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Autonomous GNC/IP for Approach and Hovering of irregular small bodies

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Abstract
This paper addresses the autonomous Guidance, Navigation and Control with embedded Image Processing (GNC/IP) developed and validated in the context of the reconnaissance spacecraft technology branch of the European H2020 NEOShield-2 project. These are classified as critical technologies of the GNC/AOCS subsystem, aimed to operate in the approach and hovering phases of missions to irregular small bodies, such as asteroids, comets and small moons. In the mission phases with close approach, subsequent arrival and body-fixed hovering operations the GNC/IP autonomy is deemed valuable/mandatory.

1. Introduction
The threat from Near-Earth Objects (NEOs) to the future of human civilization is measurable and scientifically well-founded ([1], [2]). The European industry is therefore focusing efforts on establishing mission baselines and maturing technologies for mitigation actions against this threat. **A critical technology is the Guidance, Navigation and Control with embedded Image Processing (GNC/IP) for Reconnaissance of NEOs, and increase of TRL is deemed crucial for European industry.** This technology is also usable and scalable to small moons and other minor irregular bodies.
This paper addresses the autonomous GNC/IP developed and validated in the context of the reconnaissance spacecraft technology branch of the European H2020 NEOShield-2 project ([3]). The aim is that of raising the maturity of the current GNC technology to TRL 5-6, according to tailored ECSS standards.
In the NEOShield-2 project a reference mission was established with the primary goal of deflecting an asteroid using the kinetic impactor mitigation technique and measuring this deflection. A reconnaissance spacecraft is intended to provide means to determine the NEO orbit before and after deflection impact, as well as to determine its exact size/shape, rotational state and surface properties. To achieve it, and in general necessary for missions to minor bodies and moons, an **autonomous GNC/IP is deemed mandatory/valuable in three mission phases**:

- <u>Close Approach</u>: starting 3 days before arrival (ground loop delays become relevant) for safe operations;
- <u>Arrival Inertial Hovering for 6h</u>: starting at arrival, ensuring a safe arrival and maintenance for a few hours, before mission control centre and navigation solutions can be established and transferred to ground control;
- <u>Body-Fixed Hovering</u>: starting at later time of the mission, activated by ground, and enabling surface characterisation and/or preparation of landing operations.

The design is focused on the critical set of GNC/AOCS modes and the necessary equipment (with space qualified off-the-shelf equipment). **The GNC/IP is based on two architectures (for the respective mission phases and modes)** that include:

- <u>GNC and ADCS Executive functions</u>: higher-level management functions that provide the means to autonomously operate the GNC/IP, to "glue" the different functional elements together and provide the necessary interfaces within the GNC/AOCS subsystem.
- <u>Image processing functions</u> to generate on-board line-of-sight (LoS) and relative velocity observables for translational navigation but also for attitude guidance (for target lock) algorithms.
- <u>Navigation functions</u> to estimate on-board and recursively in realtime the translational states by processing two different sets of measurements/observables depending on the mission phases.
- <u>Guidance and control functions</u> to guide the S/C in the autonomous phases using chemical propulsion thrusters, implemented as on-board impulsive manoeuvring or discrete-time periodic controllers.

The **GNC/IP functional and performance validation was performed in three distinct scenarios** based on extensive Monte Carlo campaigns in a high-fidelity functional engineering simulator.

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The **study participants' roles** for the contents of this publication are:

- Deimos – Madrid (DMS): Reconnaissance GNC WP Leader, including the following main tasks:
  - Mission analysis refinement (from previous NEOShield activities) for phases with autonomy and selected reference scenarios;
  - Visual GNC engineering with refinement of GNC/AOCS subsystem design, analysis of critical GNC/IP technologies in autonomous phases, functional and performance validation of GNC/IP technologies in each and all scenarios, and in general all engineering activities to reach the study objectives;
  - Visual GNC development including algorithms analysis, implementation, verification and tuning;
  - Visual GNC model in-the-loop (MIL) simulator design & validation
- Airbus Defense and Space – Friedrichshafen (ADS-D): Study Coordinator and GNC Validation Interface, including the following main tasks:
  - Reconnaissance reference mission definition and requirements
  - Coordination of GNC validation activities among the partners
  - Test plan definition with partners, performance evaluation and ultimately independent TRL certification.

The **project milestones** applicable to the Reconnaissance GNC activities, for the contents of this publication, were:

- MDRR: Mission Definition and Requirements Review (May 2015)
- ADR: GNC Architectural Design Review (October 2015)
- DMR: GNC Design and MIL Testing Review (May 2016)

The results presented in this paper result from the **successful close-out of the DMR milestone**, in which the critical GNC/IP MIL test results were evaluated against the TRL 4 objectives and responded to agreed DMR close-out actions.

2. Reconnaissance Mission, GNC/AOCS Autonomy and Operations Concept

The mission baseline is based on a **kinetic impactor concept** ([3]), in this case **relying on two separate spacecraft**. One, named the Impactor S/C, is the spacecraft used for impact (momentum transfer) to the asteroid. Another, the Explorer S/C, is the spacecraft that arrives to the asteroid vicinity prior to the former, with the following **Reconnaissance mission objectives**:

- Asteroid reconnaissance and determination of physical properties, such as size, shape, surface properties, rotation state and gravity field;
- Observation (at safe distance) of the Impactor S/C approach and impact;
- Perform Orbit Determination campaigns, before and after impact, to assess the impact effect;

The **Reconnaissance mission phases** are summarized in Table 1, with reference durations applicable to this mission concept and the autonomy that is deemed valuable/mandatory, namely for the GNC/IP technologies (marked in bold) treated in this article. The autonomy needs for translational GNC/IP consider the extensive capabilities available at ESOC/ESA and are focused on the mission phases that entail mandatory need and/or high risk for mission safety ([4], [5], [6]) when involving ground operations (turnaround delays). On other hand, the Attitude Determination and Control System (ADCS) autonomy is needed in all phases, also acting as a service for GNC/IP in phases with autonomy.
After the Cruise Phase there is a split into three sub-phases: the NEA Drift Phase, the Far Approach Phase and the Close Approach Phase. At start of the close approach phase the GNC/IP autonomy is enabled, and is maintained until the Explorer S/C performs/concludes an Arrival Inertial Hovering Phase, to ensure safe approach and arrival until ground takes over. After switch to ground control, it starts the Observation Inertial Hovering Phase. The mission analysis indicates that ground control can operate with acceptable fuel consumption in the [1 5] [km] range. After accomplishing these objectives, and based on ground authorisation to proceed (ATP), this phase can be complemented with autonomous Body-Fixed Hovering Phase. The target is chosen to hover at an altitude of 1 km (above the largest sphere that contains the ellipsoid dimensions) over a point at 30 deg of spherical latitude. This point is an arbitrary choice in order to show the stability of the trajectory when the trajectory is not equatorial, although the ΔV required to hover over the equator would be slightly larger to compensate the increased rotational speed. At least one month before the planned impact epoch, the S/C moves away from the asteroid to a safe location where it will observe the impact (Impact Observation Phase). Finally, a second orbit determination campaign will be conducted to measure the achieved asteroid deflection (Impact Deflection Estimation Phase). After accomplishing these objectives, and based on another ground ATP, it can be

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complemented with autonomous Body-Fixed Hovering Phase to support impact area observation and/or prepare for descent & landing operations.

The **chosen target NEO** for the study, selected for feasible demonstration of mission concept whilst ensuring Earth safety, and being representative in future missions of a small irregular body (in general the most constraining case), was the **asteroid 2001QC34**.

Table 1: Reconnaissance mission phases and autonomy

Mission Phase	Start Event	Objectives	Reference Duration	GNC/AOCS Autonomy
Cruise	End of S/C commissioning	Cruise trajectory with ground-based tracking and manoeuvring.	4-5 years	ADCS
NEA Drift	Arrival at a distance of ~1 million km	Series of burns to inject the S/C into a low velocity drift trajectory (approximately 100 m/s at end).	~3 weeks	ADCS
Far Approach	Arrival to the NEO Acquisition Point (~$2 \cdot 10^5$ km)	Scanning campaign to detect the asteroid, with the first estimation of the asteroid rotational state and shape, and then a second series of burns further reduces the relative velocity down to a few m/s. Burns are designed to point consistently off the target to ensure a nonzero impact parameter on the b-plane, reduced by each subsequent burn.	~35 days	ADCS
Close Approach	Arrival to the NEO Transition Point (~200 km)	Safely approach the asteroid along the Sun-asteroid direction, allowing for the direct observation of the NEO under optimal illumination conditions. At start the NEO diameter occupies at least 10 pixels as seen by the narrow angle camera. Perform a series of burns that further reduce the relative velocity ending with a final burn to nullify the relative velocity.	3 days	ADCS **GNC/IP**
Arrival Inertial Hovering	Arrival to the NEO Hovering Point (~5 km)	Maintenance of S/C in safe condition (terrain features can be distinguished) to avoid collision by drift before ground takes over. Inertial hovering state, so that the S/C will maintain zero velocity in average in a quasi-inertial frame (in the Sun-NEO line).	6 hours	ADCS **GNC/IP**
Observation Inertial Hovering	Switch to ground control	Perform global characterization and obtain precise knowledge of the asteroid rotational state and orbit (before impact), the altitude range of [1 5] [km].	Weeks or months	ADCS
Body-Fixed Hovering	Ground ATP (~1 km)	Support additional NEO surface observation and/or release of a lander module. Control strategy keeps the S/C nearly stationary in the target body-fixed frame.	~2 hours	ADCS **GNC/IP**
Impact Observation	Before the impactor S/C arrival	Acquire a safe location (tens of km's) away from the asteroid with favourable illumination conditions to observe the impact.	1 month	ADCS
Impact Deflection Estimation	After Impactor S/C collision	Re-acquire the observation inertial hovering location and perform the post-impact orbit determination campaign.	Weeks or months	ADCS
Body-Fixed Hovering	Ground ATP	Support impact area observation and/or prepare for descent & landing operations.	~2 hours	ADCS **GNC/IP**

