# FUTURE (Fully aUtonomous feaTUre Recognition planetary Explorer) - Revolutionizing Nanosatellite Autonomy through Visual Navigation

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## ABSTRACT

FUTURE is an Italian mission designed to redefine autonomous navigation by exclusively relying on visual observations, eliminating the need for conventional ranging measurements and Global Navigation Satellite System (GNSS) dependencies. The mission is developed in the frame of the ALCOR program [1] of the Italian Space Agency.

FUTURE LEO nanosatellite mission has the objective to demonstrate in orbit the capability of determining the spacecraft orbit with only visual observation, without relying on radiometric measurements (range and range-rate), or on the GNSS positioning systems. Given the current state of the art, this project enhances autonomous navigation capabilities in LEO via natural and artificial features on the surface of the Earth. This project can prove an innovative low-cost and autonomous navigation technique possibly applicable to any planetary orbiter. By orbiting in LEO, it was possible to exploit available GNSS signals as a source of truth, to validate the performance and of the payload data. Furthermore, opportunistic observations with other celestial objects, or in different observation spectrum ranges (Thermal IR), can be carried out to validate autonomous navigation techniques spanning different scales.

The solution will make use of state of art automation algorithms, sensors, processing units and software solutions to obtain spacecraft position and velocity information. The proposed mission is composed by one Tyvak 6U nanosatellite based on the Triumph platform and leverages the extensive background of the consortium in on-board image processing, artificial intelligence and navigation.

The payload hardware and the software were traded off and selected during the preliminary design phase of the project, considering different options available with relative advantages and disadvantages. The payload hardware will be provided by Tyvak, while the payload software and algorithms will be developed and provided by AIKO and Politecnico di Milano. Finally, a combination of Tyvak's and ALTEC's ground infrastructure will be used, to operate the spacecraft, validate the effective performance of the systems and the fulfilment of mission objectives.

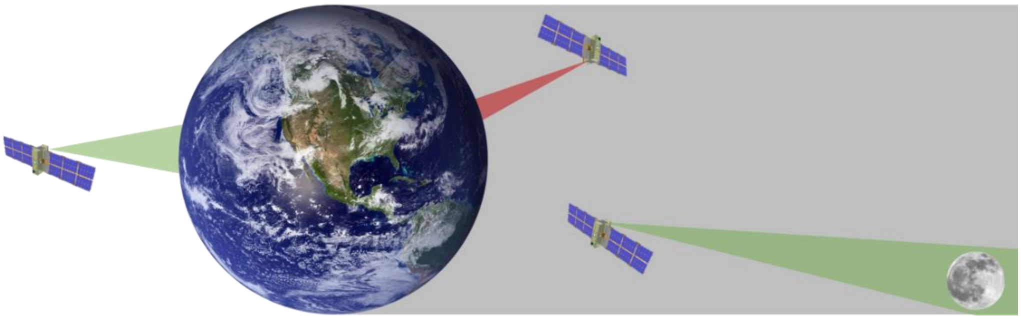

Figure 1: FUTURE mission concept

# 1 INTRODUCTION

## 1.1 Identified Problem

Since the beginning of the space era, probes have commonly been operated from the ground. Operations are conducted by flight control and involve performing numerous routine tasks, mainly of a scientific, systems engineering, and flight-related nature. Governing space flight consists of determining the spacecraft's position, planning its trajectory, and controlling its motion. Most of the deep-space spacecraft navigation techniques rely on radiometric tracking and ground-based orbit determination through the European Space Tracking Station (ESTRACK) and the Deep Space Network (DSN). Radiometric measurements yield accurate orbit determination, but the drawback is that the interactions with the ground stations are unavoidable. This in turn dictates the high costs of operations to navigate spacecraft.

The acute increase of deep-space missions will shortly lead to the saturation of ground-based facilities. The rapid proliferation of deep-space assets induces a dramatic urgency of granting autonomy to space probes [2]. At actual pace, human-in-the-loop, flight-related operations for deep-space missions will soon become unsustainable.

**The time is ripe to radically change the spacecraft modus operandi.**

The development of adequate technology is required for the next generation of satellites, keeping the overall mission cost within an acceptable cap. An area of great interest is mission autonomy, especially in the case of beyond-LEO missions, for which the long distance from Earth poses significant issues on the mission design and operations. Increasing the degree of mission autonomy might eventually overcome the issues related to ground involvement, thus reducing the overall mission cost. In this frame, the specific technological need FUTURE is addressing is related to the capability of determining the orbit / position of a space system in space, autonomously and without need of Earth-based infrastructures [3]. This goal is driven by deep space needs, although performing demonstration in LEO guarantee accessible verification and validation paths and set the cornerstone for following deep space applications.

## 1.2 Proposed Solution and Added Value

The suggested approach entails launching a low Earth orbit (LEO) nanosatellite mission aimed at incrementing the ability to determine spacecraft orbit solely through optical observations, eliminating the need for ranging measurements or GNSS positioning systems. Cutting-edge automation algorithms, sensors, processing units, and software solutions will be utilized to acquire positional data. The mission proposal involves deploying a Tyvak 6U nanosatellite using the Triumph platform, capitalizing on the consortium’s expertise in onboard image processing, artificial intelligence, and navigation.

