POLITECNICO
MILANO 1863

# e.Inspector  Phase B

## Final Presentation

POLITECNICO
MILANO 1863

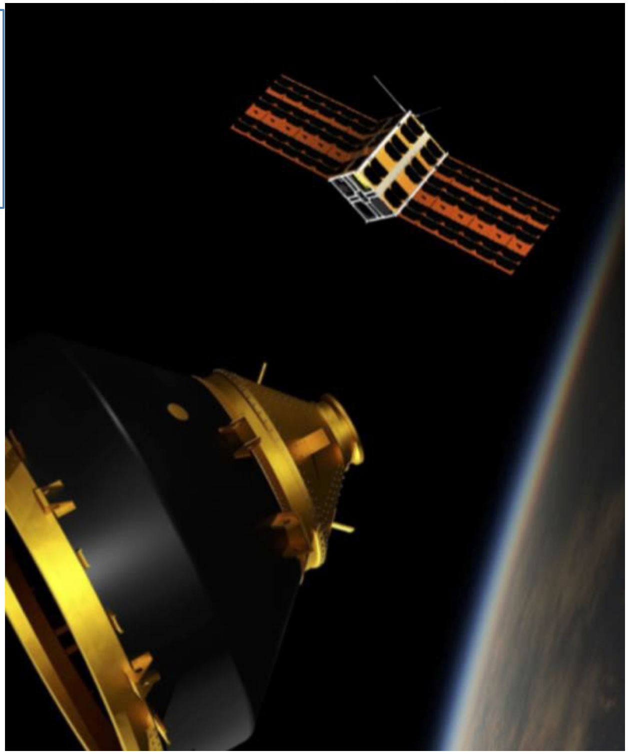
LEONARDO LEAF SPACE T4i TECHNOLOGY FOR PROPULSION AND INNOVATION

DIPARTIMENTO DI
SCIENZE E TECNOLOGIE
AEROSPAZIALI

astra

# e.Inspector – *in Orbit Servicing*

esa
POLITECNICO MILANO 1863
LEONARDO
LEAF SPACE
T4i TECHNOLOGY FOR PROPULSION AND INNOVATION



**GOAL**

- Fly around a Space Debris – VESPA adapter (NORAD object 39162)
- Shape and dynamics reconstruction to support Active Debris removal activities

- ***Safety proximity maneuvering around a non cooperative\not a priori known object***

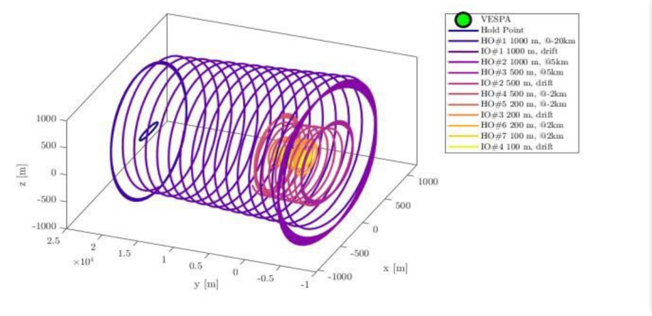
**Technology development opportunity**

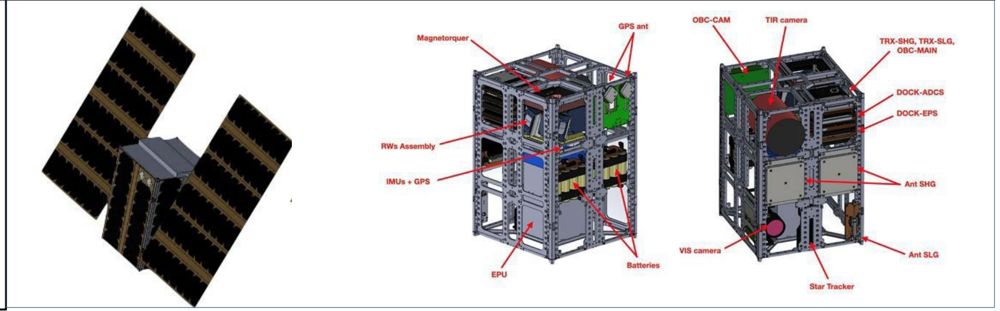
- **Complement** the VIS sensors with **IR imaging** to perform **enhanced relative navigation *on board* in closed loop with control**
- **Exploit the low thrust capabilities** – electric propulsion

**Project Engineering**

- ***Model based System Engineering***

| Advanced GNC | Image processing –on board sw | System Engineering |
| --- | --- | --- |



# e.Inspector – *the TEAM & ROLES*

***e.Inspector*** is developed with **ESA** under GSTP, financed by **ASI**

## POLIMI-DAER\ASTRA

- **PRIME** System\mission engineering, ***multispectral IP-based proximity GNC*** and related HW\SW breadboarding on **PIL and HIL**

## LEONARDO Company

- VIS\IR payload requirements, selection and characterisation\testing

## LEAF SPACE

- Ground segment requirements consolidation, baseline settling

## Techonology 4 Innovation – T4i

- Low thrust propulsion customization and qualification for endurances TRL increase

**PHASE A\B**

July 2024, Board

……….

**PHASE C\D\E\F**

# e.Inspector- *B mission\study goals*

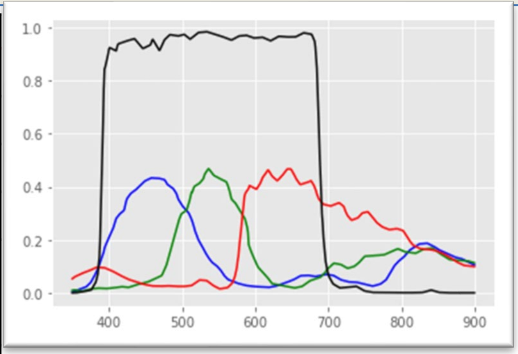
The main **mission goal** kept along phase B was to carry out a close-up visual inspection of VESPA Upper Part (NORAD object 39162)

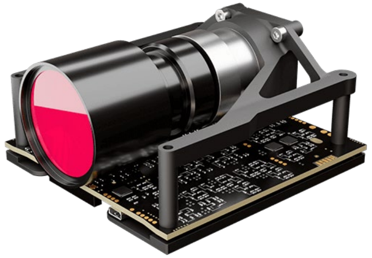
1. Design mission-critical technologies such as **IP multi-spectral based** relative **GNC for all mission phases**
2. Define the **breadboard for the OBC motherboard**, and perform functional tests to support baseline selection
3. **Obtain** EM for the VIS and IR **payloads**
4. **Assess the validity** of the proposed **image payload** and perform functional tests
5. Consolidate the **mission analysis and launch strategy**
6. strengthen the technology readiness for the **low thrust equipment**
7. Design the **platform, payload and ground segment** baseline to match the technical requirements, supported by analyses

# e.Inspector - *VIS-IR Instruments*

## Gecko imager - VIS

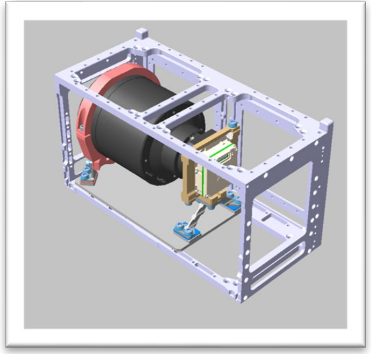
| Parameter | Value |
|---|---|
| GSD @500 km (nadir pointing) | 39 m |
| Spectral bands | RGB |
| Swath @500 km | 80 km |
| Integrated storage | 128 Gigabytes |
| Image data format | Raw (up to 16 bit per pixel), JPEG2000 lossless or JPEG2000 lossy (10 bit per pixel) |
| Physical size | 100 mm x 100 mm x 65 mm |
| Mass | 0.38 kg (TBC) |
| Data interfaces | LVDS, SPI, 12C RS422, CAN |
| Timing interface (1pps) | TTL, RS422 |
| Power usage | 2.7 W (imaging mode)<br>1.4 W (Readout mode)<br>5V Power supply |
| Operating temperature | +0°C to +30°C |
| Survival temperature | -25°C to +55°C |
| Radiation Tolerance (TID) | Tested to 30kRad |



## FLIR Tau 2 Camera + 100 mm lenses

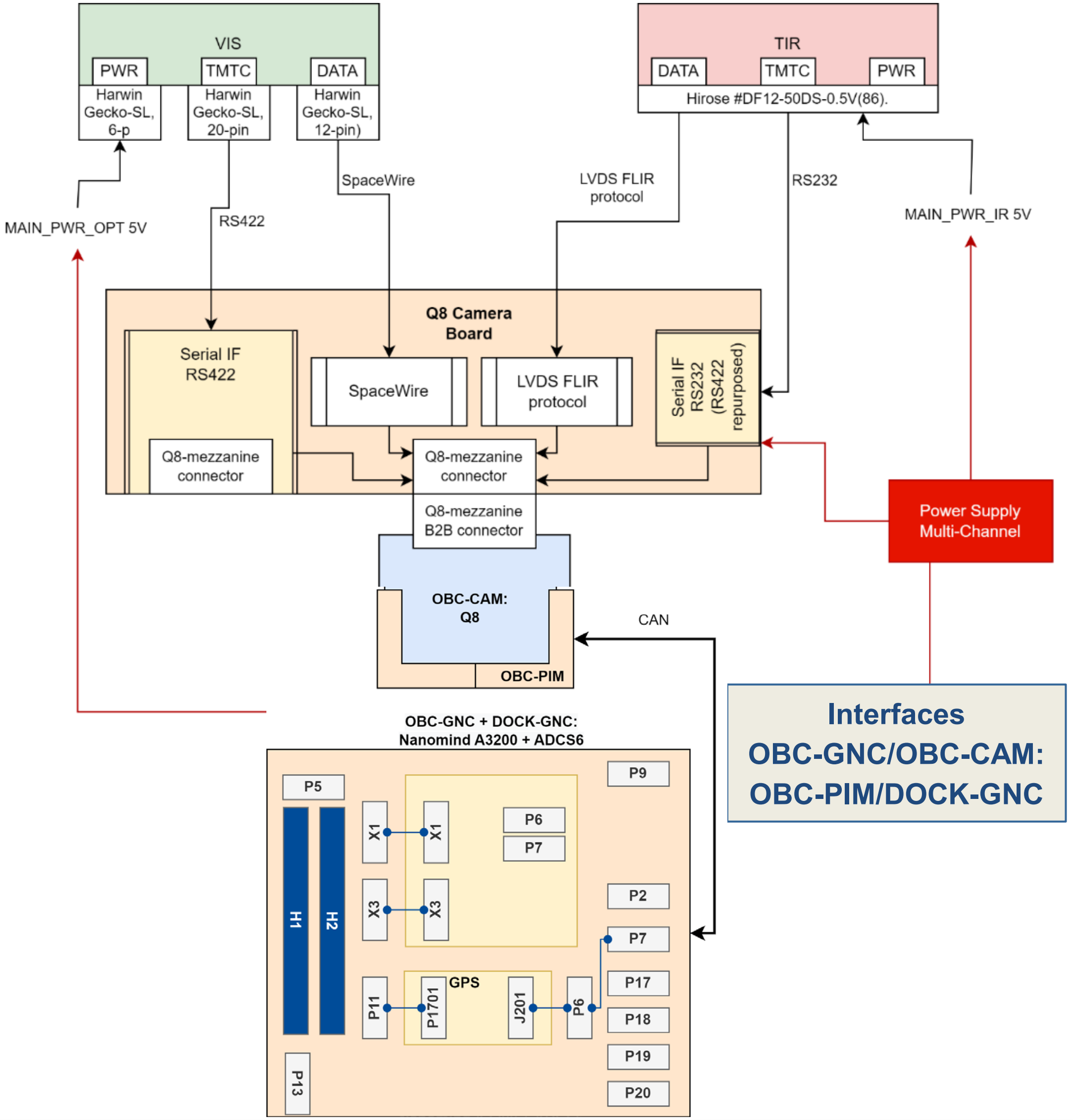
| Parameter | Value |
|---|---|
| Detector type | Uncooled VOx Microbolometer |
| Number of pixels | 640 x 512 |
| Pixel size | 17 µm |
| Spectral band | 7.5 – 13.5 micron |
| Performance | <50 mK @f/1.0 |
| Frame rate | 30 Hz / 60 Hz |
| Digital Video | 8 or 14 bit serial LVDS<br>8 or 14 bit parallel CMOS<br>8 bit BT.656 |
| Signal interface | Camera Link<br>RS-232 compatible |
| Size (without lenses) | 45 mm x 45 mm x 30 mm |
| Mass | ≤ 500 g (from datasheet) |
| Input voltage | 4.0 – 6.0 VDC |
| Primary Electrical Connector | 50-pin Hirose |
| Power dissipation | <1.3 W |
| Operating temperature range | -40°C to +80°C |
| Storage temperature range | -55°C to +95°C |
| Scene temperature range | High gain: -40°C to +160° |



| Parameter | Value |
|---|---|
| FoV | 6.2° x 5° |
| F# | 1.6 |
| Focal length | 100 mm |
| Aperture diameter | 82 mm |
| Length | 110 mm |

