Attitude Determination and Control System (ADCS) with its associated FDI, AMF (Actuator Management Function) and GNC-MM (GNC Mode Manager). They are called high priority because they are meant to be executed to minimize the delay between the measurement collection from sensors and the actuators execution. This is a critical point for the ADCS to guarantee the phase margin requirement from ECSS.

- LP (Low Priority): this group of functions includes at least the ODCS (Orbit Determination and Control System). They are called low priority because they are part of a slower dynamic (the transitional one) that can be executed whenever the OBSW responsible deems it feasible (still within the GNC cycle). The commands to the AMF that comes from this group of functions will be executed in the next cycle of the OBSW.

It is important to specify that both groups of functions, HP, and LP, will run at 1 Hz and in the OBSW scheduler will appear like in the conceptual scheme below.

3.2 GNC modes and sub-modes

There are 8 major GNC modes and a stand-by mode to be used as initialization/testing mode. The GNC modes identification/definition also considers the separation between nominal part of the mission (to fulfil core requirements) and experimental part of the mission (to fulfil opportunistic requirements). This way it is possible to clearly separate the higher autonomy (and higher risk) modes from the nominal modes necessary to fulfil core mission requirements.

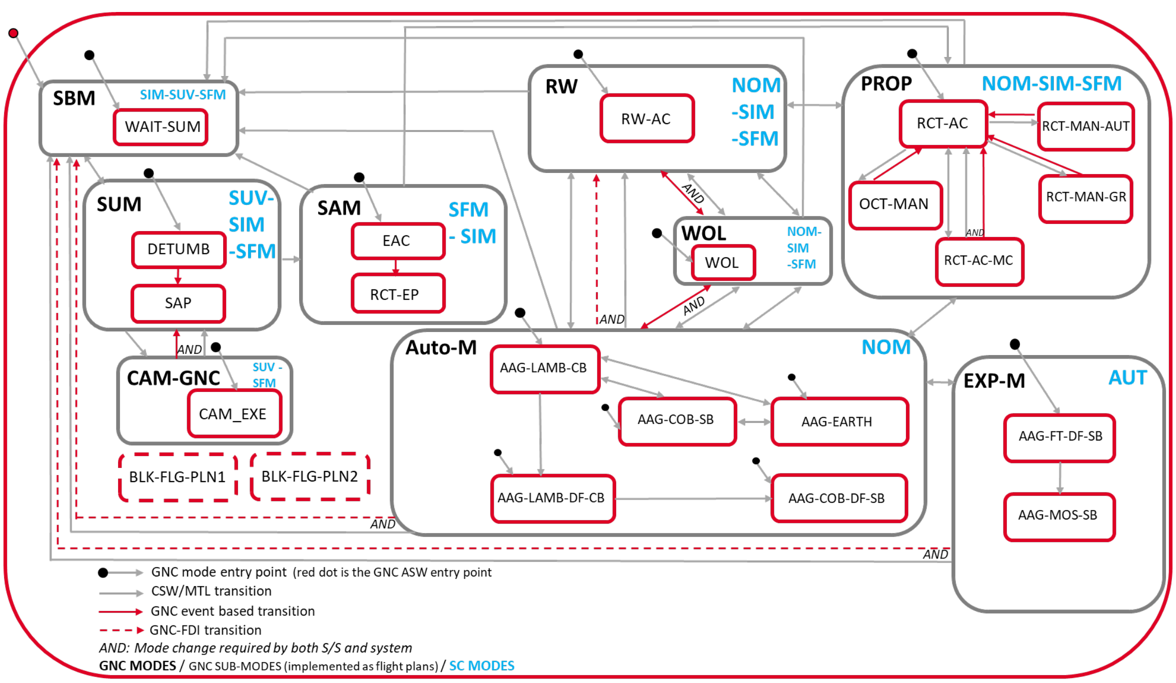


Figure 3-3: GNC modes, sub-modes, and transitions

A high-level description of the GNC modes and sub-modes is given below):

- **SBM (Stand-by GNC mode):**

This mode is the entry point of the GNC ASW. No GNC functions are active in this mode and the GNC ASW is only waiting for the CSW to activate the SUM mode. In case of failure, this mode will be activated before SUM to guarantee the entry conditions of SUM (Sun Sensors and RCT availability).

At the end of SBM it is expected that the units required for SUM are considered ready.

- **SUM (Survival GNC mode)**:

This mode is the first active (the GNC control the S/C) mode at the boot of the system and every time the S/C mode is set to Survival. It is composed by two sub-modes:

  - DETUMB, to achieve the required rotational state of the S/C (first sub-mode triggered), using RCT and gyros.
  - SAP (Sun acquisition and pointing), the SADM is a locked position that will point the solar panel towards the Sun when the SC +X points to the Sun (SC can communicate to ground through Low Gain Antenna). The attitude navigation used in the control loop in this mode consists only of IMU and Sun sensors, but the gyro-stellar algorithm is processing star tracker measurements to be ready to enter the following mode (SAM).

SUM final state ensures the SC pointing +X towards the Sun while keeping a specific angular rate around +X (tuneable parameter from ground).

- **SAM (Safe GNC mode)**:

The GNC-MM enters this mode once the star tracker is ready to enter in the control loop and the gyro-stellar estimation is expected to have converged. It is composed by two sub-modes:

  - EAC (Earth acquisition), to achieve Earth primary pointing using the Reaction Control Thrusters (RCT) and the gyro-stellar based attitude navigation. To go from the SUM attitude (+X pointing toward the sun and random phase angle in the YZ plane) to the ground-based quaternion used for contingency, an autonomous attitude profile is generated to achieve the transition while keeping the +Y axis orthogonal to the Sun.
  - RCT-EP is the Earth pointing mode with RCT (reference quaternion profile provided by ground).

SAM final state will be with the SC pointing +X towards the Earth, following the ground based (contingency) attitude quaternion.