Extensive compatibility and performance analyses were done during the initial phases of the project to trade off and decide the payload hardware, as different alternatives are available, same applies to

the payload software, as the features, landmarks or other celestial bodies to be used, have to be identified, traded off and a selection done.
Visually, the flow of operations that represent the core experiment to be demonstrated in orbit is represented in Figure 2.

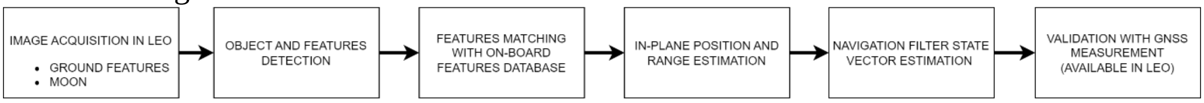


Figure 2: High level mission process flow

Given the current state of the art, this project is aimed to enhance autonomous navigation capabilities [4] in LEO via natural and artificial features on the surface of the Earth. Leveraging the current trends in the field of AI [5], the project is expected to prove an innovative low-cost and autonomous navigation technique for LEO applications. Furthermore, opportunistic observations can be carried on concurrently in order to validate autonomous navigation techniques spanning different scales and imaging spectra, acquiring images of other celestial objects (e.g., the Moon) and using a dedicated infrared camera to obtain images during opportunistic eclipses scenarios where it can provide insight into the scene when the visible cameras cannot.
Technology transfer is key of the mission proposal: the outcome of the project can be directed for future applications beyond LEO, such as in missions about planets and moons, so enhancing autonomous operation and navigation in the proximity of different celestial bodies.

# 2 OPERATIONAL SCENARIO

## 2.1 Concept Of Operations

The Mission Concept of Operations has been initially derived based on Mission Objectives, and subsequently refined based on technical considerations related to the Space and Ground segment. It's graphically reported in the following Figure 3.

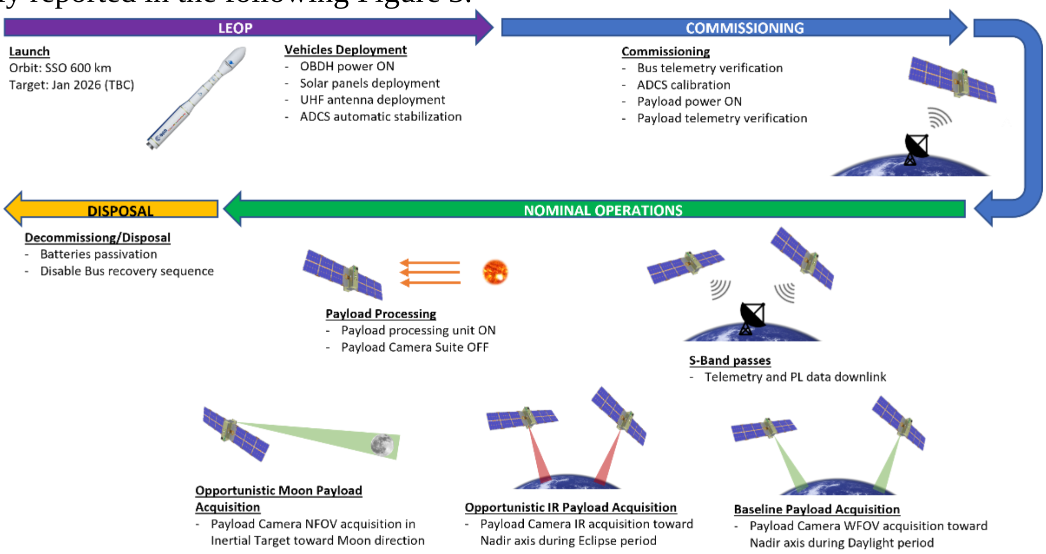


Figure 3: FUTURE Mission ConOps

## 2.2 Mission Phases

As an In-Orbit Demonstration (IOD) mission, FUTURE goal is to prove the capability of determining the spacecraft orbit only with visual observation, without relying on Ground Station ranging measurements, or on the GNSS positioning systems. For this reason, during FUTURE nominal operations, the spacecraft will conduct dedicated navigation experiments, during which the entire

navigation process chain will be tested, and the performances will be compared with the GPS information generated by the platform.
The Nominal Operation Phase can be divided into different Mission Phases, each of them focused on different objectives to increase the demonstration return:
The description of the Mission Phases will be here reported:

- **Mission Phase 1**: the *Baseline Experiment*, period dedicated to demonstrating in orbit the optical navigation capabilities, focusing primarily on the baseline scenario (acquisition of Earth macro-sized target, in daylight periods). The key objective is to maximize the WFOV VIS camera acquisitions, in order to verify the associated performance requirements.
- **Mission Phase 2**: the *Realistic Acquisition Windows Experiment*, period dedicated to the In-Orbit-Demonstration of a realistic operative for a potential future mission integrating FUTURE Payload to support navigation functionality. In this phase, assuming the presence of a different primary Payload requiring its own operational duty cycle, the number acquisition windows is reduced.
- **Mission Phase 3**: the Autonomous Navigation Experiment, period dedicated to the In-Orbit-Demonstration of the Payload autonomous navigation capabilities. The key objectives will be to verify the Payload capability to command a pointing direction starting from the attitude information received from the ADCS and the internally propagated state vector. The commanded pointing direction aims to orient the WFOV camera boresight to Nadir axis to execute an acquisition window. This will test the autonomy of the Payload on perform optical navigation in line with the target E3 level requested by Mission Objectives.