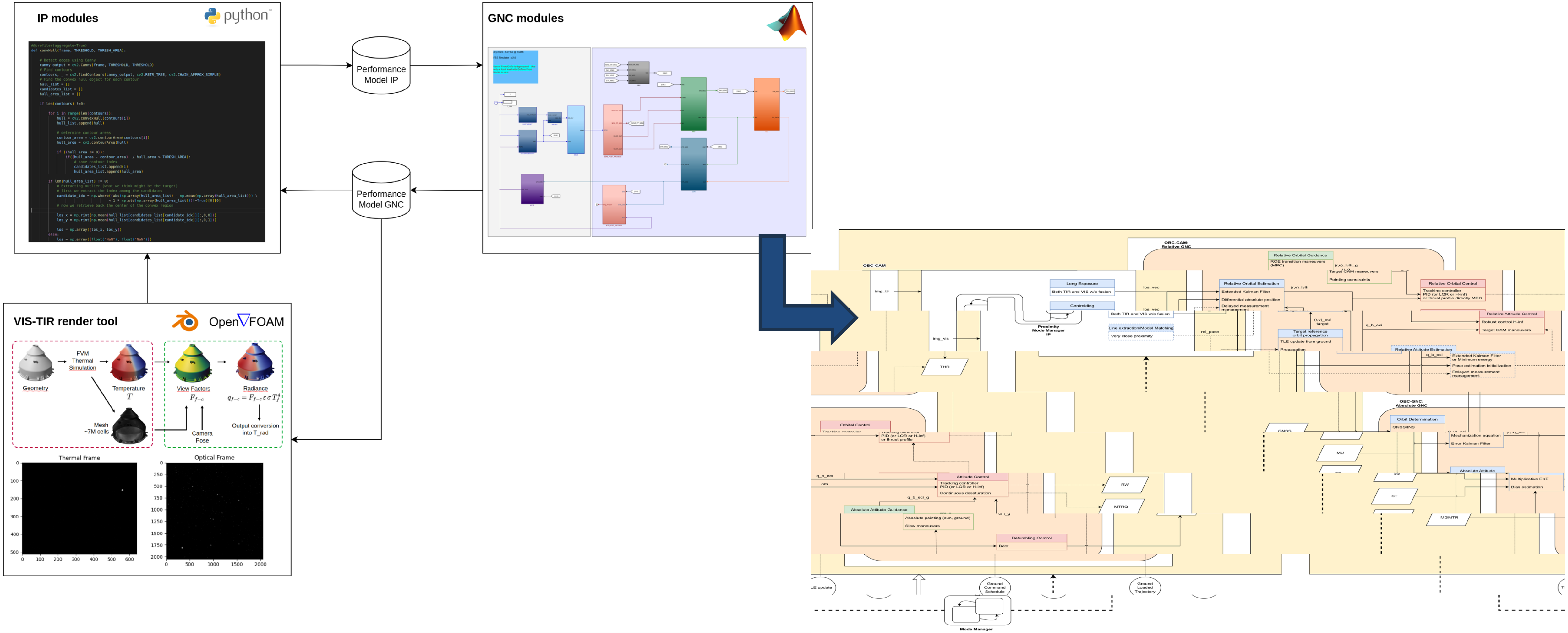
# e.Inspector - *OBC motherboard design and breadboarding*

| Component | Functionalities |
|---|---|
| TIR | Emulator or functional model of TIR camera |
| VIS | Emulator or functional model of TIR camera. |
| **CAM-BOARD** | Interface daughterboard to exploit full compatibility between cameras output (DATA and TMTC) and Q8 inputs. |
| **OBC-CAM** | OBC in charge of execution of image processing + GNC modules strongly linked to the IP output. |
| **OBC-PIM** | Inteface exposing Ultrascale+ CAN bus from the Q8 board. |
| **OBC-GNC** | OBC in charge for acquisition of sensor readings, control actuation, part of GNC algorithms |
| **DOCK-GNC** | Routing for OBC-GNC to sensors and actuators. |
| **PIL-TESTBENCH** | |




**Interfaces OBC-GNC/OBC-CAM: OBC-PIM/DOCK-GNC**

## Virtual Model Environment and Development

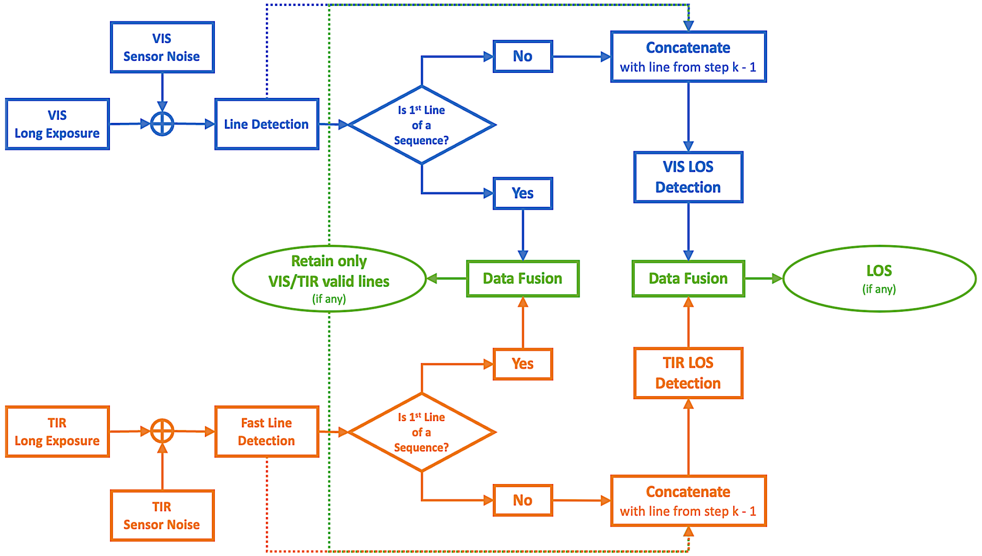


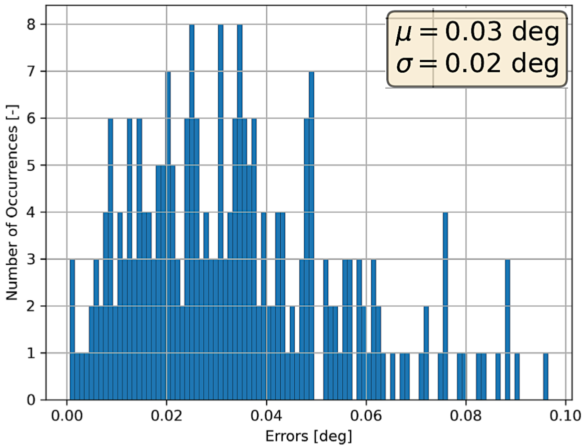
## GNC - IP algorithms design overview - Relative

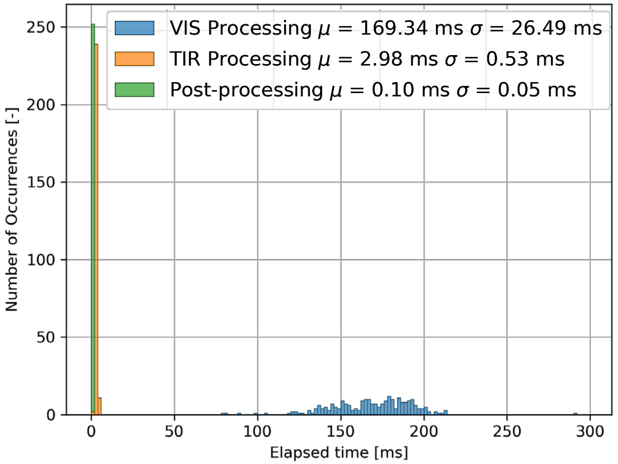
| Mode | Distance | IO | Sensor | IP technique | EF technique |
|---|---|---|---|---|---|
| **State estimation - far** | 20km - 900m | #1, 2, 3, 4 | VIS+IR<br>TLE | Long exposure images - centroid | MSE Optimal – full state **r, v** |
| **State estimation - close** | 900m - 100m | #1, 2, 3, 4 | VIS+IR | Centroid - blob detector | MSE Optimal – full state **r, v** |
| **Pose estimation** | 200m - 100m | #4 | VIS+IR | Model matching | 6DoF decoupled<br>• MSE Optimal (rel position) |

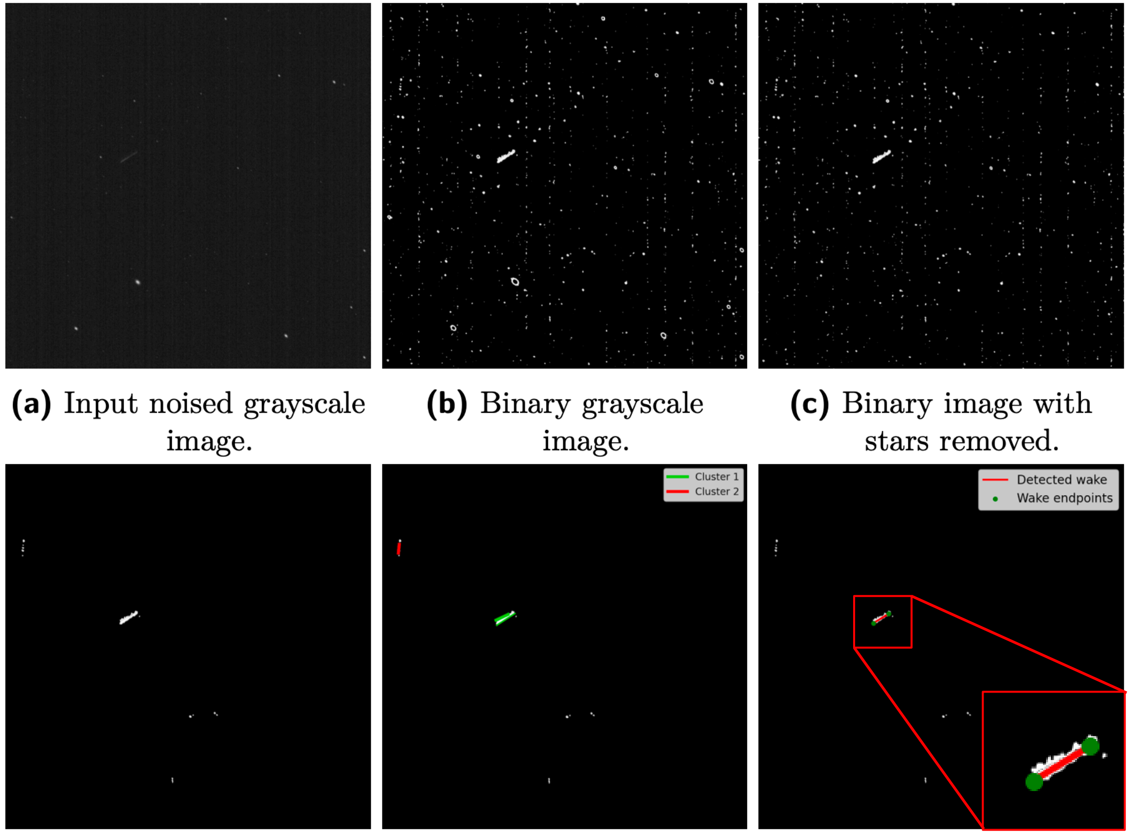
# e.Inspector: *Far Range – Long Exposure – Inertial Pointing*

## Common IP for both VIS and TIR images in Long Exposure - Inertial Pointing mode



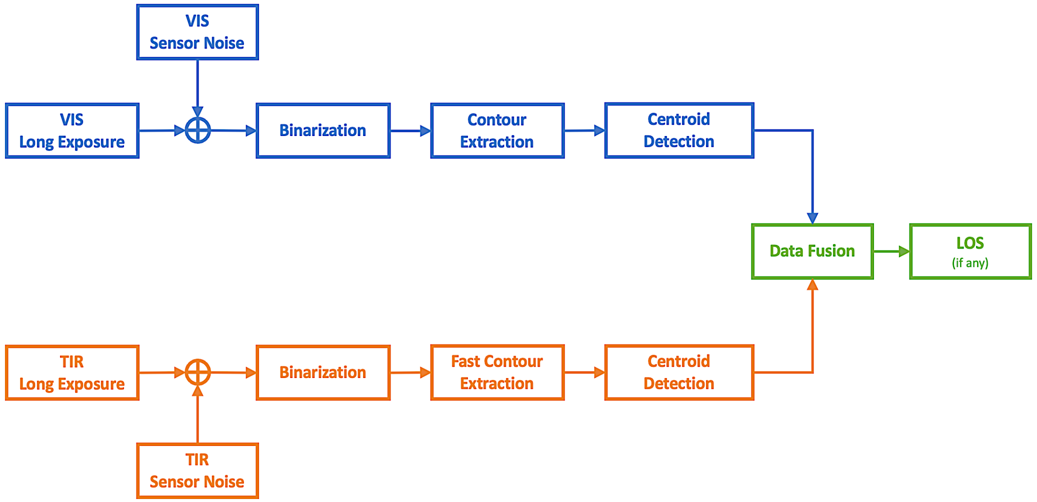



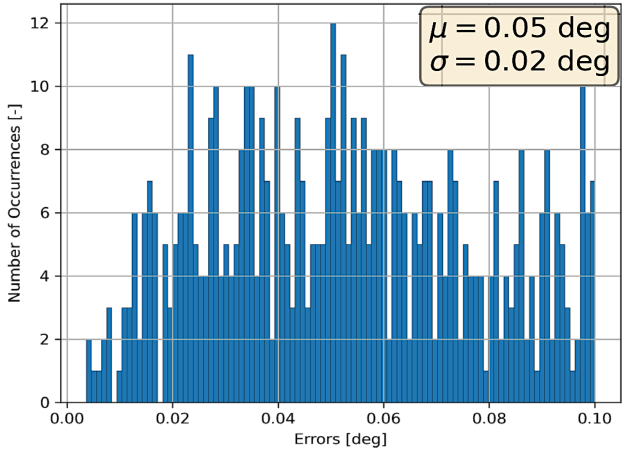

**(a)** Input noised grayscale image. **(b)** Binary grayscale image. **(c)** Binary image with stars removed.

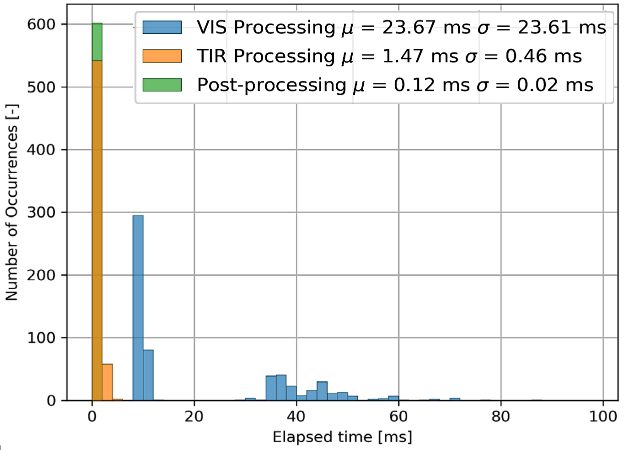
**(d)** Binary image with noise removed. **(e)** Lines detected and clusterization outputs. **(f)** Detected wake and its endpoints.