- **PROP (GNC Propulsion mode)**:

The GNC MM enters this mode after SAM to spin-up the Reaction Wheels or when a manoeuvre must be performed. Five main sub-modes are considered:

  - RCT-AC, that act as the entry point to this mode and attempts to stabilize the attitude using the RCT as actuators while maintaining the reaction wheels at constant speed.
  - RCT-AC-MC, where the momentum of the wheels is controlled and set to a desired value (also used for Reaction Wheels run-in and spin-up).
  - RCT-MAN-GR where RCT ground-based manoeuvres are performed (the attitude is controlled by RCT – open loop translational control with Delta-V counting).
  - RCT-MAN-AUT where RCT autonomous manoeuvres are performed (the attitude is controlled by RCT – open loop translational control with Delta-V counting).
  - OCT-MAN where manoeuvres are performed using the Orbit Control Thrusters (OCT). The attitude is controlled by Orbit Control Thrusters (OCT off-modulation and RCT –

open loop translational control with DV counting).

PROP final state will be defined by an attitude pointing (using RCT) after translational manoeuvre and/or reaction wheel momentum control is performed.

- **RW (Operational Reaction wheels attitude-based mode)**:

The GNC MM stays in this mode most of the mission lifetime. It is composed only by:

- RW-AC where the attitude is controlled using RW. The Wheels momentum is monitored.

RW final state will be with the SC following a ground-based attitude profile.

- **WOL (Wheels Off-Loading mode)**:

This mode is entered to off-load the wheels (it can be entered by nominal operations of the mission timeline or by CSW reacting to wheels momentum on-board monitoring):

- WOL, while the attitude is maintained with the Reaction wheels, a train of pulses is provided by the RCT to desaturate the wheels via the reaction of control loop to attitude errors.

WOL final state will be with the Reaction wheels set to a specific angular momentum.

- **Auto-M (Autonomous Mode)**:

This mode is part of the core mission (apart from the data-fusion sub-modes) and allows an autonomous attitude profile that will maintain Didymos or Dimorphos in the FoV of the camera during the DCP and COP phase (closest approach to Didymos of about 4 km). It is composed of five sub-modes:

- AAG-LAMB-CB where the attitude guidance is fully autonomous, the translational navigation is based on the Lambertian Sphere correlation technique over Didymos, and the attitude is achieved through the RW.
- AAG-COB-SB where the attitude guidance is fully autonomous, the translational navigation is based on the Centre of Brightness over Dimorphos, and the attitude is achieved through the RW.
- AAG-EARTH where the attitude guidance is ground-based, and the navigation filter is just propagating the state due to the lack of availability of new measurements.
- AAG-LAMB-DF-CB where the attitude guidance is fully autonomous, the translational navigation is based on the fusion of data coming from the Lambertian Sphere correlation technique over Didymos and the information available from the PALT. The attitude is achieved through the RW.
- AAG-COB-DF-SB where the attitude guidance is fully autonomous, translational Navigation based on Centre of Brightness over Dimorphos and data fusion with PALT, and the attitude is achieved through the RW.

- **EXP-M (Experimental Mode)**:

This is part of the experimental modes / technology demonstrations that allows the SC to flight to distances of about 1 km with respect to Dimorphos:

- AAG-FT-DF-SB where no manoeuvres are performed, and the attitude is achieved through the RW. The autonomous translational navigation filter uses fuses feature tracking measurements over Dimorphos and the information available from the PALT.

- AAG-MOS-SB where no manoeuvres are performed, and the attitude is achieved through the RW. The autonomous translational navigation filter is no longer accounting for new measurements and provides the propagated state of the S/C. A specific attitude guidance mode, called mosaic, is active to take 4 consecutive pictures around the crater to guarantee the imaging of the crater.

EXP-M final state will be with the SC following an autonomous attitude profile.

- **CAM-GNC (Collision Avoidance Mode)**:

The GNC MM enters this mode when collision risk is detected. This mode can only be activated after SUM, guaranteeing the possible tumbling has been stopped and the Sun pointing has been achieved beforehand:

- CAM_EXE in this mode the pre-planned manoeuvre is executed (CAM direction is the Sun direction, fixed per design, and magnitude is a tuneable parameter).

CAM-GNC final state will be with the SC pointing +X towards the Sun and after the CAM is performed.

3.3 GNC FDI

The GNC Failure Detection and Isolation (GNC-FDI) system within the HERA spacecraft is designed to provide the necessary autonomy in the event of failures, with the aim of preserving the operational conditions of the spacecraft through autonomous software actions. It should be noted that the GNC-FDI system detects failures, isolates them (such as failures resulting from inaccurate measurements or GNC application malfunctions), and proposes a recovery plan to the Fault Detection, Isolation, and Recovery (FDIR) system. The FDIR system possesses comprehensive knowledge of the overall status of all subsystems and determines further actions for isolation and recovery. For proximity operations, an independent software-based sensor data fusion is employed to validate the GNC's nominal output using collision detection and avoidance techniques. This includes assessing collision risks and implementing collision avoidance manoeuvres (CAMs) if deemed necessary.

During operation of the GNC-FDI unit, the equipment function is required to report hardware configuration states to the ground for verification purposes. Furthermore, it is envisaged that the enabling or disabling of GNC-FDI units will be carried out autonomously by the system FDIR or as directed by ground commands.

The general GNC-FDI architecture is presented in Figure 3-4 and follow two main objectives: A hierarchical structure of the GNC-FDI related functionality over several levels and a clear definition of responsibilities for each FDI level (from low level input monitoring to high level recovery suggestion.). The GNC-FDI system can be fully configured from the ground, including the enabling or disabling of GNC-FDI units, threshold settings, and confirmation parameters. Additionally, the execution of collision avoidance manoeuvres can be commanded via ground telecommand.