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The flowdown of mission requirements to GNC/AOCS subsystem leads to a wide set of requirements that are not all included in this article. Having the AOCS technologies at high TRL, instead the critical GNC/IP technologies were identified and developed. In the scope of **autonomous GNC/IP technologies the main functional requirements** are:

- Feature a GNC/IP subsystem for the injection into the NEO vicinity and the operations in the NEO vicinity
  - *No autonomous GNC developments for the remaining phases are considered necessary because communications delays and ground processing (navigation, manoeuvres generations, timeline preparation) are considered negligible wrt durations of these phases.*
  - *For mission phases starting from the close approach phase, GNC functions with a high degree of autonomy are considered necessary for future missions, namely for S/C safety aspects.*
- Autonomous translational GNC/IP during close approach and arrival (inertial hovering for at least 6 h)
- Autonomous translational body-fixed hovering GNC/IP to support NEO surface observation, preparation for descent & landing operations and/or lander release.
- Implement and autonomous collision detection and avoidance capability.

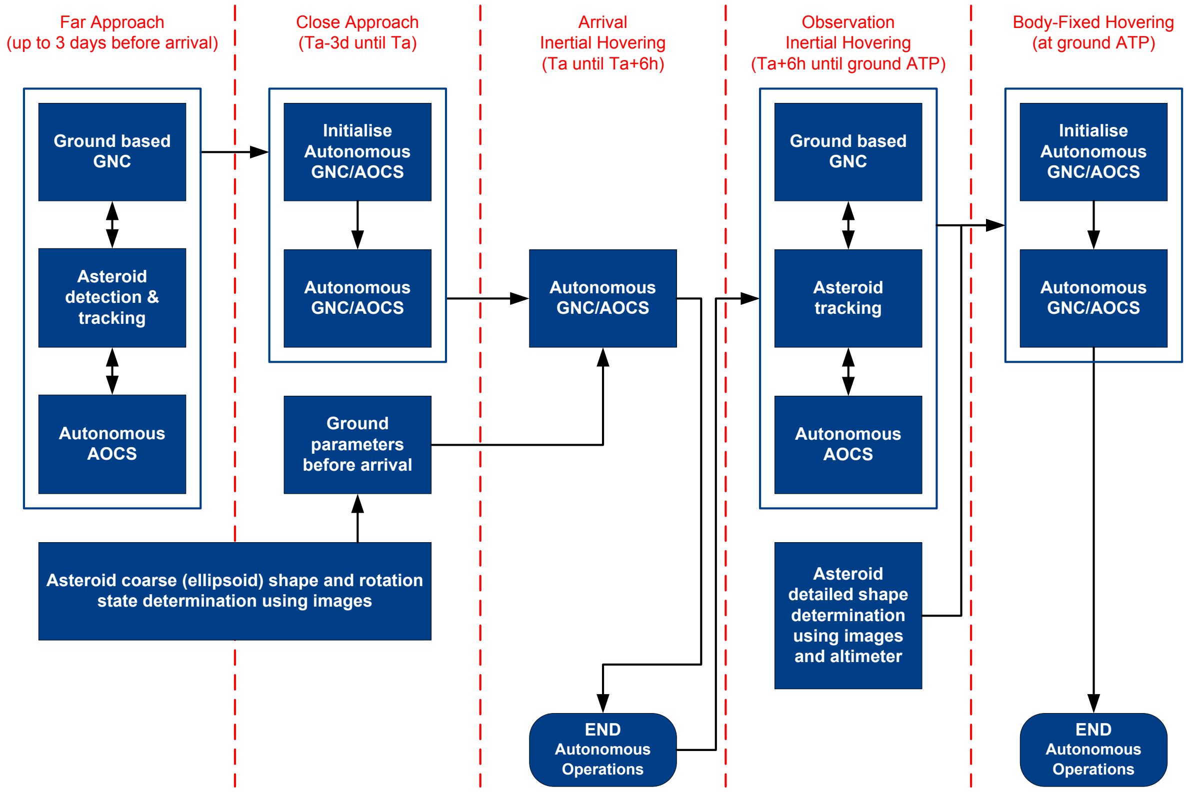

Figure 1: GNC/AOCS operations concept

The **GNC/AOCS operations concept** focusing on the required parameters knowledge for proper GNC/AOCS operation is depicted in Figure 1 and summarised as:

- During far approach (and since LEOP) a ground-based GNC and autonomous AOCS (with ground-based attitude reference) maintain the S/C in a stable and correct operation during these parts of the interplanetary trajectory.
- <u>Close Approach</u> (autonomous 3 days operations)
  - Coarse initial knowledge of asteroid ephemerides and S/C position/velocity from ground (refined by navigation along the 3 days), especially in the SC-asteroid direction due to lack of observables, but sufficient to initialise the S/C attitude to point the camera and altimeter towards the asteroid.
  - Knowledge of asteroid mean radius (estimated from ground or far approach observations). The system only requires mean radius knowledge of the asteroid, to improve the use of altimeter measurements.
  - The system automatically detects the arrival condition (when issuing a final braking manoeuvre).

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- Arrival Inertial Hovering (autonomous 6h operations @ 5km altitude)
  - Refined knowledge of asteroid ephemerides and S/C position/velocity (from last on-board navigation)
  - Accurate knowledge of ellipsoid shape parameters that better fit the visible asteroid properties (from ground, using far and close approach images, uploaded to the S/C several hours before being needed)
  - Accurate knowledge of asteroid rotation state (from ground, using far and close approach images)
  - The autonomous operation ends when ground takes over, estimated to be after 6 hours (worst-case occultation of typical ESA deep space network).
- For Observation Inertial Hovering the system is then switched to ground-based GNC and autonomous AOCS, the same concept that is used in far approach (and since LEOP).
- Upon ground authorisation/command, in need of surface characterisation and/or preparation of descent/landing operations, an autonomous body-fixed hovering mode is activated.
- Body-fixed Hovering (autonomous ~2h operations)
  - Very accurate knowledge of asteroid ephemerides and initial S/C position/velocity (from refined ground orbit determination during observation inertial hovering)
  - Very accurate knowledge of ellipsoid shape and rotation state parameters that better fit the visible asteroid properties (from observation inertial hovering images)
  - The mode/phase ends when ground takes over control again.

3. GNC/AOCS Design and GNC/IP Technologies

The **GNC/AOCS modes** are intrinsically associated with the mission phases in what concerns the operational needs. The selected strategy was to find commonalities between mission phases needs and generate a minimal set of GNC/AOCS modes that may be active in different mission phases. The set of GNC/AOCS modes is presented in Table 2, with the transitions shown in Figure 2 (the autonomous modes treated in this article are marked in red), and defined as:

- Inertial Pointing Mode (IPM): It is used to point the S/C to an inertial attitude commanded by ground or the on-board ADCS Executive function. Also used in-between mode transitions that require ground check-out.
- Ground Trajectory Control Mode (GTCM): It is used to execute the trajectory commands using an uploaded ground timeline. The timeline includes the inertial attitude profile and actuator activation duration commands.
- Autonomous Trajectory Control Mode (ATCM): It is used to execute the trajectory commands requested by the GNC. The commands consist on an inertial attitude and actuator activation duration commands.
- Target Pointing Mode (TPM): It is used to point the navigation camera and altimeter towards the target NEA, and enabling acquisition of high-quality images and stable measurements.
- Arrival Inertial Hovering for 6h Mode (AIHM): It is used to acquire and maintain a null relative velocity wrt the target NEA after arrival and during 6h, thus maintaining a quasi-inertial relative position.
- Body-Fixed Hovering Mode (BFHM): It is used to acquire and maintain a fixed relative position wrt to the sub-satellite point of the target NEA at (and from) the moment that ground command is received.
- Collision Avoidance Mode (CAM): It is used in case of contingency to avoid collision with the target NEA. It uses omnidirectional sun sensors to generate an escape manoeuvre (in the direction of the Sun).