# e.Inspector: *Far Range – Long Exposure – Target Pointing*

Common IP for both VIS and TIR images in Long Exposure - Target Pointing mode



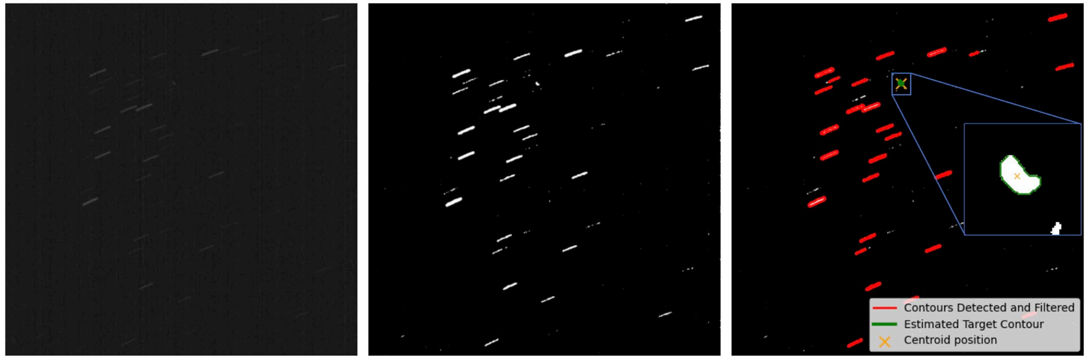




## TIR Detailed Processing

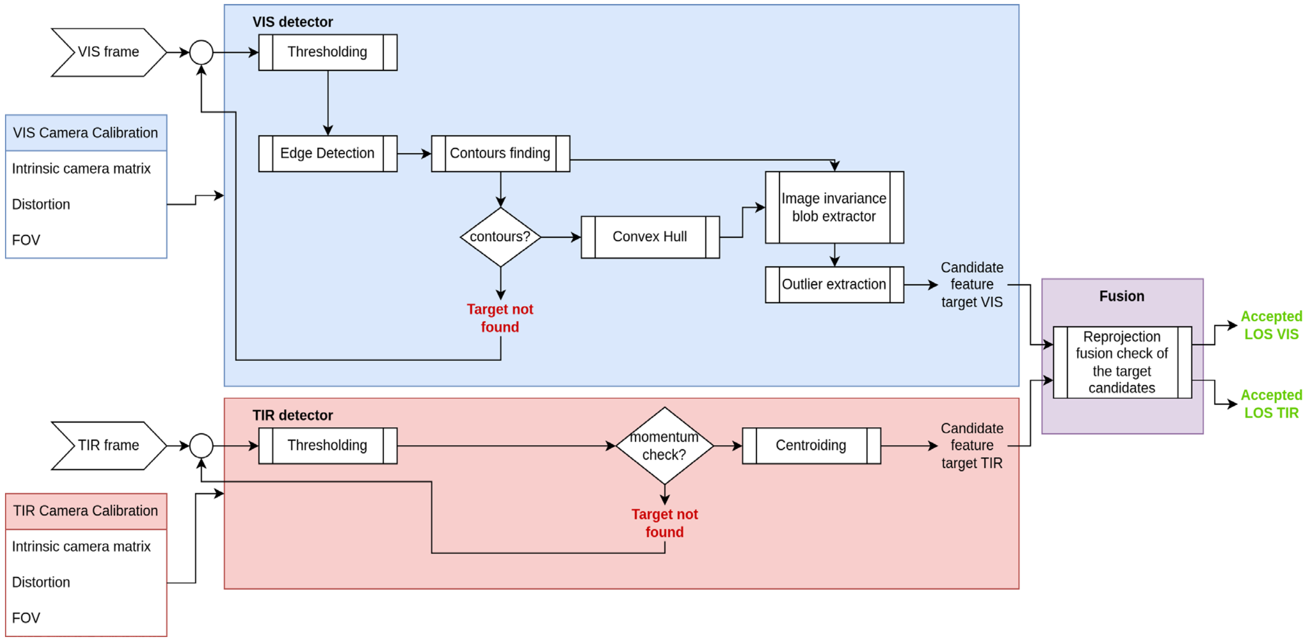

**(a)** Input noised grayscale image. **(b)** Thresholded binary image. **(c)** Detected contours and computed centroid.

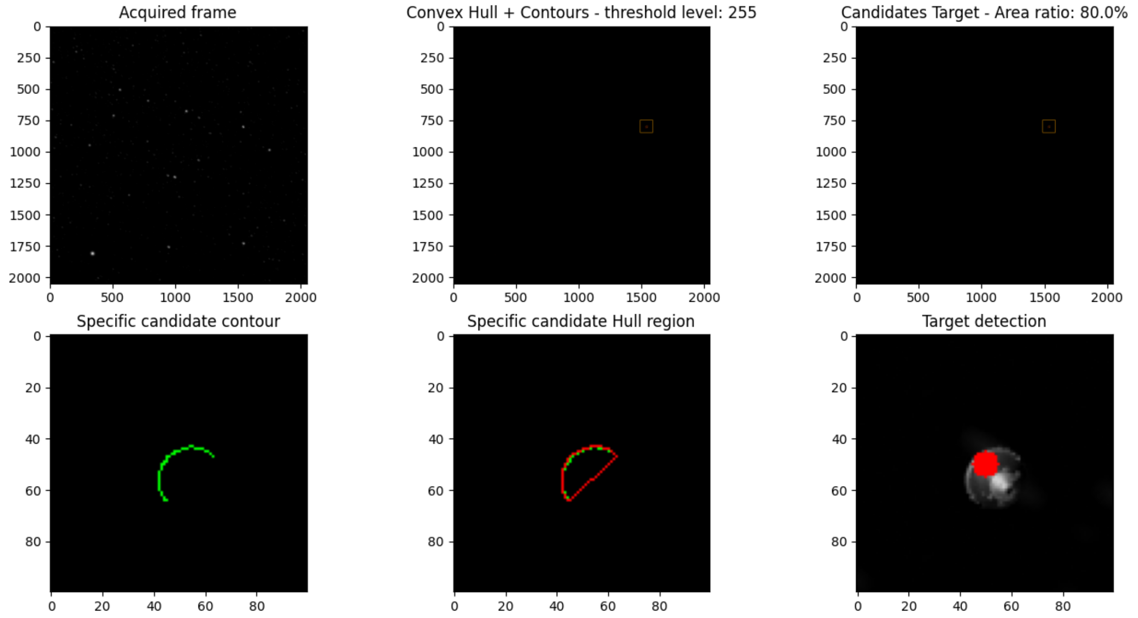
## VIS Detailed Processing

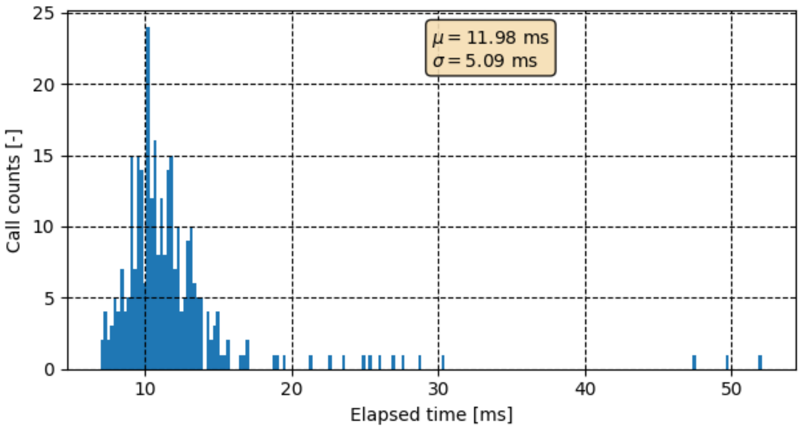


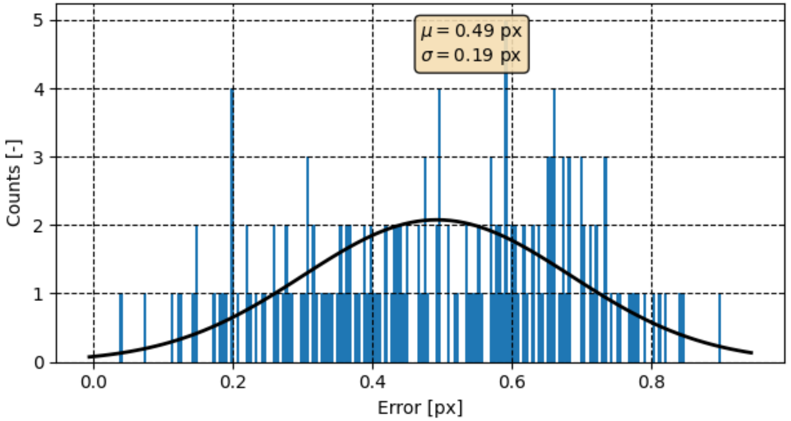

**(a)** Input noised grayscale image. **(b)** Thresholded binary image. **(c)** Detected contours and computed centroid.

# e.Inspector: *Close Range – IP algorithm design*



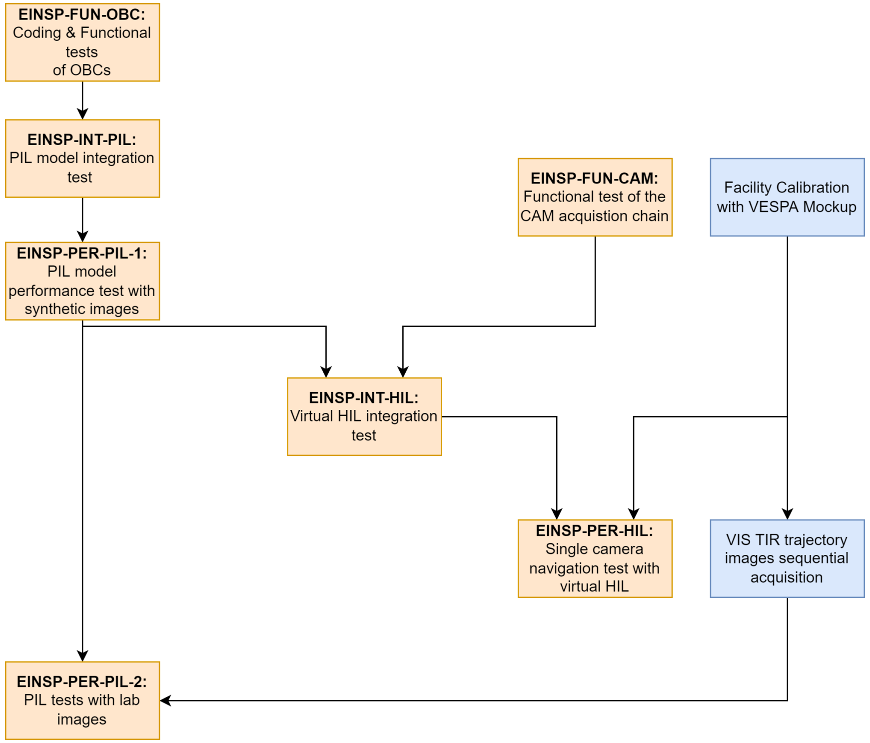



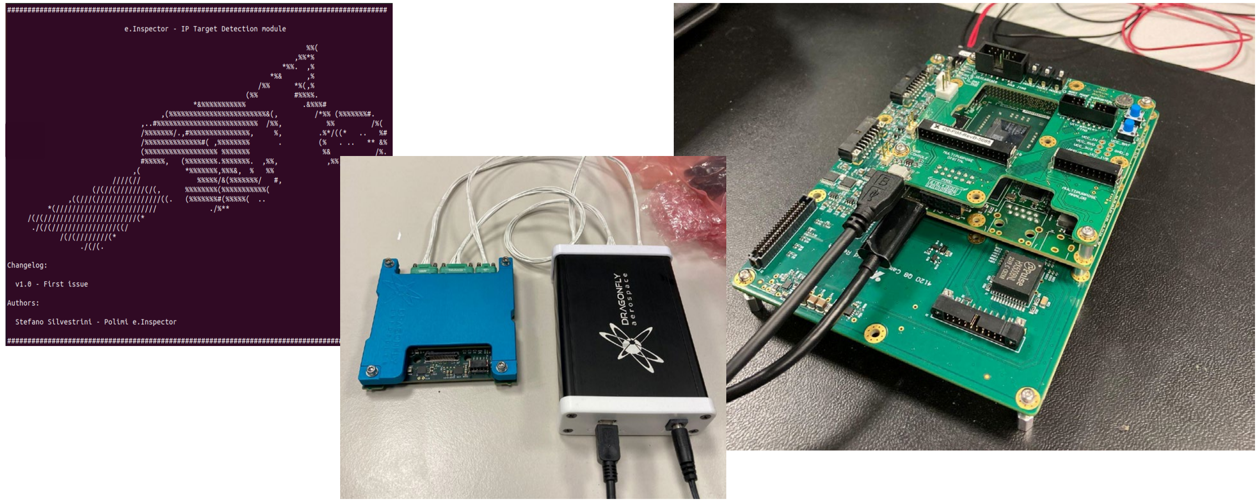




- VIS frame: 2048 x 1024 px
- TIR frame: 640 x 512 px

- Frame acquisition: 0.1 Hz

# e.Inspector: *PIL test of IP algorithms*

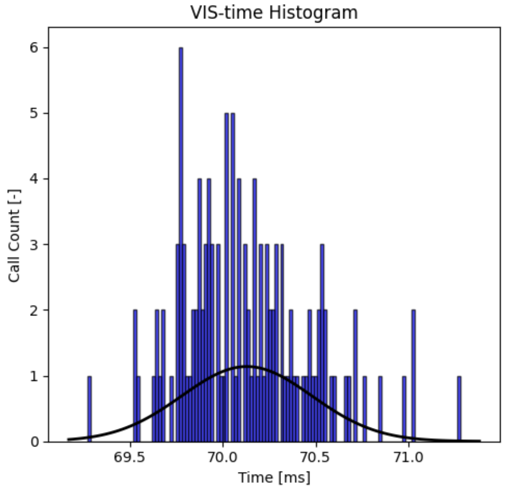


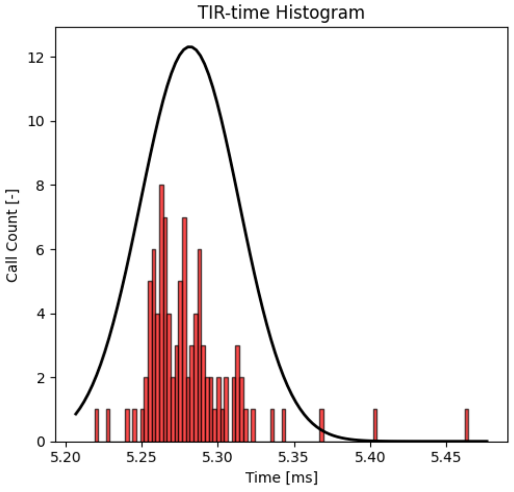




## PIL Execution Times

The computational times for the VIS detection is **~70.1 ms** on average with a limited standard deviation.

The centroiding TIR algorithm is much faster than the VIS, as expected, with a mean computational time of **~5.27 ms**.

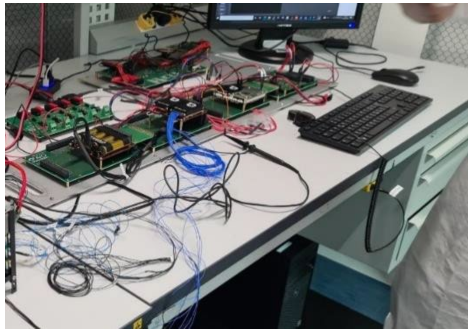


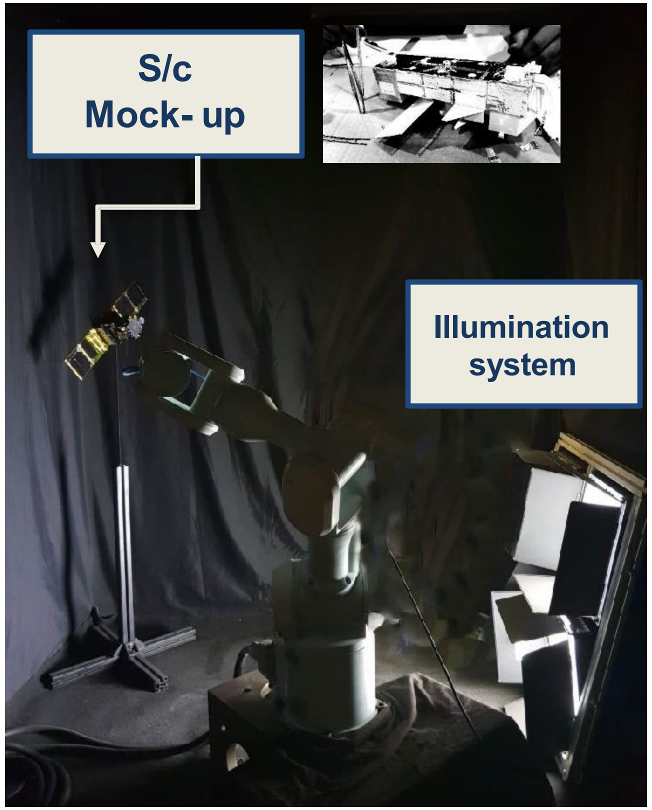
# e.Inspector – *IP-GNC HIL testing*

**IP-GNC ARGOS ASTRA-PoliMi facility+ HW\SW GSE – calibrated, with heritage on other ESA IP\RVD studies**

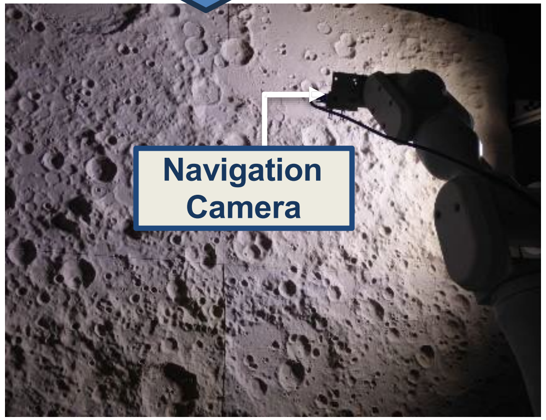