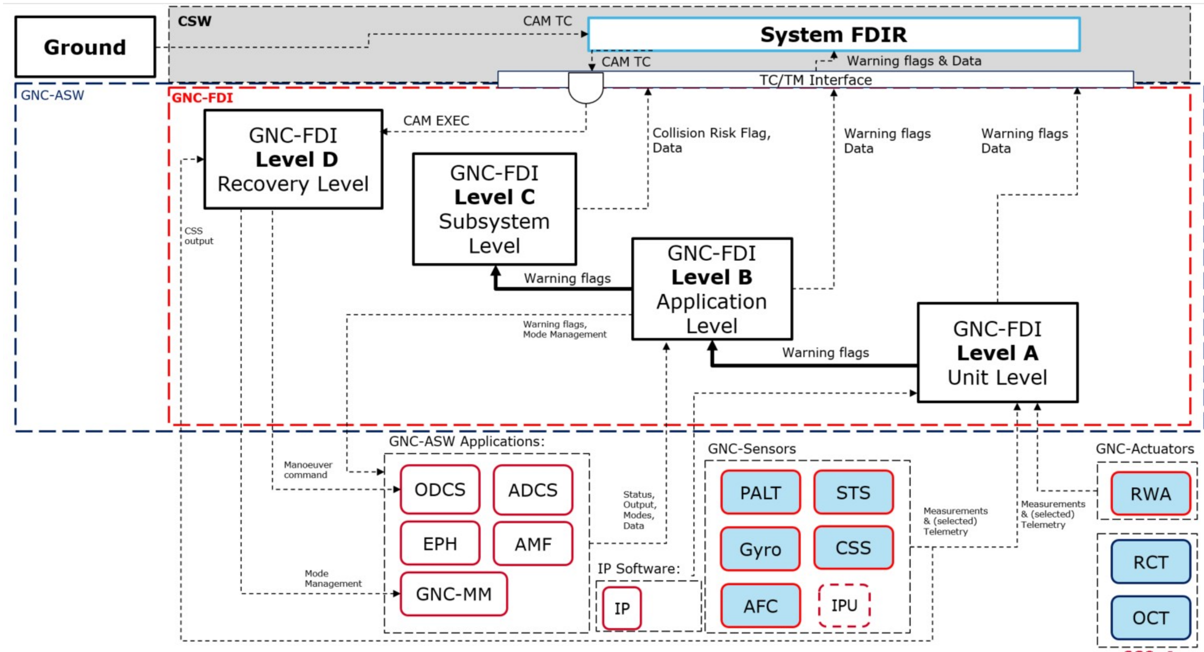


Figure 3-4: GNC-FDI subsystem design

The four hierarchical levels of the GNC-FDI are:

- Unit/local level: This level is responsible for monitoring all received sensor signals, provided they are active and selected. It ensures measurement continuity, checks the health status of sensors, and verifies if the measurements are within the expected range. Additionally, crosschecks are performed between sensors, and response checks are conducted for all GNC actuators.

- Application level: At this level, tailored monitoring is implemented for specific GNC applications such as Attitude Determination and Control System (ADCS), Orbit Determination and Control System (ODCS), GNC Mission Management (GNC-MM), and Autonomous Mission Functions (AMF).

- Sub-system level: This level focuses on trajectory safety checks. It involves two independent estimations of collision risks with the asteroid. The sub-system level also monitors autonomously commanded manoeuvres, ensuring their proper execution and safety.

- Recovery level: If a collision avoidance manoeuvre is commanded by the CSW, the GNC-FDI level D takes charge of managing the necessary sub-mode changes. It also ensures the correct generation and execution of the Collision Avoidance Manoeuvre (CAM) to mitigate the collision risk effectively.

4 AUTONOMOUS OPERATIONS

This section delineates the necessary functionalities that have been devised to enable the autonomy of the S/C and present a relation of scenarios that achieve the required objectives making use of these technologies. The technologies developed are image processing algorithms and tailored Kalman filters to process the information coming from these image processing algorithms and from the altimeter. Schemes to generate attitude guidance profiles and compute manoeuvre corrections have also been implemented. These integrated technologies collectively contribute to the achievement of the desired objectives for enabling S/C autonomy.

4.1 IP Algorithms

Three main IP algorithms have been implemented and tailored to each mission phase.

- **Maximum correlation with a Lambertian sphere** for images in the visible range (baseline when the entire primary body can be seen in the images – according to the body size and the Asteroid Framing Camera (AFC) characteristics, this occurs when the range is higher than 9.5 km). The algorithm has been developed by GMV and performs a convolution of the image with a Lambertian sphere. Considering the dimension ratio between the bodies and the sphere-like shape of the primary body, this algorithm is robust to different illumination conditions and to the presence of the secondary body in the camera field of view.

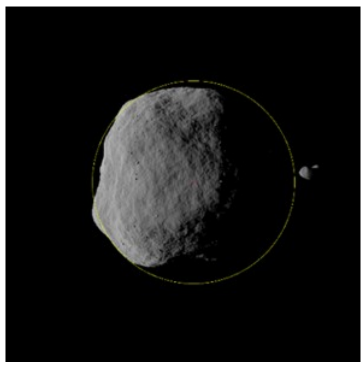


Figure 4-1: Lambertian sphere correlation

- **Centre of brightness (CoB) over Dimorphos**. The objective of this CoB is to autonomously determine the Line of Sight (LOS) to the centre of Dimorphos. The Lambertian sphere cannot be optimally used for Dimorphos as its shape is not assumed to be regular and sphere-like as it is for Didymos. To properly use the CoB over Dimorphos, a procedure to remove Didymos from the image is included in the algorithm.

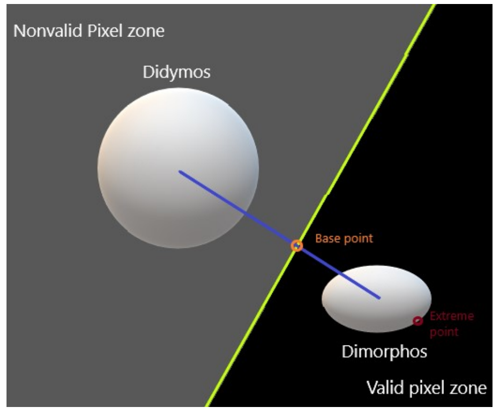


Figure 4-2 Masking scheme to remove Didymos from the image.

- **Feature tracking** algorithms (baseline for close fly-by, GMV in-house implementation of [1]). This algorithm is based on detecting representative features and track them in time (see Figure 4-3). The information is then used by the navigation filter to reconstruct the spacecraft state.