# 3 BASELINE DESIGN

## 3.1 Baseline Bus Specifications

The FUTURE space segment is a 6U CubeSat based on a standard Tyvak 6U Triumph Platform, customized for the specific mission needs. The processing platform is a system designed by Tyvak with a radiation hardened watchdog microcontroller. The ADCS software can interface with multiple star trackers for guaranteed stellar coverage and a state-of the art Inertial Measurement Unit (IMU). As a backup, sets of redundant coarse sensors and magnetometers allow performing attitude determination functionality independent of the IMU and star trackers. For actuation, the system uses a family of reaction wheels depending on vehicle size and agility, along with torque rods for momentum management (in LEO missions). A combination of UHF, S, and X band radios options are available for telemetry and command of the satellite.
The Triumph platform power generation subsystem is highly modular to satisfy the power requirements of a vast range of missions. A standard deployable solar array configuration is generally proposed to maximize power generation. A single, high-efficiency MPPT transfers the energy sourced from solar arrays to the two parallelly-installed battery modules. The details of mechanical mounting of the payload are refined for each project and Tyvak works with payload project engineers to determine if a standard mounting configuration is appropriate for the mission payload. Tyvak conducts analyses to understand how thermal control should be implemented as required by the payloads, in addition to the standard thermal paths that are defined between the mounting points and the primary radiators. The baseline capabilities of the Triumph Platform are listed in Table 1 below.

Table 1: Triumph platform specifications (NB: LEO Application)

| Specification | Capabilities |
|---|---|
| **Spacecraft Platform** | 6U |
| **Payload Mass** | ~3kg |
| **Payload Volume** | ~3U |

| | |
|---|---|
| **Data Buses** | RS-422, USB2.0, CAN-bus, Ethernet |
| **Power Rails** | 9-12.6V Unregulated, 3.3V & 5V |
| **System Position Knowledge** | +/- 5m |
| **Peak deployable array Power** | Up to ~120W |
| **Energy Storage** | Up to ~150Wh |

### 3.2 Mechanical Design

The following pictures illustrate the general mechanical configuration and subsystem accommodation, with the aid of the conceptual CAD up to the PDR details level reached.
Views are shown in Solar arrays deployed mechanical configurations in Figure 4 and Figure 5.

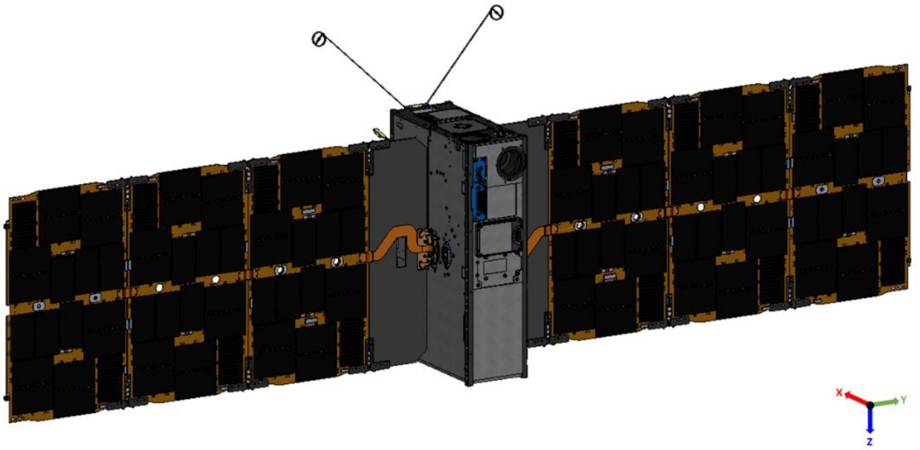

Figure 4: Deployed Configuration (solar cells side)

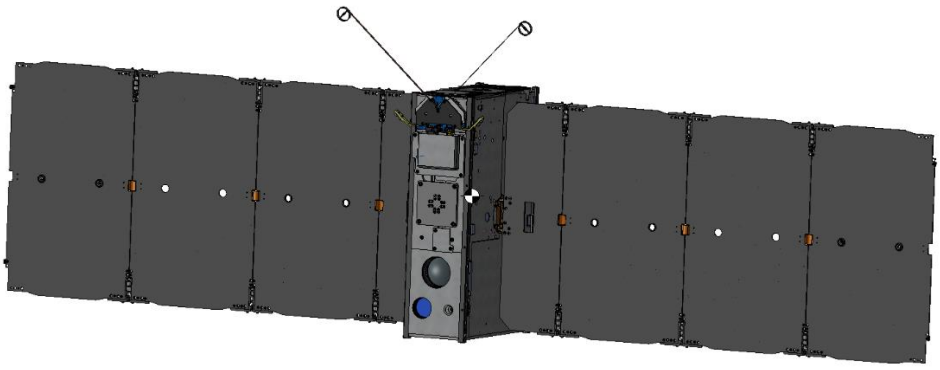

Figure 5: Deployed Configuration (payload's boresight side)

### 3.3 Payload Sub-units

The Tyvak Triumph platform features a discrete bus and payload volumes separated by a divider plate. The primary structure of the payload will be an aluminum frame with a divider plate between the bus and payload volumes and covers to wrap the frame to create enclosed volumes and will act as both structural stiffeners and thermal control radiators.
The most important requirement for accommodation of the PL subunits comes from the configuration design, that demands arranging the Camera Suite pointing toward the direction envisioned to be Nadir pointing for the nominal operation phases (X+). Once verified this condition, the main distribution of the cameras' opening view within the X+ panel was an optimization of the available surface with respect to the effective aperture of the lenses and the baffles, with the help of a dedicated payload support structure to hold as a unique block the three Payload cameras.