**AVIONIC testbench**

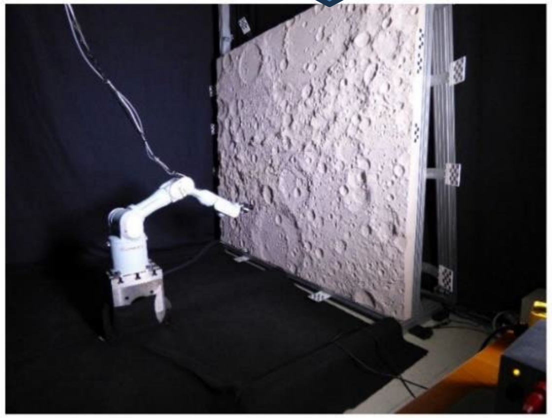


- *1:50 satellite mockup*
- *5700 K tuneable illumination*
- *VIS camera – IR camera upcoming*
- *6 dof Robotic arm*
- *3x2,4m calibrated Moon diorama*

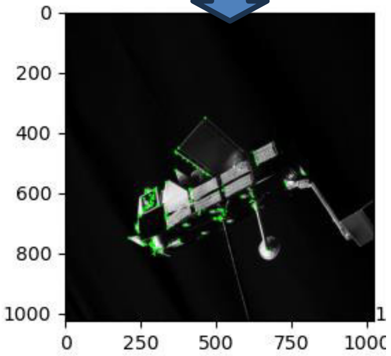


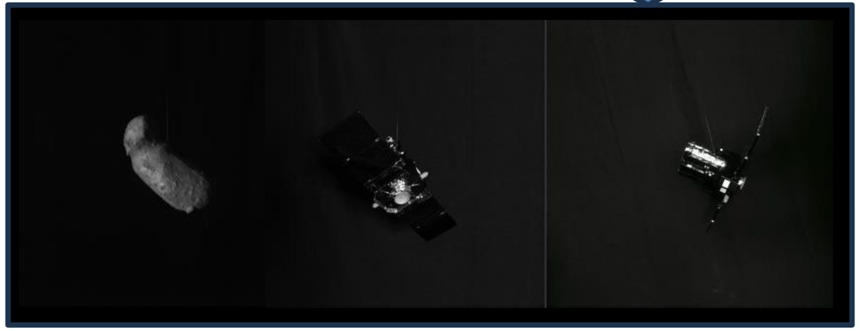

**Dark room calibrated facility (8mx5m)**



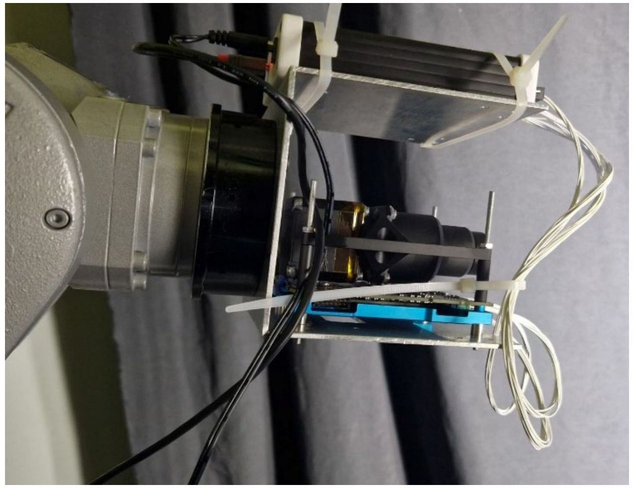
**Real in lab images**



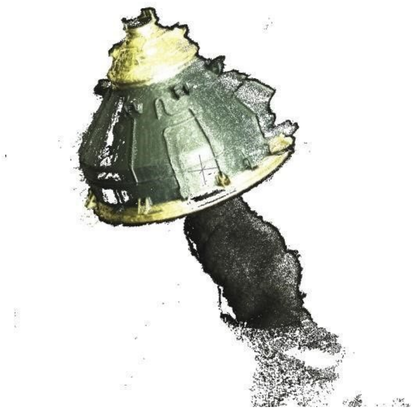



Facility and mockup calibration to retrieve groundtruth poses of ARGOS elements:

- Robotic arm
- Camera
- Mockup



Set-up



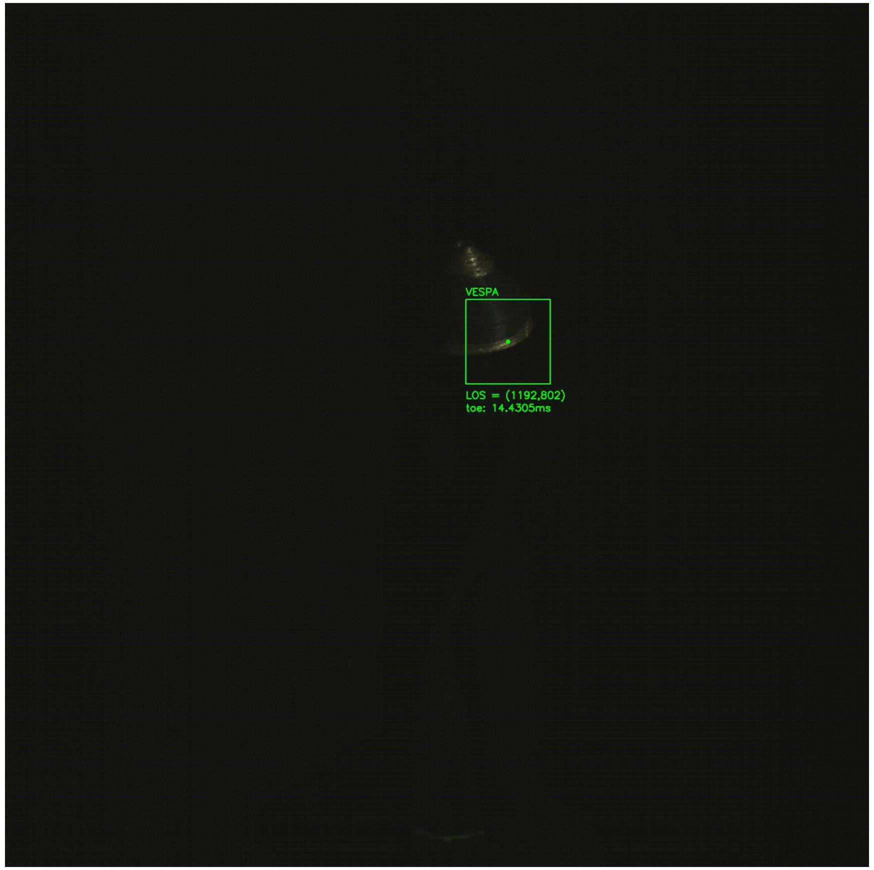
Calibration

Acquisition

Two mockups different scales:
more representative achievable trajectories

# e.Inspector: *HIL - VIS camera-mockup calibration*

**The IP algorithm is cross-compiled and tested on a sample trajectory taken with the robotic arm.**



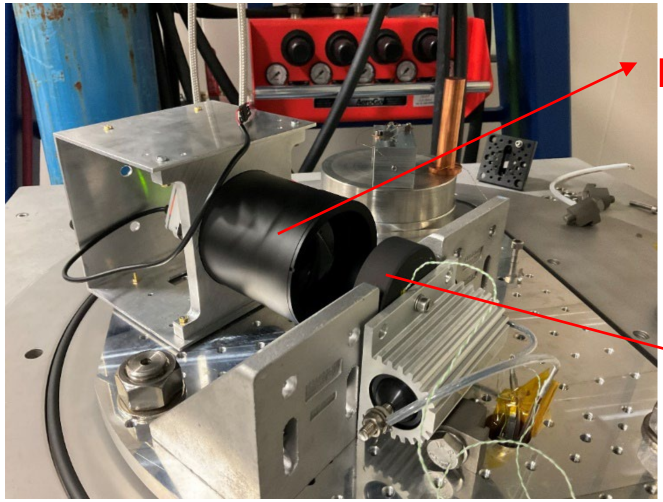

Detection tends to be **slightly degraded in performance** due to the camera noise and remaining diffusive light of the real camera.

- Convex hull identification tends to move the momentum towards the golden plates
- Diffusive light makes the **background (black curtains) more illuminated** than the deep space of the rendered images, making VESPA body less recognizable

An important remark is that the acquisition time through LVDS can reach up to 1s.