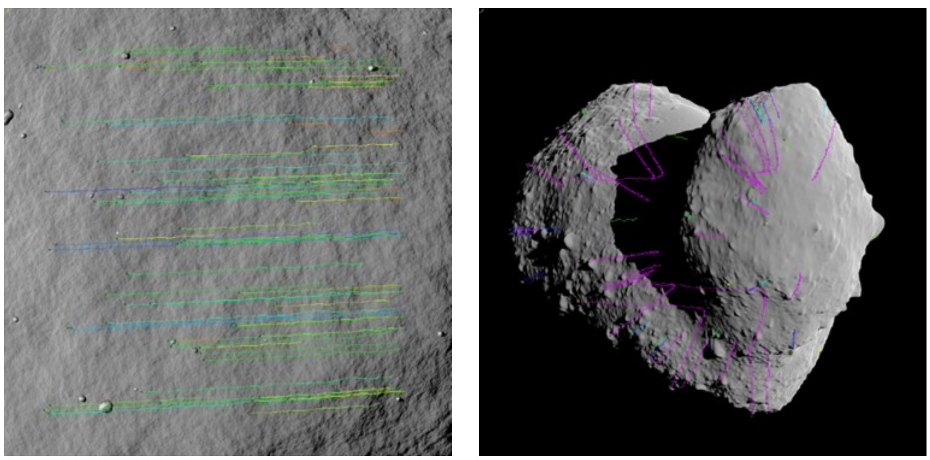


Figure 4-3: Feature tracks on surface of primary (left) and secondary (right)

- **Mosaicking**: Despite it is not an IP algorithm used for navigation, it has been included here as it allows to artificially increase the FoV by taking several pictures over a specified path. This technique is used to guarantee the imaging of the crater in the closest approach when angular errors become maximum due to the reduced distances to the asteroid. The mosaic is a 2x2 and sequence of images that are taken as per Figure 4-4, starting from the middle of the composed image (point A) and following the sequence A-B-C-D-E.

.

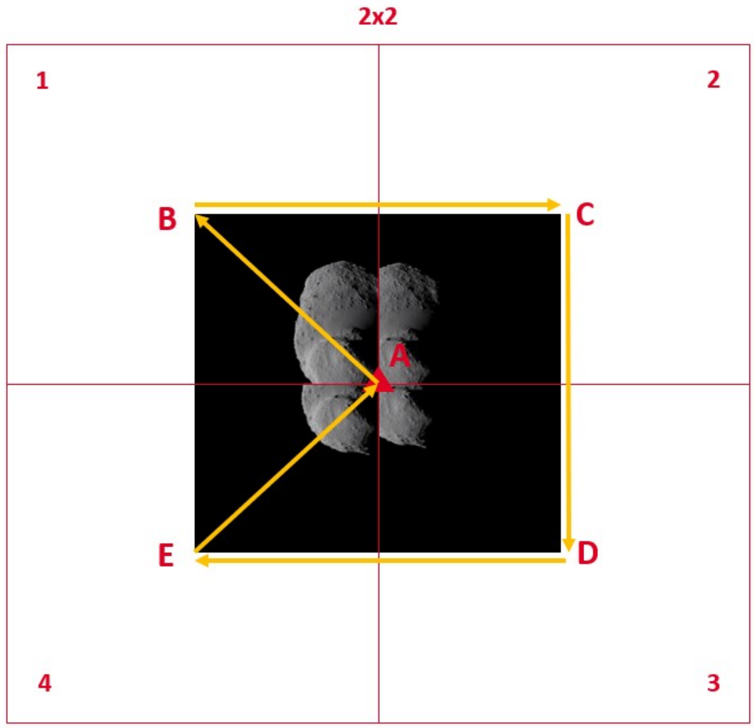


Figure 4-4 Mosaicking Scheme.

4.2 Autonomous Translational Navigation technology

The purpose of the translational navigation is to perform data fusion with the measurements available according to the specific phase and to estimate the relative position and velocity of the S/C with respect to the binary asteroid system. The navigation filter design is meant to be flexible for all the phases, to reuse the same core functions. From the previous phases, the filter has undergone a redesign and has become a pure Extended Kalman Filter (EKF). The augmented states for the different filters have also been modified and now, they account for extra uncertainties, which makes the estimation more robust. Current design consists of two main functionalities:

- OD-CENT-DF (Orbit Determination using Lambertian Sphere or Centre of Brightness and Data Fusion with Altimeter if available). The use of the image processing technique is based on the distance to the bodies and their relative size within the field of view of the camera. Due to its smaller size, Centre of Brightness over Dimorphos allows to flight closer distances as the FoV is still not saturated.

- OD-FT-DF (Orbit Determination using Feature Tracking IP and Data Fusion with Altimeter) – working at close range, with feature tracking image processing. The design of this filter exhibits a high level of complexity due to the need for incorporating a substantial number of states. This complexity arises from the need to account for various uncertainties encountered during the process of reconstructing the position of features in the Dimorphos body frame.

The two of the functionalities (OD-CENT-DF and OD-COB-DF) can work using the image processing data only or can operate in a state that allows sensor fusion with the altimeter data to both bodies. The feature tracking functionality must work together with altimeter data to the bodies.

The S/C state that is retrieved from the filters can later serve to either generate an autonomous attitude profile that tracks the desired pointing or to compute corrections to pre-planned manoeuvres by means of the Fixed Time Of Arrival (FTOA) algorithm.

4.3 DCP and Lambertian Sphere IP

During the DCP phase, the Hera SC will fly from 20 to 10 km distance with respect to Didymos, varying the phase angle but always maintaining the SC between the asteroids and the Sun (never going beyond the terminator line). The Lambertian sphere correlation is used during this phase, as both bodies can appear in the FoV of the camera, and a robust technique is needed to estimate the centre of the primary body while having the disturbance of the secondary in the image. Along the scenario, the autonomous GNC computes the attitude of the spacecraft to avoid losing the asteroids from the field of view. The ground predicted solution would be unable to meet the pointing requirements due to the uncertainties both in the state estimation and in the manoeuvre execution.