Table 2: GNC/AOCS modes vs. mission phases

GNC/AOCS modes // Mission phase	IPM	GTCM	ATCM	TPM	AIHM	BFHM	CAM
Cruise	X	X					
NEA Drift	X	X					
Far Approach	X	X					
Close Approach	X		X	X			
Arrival Inertial Hovering					X		(X)
Observation Inertial Hovering	X	X					(X)
Body-Fixed Hovering						X	(X)
Impact Observation	X	X					
Impact Deflection Estimation	X	X					(X)

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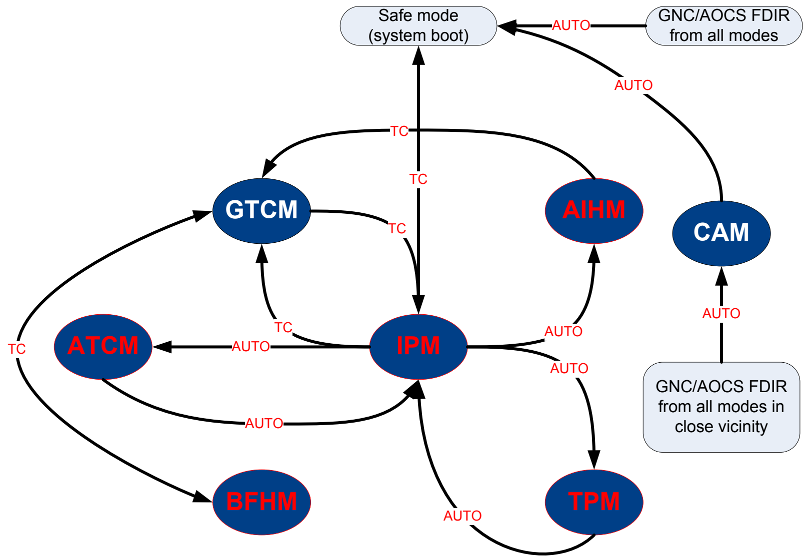

Figure 2: GNC/AOCS Modes Transitions

The **correspondence between GNC/AOCS modes and active ADCS modes** is not shown but can be summarised as having five ADCS modes that ensure a) inertial pointing with ground or on-board reference attitude and on-board gyrostellar/control, b) target pointing in the same configuration but fine control to ensure good images, and c) a dedicated mode for the collision avoidance mode (no attitude control but estimating sun vector for escape manoeuvre).

The design, development and verification (DDV) plan employed in the NEOShield-2 study serve the purpose of increasing to TRL 5-6 the classification of critical GNC/IP technologies useful in future European missions. The whole plan includes processor and camera hardware in-the-loop, but limited in this article to the achievements for TRL 4 objectives for the identified critical technologies. The **selected GNC/IP technologies for the critical modes, aimed in the study for increase in TRL, and inherent SW development matrix** is presented in Table 3.

Table 3: Selected GNC/IP technologies and SW functional development matrix

GNC/IP functionality	Close Approach (IPM, ATCM, TPM)	Arrival Inertial Hovering for 6h (AIHM)	Body-Fixed Hovering (BFHM)
Absolute Navigation based on target LoS, altimeter and radiometric measurements	IP: centre of brightness(CoB) NAV: square-root info filter fusing radiometric, CoB observables and altimeter		
Guidance / Control: Sun direction targeting	Sun direction targeting impulse guidance algorithm and thrusters management		
Features-based navigation with camera and altimeter measurements		IP: features detection and tracking (FDT) NAV: square-root information filter fusing IP velocity observables and altimeter	
Guidance / Control: PD control		Low gains proportional-derivative (PD) controllers and thrusters management	
GNC and ADCS Executive	State machines and simple geometrical calculations that "glue" the different functional elements together and provide the interfaces within the GNC/AOCS subsystem		

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The **GNC/AOCS architecture during the Close Approach phase**, in which the active modes are IPM, ATPM and TPM, is shown in Figure 3:

- <u>Mode Manager</u>: in charge of GNC/AOCS modes and enabling the active ADCS and GNC modes.
- <u>GNC/AOCS FDIR</u>: in charge of receiving FDIR monitoring data, and if necessary interface with equipment or mode manager to isolate and recover from a failure.
- <u>Attitude Guidance, Determination and Control (ADCS)</u>: detailed description is not relevant here, and modelled as a performance model.
- <u>Approach Guidance Navigation and Control (GNC)</u>
    - <u>GNC Executive and Approach Guidance</u>: it presents two features, being
        - Computation of the reference profile according to the objectives, for both position and attitude;
        - Control the execution of Approach Guidance and Control and camera acquisitions.
    - <u>Approach Navigation & IP</u>: in charge of estimating the translational state of the S/C (position and velocity) wrt asteroid CoM.
    - <u>Approach Control</u>: in charge of executing the delta-V manoeuvres.
- <u>Thrusters Management</u>: it is a function responsible of distributing the commanded force and torque to the available actuators. It is used by the approach control function to generate the necessary thrusters' commands to exert the desired force, and by ADCS to distribute torque commands to reaction wheels (or thrusters for wheels unloading).
- <u>Actuators</u>: set of equipment responsible of delivering commanded force and torque to the system.
- <u>Sensors</u>: set of equipment responsible of generating images and distance data to feed navigation with the purpose of obtaining the best possible estimation of S/C relative position and velocity with respect to the asteroid.
- <u>Ground Link</u>: set of equipment responsible to link with ground stations and pass radiometric measurements to the Approach Navigation function.

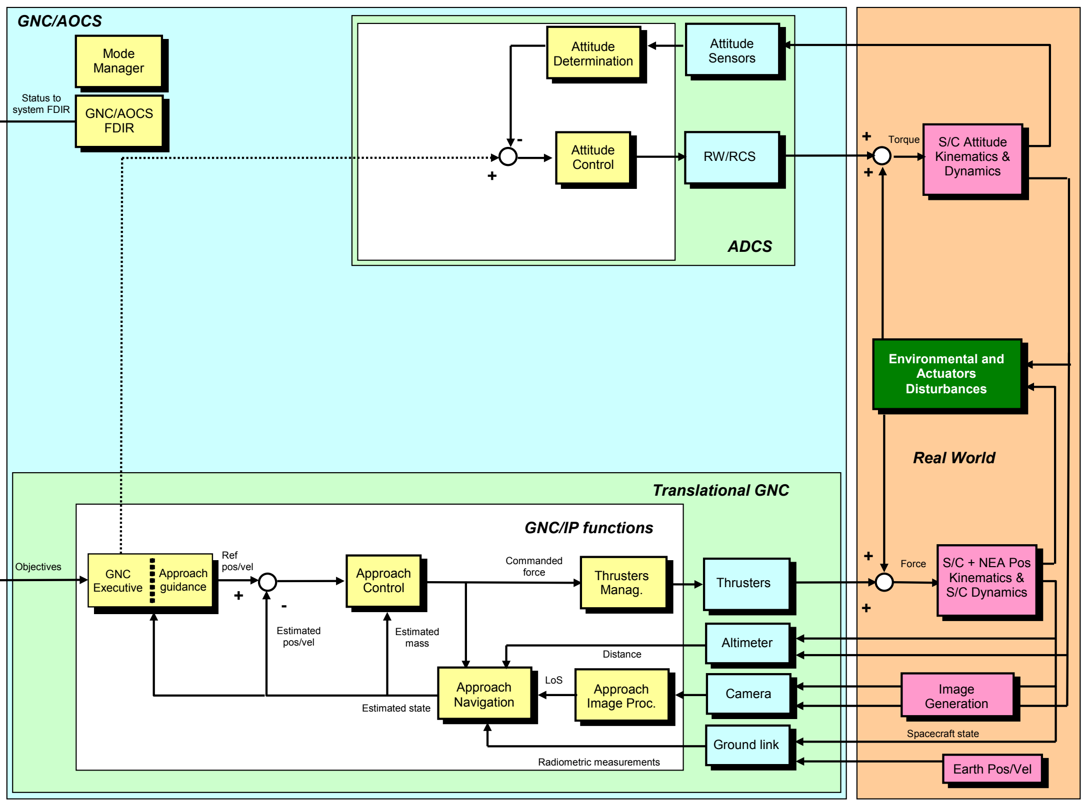

Figure 3: Functional architecture during Close Approach (IPM, ATPM, TPM)

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The employed **equipment and redundancy for the IPM, ATPM and TPM** is listed:

- 2x Navigation cameras (Wide AMIE) in hot redundancy (stable thermal environment of redundant unit)
- Altimeter(s) - shared with scientific equipment
- Ground link for radiometric measurements (part of telecommunications subsystem) in cold redundancy
- Omnidirectional sun sensors (Jena Optronik FSS) for solar panels pointing in cold redundancy
- 2x Star Trackers heads (SSTL Rigel-L) with one additional head in cold redundancy
- 2x Gyroscopes (SAGEM REGYS20) in cold redundancy
- 4 Reaction Wheels Assembly (Rockwell Collins RSI 12) in (inherent) hot redundancy
- Chemical propulsion (Airbus DS Monopropellant CHT-20N) in cold redundancy

The **GNC/AOCS architecture during the NEA vicinity phases**, in which the active modes are AIHM and BFHM, is shown in Figure 4:

- Same functions described in close approach phase architecture, except those explicitly described in bullets below.
- GNC/AOCS FDIR and Collision Detection[1]: in charge of receiving FDIR monitoring data, and if necessary interface with equipment or mode manager to isolate and recover from a failure. The collision detection is based on an independent chain, relying on camera images (FoV checks) and altimetry data, and signalling the FDIR in case of collision risk.
- Hovering Guidance Navigation and Control (GNC)
    - GNC Executive and Hovering Guidance: it presents three features, being
        - Computation of the reference profile according to the objectives, both for position and attitude
        - Control the camera acquisitions
        - Computation of the feedforward commands according to reference profile
    - Hovering Navigation & IP: in charge of estimating the translational state of the S/C (position and velocity) wrt asteroid CoM. The image processing provides relative velocity observables (features matching). The navigation processes the velocity observables in both modes, aided by altimetry data.
    - Hovering control: in charge of calculating commands in order to minimize the error between observed state and reference one, to within requirements.

The employed **equipment and redundancy in the AIHM and BFHM** is listed:

- AIHM: 2x Navigation cameras (Wide AMIE) in hot redundancy (stable thermal environment of redundant unit)
- BFHM: 2x Navigation cameras (EADS Optical Head) in hot redundancy (stable thermal environment of redundant unit)
- 2x Altimeters (Neptec Hawkeye Laser Rangefinder) in cold redundancy *(if not relying on close approach long range altimeter)*
- Remaining equipment as listed above for close approach modes, except radiometric measurements.

[1] The collision detection function is included in the FDIR system, in possible accordance to AIM requirement, taken as the most similar application to the one of WP5 GNC/IP SW: "*GNC-040: The FDIR system shall avoid collisions with both asteroid bodies during an approach to drop guest payloads.*".

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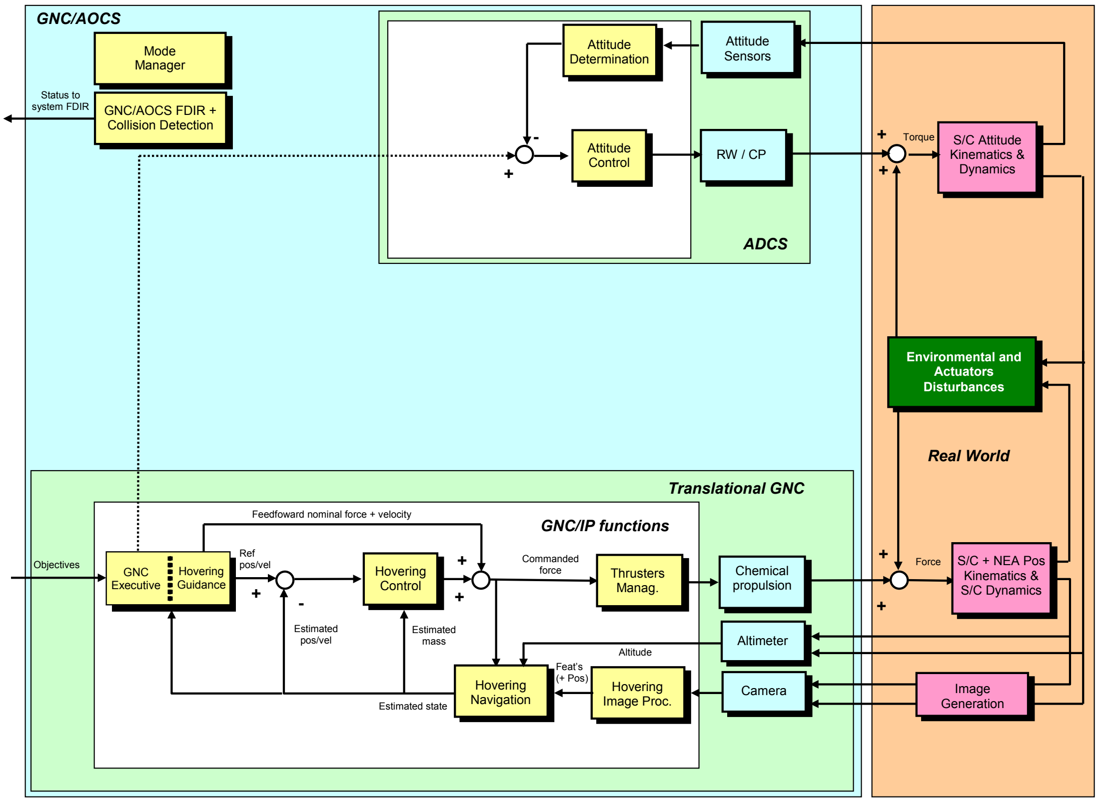

Figure 4: Functional architecture during Arrival Inertial for 6h (AIHM) and Body-Fixed Hovering (BFHM)

4. GNC/IP Functional and Performance Validation

The MIL (Model-In-the-Loop) simulator is a functional engineering simulator (FES) whose purpose is the validation of the functional and performance requirements of the Visual GNC design for the Reconnaissance S/C mission. It is the software tool used to conduct the MIL testing campaign. The MIL simulator includes the following **mission scenarios**:

- Close Approach
- Arrival Inertial Hovering for 6h
- Body-fixed Hovering

The MIL tool has an interface with the **Surrender Synthetic Image Simulator** (software product by Airbus Defense & Space – Toulouse), for the rendering of asteroid surface images, simulating the performance of the navigation cameras.

The **software architecture** of the MIL simulator is based on SIMPLAT, a simulation infrastructure designed and developed by DEIMOS for the development of functional engineering simulators. The SIMPLAT infrastructure is based on the MATLAB™/Simulink™ modelling & simulation environment and provides all the basic functionalities needed by a FES tool, so that project-specific elements can be rapidly built on top of it. SIMPLAT operation largely relies on its XML database, which stores model, scenario and simulation parameters. SIMPLAT includes Monte Carlo simulation and analysis capabilities and several generic toolboxes and blocksets.

The **MIL models, parameters and dispersions** are summarised in Table 4. The models are in majority based on Deimos legacy and some newly developed/validated, except for the image generation model/tool that is based on Surrender. The models parameters are derived from two main sources: overall mission and system data (from ADS-D, the study coordinator and responsible for system design) and equipment data from manufacturers (includes navigation camera used in GMV hardware in-the-loop facilities, representative of space equipment).

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Table 4: MIL models, parameters and dispersions

Model	Description	Dispersions
Orbit propagator	Model: Cowell orbit propagator Parameters: Deimos mission analysis and S/C properties	Initial position/velocity and S/C mass based on performance in previous phases
Asteroid Ephemeris and Rotation	Model: wrapper of NASA SPICE tool (ephemerides) and kinematics model for rotation Parameters: 2001QC34 for mission phases epochs	Initial position/velocity (ground or GNC knowledge in previous phases) Spin direction and angular velocity
Perturbations: Solar Radiation Pressure	Model: based on thermal-optical properties and geometry Parameters: S/C properties	Conservative dispersion of sun radiation power and thermo-optical properties
Perturbations: Asteroid gravity harmonics	Model: spherical harmonics Parameters: based on 2001QC34 shape (ADS-D)	Conservative dispersion of asteroid gravitational constant
ADCS Performance Model	Model: state-space representation of closed-loop ADCS kinematics with estimation/control errors (noise + bias) Parameters: manufacturers data and Deimos analysis	Attitude estimation/control bias Attitude estimation/control noise seeds
Navigation Cameras	Model: Surrender (ADS-F) Camera parameters: as per representative camera mounted on hardware in-the-loop facilities (GMV) Mounting parameters: S/C properties	Camera measurements noise and bias (implicit in image generation process that includes detector and optics errors) Mounting positions and alignments
Long-range altimeter	Model: coarse measurements, based on low divergence laser beam intersection with ellipsoid shape, and added by measurement errors (bias + noise) Shape parameters: envelope 2001QC34 shape (ADS-D) Altimeter parameters: manufacturer data Mounting parameters: S/C properties	Measurements bias Measurements noise seeds Mounting positions and alignments
Short-range altimeter	Model: detailed shape measurements, based on low divergence laser beam intersection with 2001QC34 shape, and added by measurement errors (noise + bias) Asteroid shape model: 2001QC34 shape (ADS-D) Altimeter parameters: manufacturer data Mounting parameters: S/C properties	Measurements bias Measurements noise seeds Mounting positions and alignments
Ground Link	Model: range, range-rate and delta-DOR Parameters: based on ExoMars 2018 mission	Measurements bias Measurements noise seeds
Chemical Propulsion	Model: thrust/torque matrices (independent thrusters), with roughness and repeatability errors Parameters: manufacturer data	Roughness and repeatability Mounting positions and alignments

The number of shots is fixed to an upper bound, to meet the aimed confidence level of 95% and under the assumption of no failures. If some exists, the resulting confidence level becomes lower. The requirements are stated as 99% probability and the number of necessary shots, according to [7], is 299. The selected number of shots was set to 300 and proved valid throughout the validation campaign, in which no failures or non-compliances occurred.

For the three scenarios presented hereafter, **regression closed-loop simulations have been performed**. After successful PIL and HIL implementations the functions models and/or code (of each architecture) have been re-integrated in the MIL. Moreover, the realtime behaviour and execution times of the functions have been evaluated to reflect the changes in the architecture.

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Close Approach Phase

The Close Approach GNC/IP (introduced before) was tested in a **Monte Carlo campaign of 300 shots (aiming at confidence level >95%)** under dispersed conditions and environmental perturbations. It consists of regression closed-loop simulations including the following functions and sample times:

- GNC Executive: 60s (triggering camera and altimeter every 20 minutes)
- ADCS Executive: 60s (ensuring target or manoeuvre pointing)
- Image Processing: triggered by images (polling at 60s)
- Navigation: 300s
- Guidance and Control: triggered by GNC Executive

The **objective of the Close Approach GNC/AOCS** is to ensure that the S/C safely arrives at the asteroid, at a nominal distance of 5km, and the controlled system implements this goal by progressively decreasing the relative velocity (culminating on a final braking manoeuvre) whilst forcing the S/C to travel in the Sun-asteroid line. The close approach trajectory starts at approximately 200km, 3 days before the arrival, and having the asteroid being tracked with the mean diameter of about 10px (in the camera detector of 2048x2048 pixels).
The main challenges for the GNC/AOCS are the coarse knowledge of asteroid ephemerides (with clear impact on arrival safety), the capacity to distinguish the asteroid in noisy images and keep it centred in the camera FoV, the propulsion errors and the ability to exert the final braking manoeuvre when the arrival distance has been reached. The overall duration is slightly lower than 3 days (due to pushing SRP) and the performance is within the requirements when subject to dispersed conditions.

The simulation results and applicable requirements are summarized in Table 5.
The S/C trajectory with respect to the asteroid in the APQ reference frame (MEE2000 centred on the asteroid) is shown in Figure 5.
The evolution of the sun phase angle, distance and relative velocity to the asteroid are shown in Figure 6 and Figure 7. It is possible to note the changes in distance variation slopes due to exertion of manoeuvres that progressively reduce the velocity. Moreover, it is possible to note the slight increases in the velocity between manoeuvres, resulting from the dominant SRP perturbation, which pushes the S/C towards the asteroid (the Sun phase angle is nearly zero, and having the solar panels normal to the Sun direction).
The statistics of the position and velocity errors at arrival are shown in Figure 6.

Table 5: Close Approach performance in MIL Monte Carlo simulations

Performance Metric	Units	Requirement	Values 99% (conf. level 95%)
Mission phase duration	days	-	~3
Maximum relative velocity	m/s	5.0	1.2 (Figure 7)
Final targeting accuracy @ 5 km	m deg	Distance error: 500 (99%) Sun phase angle: 5 (99%)	Error sphere: 230 Sun phase angle: <5 (Figure 6)
Residual relative velocity @ 5 km	m/s	0.035	0.030 (Figure 6)
Maximum fuel consumption	kg	-	0.27

The **navigation function** processes IP CoB observables, altimeter measurements and radiometric measurements. Despite of the several dispersions applied to the system the navigation is able to accurately estimate both the S/C and asteroid position/velocity wrt EME2000 frame, and therefore its relative state, crucial for a safe approach to the asteroid. The superimposed (all cases) navigation function results are shown in Figure 8 (only for the relative – wrt asteroid CoM – position errors). The blue lines are the estimation errors, and the green lines are the filter covariances. The position error covariance tends to decrease since the beginning of the approach, as the measurements are processed, and the position error is then kept within the arrival requirements (~500m) in the overall trajectory, therefore providing anticipated safe expectations of a correct arrival (from operations perspective). The uncertainty in the asteroid shape during the close approach phase is reflected in the bigger errors along the radial direction (camera Z axis). However the system is able

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stay within the requirements even with the limited information of the target geometry. The effect of manoeuvres and propulsion errors is visible in both estimate and covariance (especially in velocity estimation, not shown here), but able to recover the estimate within a few hours (with the help of very seldom range-rate and delta-DOR measurements). The velocity error is contained in the range of a few cm/s and for most of the time, after manoeuvres tranquilisation phase, within the arrival requirements (again providing anticipated safe expectations of arrival conditions). The results show a robust performance of the navigation against a wide range of dispersions.

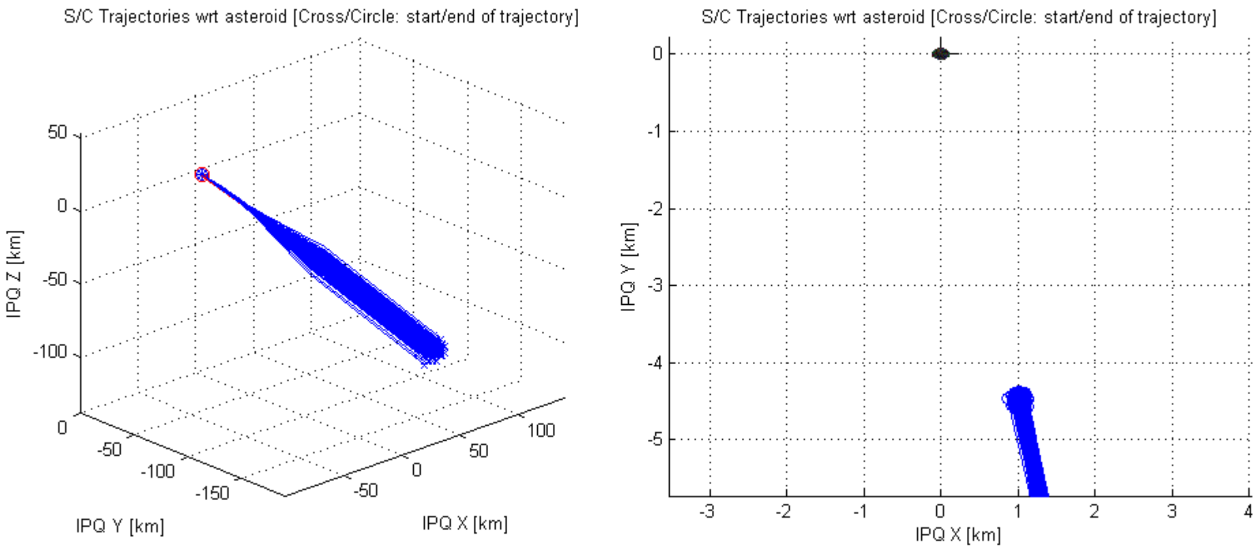

Figure 5: Close Approach trajectories in Monte Carlo simulation (left: full-scale // right: zoomed at arrival)

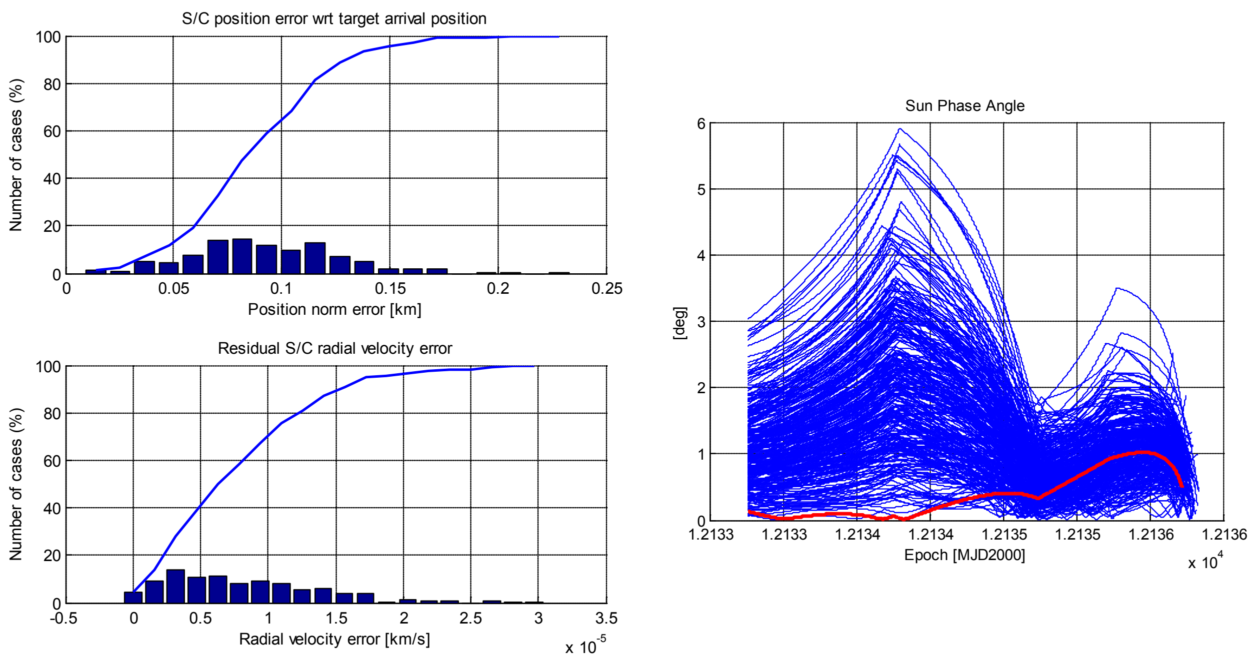

Figure 6: Close Approach arrival position and velocity errors statistics (left), and sun phase angle (right), in Monte Carlo simulation

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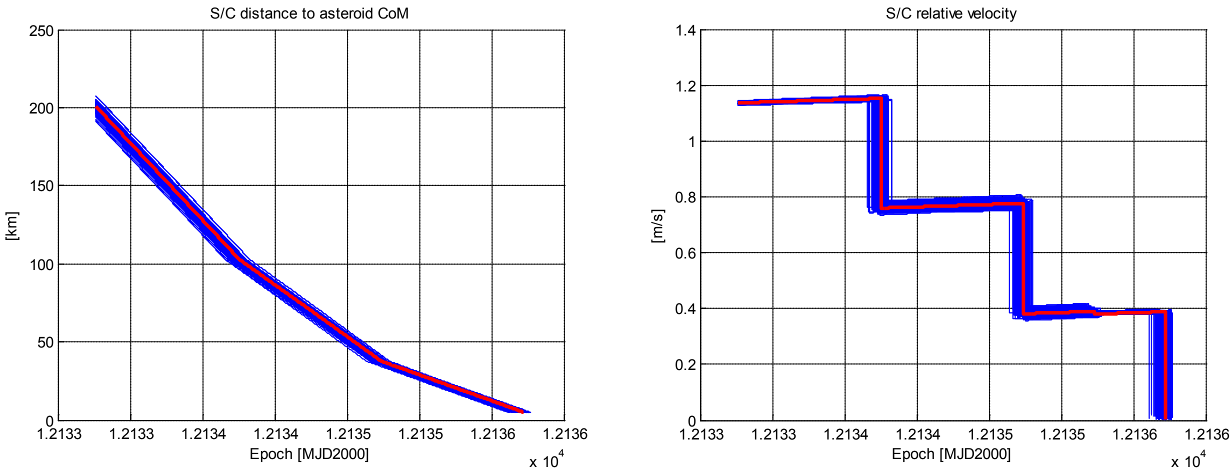