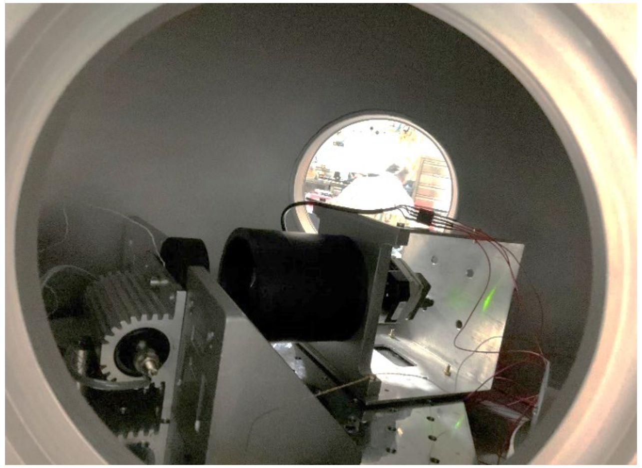
# e.Inspector: *TIR camera calibration setup*

- **Goal**: recover camera gain and camera offset
- Experimental setup of TIR performance test using metal plate at controlled temperature coated with black paint

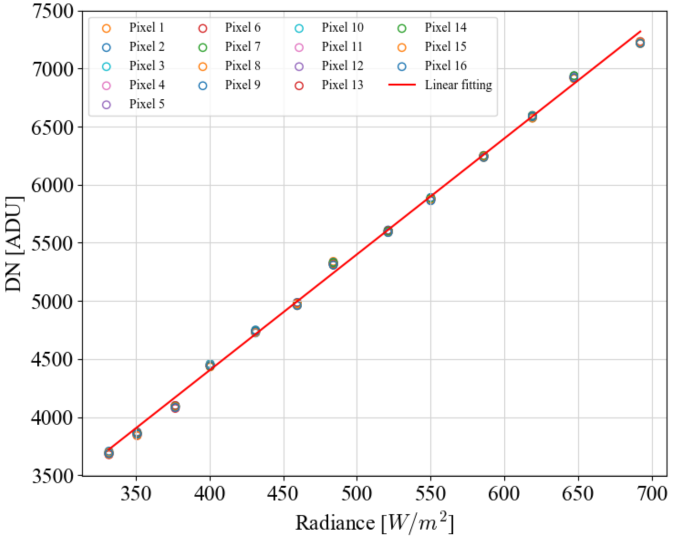


FLIR Tau2

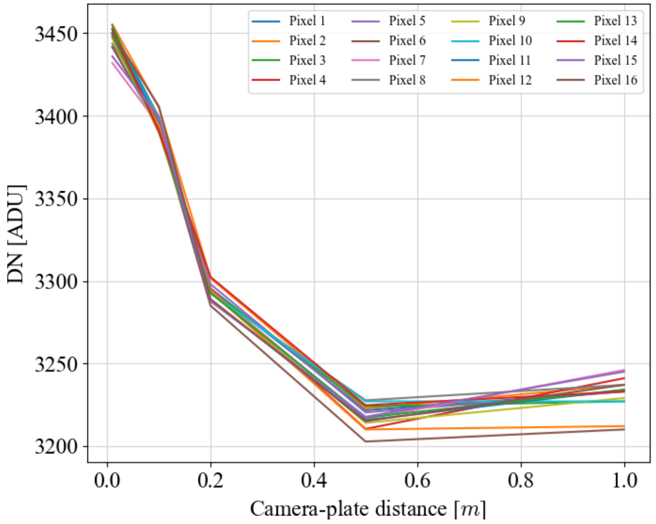
Metal plate



Camera response function: $DN = A \cdot q_{fc} + B$




Camera response function varying camera-plate distances in **non vacuum;** plate temperature fixed at 39 °C.

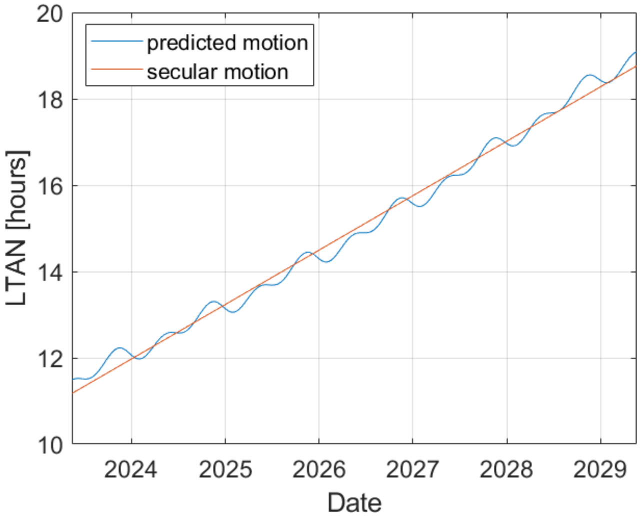



Vacuum conditions: 1e-4 mbar

Two thermal scenarios:

- <u>Hot case:</u> [+35 °C, +100 °C] with camera-plate distance fixed at 2.85 cm
- <u>Cold case:</u> [-30 °C, +20 °C] with camera-plate distance fixed at 4.50 cm

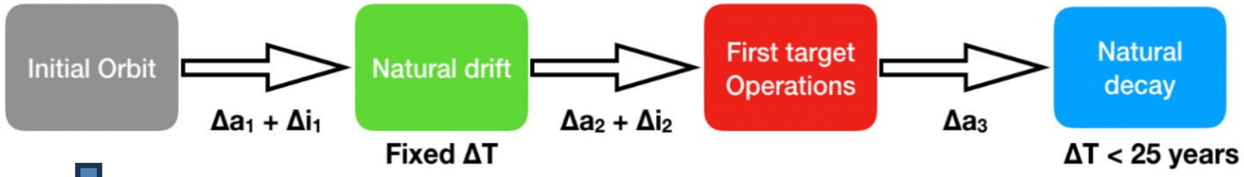
## *Baseline target debris motion*

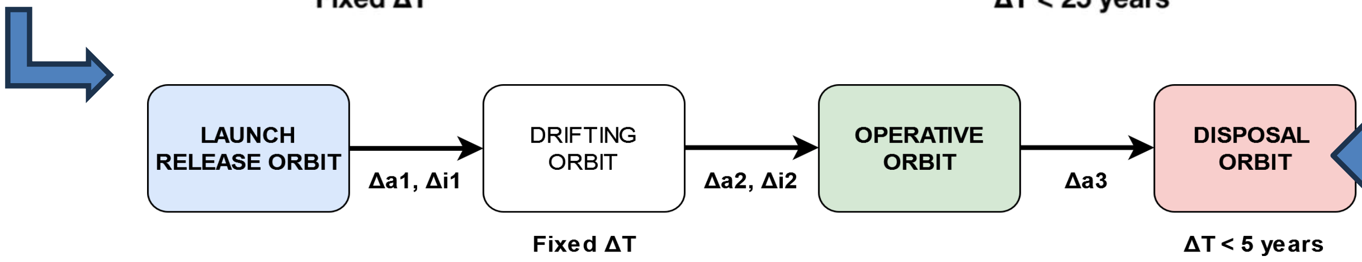


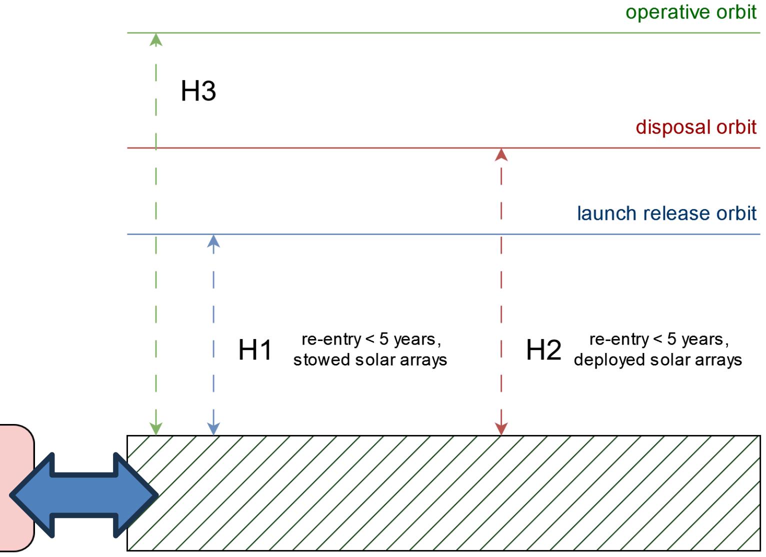

| | |
|---|---|
| **Semi-major axis [km]** | 7103.86 |
| **Eccentricity [-]** | 0.009185 |
| **Inclination [deg]** | 98.72 |
| **RAAN [deg]** | 219.19 |
| **Arg. Of perigee [deg]** | 41.96 |

*39162 VESPA I.C. →13/05/2023*
*Impacted Aug 2023 →increased interest*

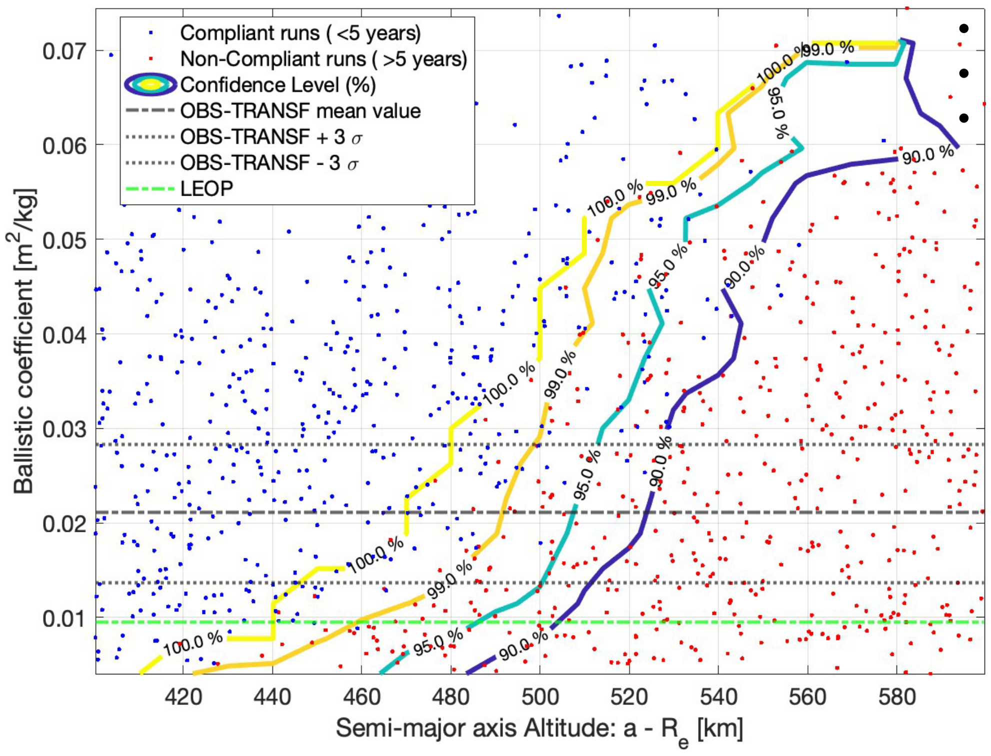
## *Transfer strategy*



# e.Inspector - *disposal new regulations effects*




**Ballistic coefficient** and **initial mean altitude** strongly influence the decay time.
During **LEOP** the panels are folded: lower ballistic coefficient → lower safe altitude
During **TRANSFER** and **INSPECTION** phases the panels are deployed: higher ballistic coefficient → higher safe altitude

**LEOP**: h<475 km (TBC)
**OBS-TRANSF**: h<500 km

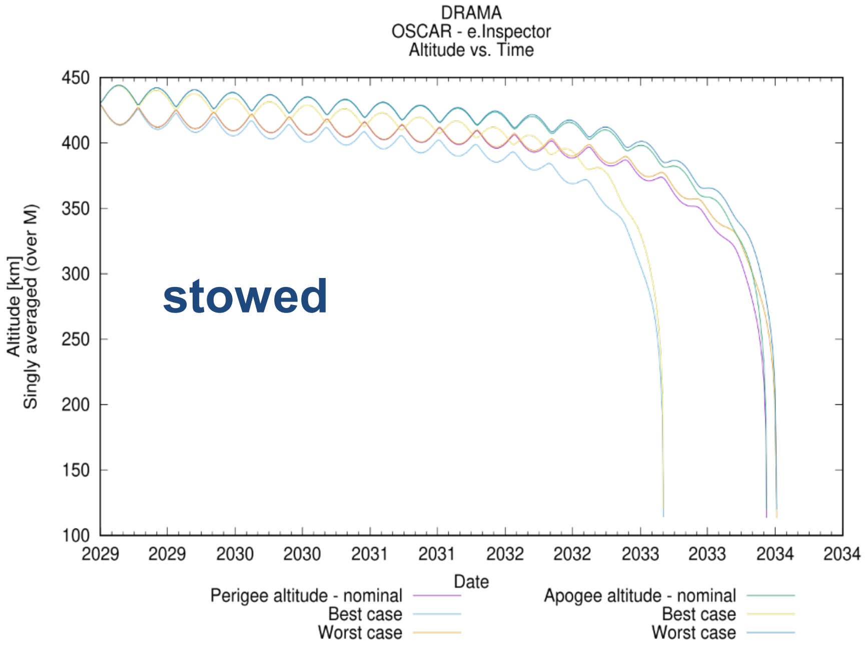
| Natural reentry time | 25 years (h<575km) | 5 years (h<500km) |
|---|---|---|
| All debris | 777 | 394 |
| **All debris (European)** | **11** | **3** |
| Rocket bodies | 146 | 71 |
| **Rocket bodies (European)** | **4** | **0** |