All the remaining available surface on the Y- panel was allocated to the PPU Motherboard.
The PPU COTS was selected during the Phase-B of the project ensuring a flight heritage being adopted in multiple missions as image processing unit. This Payload Item that will be integrated on top of the PPU Motherboard. Finally, a shielding cover will protect the PPU and PPU Motherboard electric components, for additional EMC protection and thermal management.
Harnesses will complete the connections among payload modules and toward the platform.

### 3.3.1 Camera Suite – Visible Imagers

The baseline selected foresees the utilization of two Tyvak optical cameras: the WFOV (Wide Field of View) and the NFOV (Narrow Field of View) cameras, utilizing both the enhanced version of the Tyvak VIS IMG (Visible Imager) PCBA and changing only lenses and mechanical support structure.
The main common characteristics are:

- COTS CMOS sensor assembled on the Tyvak Visible Imager PCBA
- 3.1 Mpixels, RGB Bayer Color Filter Array
- Sensor assembled in the PCBA allowing harness interface and internal image sensor temperature monitoring
- Fixed aperture and fixed focus lenses (no moving parts in orbit)

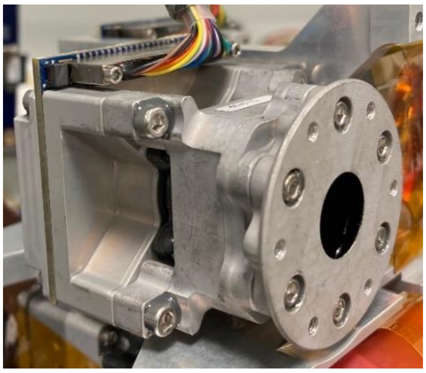

Figure 6. Wide Field Of View (WFOV) Camera

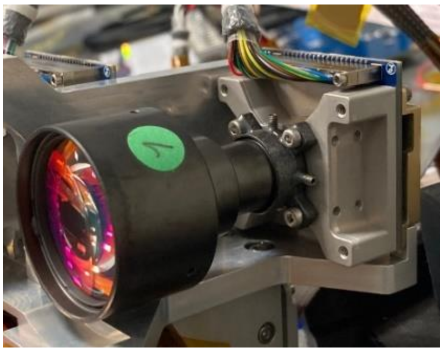

Figure 7. Narrow Field Of View (NFOV) Camera

### 3.3.2 Camera Suite – InfraRed Imager

After a trade-off between the Teledyne FLIR products, the TAU 2+ model was selected to maintain heritage and to ease the integration with the platform and the software development.

Figure 8. InfraRed Camera

### 3.3.3 Payload Processing Unit (PPU)

The selection of this component was a joint effort between AIKO and Tyvak International, in order to select the most suitable and valid component for both the payload processing point of view and for the physical integration and interface with the satellite.

Among the possibilities, a commercial GPU COTS was selected. This HW accelerator is a Graphic Processing Units (GPU), originally developed for use in generating computer graphics, virtual reality training environments and video that rely on advanced computations and floating-point capabilities for drawing geometric objects, lighting, and color depth. AI algorithms need a lot of data to analyze and learn from: this requires substantial computing power for executions and shift large amounts of data. GPUs can perform these operations because they are specifically designed to quickly process large amounts of data used in rendering video and graphics. Their strong computational abilities have helped to make them popular in machine learning and artificial intelligence applications. The COTS HW was selected having in mind Flight heritage & TRL, Space-grade certification, Algorithms compatibility, Voltage/power characteristics, interfaces and processing power limitations.

The configuration selected as baselined for the integration of the PPU on the satellite payload bay is through a dedicated interface board that will serve as mechanical and electrical mounting point for the processing unit, the PPU Motherboard.

### 3.3.4 Payload Processing Unit Motherboard (PPUM)

The study of this Payload component started from the functionalities wanted this interface board to have:

- Interface with Payload Camera Suite, Payload Interface Board (PIB), PPU
- Integrate passthrough Cameras data lines toward Umbilical Interface Board (UIB), backup data lines toward PPU and the Flight Computer Module (FCM)
- Host IR Camera's processor and controller (SOM)
- Cameras' power lines conversion and distribution, along with data connections
- Safe mechanical mating of the PPU to the structure
- Minimization of the connectors on motherboard side to reduce the complexity of organization of the harnesses, routing and AIT steps

In doing so, at present, the design of the PIB (interface board between payload and platform) is practically unchanged, while the design focus is on the motherboard, which although simple and with heritage of design, must still be declined to the specific use.

The cameras, the PPU and the Bus will all be connected through a dedicated Ethernet Switch mounted on the PPU Motherboard, element that will act as node of the Local Ethernet Network, used as nominal data transfer channel.