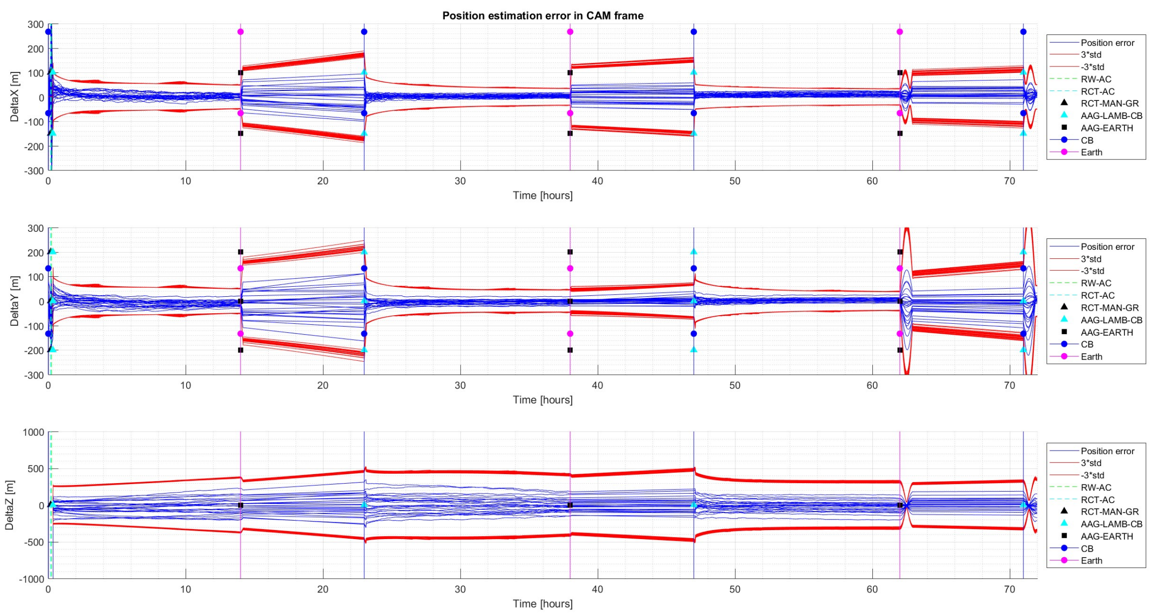


Figure 4-5: Position estimation error in camera frame during a DCP arc

Several considerations can be made looking at Figure 4-5, that shows the position estimation error of the navigation filter in one of the DCP arc:

- A healthy behaviour of a navigation filter, with the 3-sigma estimation (red lines) containing the estimation error.
- Better performances in the XY plane of the camera. Indeed, the Z axis (radial direction) is not directly observable by means of only images (the altimeter is not used in this scenario). However, the rotation of the camera as long as the S/C moves along the hyperbolic arc, allows to keep the radial estimation constrained up to certain limits.
- The scenario lasts for 3 days and there are 3 events (of the length of about 8h each) in which the covariance and the estimation error increase. The effect is expected, and corresponds to communication windows with Earth, during which no images can be taken. Thus, the

navigation filter is just propagating the dynamics and no updates are done.

The estimation translates into very moderate overall pointing errors as per Figure 4-6 (below 0.2 degrees) when pointing to the asteroid, which means the asteroid is kept in the FoV. When pointing towards the Earth, the pointing error is even smaller due to the error in the navigation with respect to the asteroid does not influence this pointing.

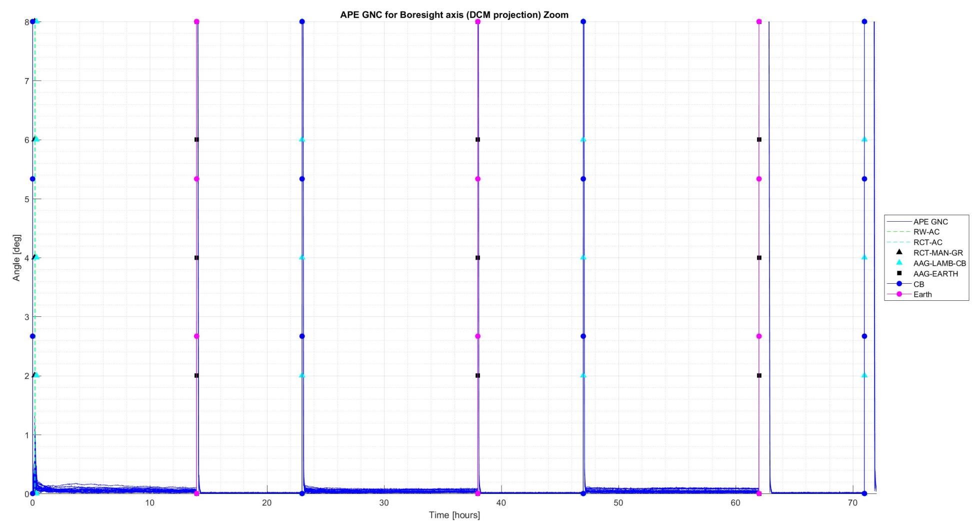


Figure 4-6 Absolute Pointing Error (APE) during a DCP arc.

4.4 COP and Centre of Brightness over Dimorphos

During the COP phase, the HERA SC will fly from 20 to 4 km distance with respect to Didymos, varying the phase angle but always maintaining the SC between the asteroids and the Sun (never going beyond the terminator line). From 20 to 10 km distance, the same strategy adopted for DCP is used. When the distance is such that the Lambertian sphere cannot be used anymore (about 9-10 km), the centre of brightness over Dimorphos allows to keep having measurements, avoiding a long blind phase.

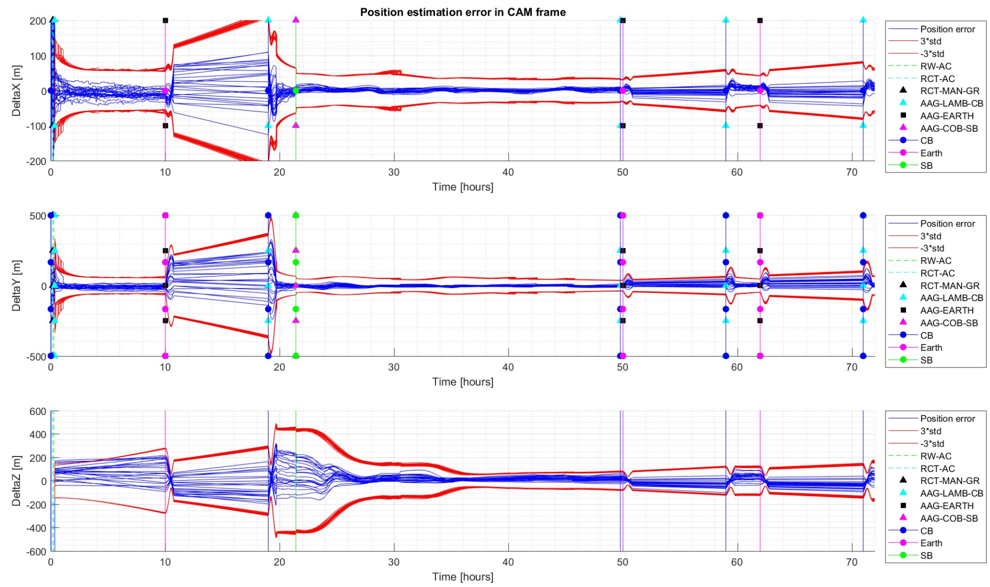


Figure 4-7: Position estimation error in camera frame during a COP arc

Several considerations can be made looking at Figure 4-7, that shows the position estimation error of the navigation filter in one of the COP arc:

- All the considerations reported in 4.3.

- A considerable performance improvement when the centre of brightness is used (so when the SC during its hyperbolic arc has a distance relative to Didymos of 4 to 10 km – this happens in the middle of the scenario). This can be explained for several reasons. Despite, the precision of the measurement relative to the radius of the body is worse than for the Lambertian Sphere over Dimorphos, the smaller size of Dimorphos makes that in absolute value of distance, the error is smaller. Additionally, the movement of Dimorphos along its orbit, makes that the rotation of the camera is more continuous causing the transference of knowledge between axes.

- Despite the distance is smaller, which can multiply the pointing errors, as the same error in absolute position translates into bigger error, the errors are kept below 0.5 degrees as it can be observed in Figure 4-8, meaning that the asteroid is kept in the FoV.

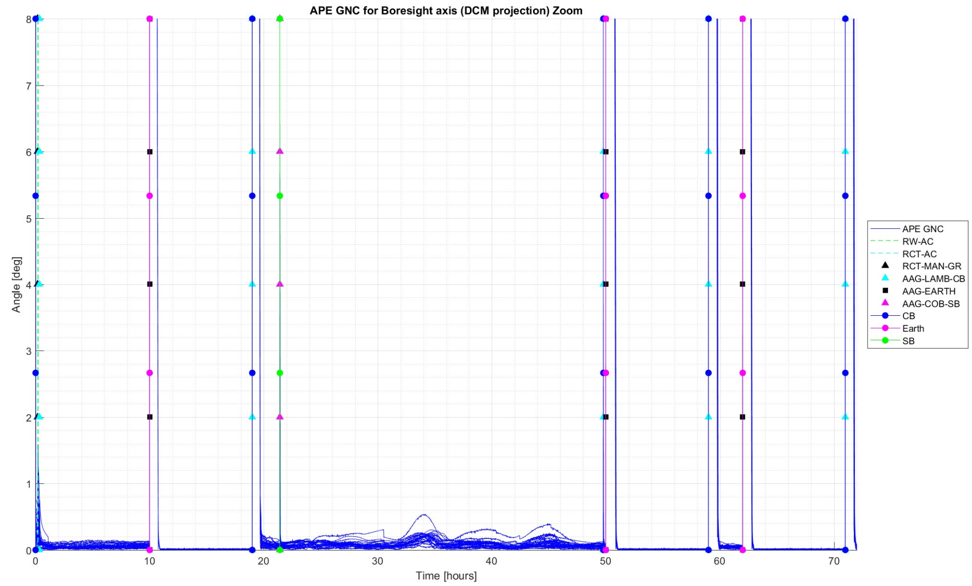


Figure 4-8 Absolute Pointing Error during a COP arc.

4.5 EXP and Feature tracking with PALT

During the EXP phase, the HERA SC will fly from 20 to almost 1.5 km distance wrt Didymos, varying the phase angle and in the last part of the scenario can also go slightly beyond the terminator line. This scenario combines a sequence of navigation technologies that are suitable for the different distances to the binary asteroid: Lambertian Sphere on Didymos, Centre of Brightness on Dimorphos and Feature-Tracking on Dimorphos. Finally, the S/C executes the mosaicking at the closest approach. When the distance falls below 14 km relative to Didymos, the altimeter becomes available, and its measurements are fused with the Centroiding or Feature Tracking information. Along this phase, the autonomous GNC will correct the attitude of the spacecraft to avoid losing the asteroids from the FoV and will also compute the corrections to the manoeuvres that will progressively reduce the pericentre of the hyperbolic arc allowing the SC to safely go down to 1.5 km distance relative to Didymos and less than 1 km distance relative to Dimorphos.

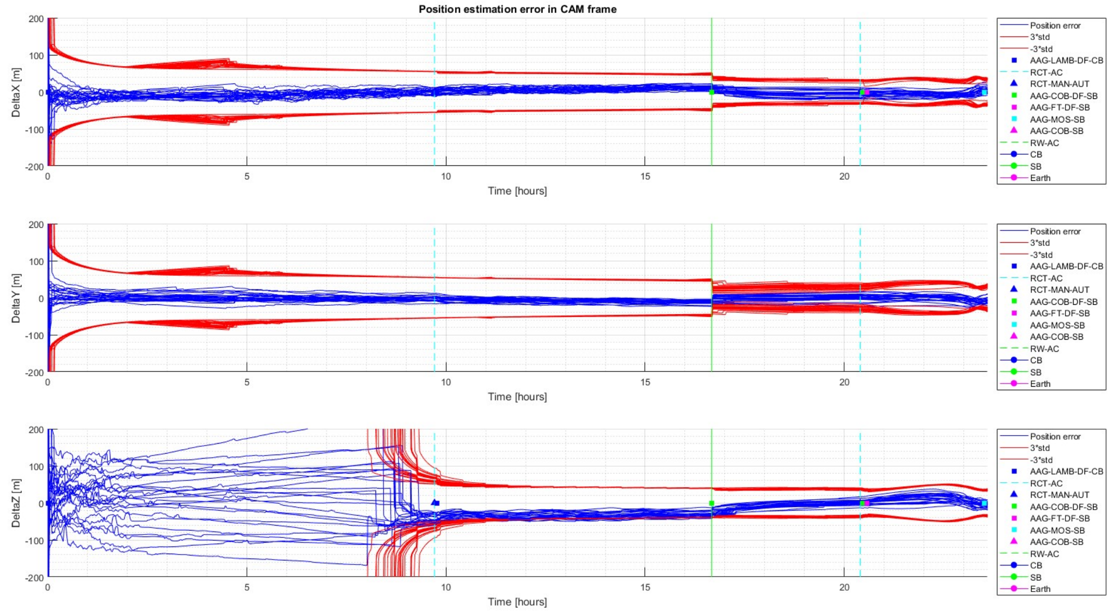


Figure 4-9: Position estimation error in camera frame during a EXP arc

Several considerations can be made looking at Figure 4-9, that shows the position estimation error of the navigation filter in one of the EXP arc:

- The navigation is performed with respect to Didymos till the repointing towards Dimorphos (green line) which occurs at 17 hours approximately. After that, Centre of Brigthness over Dimorphos is used till the saturation of the FoV.