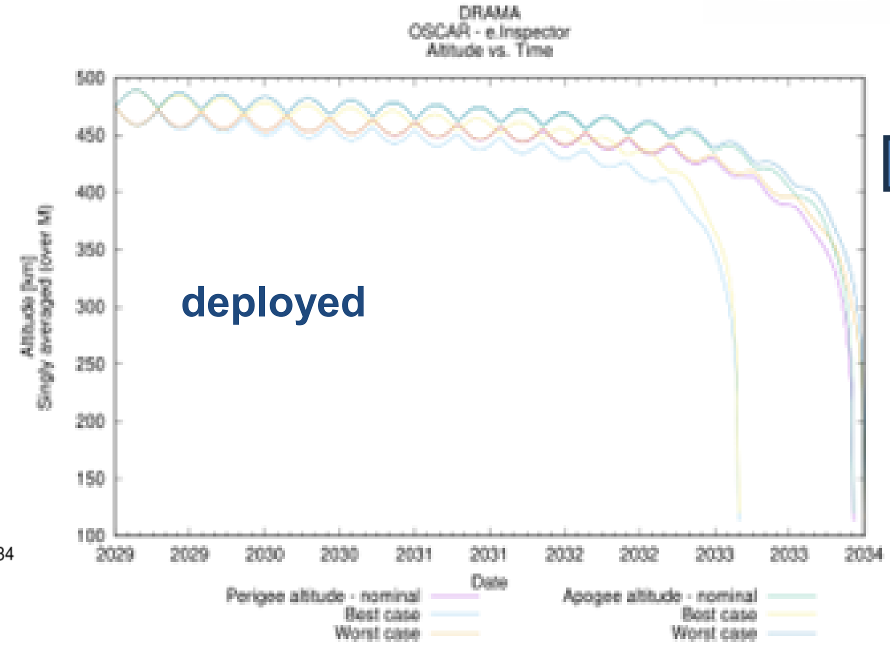
| Natural reentry time | 25 years (h<575km) | 5 years (h<500km) |
|---|---|---|
| All debris | 67 | 22 |
| **All debris (European)** | **5** | **1** |
| Rocket bodies | 54 | 16 |
| **Rocket bodies (European)** | **3** | **0** |

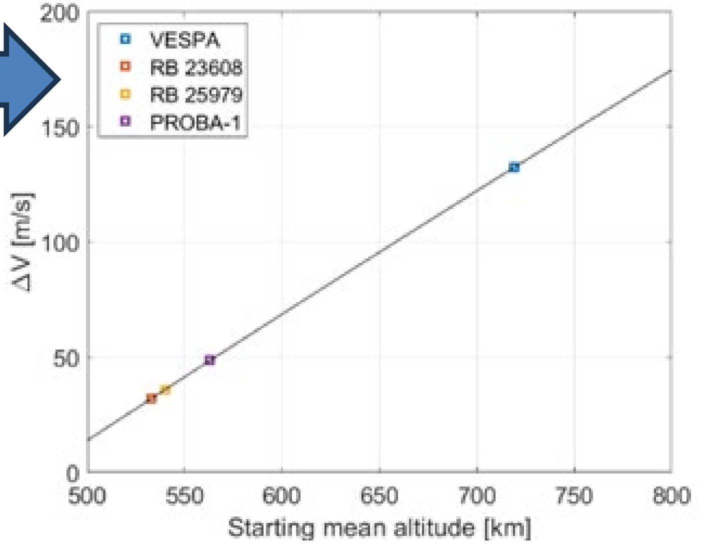
H<575 km accepted →

- **Target 39162 (VESPA)**
- **Target 23608**
- **Target 25979**
- **PROBA-1 (26958)**

# e.Inspector - *disposal new regulations effects*

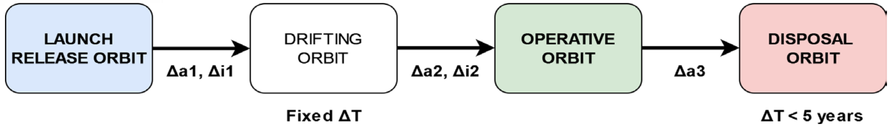



| Target ID | ΔV [m/s] | Time of flight [days] |
|---|---|---|
| 39162 (VESPA) | 132.25 | 95.24 |
| 23608 | 32.07 | 23.09 |
| 25979 | 35.91 | 25.86 |
| 26958 (PROBA-1) | 48.50 | 34.93 |

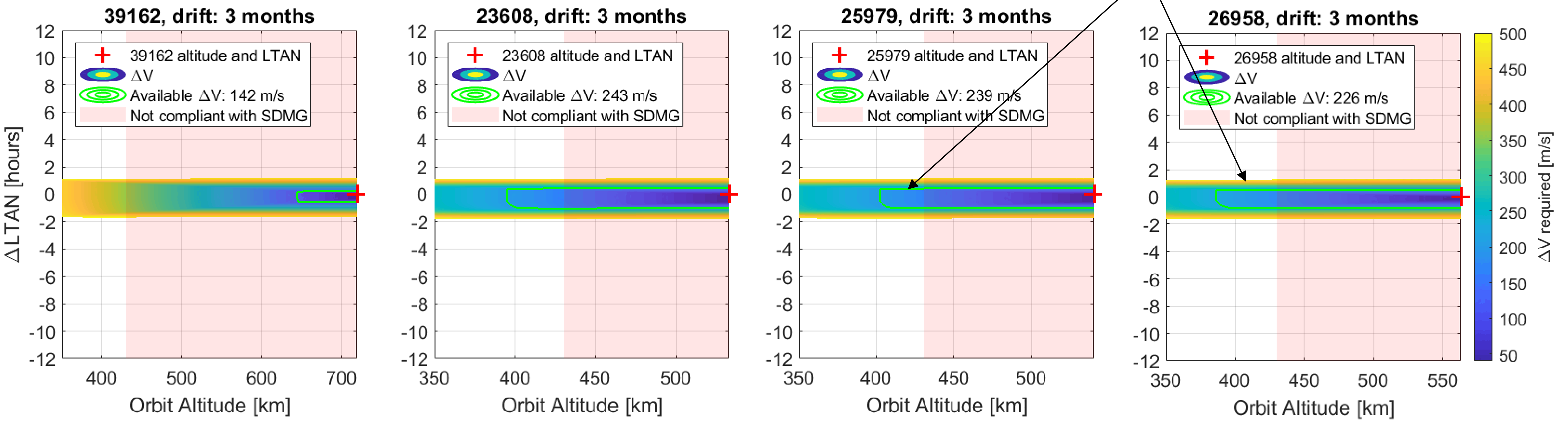
# e.Inspector target selection: *Mission Analysis*




**Release-to-Operational transfer (H1 → H3)**

***Thruster selected***

*Feasible launches lie in the green contour line not crossing the pink region*



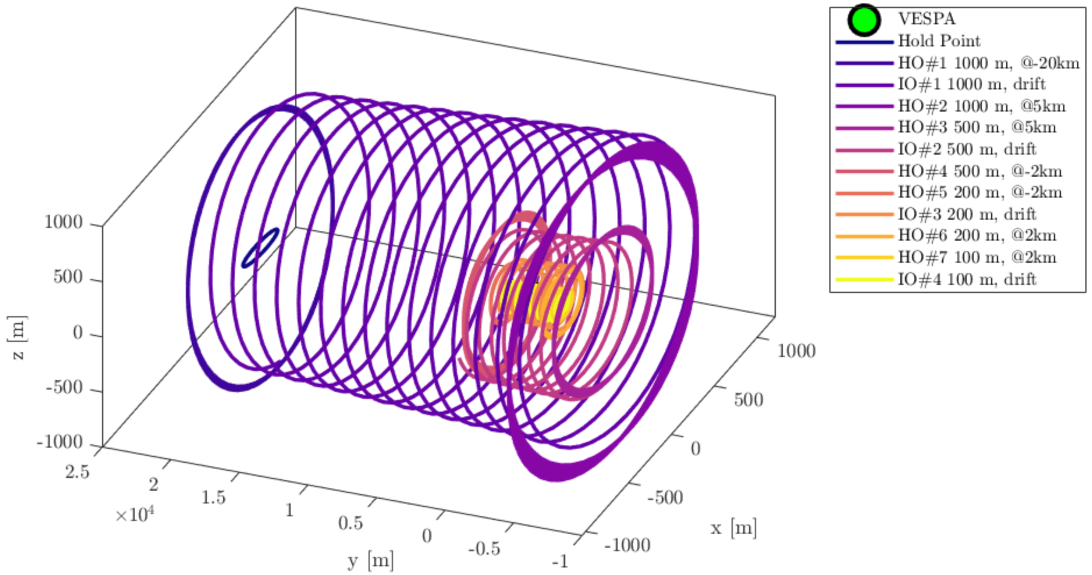

**Minimum altitude**
655 km

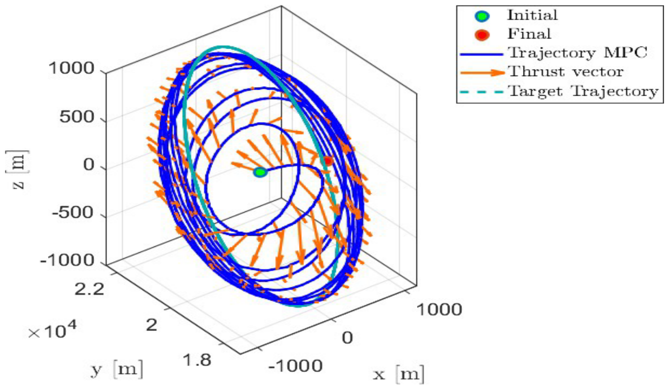
**Minimum altitude**
398 km

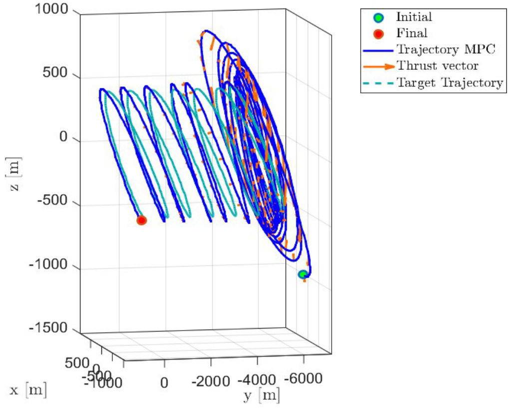
**Minimum altitude**
405 km

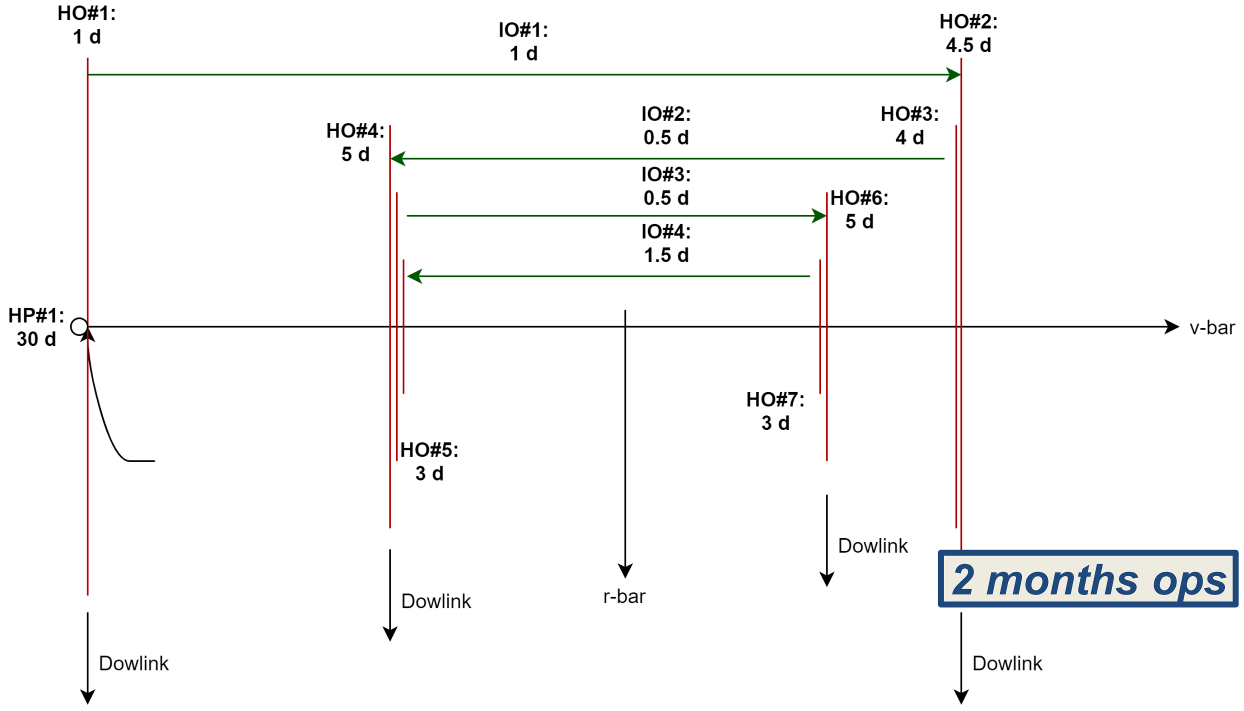
**Minimum altitude**
388 km

## *Imaging orbits*



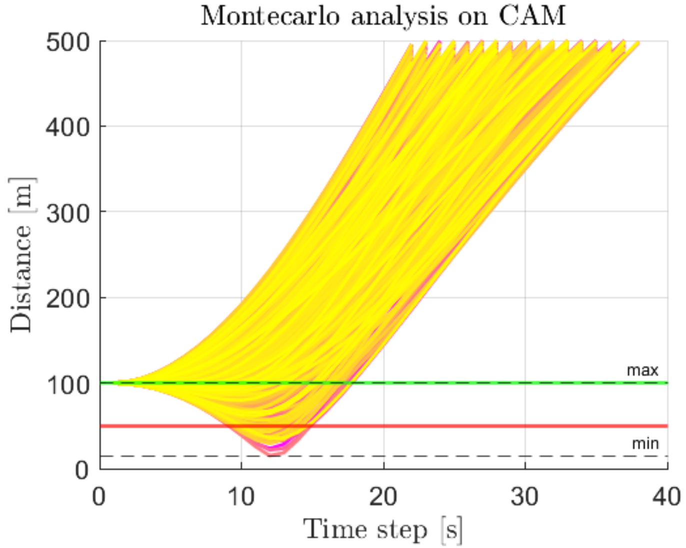



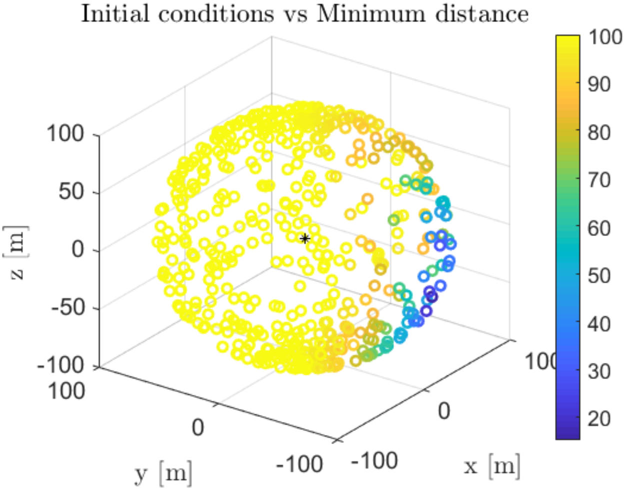




GS contact is established during the hold orbits, in the Communication phase, to **downlink data** and to **check the spacecraft conditions** before re-entering in the Inspection phase.