## 3.4 Payload Software Component

### 3.4.1 AI Image Processing

The most important building blocks of the AI Image Processing pipeline will be explored in an higher detail:

- **Feature detection:** step performed by a state-of-the-art AI feature detector to extract interesting keypoints and associated descriptors from the live acquisition.
- **Total feature database:** database of Earth surface features related to coastlines and permanent water bodies. Generated offline on ground in dedicated computational environments and then uploaded in the onboard software to allow the matching step.
- **Feature matching:** step dedicated to match corresponding features between the ones detected in the considered acquisition and the ones stored in the feature database (applying an algorithm suited for large databases).

This workflow can be associated to a real operational scenario: the payload camera acquires a new frame. Here the *m* most confident features are retained together with their local coordinates and associated descriptors. Filtering step is applied by receiving estimated position from the navigation block, reducing the global feature database to avoid feature mismatch and algorithmic failures. After this filtering process, the feature matching can be performed, and the matches are stored. Each match is characterized by a distance/quality score. Those matches contain features indexes and associated metadata such as latitude, longitude, and the tile of the Earth surface database from which they have been retrieved. That information is then passed to the post-processing step to obtain:

- **Scene coordinates:** when at least two matches are found with high quality index, it is possible to exploit the two most confident matches and the associated features coordinates to retrieve the (lat, lon) of the scene centroid through an interpolation.
- **Range from scene:** when at least 4 matches with a distance score lower than a certain threshold are available, it is possible to retrieve the scene bounding box. The coordinates of each feature are mapped to this new reference frame and passed to an homography process. This allows to retrieve the width and height (in pixels) of the sensed scene.

That information is then passed to the navigation block through the second interface message.

#### *3.4.1.1* IR Scenario

For what concerns instead IR scenario, a preliminary assessment on attainable performance is carried out with poor results. Since it's not easy to recover ground truth data in thermal infrared bands from a structured large database that covers the whole Earth surface, the preliminary approach was to rely on Landsat 8-9 missions' data coming from the Thermal Infrared Sensor (TIRS) sensors, adapting them to FUTURE IR Camera specifications: downscaled to 200 m resolution, framed to 640x512 px and rescaled to a 0-1 range.

Unfortunately, the normalized pixel values do not span properly the allowed dynamic range, so this represents a problem in features recognition. In fact, when the same IP pipeline developed for the VIS WFOV baseline scenario is applied, the test outcomes are definitely not positive.

There is the need to find a workaround to obtain useful information also through the analysis of thermal infrared acquisitions that will be available onboard. Dedicated effort devoted to the understanding of the viable strategies and the identification of a solution suitable for FUTURE mission in the following phases of the project.

#### *3.4.1.2* AI IP Algorithm performance results analysis

Different scenarios have been tested, starting with ideal case and then applying different environmental disturbances to foresee realistic operational activities.

**Disturbance-free tests** are performed to assess the maximum theoretical performance of the developed AI algorithms on the test dataset.

In a condition where the navigation block is able to provide rough coordinates estimation to filter the global feature database, the latitude/longitude boundaries are set to +/-10°, and results are presented in Table 2. As it is possible to see, scene coordinates and range estimations have been completed in the majority of the 50 simulations.

Table 2 IP performance on tests in nominal conditions (lat/lon boundaries +/-10°).

| | **Scene coordinates** | **Range from scene** |
|---|---|---|
| **Early stopped tests** | 6 | 7 |
| **Accomplished tests** | 44 | 43 |
| **Outliers** | 3 | 9 |
| **Valid outputs** | 41 | 34 |

In Figure 9 it is possible to see the cumulative distribution functions (CDF) of both the scene coordinates and range from scene errors. This is an important input for the fine tuning of the navigation filter and for the error statistics which is carried out by Polimi. In more than 80% of the cases, the error in the reconstructed state is below 7 km for the centroid and less than 30 km in range.

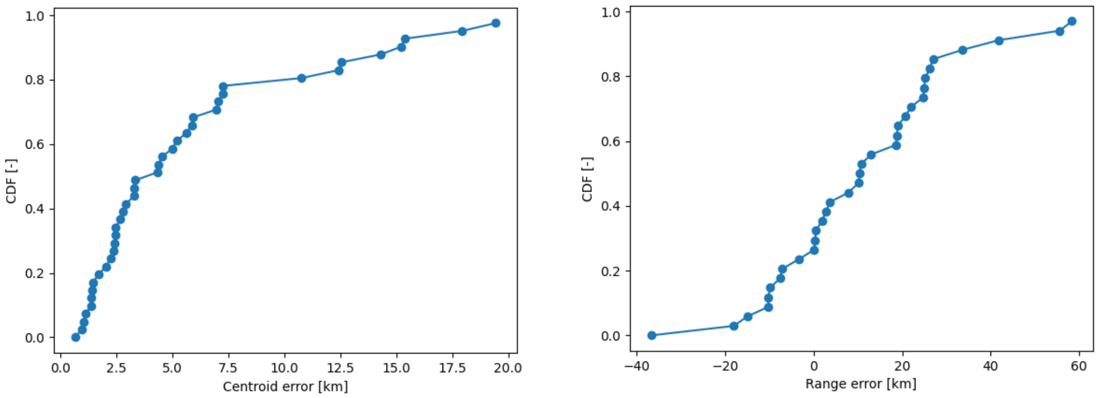


Figure 9: Nominal tests - Scene coordinates and range errors CDFs.

**The first environmental disturbance** introduced in the tests is the variation of illumination conditions. At this stage, a uniform brightness factor BF is applied to the whole acquisition, with values ranging between $0.5 \leq BF \leq 1.5$.

There are several behaviors that the algorithm can exhibit depending on the processed acquisition:

- Results remain constant despite the perturbation included.
- Scene coordinates and range estimation have bounded variations at different BF.
- Scene centroid error remains bounded while range from scene error explodes starting from a certain brightness factor.

Overall, in the accomplished tests, the scene coordinates estimation has shown a 100% robustness with respect to illumination conditions variation, while the range from scene estimation is robust in 70% of the cases.

**The second environmental disturbance** introduced is the presence of clouds in the snapshots acquired by the VIS WFOV camera. Considering that, at each instant, 50-60% of the Earth surface as seen from satellites is covered by clouds, this is a high influent disturbance for EO applications and FUTURE use case as well. For FUTURE mission, it is possible to exploit the knowledge about the cloud coverage by leveraging *cloudy_CHARLES* in the operational scenario. AIKO's algorithm *cloudy_CHARLES* receives as input the acquisition and processes it to provide the cloud mask.

The main way to envision its use is the rejection of images (or sub-patches) characterized by a cloud coverage which is above a certain threshold, or the possibility of discarding features detected in the neighbourhood of coordinates in which cloud pixels are identified (as they may represent false

positives in feature detection). Considering the needs of the FUTURE mission, saving processing time and computational power could be of high impact for the IOD accomplishment, therefore a first analysis concerning useless image discarding is carried out.
For the IP algorithm, it is difficult to find valid and robust feature matches when the cloud coverage increases, so this can be considered as a reasonable outcome.
Therefore, by setting a threshold of, for instance, an average of 50% maximum cloud coverage allowed on the whole image, it would be possible for the IP algorithm to avoid performing 11 tests on the test dataset. This would reduce by 64% the number of tests that are early stopped in the "blind" tests with cloudy images and were instead accomplished in the disturbance-free case, resulting in a noticeable saving of computational power and processing time.

### 3.4.2 Navigation Filter

The functional overview of the flow of operations during normal operations is provided in Figure 10. The on-board navigation block is characterized by three functional components:

- **Artificial Intelligence Image Processing block**: it receives as input the WFOV and IR images acquired and computes the associated observables via feature matching. The observables (centroid latitude/longitude and range) provided by this block are determined independently, each with a quality indicator about the reliability of the AI IP measurements.
- **Moon Image Processing block**: it receives as input images taken with the NFOV camera and performs edge and limb detection to extract the Camera-to-Moon position vector in Camera Frame.
- **Observable processing block**: it performs reference frame conversions to provide to the filter the observables in the reference frame used for the propagation and update. The AI-based observables are in ECEF frame while the propagation is performed in ECI frame.
- **Kalman filter block**: it implements the Kalman filter, which oversees the processing of the observables (update) and propagating the trajectory knowledge (predict).

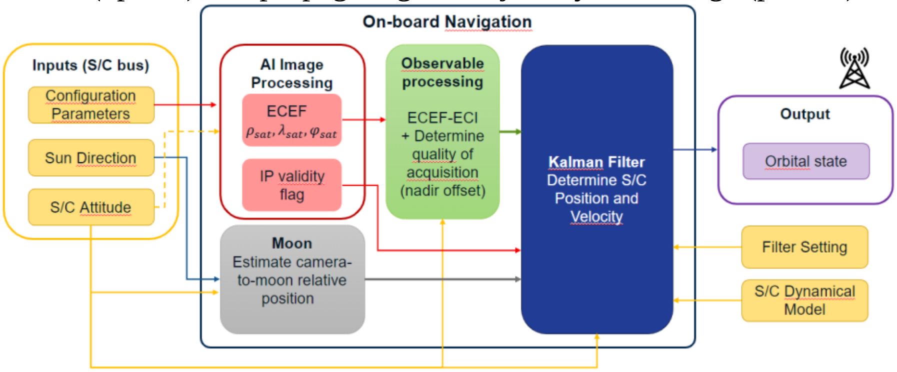


Figure 10: On-board Navigation Architecture Overview

The interfaces with the spacecraft bus are instead highlighted in yellow in Figure 10. The spacecraft ADCS system maintains the correct pointing and provides the estimate of the spacecraft attitude in form of quaternions. Similarly, the Sun direction is available and is used by the Moon IP algorithm. As this is an IOD mission, it is foreseen the possibility to perform updates of the AI IP algorithm parameters following on-ground calibrations and tuning. The same is foreseen for updating the settings (gains, parameters) of the Kalman filter block.
Finally, the last functional block involves the storage and generation of the output files which contain the state vectors and their associated covariance matrix that is estimated by the Kalman filter.

#### *3.4.2.1* Navigation Filter Scenarios

In a **nominal scenario** the navigation algorithm works by acquiring and processing images containing Earth's features with the AI algorithm. This is the baseline situation for Mission Phases 1 and 2.

In an **opportunistic scenario**, the Moon acquisition opportunities that are present between Earth visibility gaps are exploited. The NFOV camera is used to take pictures of the Moon between “no-features window”, which are then processed by the Moon IP algorithm and passed to the navigation filter. Despite the lower accuracy of these types of measurements, the main advantage is that it is possible to limit the covariance increase during long time intervals in which the spacecraft is in eclipse or above oceans. The same scenario is applicable for opportunistic IR acquisitions, with the caveat that such acquisitions are possible only above the night side of the Earth.