- The Feature Tracking starts after the second manoeuvre at approximately 20.3 hours. Despite it cannot maintain the performance of filter that fuses Centre of Brightness over Dimorphos, the performance is good enough and keeps a healthy covariance.

- The effect of the altimeter (when below 14 km at approximately 8 h point) on the Z axis is evident and directly translated into an improvement of the radial direction (distance to the target). This information is very valuable as it is also used by the independent collision risk estimator. However, it seems to be biasing the solution to have negative error, which might mean that the shape model under used is biasing the altimeter measurements.

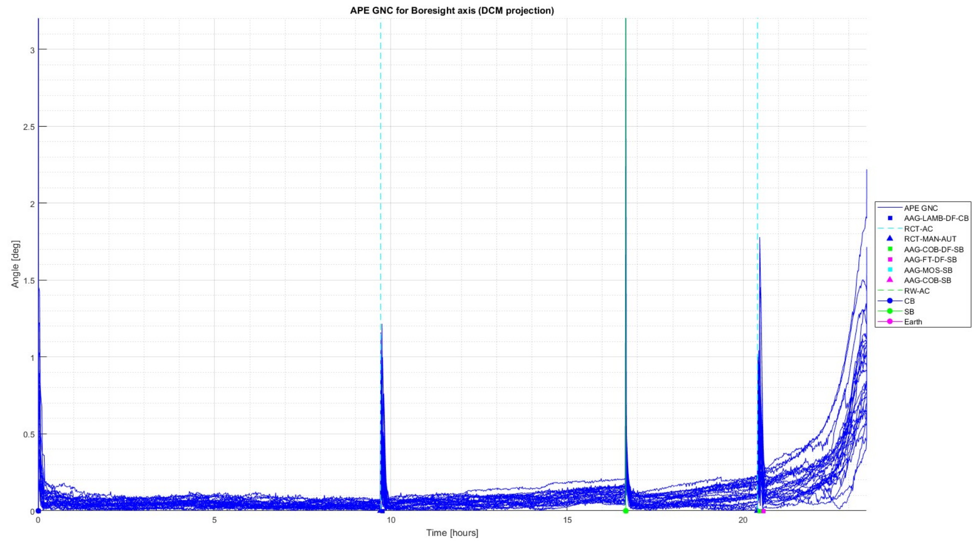


Figure 4-10 Absolute Pointing Error (APE) during the Very Close Fly-by.

The effect of going to such small distances is that the APE increases a lot. While a performance below 2 degrees (as per Figure 4-10) should be able to keep the crater within the FoV, the mosaicking technique is executed to ensure the imaging of the crater resulting in Figure 4-11.

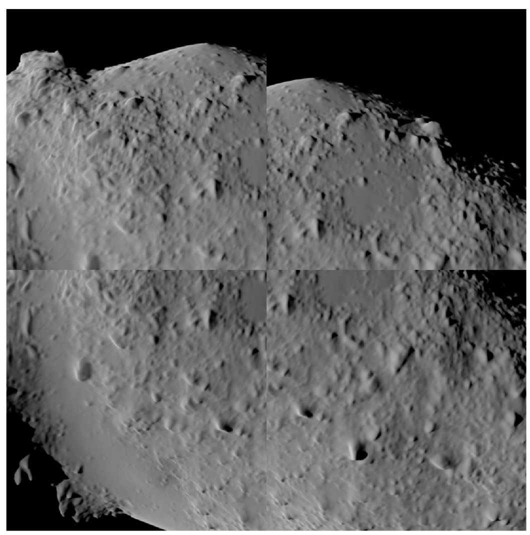


Figure 4-11 Reconstructed Image from the mosaic.

5 VERIFICATION AND VALIDATION

The proposed GNC/IP software and GNC FDI design, development and verification strategy is based on auto coding of the GNC/IP and GNC FDI MATLAB/Simulink models to generate ANSI C-code optimized for embedded systems. This development strategy is part of an integrated, coherent, and incremental Design, Development, Validation and Verification (DDVV) approach based on the chain:

- Functional Engineering Simulator (FES) / Model In the Loop (MIL)

- Autocoding
- Software in the Loop (SIL)
- Software Test Bench (STB) (emulated Processor in the Loop (PIL))
- Hardaware In the Loop (HIL) (GNC Avionics Test Bench (GNC-ATB), Spacecraft Avionics Test Bench (SC-ATB), Proto Flight Model (PFM))

This auto coding chain can provide fundamental support during the Design and Development phases and possibility to test V&V requirements already at early and intermediate design phases, allowing fast design iterations and feedback and the possibility to correct design problems, thus minimizing the required effort. Furthermore, this approach provides an additional flexibility in the GNC/IP design and the associated iterations with the industrial team and the Agency.

It shall be noticed that with this approach the GNC (together with IP and GNC-FDI) will be designed in Matlab/Simulink, using the Functional Engineering Simulator (FES) and model driven software engineering. This Matlab/Simulink implementation evolves in flight code through the autocoding tool chain. The autocoding development strategy consists in generating the GNC ASW C-code in a straightforward way, directly from the Simulink model of the GNC. Nevertheless, the compliance with ESA S/W development and quality standards shall be maintained.

Figure 5-1 depicts the V-cycle workflow between GNC/IP and GNC-FDI design and prototyping and the GNC/IP specification, development, and testing in across the different environments.

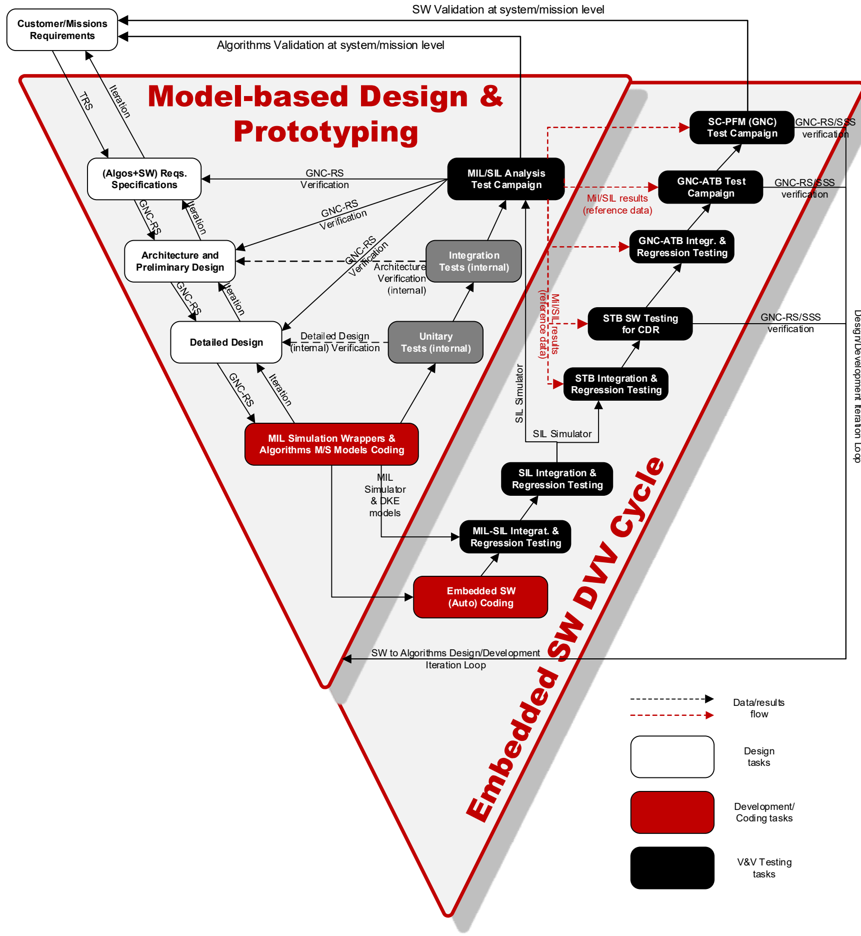


Figure 5-1: HERA Design, Development, Validation and Verification approach

The GNC/IP and GNC-FDI DDVV will be based on the following steps:

- **Analysis of scenario and derivation of GNC/AOCS Software Specification** The process of derivation follows the classical top-down approach.
- **Set-up of a Control Set-up and Simulation Environment (FES)** with the use of reference models of the selected algorithms and solutions for the GNC system, allowing having an environment to define, analyse and maintain the S/W lifecycle.
- **Autocoding of FES-validated GNC algorithm models**: the GNC ASW C code is generated, and the S/W V&V process is started. In this environment static and dynamic verification of the C-code functions are performed. Regression MIL-SIL tests are realised.
- **Preliminary GNC/IP SW validation environments**: preliminary functional validation tests (main GNC/IP SW requirements verification versus technical specifications) are performed in MIL (for IP SW whose native source is C manual code already used in MIL via embedded in S-function) and SIL environment, by integrating the produced ASW C-code in the FES simulator and test it in closed loop.
- **Test Plan and Verification environments assignation**: the ultimate objective is to develop a test plan where the GNC Requirement Specification (GNC-RS) can be

verified in a representative environment.

- **Validation and Verification phase in the GNC-STB**: the GNC-STB is a S/W based verification setup running the S/W image inside a processor emulator in no real-time conditions and fully simulated open or closed-loop environment. It also includes the autocoded models of the FES Real World (dynamics, actuators, sensors, etc.). It allows S/W integration between the GNC/IP SW and an GNC SW wrapper (not the Central Software (CSW)), which is a minimum set of basic C functions needed to execute the GNC/IP SW.
- **Validation and Verification phase in the HIL facility (GNC-ATB) at GMV level:** the GNC/IP SW, integrated in the OBSW, is then validated as per validation Test Plan (GNC-ATB part) in the HIL Facility (GNC-ATB), which includes the engineering model of the OBC (on-board computer) and the GNC Special Check Out Equipment (SCOE) with GNC units Engineering Models (EM) / emulators running in real time and closed loop environment. This facility is used for testing the correct integration of the GNC/IP SW and OBSW in the on-board computer and real time conditions and verification of the GNC/IP SW requirements. It is possible to also include qualification / engineering models of on-board sensors in the closed loop, like the Asteroid Framing Camera (AFC). The camera would take pictures of the asteroid projected on a screen (optical lab)**.**
- **Validation and Verification phase in the HIL facility (GNC-ATB and PFM) at System level:**
  - GNC Software System Specification (SSS) and System Requirement Specification (SRS) will be verified at GNC-STB/ATB level and it is expected that some GNC-RS requirements, not verifiable at GNC-STB/ATB levels because of lack of representativeness of the GNC-STB/ATB environments, will be verified at this level as per validation Test Plan.
  - The full GNC S/S integration into the SC, including TM/TC testing across the GNC S/S chain including HW/SW, will be verified at this level as per validation Test Plan.
  - The final GNC S/S qualification/acceptance testing will also be done in the SC PFM at System level: The full acceptance of the GNC S/S can only be performed in this environment. For this purpose, the validation Test Plan will define a dedicated set of GNC subsystem end-to-end tests (previously performed at GNC-ATB level to have reference data), to verify the GNC functionalities in the PFM integrated environment for final qualification/acceptance purposes.

In summary, the proposed DDVV approach includes an incremental verification/qualification approach with GNC requirements being verified in the most adequate testing environment (including MIL, SIL, GNC-STB (emulated PIL), GNC-ATB, SC-ATB and SC-PFM), using the criteria that each requirement shall be verified in the lowest possible level testing environment, assumed that the selected testing environment is representative enough and that the different testing environments are cross-validated among them.

6 Conclusions

The design of the HERA GNC subsystem has been presented in this paper, with an overview of the major and most new technologies implemented and including validation of the functionalities and performance. The project is currently going through the phase D and strategy is well consolidated. The feasibility of the GNC strategy has been proven at all levels, not only from performance point of view but also considering the computational cost and the implementation of the vision-based technologies. The subsystem is now undergoing the procedure to test it in the hardware facilities and is expected to be ready for its launch in 2024.

7 REFERENCES

[1] J. Shi, C. Tomasi, Good features to track, Computer Vision and Pattern Recognition, 1994. Proceedings CVPR'94, 1994, IEEE Computer Society Conference on. IEEE, 1994.