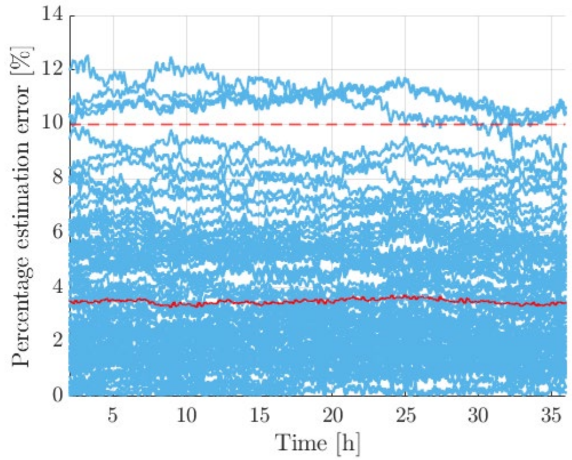
# e.Inspector - *Mission Design robustness*

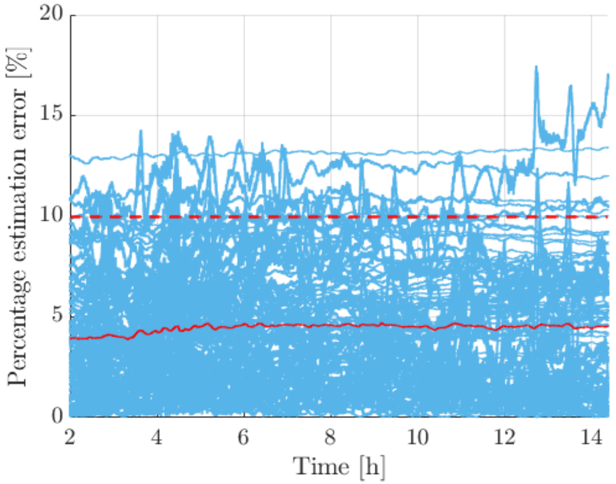
- CAM robustness at KOZ



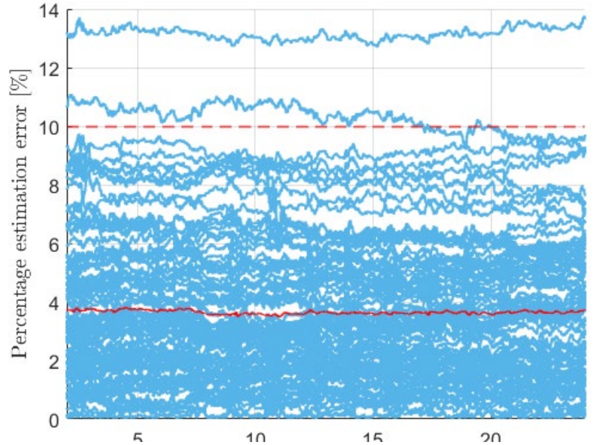



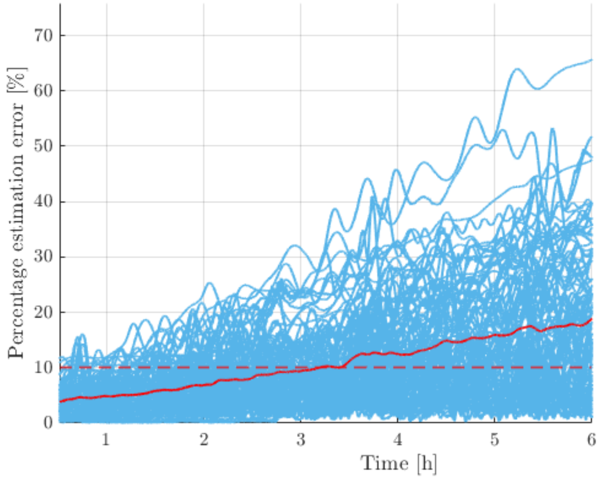

- HO\IO robustness




- Loss of target\loss of STR



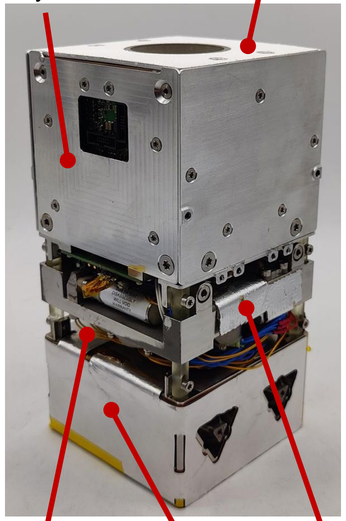
# e.Inspector - *critical items*

**Propulsion**→ low thrust for CubeSat to mature in endurance

development of REGULUS-50-I2 M system ($I_{tot}$ 7 kNs), based on REGULUS-50-I2 S ($I_{tot}$ 3 kNs)

| P from bus [W] | Nominal T [mN] | Nominal Isp [s] |
|---|---|---|
| 30 | 0,29 | 292 |
| 40 | 0,40 | 403 |
| 50 | 0,5 | 510 |
| 60 | 0,6 | 600 |

| Volume and mass (wet) |
|---|
| 93,8 x 95 x 200 mm – 4,1 kg ($I_{tot}$ = 7 kNs) |




*REGULUS-50-I2 M*

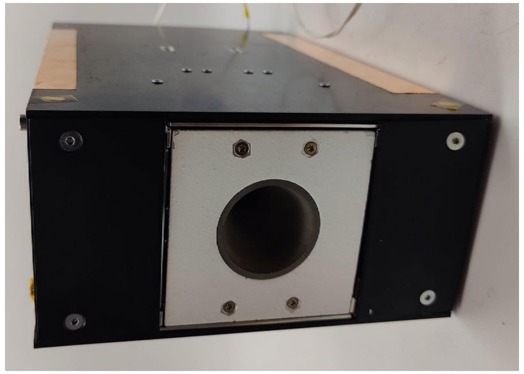
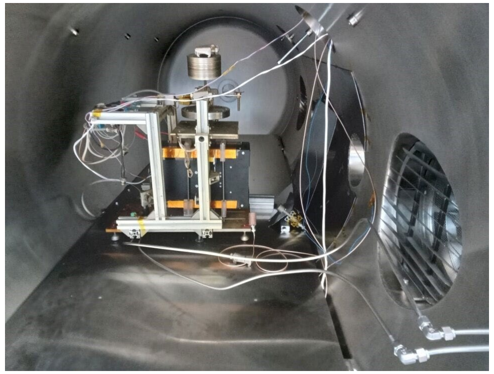
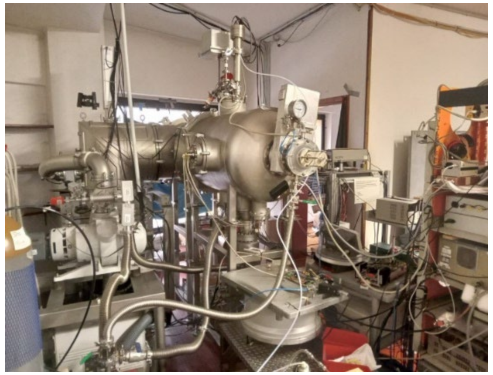


*Photo of REGULUS-50-I2-M integrated in the 6U module (right).*



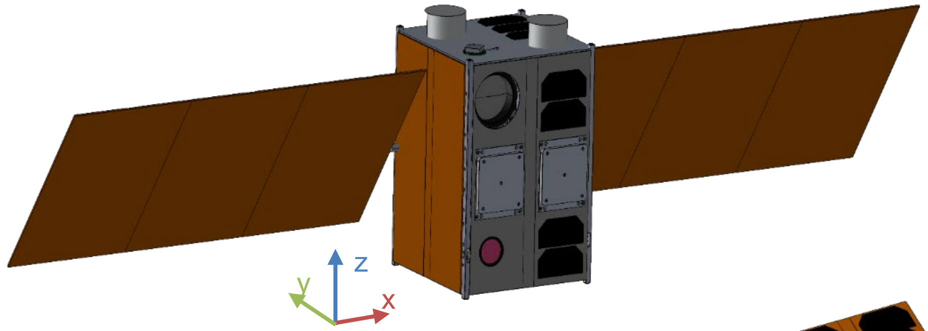
*Test setup in vacuum chamber.*

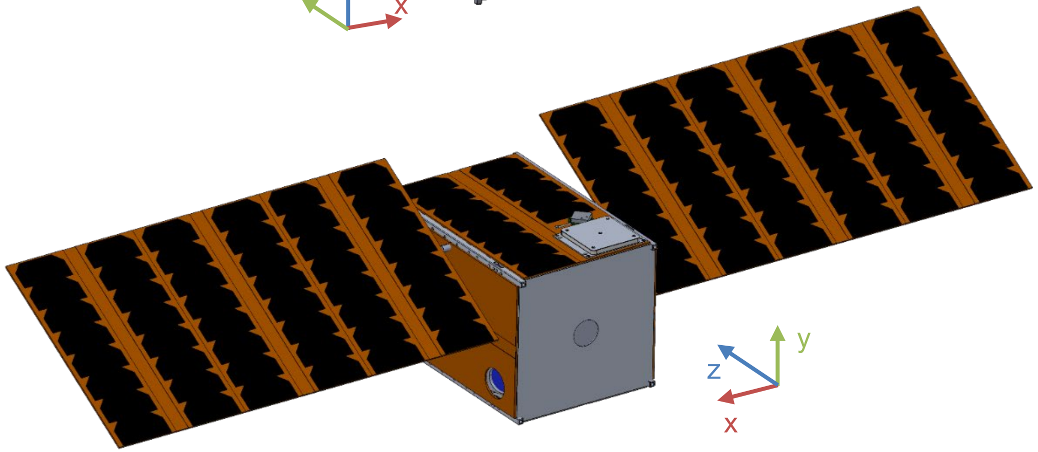


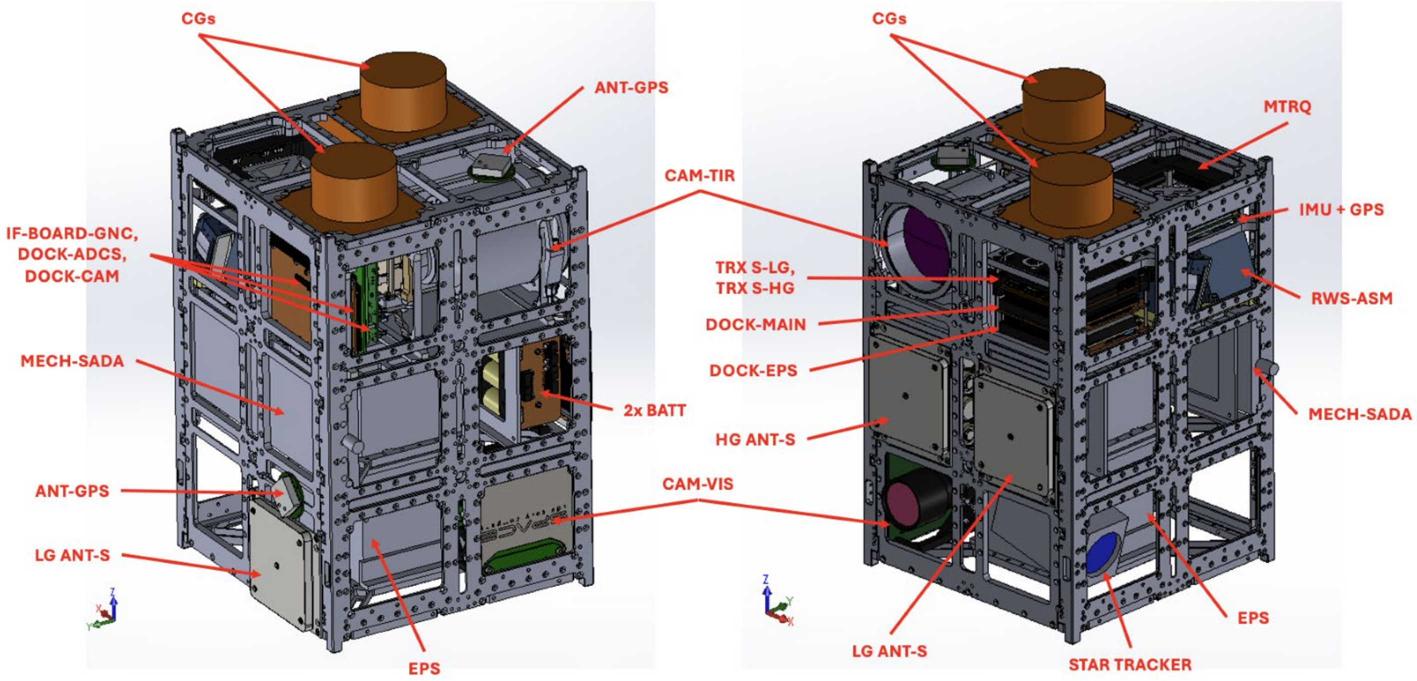
*Vacuum chamber at CISAS.*

# e.Inspector - System design

## *Configuration* 12U CubeSat




22,88 kg, margined
102, 4 W max, margined

## Mass budget

| | MASS, unmargined | MASS, margined at component level** |
|---|---|---|
| Payloads | 0.865 kg | 0.951 kg |
| ADCS | 2.454 kg | 2.596 kg |
| EPS | 5.494 kg | 6.327 kg |
| OBDH | 0.217 kg | 0.241 kg |
| PROP | 5.178 kg | 5.496 kg |
| TCS | - | - |
| TMTC | 0.599 kg | 0.657 kg |
| STRUCTURE | 3.374 kg | 4.047 kg |
| HARNESS | 0.400 kg | 0.480 kg |
| **TOTAL** | **18.581 kg** | **20.796 kg** |

| | |
|---|---|
| + System margin, 10%* of total, **single Item margin reported in DEL | + 2.080 kg |
| **TOTAL MARGINED** | **22.876 kg** |