Figure 7: Close Approach distance (left) and relative velocity (right) to asteroid in Monte Carlo simulation

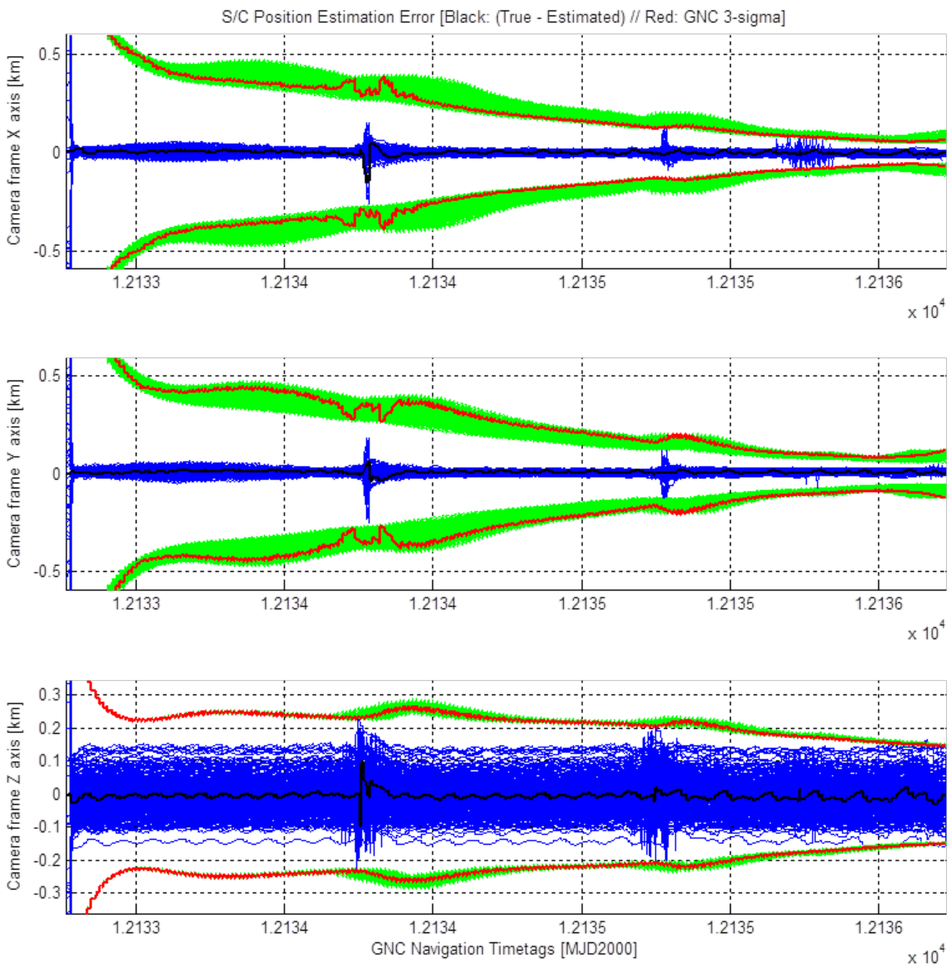

Figure 8: Close Approach navigation relative position estimation errors in Monte Carlo simulation (black-blue: error in all cases // red-green: filter 3-sigma knowledge in all cases)

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Arrival Inertial Hovering Phase

The Arrival Inertial Hovering GNC/IP (introduced before) was tested in a **Monte Carlo campaign of 300 shots (aiming at confidence level >95%)** under dispersed conditions and environmental perturbations. It consists of regression closed-loop simulations including the following functions and sample times:

- GNC Executive: 1s (triggering camera and altimeter every 60s)
- ADCS Executive: 1s
- Image Processing: triggered by images (polling at 1s)
- Navigation: 60s
- Guidance and Control: 60s

The **objective of the GNC/AOCS** is to maintain the S/C in a stable and safe state after the arrival to the asteroid (i.e. immediately after the close approach phase), and for a duration compatible with the establishment of a link with the ESA DSN ground stations, and therefore the system shall be kept stable for at least 6h. The distance to the asteroid surface (chosen in the study to be 5km from largest sphere that contains the ellipsoid dimensions) is to be kept within bounded range, as well as the lateral position errors. This task is achieved using a precise system that resorts to narrow angle camera (same as for close approach) and short-range altimeter measurements, and chemical propulsion as actuators.
The long duration of the phase and the nature of the available observables (resulting from lack of precise knowledge of NEO shape and landmarks) are the main constraints. The main challenges for the GNC/AOCS are therefore the long duration of the scenario and the ability to track features on the surface with sufficiently low errors, to minimise drift in the referred long duration. The nature of the observables reflect the relative velocity (wrt asteroid surface), and without explicit position observables, the position drift is to be bounded within acceptable limits. The main difficulty from navigation perspective is to maintain the lateral position estimate error bounded, especially in the apparent movement of the features due to asteroid rotation, the very irregular shape and small size in camera FoV. Another contributor to the velocity estimation/control error is the considerable propulsion error. All these challenges are further complicated by the assumed poor knowledge of the asteroid shape (ellipsoidal envelope from previous observations).

The simulation results and applicable requirements are summarized in Table 6.
The superimposed (all cases) S/C trajectories around the asteroid and altimeter data are shown in Figure 9. The lines in blue are the Monte Carlo shots and the red line is the nominal trajectory.
The maximum sun phase angle and distance errors statistics are shown in Figure 10.

Table 6: Arrival Inertial Hovering performance in MIL Monte Carlo simulation

Performance Metric	Units	Requirement	Values 99% (conf level 95%)
Mission phase duration	hour	6 (all cases)	6
Min distance to asteroid surface	m	No collision (all cases)	4500 (Figure 9)
Maximum lateral velocity	cm/s	33.4 (99%)	2.5
Mean sun phase angle	deg	18.0 (99%)	4.4
Maximum sun phase angle	deg	25.0 (99%)	5.3 (Figure 10)
Maximum radial position error	%	10.0 (99%)	8.9 (Figure 10)
Maximum knowledge error variation of sun phase angle	deg	20.0 (99%)	2.6
Maximum knowledge error of radial position	%	10.0 (99%)	3.2
Maximum fuel consumption	kg	-	0.15

In this phase the FDT IP is active and providing data to navigation (described further in following subsection). The IP always has solutions, with a considerable number of precise matched features (between two consecutive images), crucial for the navigation function to maintain sufficient estimation quality. The navigation function processes matched features, altimeter measurements and attitude information to estimate the S/C position/velocity wrt asteroid CoM estimate.

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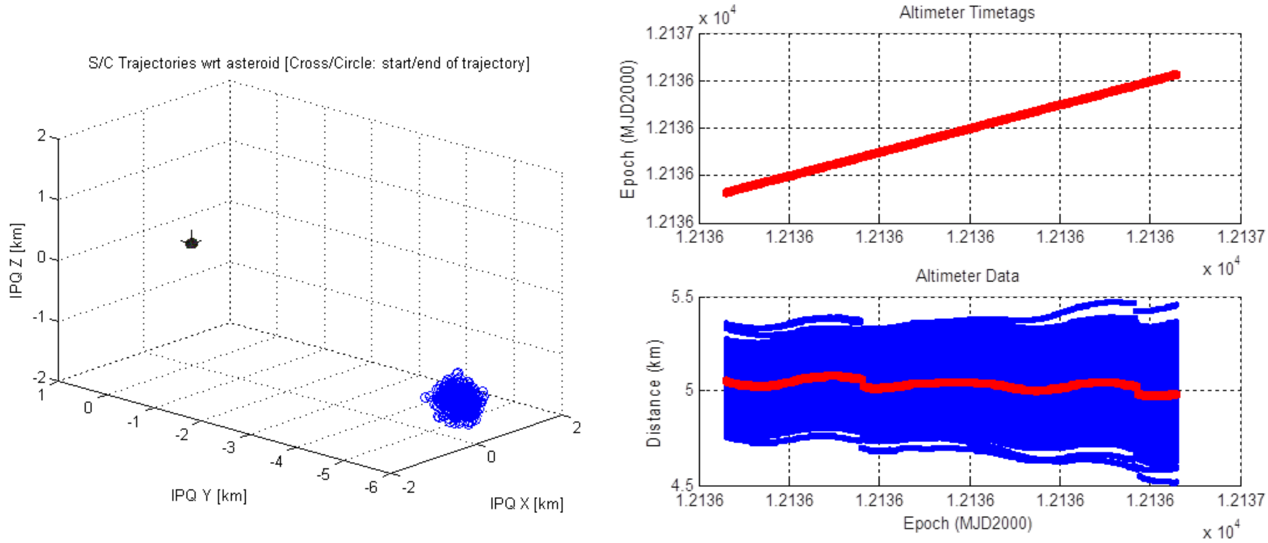

Figure 9: Arrival Inertial Hovering for 6h trajectories (left) and altimeter data (right) in Monte Carlo simulations

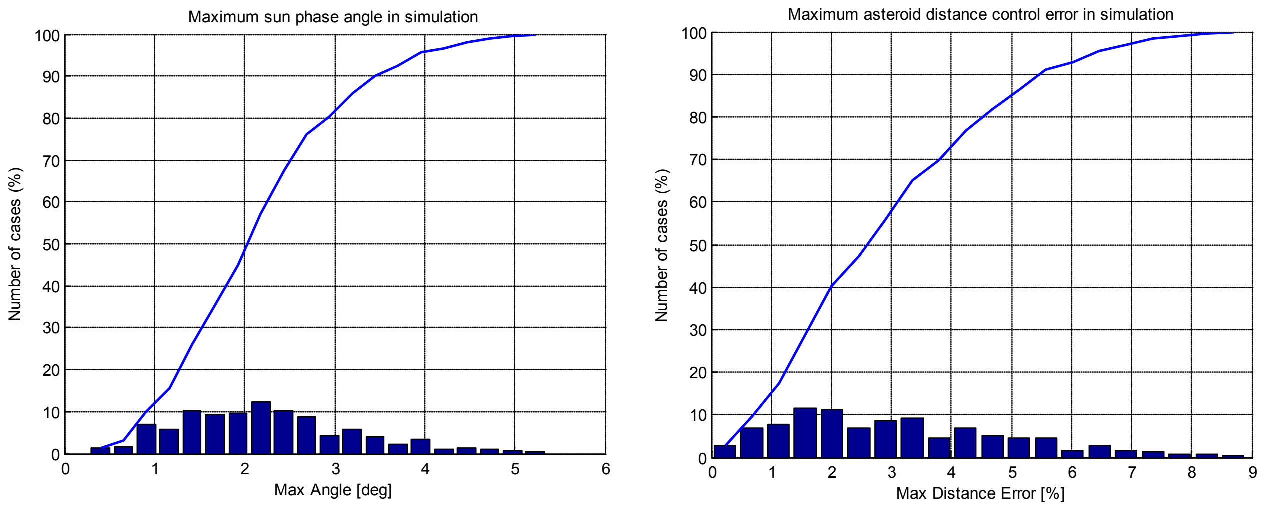

Figure 10: Arrival Inertial Hovering for 6h maximum sun phase angle (left) and maximum distance error (right) statistics in Monte Carlo simulations

Body-Fixed Hovering Phase

The Body-Fixed Hovering GNC/IP (introduced before) was tested in a **Monte Carlo campaign of 300 shots (aiming at confidence level >95%)** under dispersed conditions and environmental perturbations. It consists of regression closed-loop simulations with the same functions and sample times as those listed in previous subsection (arrival inertial hovering).

The **objective of the GNC/AOCS** is to maintain a controlled trajectory locked to an asteroid surface point, as it rotates, for surface observation and/or preparation for descent/landing. The distance to the asteroid surface (chosen in the study to be 1km distance above the largest sphere that contains the ellipsoid dimensions) is to be kept within bounded range, as

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well as the lateral position errors. Such trajectory is rapidly changing in direction when seen from an inertial frame and the asteroid gravity is so low that it becomes even more demanding for the system. This task is achieved using a precise system that resorts to wide angle camera and short-range altimeter measurements, and chemical propulsion as actuators.
The main challenges for the GNC/AOCS are the rapidly changing dynamics and observation conditions in a low gravity environment, the ability to properly track features on the surface with largely varying sun phase angle (from -90 to 90 deg, corresponding to extreme range of half a rotation period, in about 1.8h) and use this information in the navigation process. The fact that the nature of the observables reflect the relative velocity (wrt asteroid surface) also impose an important difficulty to keep the position drift bounded to acceptable limits, and added by the considerable propulsion errors that affect both the navigation and control performances. All these challenges are further complicated by the highly irregular asteroid shape and its small size (worst case), which for computational efficiency is limited to a well adjusted ellipsoidal envelope.

The simulation results and applicable requirements are summarized in Table 7.
The superimposed (all cases) S/C trajectories around the asteroid (ideally locked to a surface point) is shown in Figure 11 as seen from an inertial reference frame. The line in red is the nominal case and in blue are the Monte Carlo shots.
The angle wrt Nadir, altimeter data and distance error, and associated statistics, are shown in Figure 12 and Figure 13.

Table 7: Body-Fixed Hovering performance in MIL Monte Carlo simulations

Performance Metric	Units	Requirement	Values 99% (conf level 95%)
Mission phase duration	hour	1.8 (all cases)	1.8
Mean angle wrt nadir	deg	5.0 (99%)	4.8 (Figure 12)
Maximum angle wrt nadir	deg	10.0 (99%)	8.7 (Figure 12)
Min distance to asteroid surface	m	No collision (all cases)	1010 (Figure 13)
Maximum radial position error	%	10.0 (99%)	5.1 (Figure 13)
Maximum knowledge error of angle to nadir	deg	5.0 (99%)	3.6
Maximum knowledge error of radial position	%	10.0 (99%)	5.2
Maximum lateral velocity	cm/s	33.4 (99%)	10.0
Maximum fuel consumption	kg	-	2.9

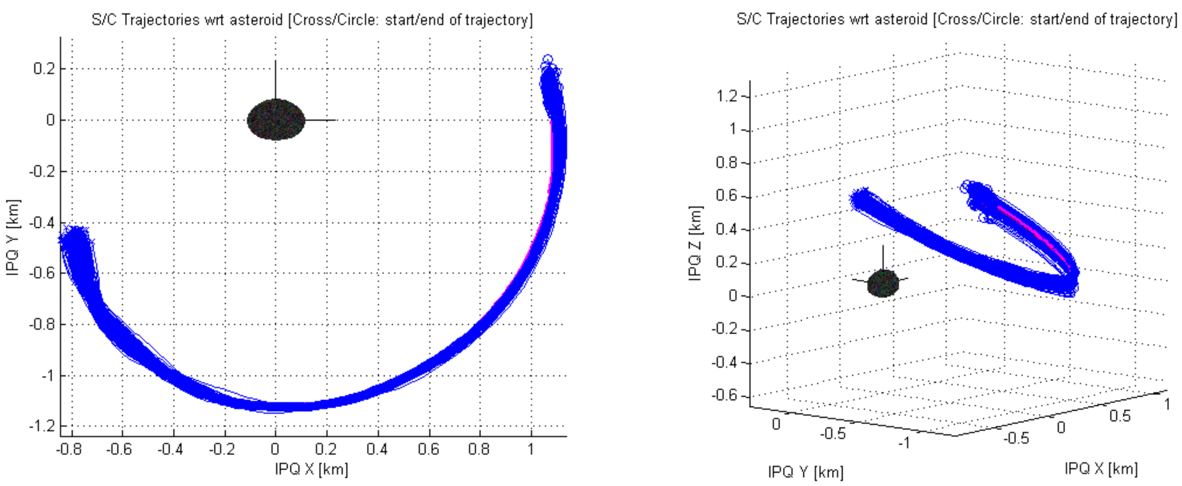

Figure 11: Body-Fixed Hovering trajectories in Monte Carlo simulation (left: X-Y // right: 3-axis view)

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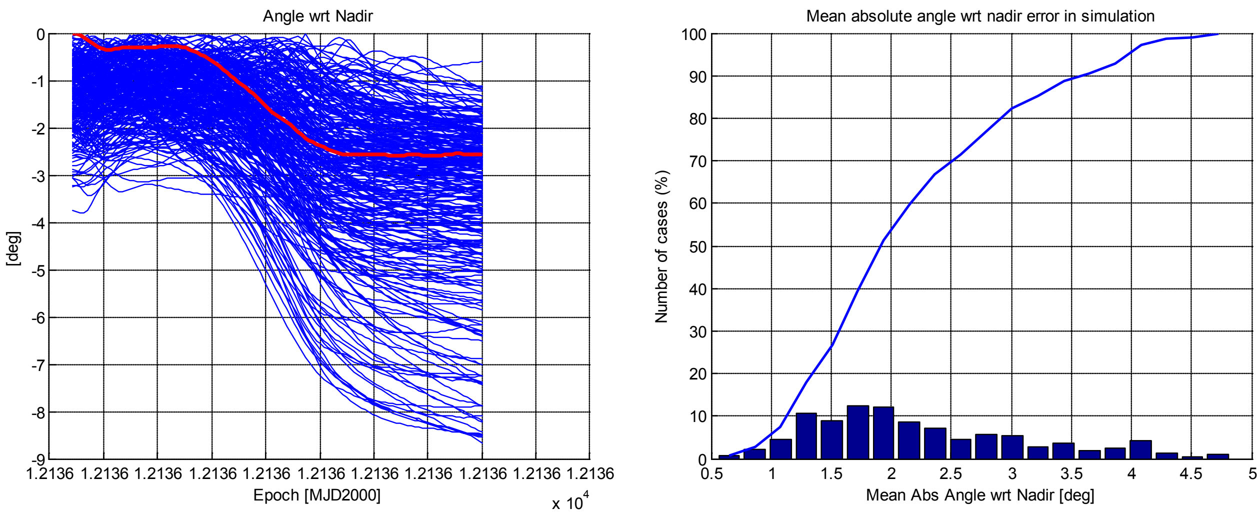

Figure 12: Body-Fixed Hovering angle wrt nadir (left) and mean angle statistics (right) in Monte Carlo simulation

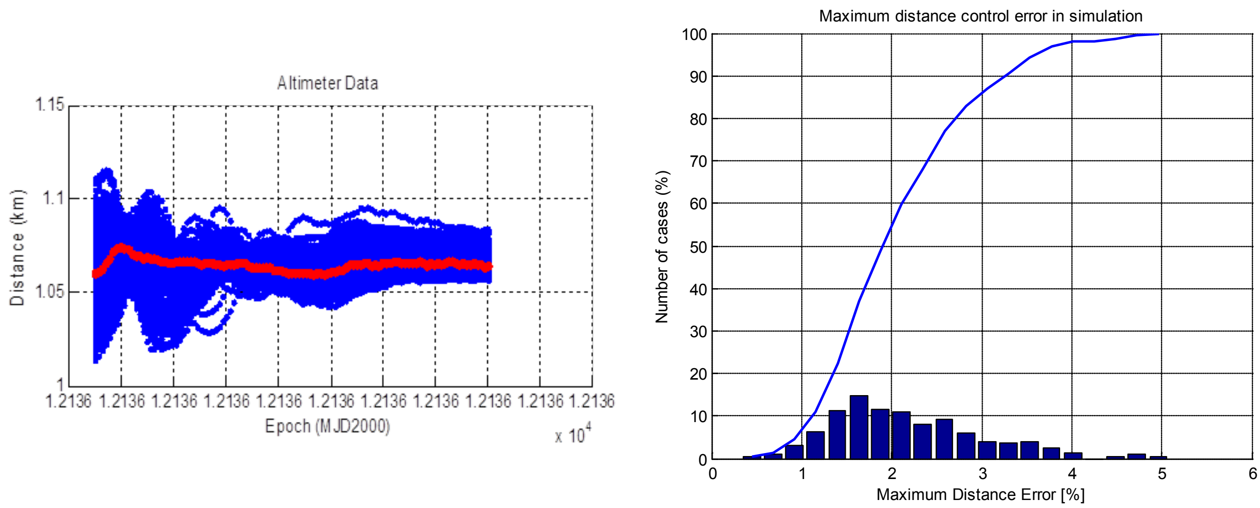

Figure 13: Body-Fixed Hovering altimeter data (left) and maximum distance error statistics (right) in Monte Carlo simulation

The **camera acquisitions and image processing function results** are shown in Figure 14. The selected images, for a total of 109 images in this scenario, show how the sun phase angle evolves widely along the (inertial) trajectory whilst observing the same surface point. The asteroid apparent rotation around the camera boresight is necessary to keep the camera boresight along nadir and the solar panels well oriented towards the Sun. The IP always has solutions along the body-fixed hovering, crucial for the navigation function to maintain an accurate estimation of the S/C state in the rapidly changing inertial dynamics. The IP results are shown as lines connecting the (extracted and) matched features from one image to the next. It is possible to note that the solutions are rather accurate, visually confirmed by the parallel lines and equal lengths. Occasionally, among the typical 50 matches detected by the IP, there are one or two outliers (not seen in these images). The navigation is designed to filter out the outliers, based on the approximated shape knowledge and altimeter measurements, but without aiding IP to filter the outliers (robust against propagation of malfunction).

The **navigation function** processes matched features, altimeter measurements and attitude information to estimate the S/C position/velocity wrt asteroid CoM. The main challenge is to deal with the frequent manoeuvres to counteract the

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centrifugal forces (corresponds to camera Z axis direction) and the navigation is able to keep the covariance bounded (i.e. not increasing as manoeuvres effect accumulates) by continuously processing the IP observables.

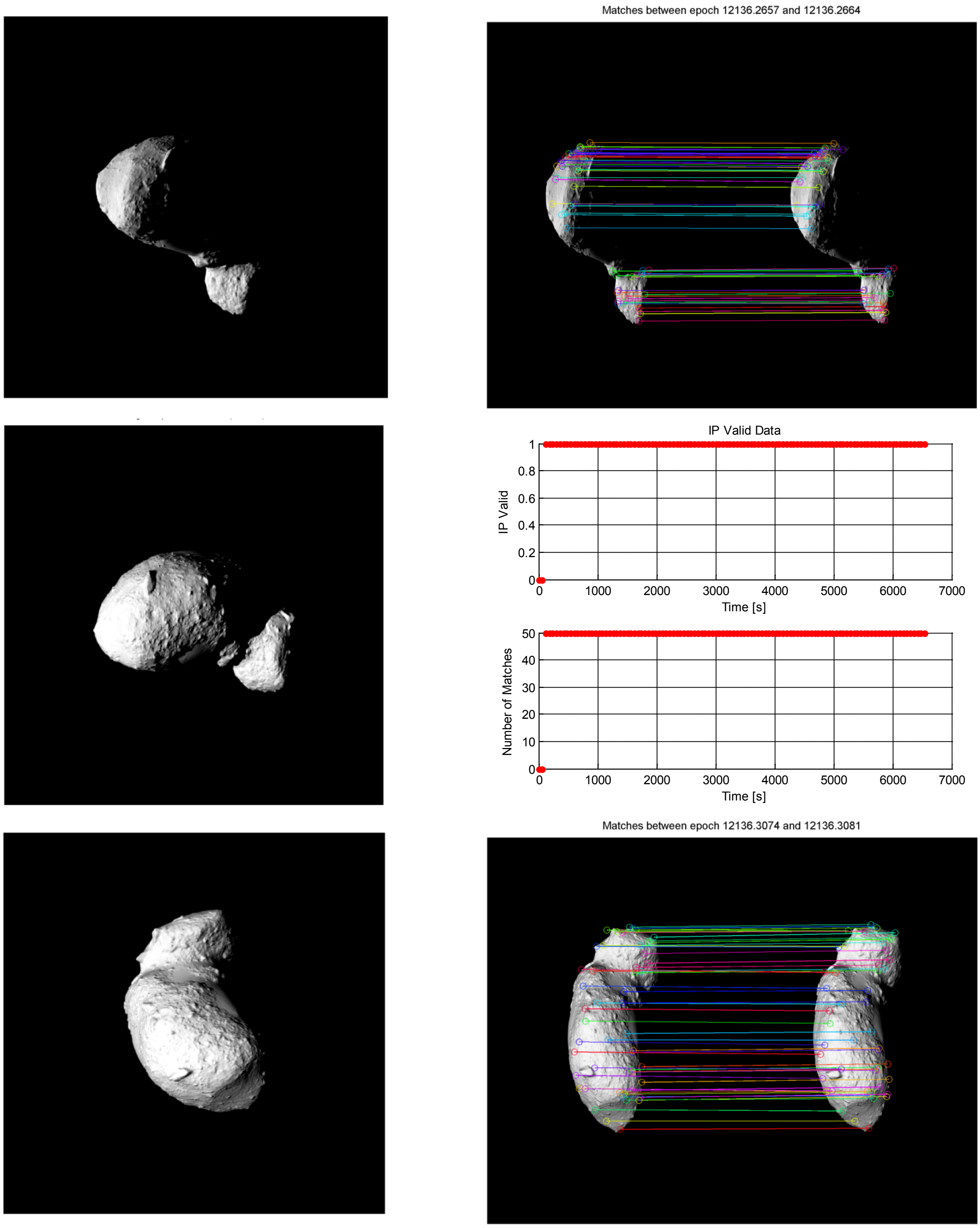

Figure 14: Body-Fixed Hovering camera images (left, selected 3 of 109) (courtesy of ADS-F) and FDT results (right, selected 2 consecutive image pairs and status in overall durations)

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5. Conclusions on technology achievements and status

The work related to NEOShield-2 WP5 (Reconnaissance GNC) has achieved the objectives of the activity, **bringing to European space industry validated elements that increase its effectiveness and competitiveness in areas related to autonomous GNC/AOCS operations in approach and hovering of small irregular bodies**, in particular NEOs that may pose potentially hazardous impacts to society and infrastructures. The TRL assessment and certification is performed by study coordinator (ADS-D) with a process and criteria on the basis of industry standards that have been tailored within the consortium to the NEOShield-2 project constraints, in view of a harmonized evaluation of (different) GNC functional modes among partners.

Meeting the objectives required the implementation of two different GNC/AOCS architectures and several functional elements, aimed at increasing to TRL 5-6 the technologies involved in three distinct scenarios: Close Approach, Arrival Inertial Hovering for 6h and Body-Fixed Hovering. The whole set of functions were integrated and operate correctly under nominal and dispersed (Monte Carlo) conditions, in which the GNC/IP lack perfect knowledge (limited to sensors and calibration information) of the environment and system in which is embedded and operating. The equipment that is used is space-qualified, from known manufacturers: SSTL, SAGEM, Jena Optronik, Rockwell Collins, Airbus DS, CSEM, EADS Sodern and Neptec. **The GNC/IP systems were developed, engineered and validated to enable:**

- **Robust and safe approach/arrival to an asteroid;**
- **Stable maintenance of relative position (between S/C and asteroid) at inertial hovering point (5km altitude), as immediate subsequent operations after arrival, during a period of 6h until ground takes over;**
- **Stable and high performance body-fixed hovering, enabling mission tasks related to surface characterisation and preparation for descent/landing.**

The results for the three scenarios exhibit superior robustness and performance that comply with the typical mission requirements. The GNC/IP requirements were verified by test and met, namely arrival position/velocity errors at close approach and trajectory errors in the two hovering phases. The AOCS requirements are met by design/analysis, demonstrating that the selected ADCS sensors/actuators should allow meeting the required performance. This has been achieved for demanding conditions: a) small and highly irregular asteroid shape, with coarse prior knowledge, b) extreme operational range with sun phase angle from -90 to 90 deg and c) large propulsion errors. Moreover, the **technology is scalable to other planetary bodies and moons.** The achieved results are therefore obtained in worst-case conditions and the reuse of the developed system is also an enabler of European industry in other applications.

Acknowledgements

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