#### *3.4.2.2* Navigation Filter performance results analysis

The noise levels listed in Table 3 have been considered for the simulated measurements. A 20% margin has been added to the AI Image processing images.

Table 3: Measurement uncertainties used in simulations

| Camera axis | Earth (Visible) | Moon |
|---|---|---|
| **X (cross-radial) [km]** | 10.3 | 13 |
| **Y (cross-radial) [km]** | 10.3 | 6 |
| **Z (range) [km]** | 30.1 | 275 |

The analysis of the navigation filter performance considering the nominal scenario have been performed in three different cases:

- No clouds: this is the ideal scenario, where each acquisition possibility (each snapshot taken) can be exploited. This scenario also matches deep-space applications, where the filter is employed around bodies with no/rarefied atmosphere.
- Clouds: the presence of clouds degrades the performances, lowering the acquisition possibilities in a range between [50; 60] % of the planned snapshots.
- Operational: in addition to clouds, quality indexes related to the performance of the AI IP are introduced, one for the centroid and one for the range measurement. The performance index is used to increase the covariance in Table 3, hence de-weighting the measurements by reducing the fidelity associated with that set of observables.

The no-cloud case has been taken as reference and example since it will be the one associated with the requirement verification.

Looking at Figure 11, the green line of the 3σ uncertainty identifies the acquisition windows, while the red line the propagation arcs. It can be noticed that within acquisition windows the uncertainty level is comparable to the ones observed in the performance estimation analysis. During propagation arcs, the covariance increases mainly in the along-track direction but is reaching a maximum of around 100 km due to the shorter duration of these arcs in this simulation. As soon as the spacecraft enterns an acquisition, the covariance in the acquisition arcs shrinks immediately in all components.

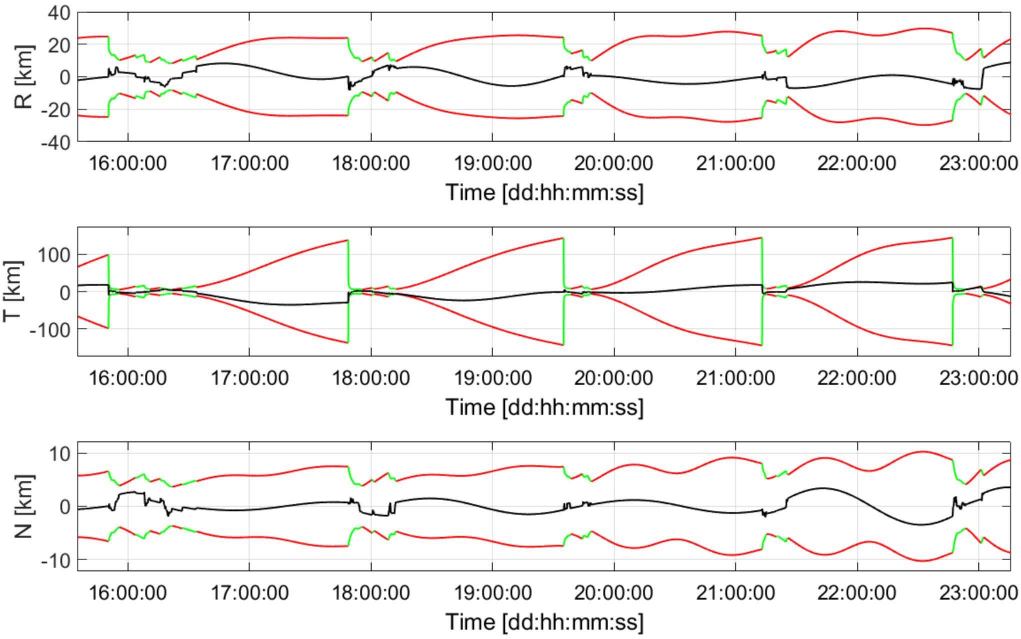


Figure 11: Position error and 3σ covariance. No cloud simulation. VIS Earth images. Small initial covariance. Zoom over the time window [+16, +23] hours

The filter performances are not heavily affected even when the simulation starts with a large initial covariance. A few acquisition windows are sufficient for the covariance and error estimates to reach the same levels of the small initial covariance case, proving the effectiveness of the filter.
The maximum 3σ errors reached at the end of each acquisition window in the no clouds case are reported in Table 4. Note that these values are uncorrelated and can appear at different moments, hence considering them all together is a conservative worst-case situation. Hence, the overall best performance of the filter is in most cases better than the values reported here.

Table 4: Maximum 3σ standard deviations of the navigation estimate at the end of the acquisition windows.

**Max 3*σ* errors reached by the filter (no clouds)**

| | |
|---|---|
| **T [km]** | 12 |
| **N [km]** | 6 |
| **R [km]** | 19 |
| **V_T [km/s]** | 0.02 |
| **V_N [km/s]** | 0.012 |
| **V_R [km/s]** | 0.02 |

To this performance metric is associated the main requirement of the mission, which verification is performed by first computing the maximum eigenvalue of the estimated covariance matrix (maximum σ in Principal Component Axes (PCA)). This is the maximum achievable error in terms of position at every time instant. This analysis is performed considering no margin on the measurement variance, which are set to 8.6 km (1σ) in the in-plane components and to 25.1 km (1σ) in the radial component. Then, the last standard deviation of each of the acquisition windows comprised in the 14-days simulation is extracted. Finally, the Cumulative Distribution Function (CDF) is plotted, and the 99.7 percentile is extracted. The CDF for the no-cloud case is given in Figure 12. In this case the selected value is **4.91 km**, corresponds to **5.89 km** when applying the 20% margin, which is compliant with the performance level reported in the requirement.

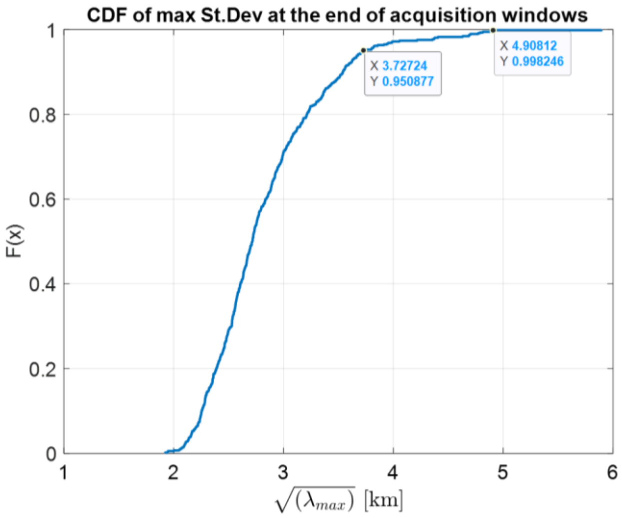


Figure 12: Cumulative Distribution Function of the maximum position uncertainty at the end of acquisition windows.

# 4 GROUND SEGMENT OVERVIEW

## 4.1 Ground Station Network

The Ground Station Network is composed of multiple antennas around the Earth. Cubesat passes are booked from Tyvak, depending on GS provider availability, so the provider can point towards the Cubesat to establish the radio link during Cubesat passage over the GS to transmit and receive all Cubesat TMs, TCs, and Payload data. The S-Band Ground Stations will support uplink and downlink of both CubeSat Platform and Payload data within all mission phases. UHF Ground Stations will be adopted as backup solution in case of contingency.

## 4.2 Ground Station Network Node

The Ground Station Network Node is responsible of receiving the real-time stream of data coming from the GSN and process them. The GSN Node decrypts and validates the data to ensure that they are coming from the right Cubesat and are well-formed.

After this process, GSN Node saves telemetry data points into a unified Database (DB).

Part of the GSN Node extracts a subset of data related to the payload from the DB and all payload-related files and makes them available for FUTURE MCC. Real-time Payload telemetry data, as well as S/C TM subset (e.g. GPS/NAV Position and Attitude, power status etc.) necessary for Payload data monitoring are published on a web socket, from which FUTURE MCC can read them after an authentication session. These files will include both payload science data files (e.g. images, navigation filter output), required to perform payload data algorithms reprocessing, verification and validation.

## 4.3 CUBESAT MCC

CUBESAT MCC interfaces with GSN Node to retrieve all the S/C data necessary to perform S/C operations. CUBESAT MCC is responsible for monitoring and controlling the Platform and Payload housekeeping telemetry during the LEOP. It is also responsible for S/C commissioning, nominal mission, and decommissioning phases.

CUBESAT MCC receives schedule requests from FUTURE MCC and notify the operator. If the schedule is accepted, it is then uploaded on the S/C by the operator using the first available passage nearest to the schedule execution specified time.

### 4.4 FUTURE MCC

FUTURE MCC is the center responsible, during Nominal Mission Phase, of performing:

- Payload housekeeping telemetry monitoring
- Payload data processing, performance evaluation and data validation
- Providing services and data accessibility to PAYLOAD engineering support centers.

The main elements that make up the FUTURE MCC are:

- FUTURE Operational Data Exchanger (FODE), which includes the services necessary for operators to manage the exchange of information with the CUBESAT MCC.
- FUTURE Data Retrieval Transformation and Repository (FDTDR), which enables the reception and management of data from the GSN Node.
- FUTURE PAYLOAD Data Processing (FDPP), which is responsible for validating the PAYLOAD data by evaluating the performance of navigation and artificial intelligence algorithms, and comparing the navigation data generated by the PAYLOAD with the navigation data generated by the GNSS.
- PAYLOAD Planning Support Tools (PPST), which includes the services required for planning Payload activities in orbit;
- PAYLOAD Engineering Support Services (PESS), manages the interface between the FUTURE MCC and the Payload Engineering Support Centers allowing report and data access of the payload.

### 4.5 Payload Engineering Support Centers

The Payload Engineering Support Centers are identified as the centers/facilities where the PAYLOAD algorithm engineering expertise resides.
Their involvement in the FUTURE MCC is foreseen during the mission to support PAYLOAD data verification and validation activities, provide input and request for new acquisition and provide support for PAYLOAD algorithms calibration and refinement during mission execution.

## 5 CONCLUSION

FUTURE's commitment to technology transfer is a cornerstone of its mission. By demonstrating the feasibility and effectiveness of autonomous navigation in LEO, using the independent GNSS propagation as truth reference for data validation, the project sets the stage for future applications beyond LEO, such as in missions about planets, moons, and deep space, so enhancing autonomous operation and navigation in the proximity of different celestial bodies. In conclusion, FUTURE represents a leap forward in the CubeSats, showcasing the potential of visual navigation as a primary navigational tool and charting a course towards enhanced autonomy in space exploration.

## 6 REFERENCES


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