**Margins are applied according to doc. TEC-SY/77/2016/POL/RW «System Margin Policy for ESA IOD CubeSat Projects»*

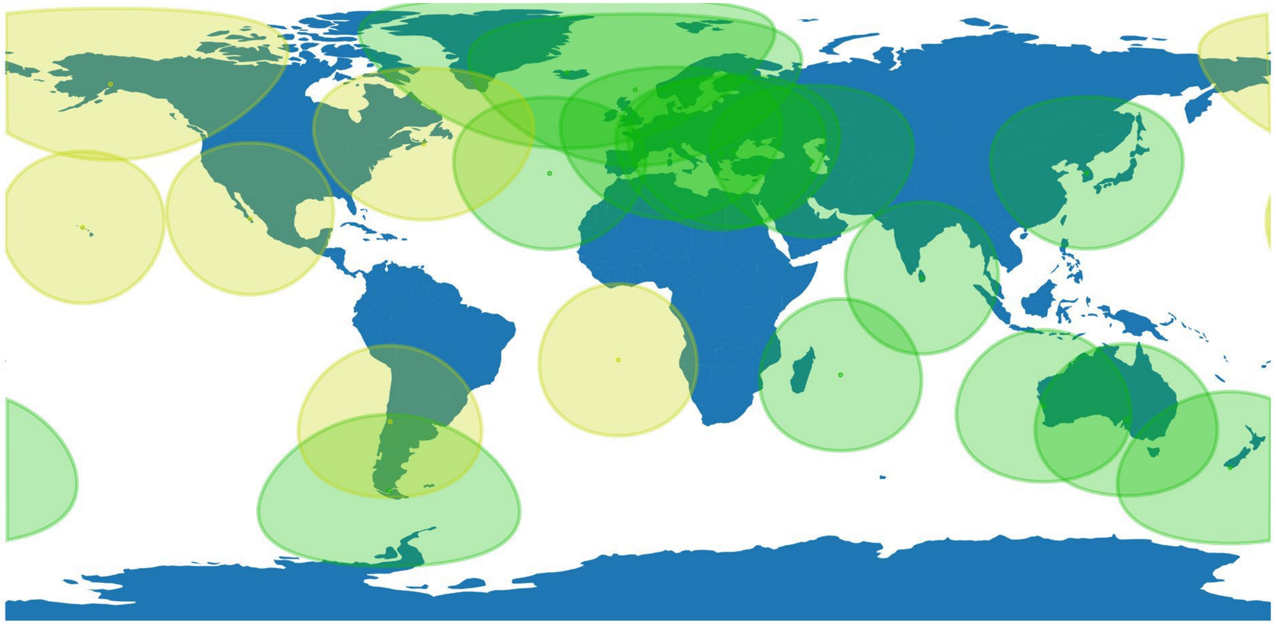
## Power budget

| Subsystem | Power consumption per mode [W] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LEOP | | TRANSFER | | INSPECTION | | COMM | | SAFE | |
| | Peak | Avg | Peak | Avg | Peak | Avg | Peak | Avg | Peak | Avg |
| Payloads | - | - | - | - | 4.6 | 4.6 | - | - | - | - |
| ADCS | 5.8 | 5.8 | 17.4 | 8.9 | 15.5 | 10.3 | 15.5 | 10.3 | 6.7 | 5.8 |
| EPS | 4.1 | 0.9 | 5.1 | 1.9 | 5.1 | 1.9 | 5.1 | 0.9 | 5.1 | 0.9 |
| OBDH | 1.1 | 0.3 | 1.1 | 0.3 | 28.7 | 3.3 | 1.1 | 0.6 | 1.1 | 0.6 |
| PROP | - | - | 66.0 | 56.1 | 17.6 | 1.8 | - | - | - | - |
| TCS | - | - | - | - | - | - | - | - | - | - |
| TMTC | 3.8 | 0.2 | 3.8 | 0.2 | - | - | 18.0 | 18.0 | 3.8 | 1.9 |
| STRUCTURE | - | - | - | - | - | - | - | - | - | - |
| **+ 10% System margin** | | | | | | | | | | |
| **TOTAL** | **16.3** | **7.9** | **102.8** | **74.1** | **78.7** | **24.1** | **43.8** | **32.8** | **18.5** | **10.2** |

**Margins are applied according to doc. TEC-SY/77/2016/POL/RW «System Margin Policy for ESA IOD CubeSat Projects»*

# e.Inspector – GS design

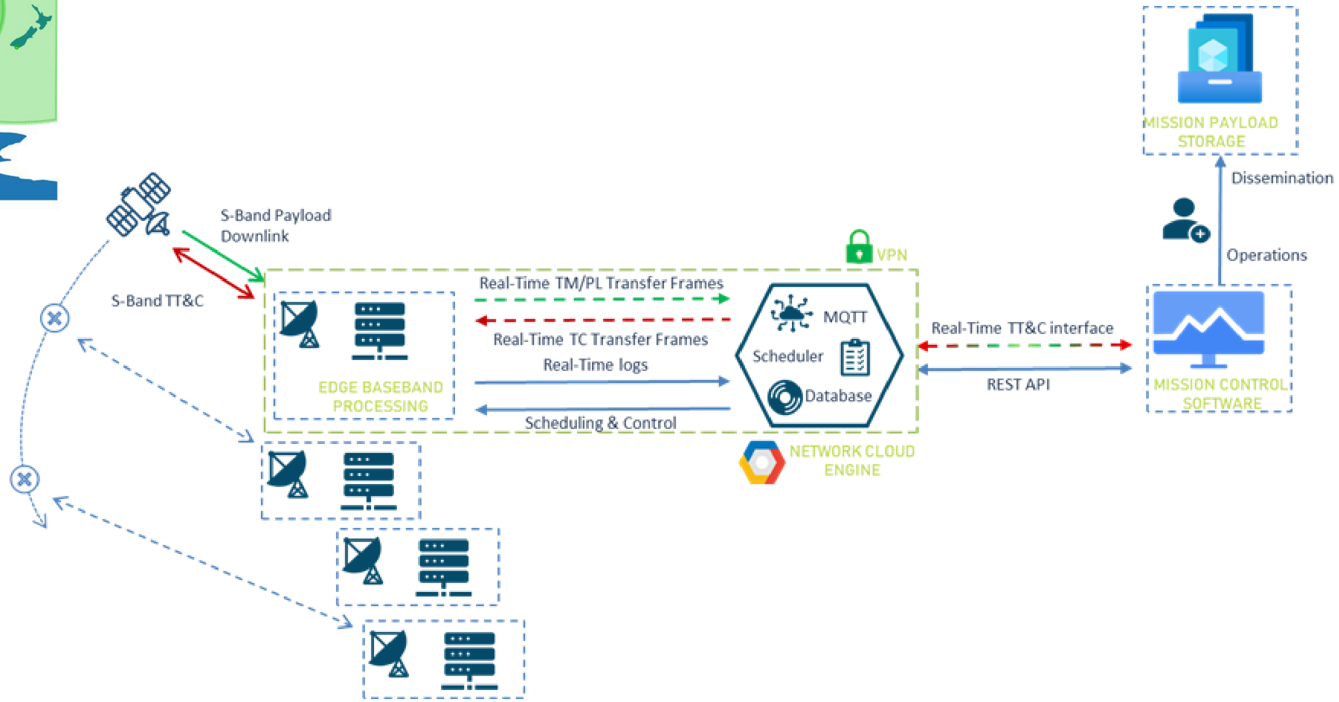
POLITECNICO MILANO 1863 · LEONARDO · LEAF SPACE · T4i TECHNOLOGY FOR PROPULSION AND INNOVATION



The Leaf Line architecture considers the following stations

Already active as of May 2024 in green

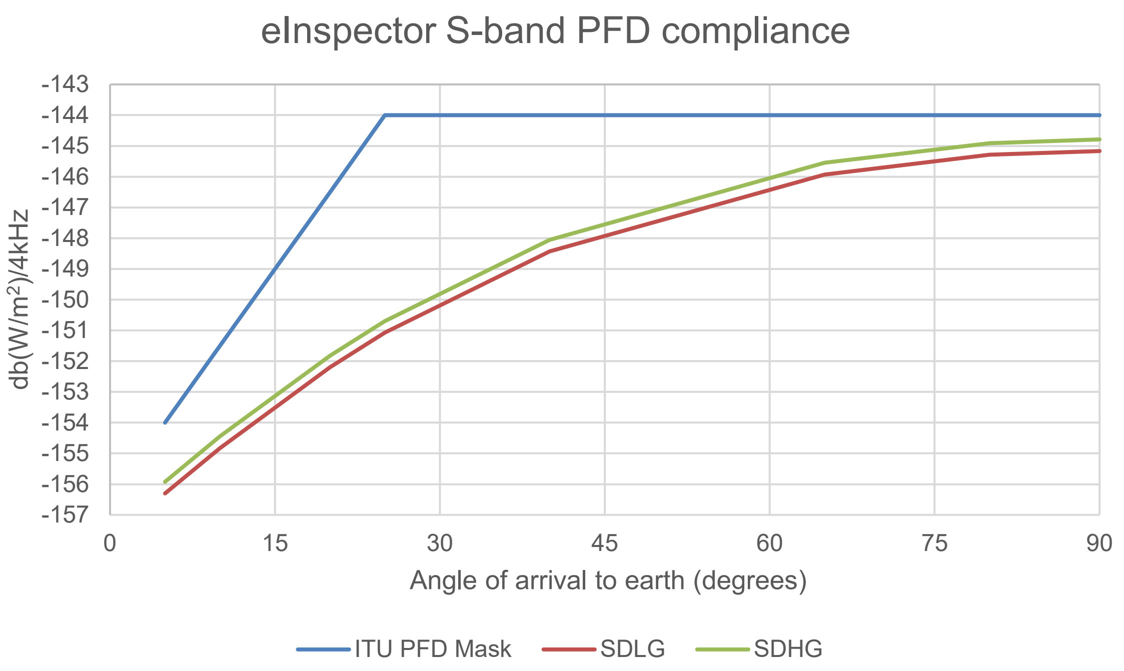
Expected by end of 2024 in yellow



ITU Frequency Allocation Plan

- Compliant with ITU frequency allocation
- Respecting the S-band PDF limits
- No criticalities foreseen in the proceeding with the ITU filing
- No criticalities are foreseen in obtaining RF ground licenses

| Uplink | | |
|---|---|---|
| **Beam** | **SULG** | **SUHG** |
| **Preliminary carrier frequency (MHz)** | 2080.0 | 2080.0 |
| **Bandwidth (MHz)** | 1.167 | 2.0 |
| **Net datarate (kbps)** | 300.0 | 897.0 |
| **GS output power (dBW)** | 14.0 | 14.0 |
| **GS antenna gain (dBi)** | 34.6 | 34.6 |
| **Link margin (dB)** | 5.1 | 9.5 |
| **Downlink** | | |
| **Beam** | **SDLG** | **SDHG** |
| **Preliminary carrier frequency (MHz)** | 2260.0 | 2260.0 |
| **Bandwidth (MHz)** | 0.156 | 1.8 |
| **Net datarate (kbps)** | 40.0 | 807.0 |
| **Satellite output power (dBW)** | -1.0 | 2.0 |
| **Satellite antenna gain (dBi)** | 0 | 8.0 |
| **Link margin (dB)** | 3.4 | 5.0 |



# e.Inspector what's next

- The current design is robust to variations (i.e. injection orbit, target fetures, etc)
- Adaptation of the whole design to and testing setup for Proba I – no criticality expected, being VESPA a quite critical target for IP
- Endurance tests continuation for the EP qualification
- Next lifecycle phases preparation

POLITECNICO
MILANO 1863

# e.Inspector Phase B

## Final Presentation

POLITECNICO MILANO 1863 LEONARDO LEAF SPACE T4i TECHNOLOGY FOR PROPULSION AND INNOVATION

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI