POLITECNICO
MILANO 1863

Clean Space Days 2024: Towards a Sustainable Future in Space

e.Inspector

a 12U microsat to support future IOS missions by VIS-IR imaging Proba I

October 9, 2024

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

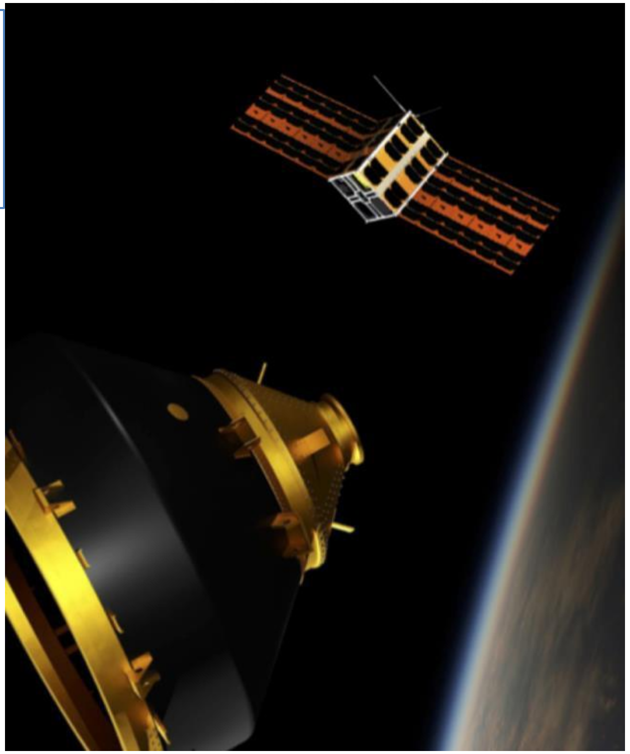
DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

astra

e.Inspector – *in Orbit Servicing*

GOAL

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



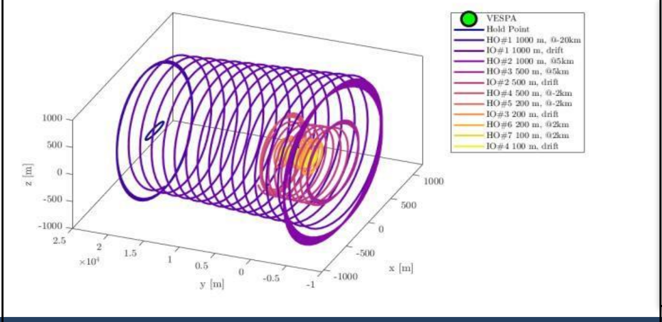
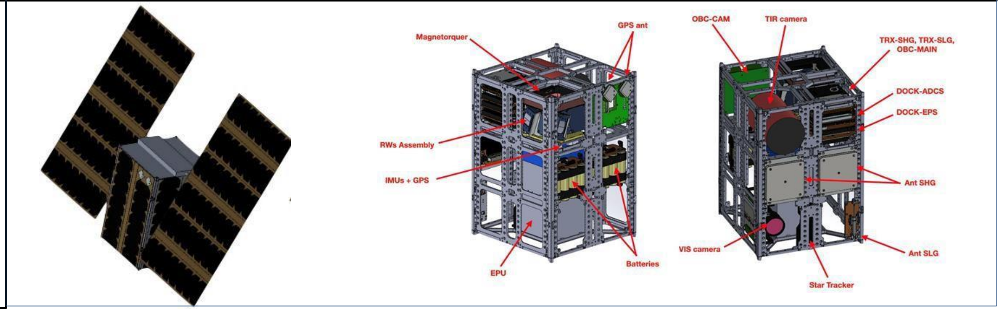
- ***Safety proximity maneuvering around a non cooperative\not a priori known object***

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

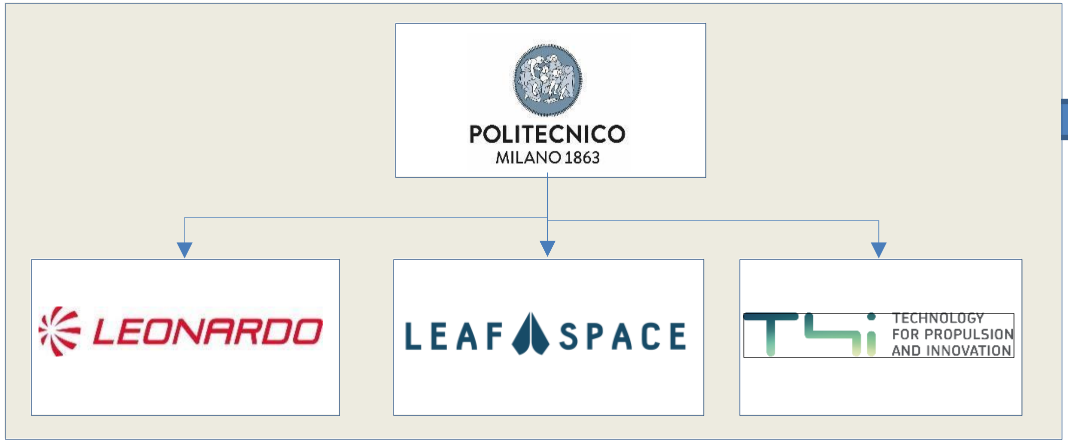
Project Engineering

- ***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*

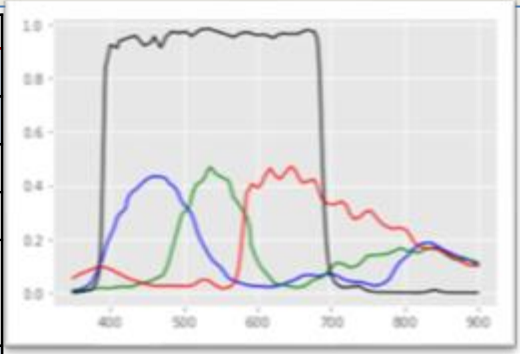
The main **mission goal** kept along phase B was to carry out a close-up visual inspection of VESPA Upper Part (NORAD object 39162)

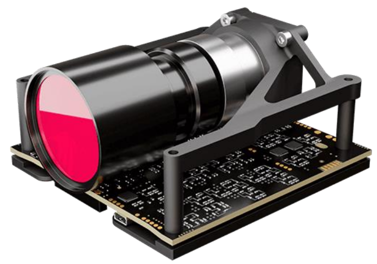
1. Design mission-critical technologies such as **IP multi-spectral based** relative **GNC for all mission phases**
2. Define the **breadboard for the OBC motherboard**, and perform functional tests to support baseline selection
3. **Obtain** EM for the VIS and IR **payloads**
4. **Assess the validity** 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) 1.4 W (Readout mode) 5V Power supply
Operating temperature	+0°C to +30°C
Survival temperature	-25°C to +55°C
Radiation Tolerance (TID)	Tested to 30kRad

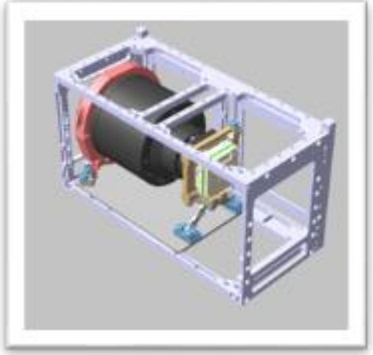




Parameter	Value
FoV	6.2° x 5°
F#	1.6
Focal length	100 mm
Aperture diameter	82 mm
Length	110 mm

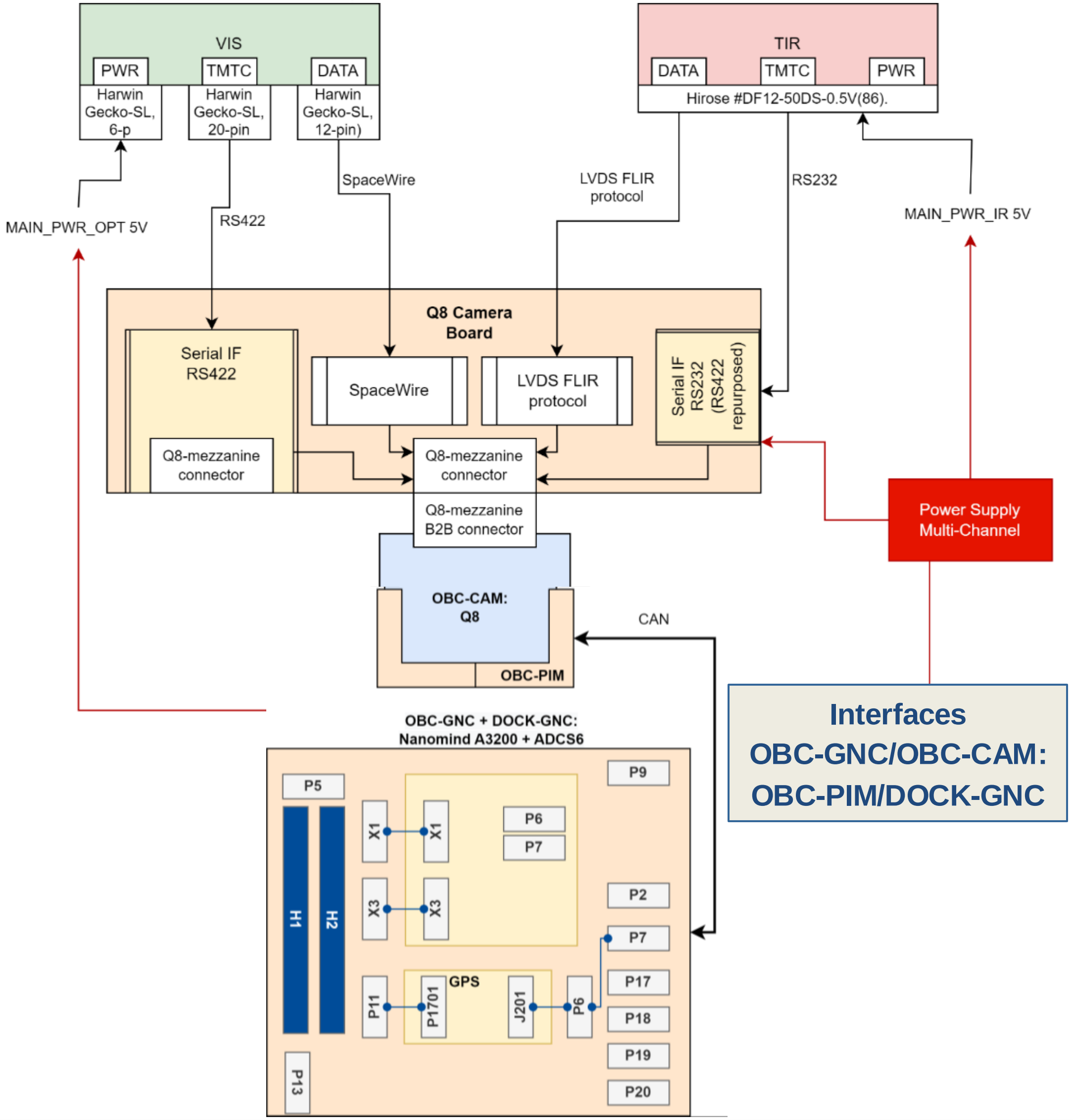
FLIR Tau 2 Camera + 100 mm lenses

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 8 or 14 bit parallel CMOS 8 bit BT.656
Signal interface	Camera Link 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°

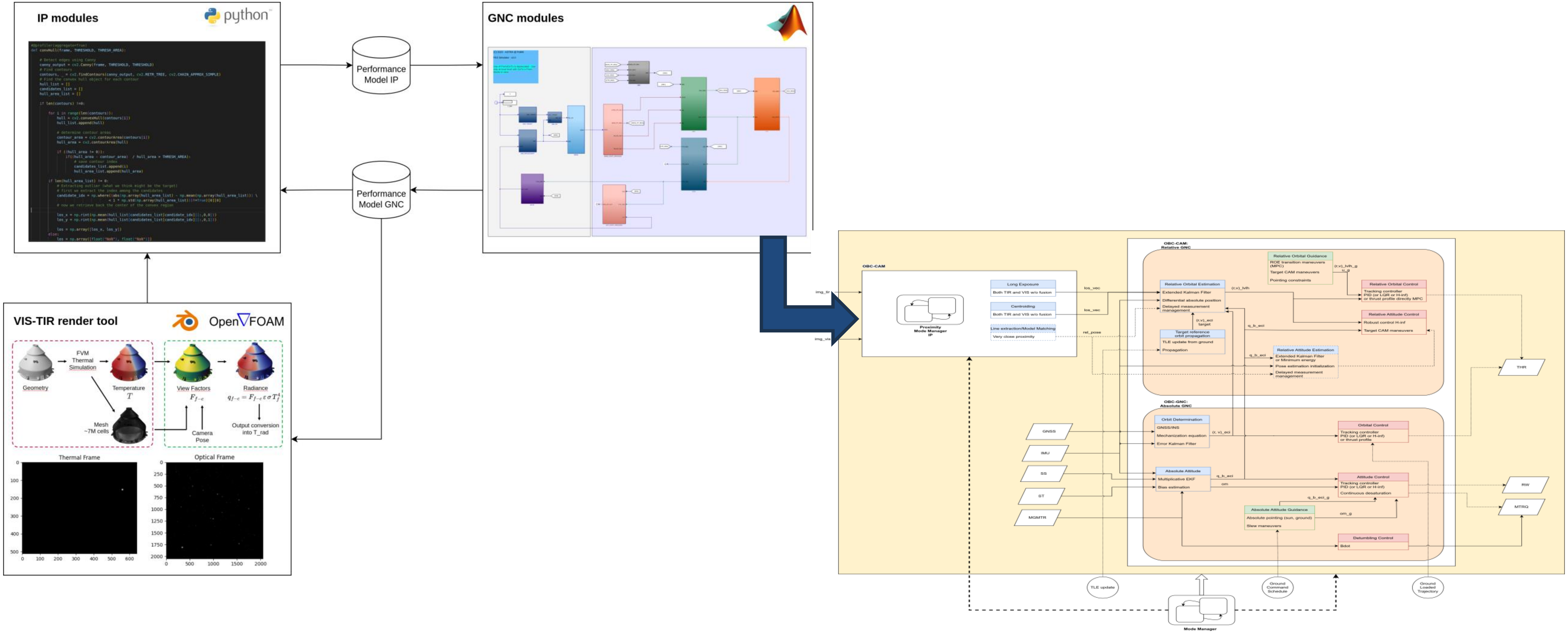


e.Inspector - *OBC motherboard design and breadboarding*

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	



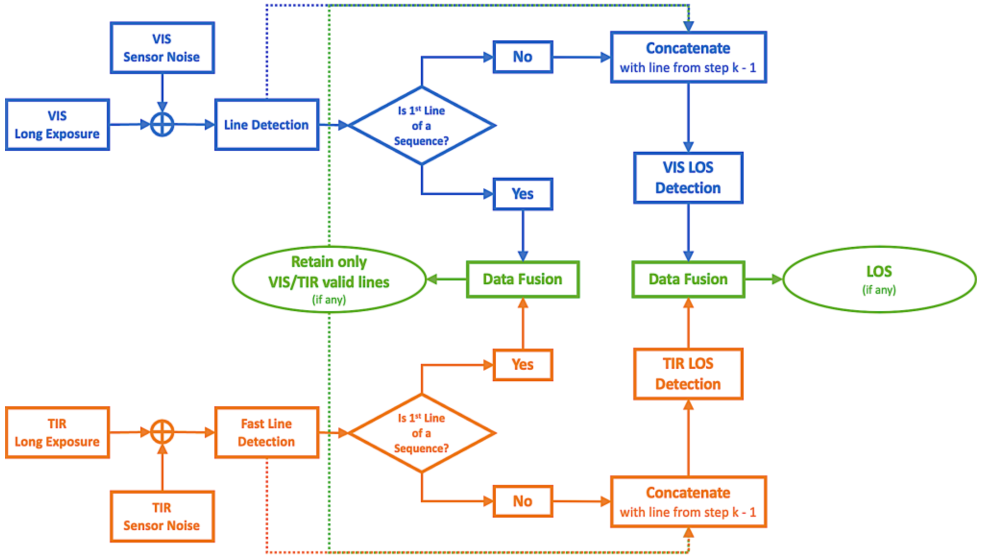
Virtual Model Environment and Development

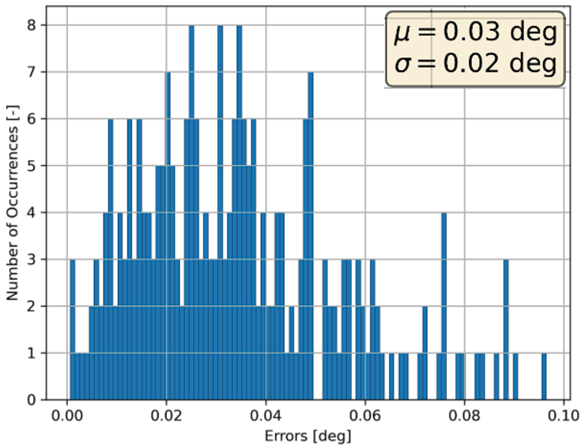


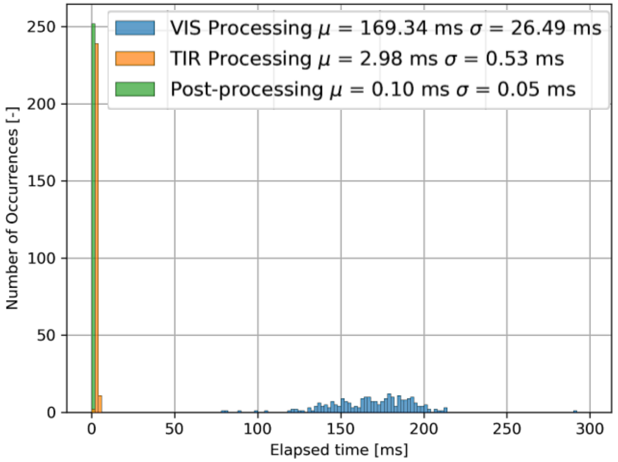
GNC - IP algorithms design overview - Relative

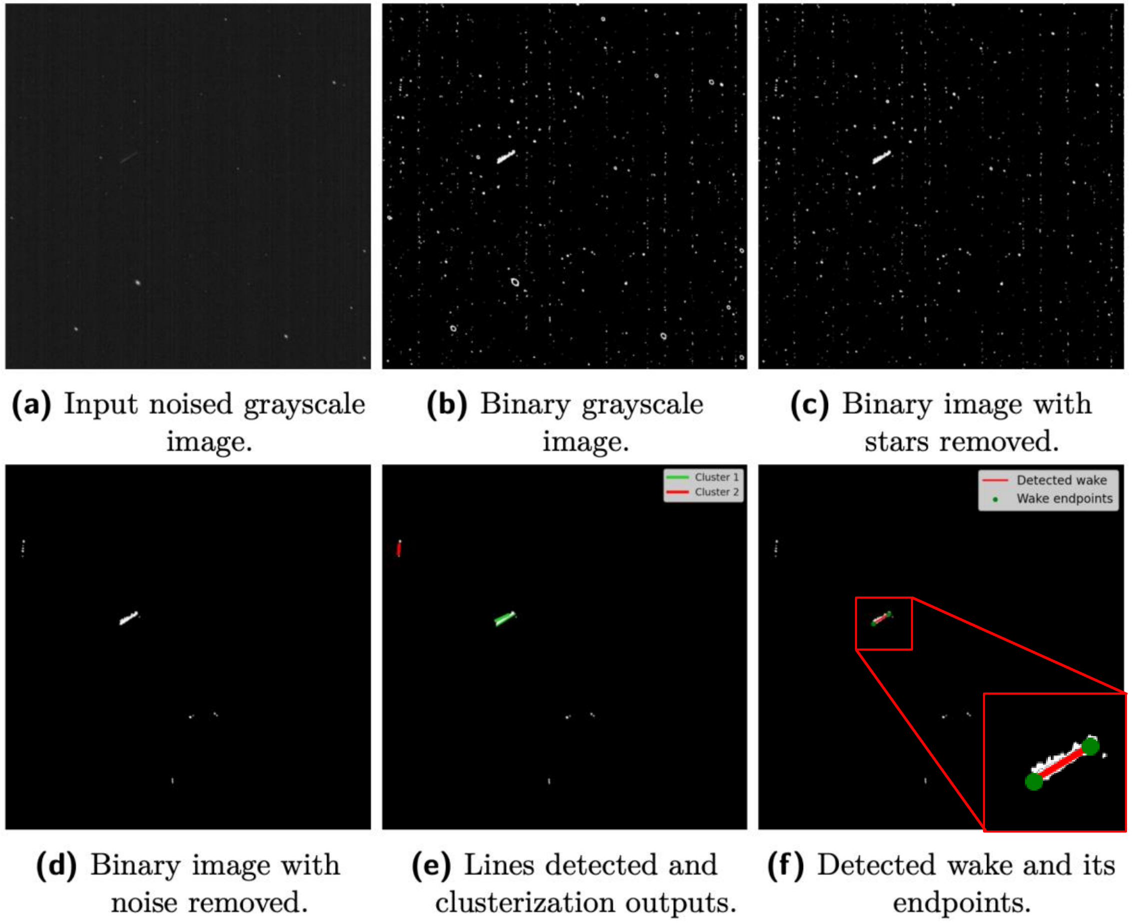
Mode	Distance	IO	Sensor	IP technique	EF technique
State estimation - far	20km - 900m	#1, 2, 3, 4	VIS+IR TLE	Long exposure images - centroid	MSE Optimal – full state **r, v**
State estimation - close	900m - 100m	#1, 2, 3, 4	VIS+IR	Centroid - blob detector	MSE Optimal – full state **r, v**
Pose estimation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

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





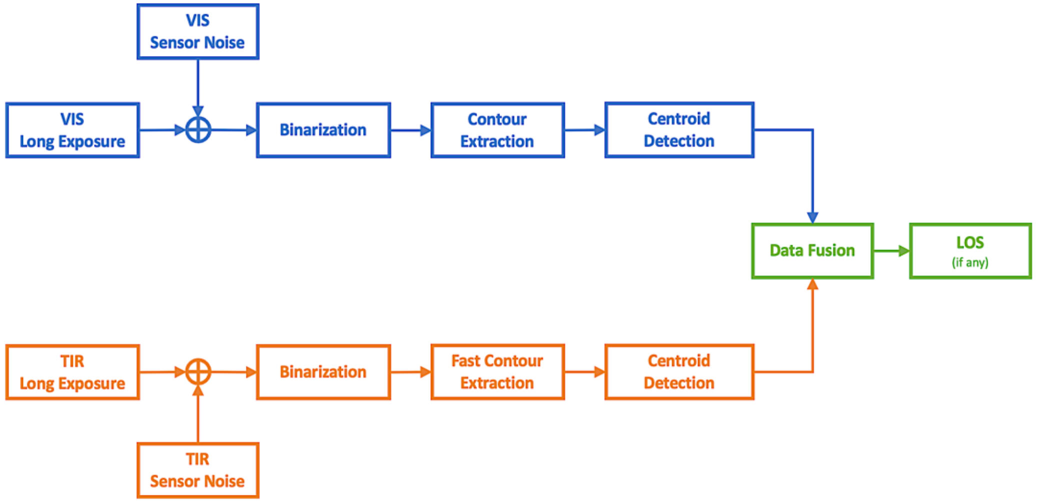


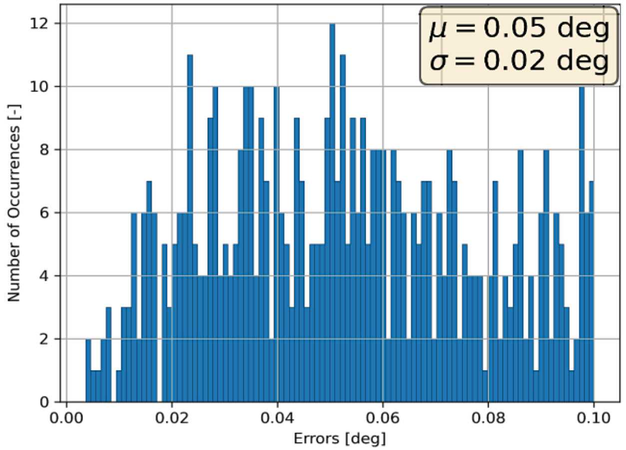


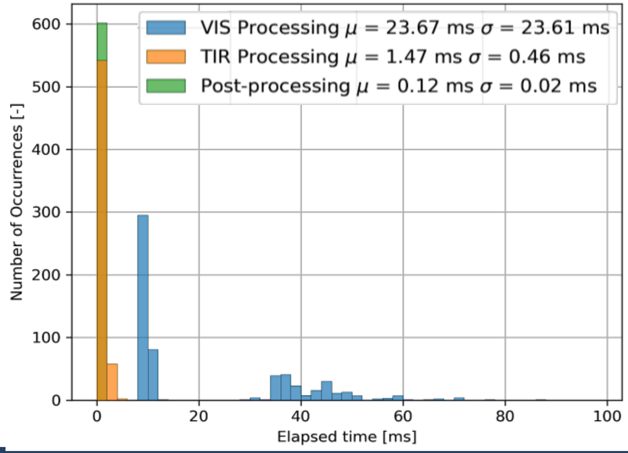
(a) Input noised grayscale image. (b) Binary grayscale image. (c) Binary image with stars removed. (d) Binary image with noise removed. (e) Lines detected and clusterization outputs. (f) Detected wake and its endpoints.

POLITECNICO MILANO 1863

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



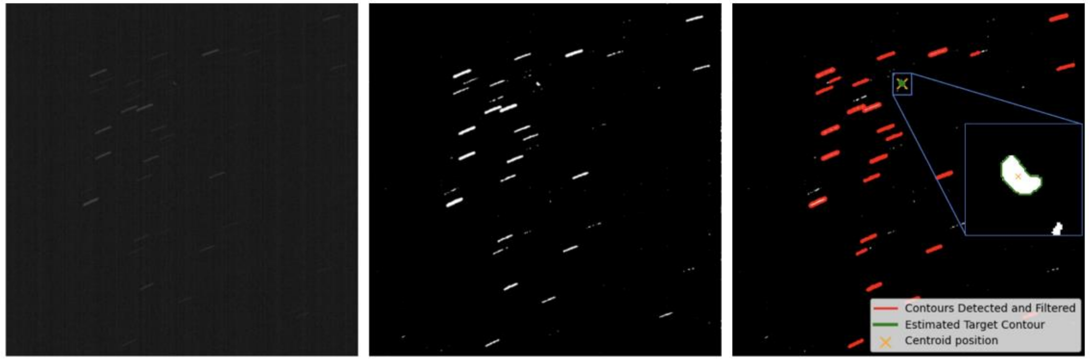




TIR Detailed Processing

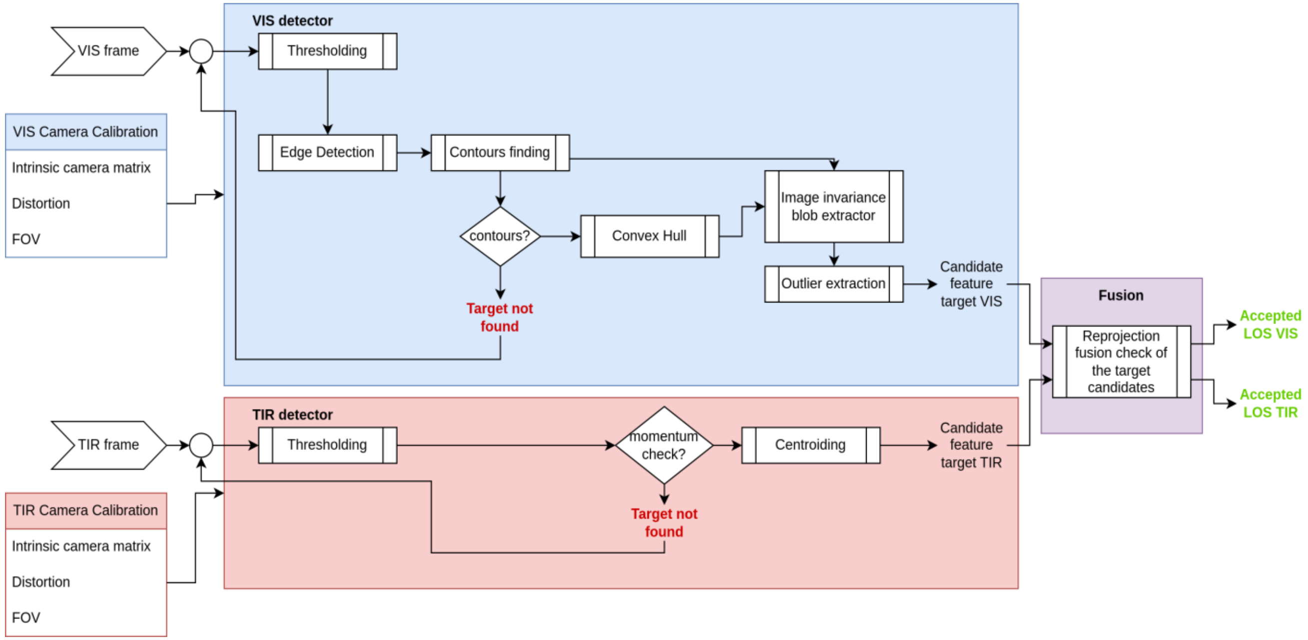
(a) Input noised grayscale image. **(b)** Thresholded binary image. **(c)** Detected contours and computed centroid.

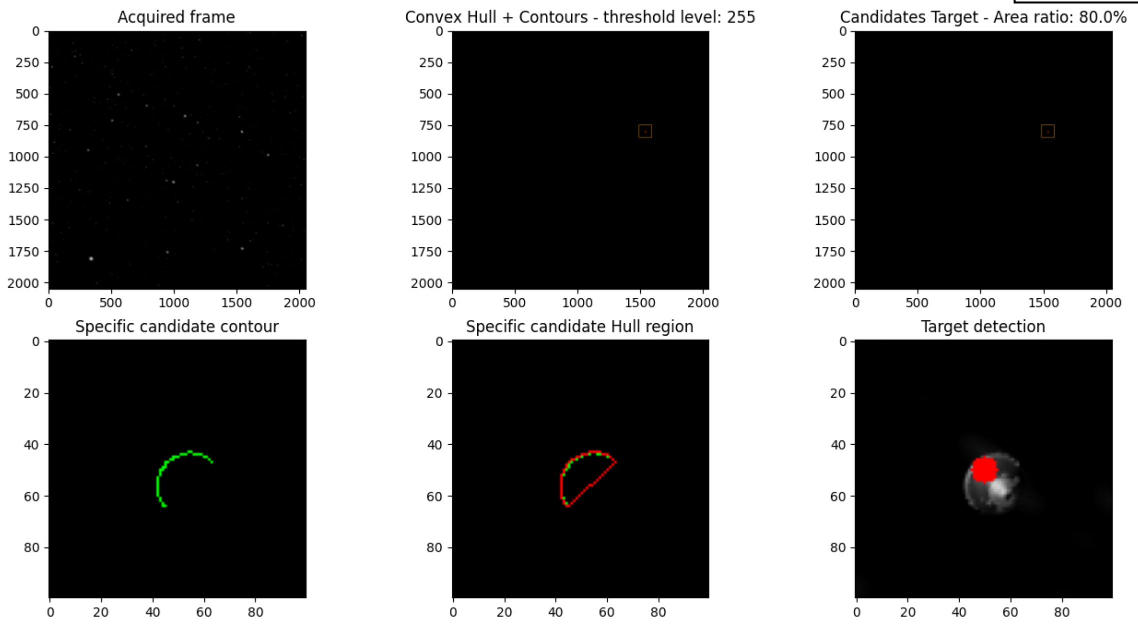
VIS Detailed Processing



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

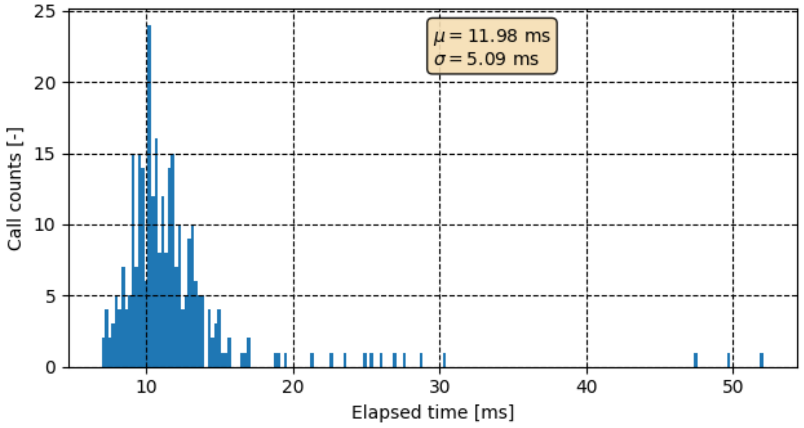
e.Inspector: *Close Range – IP algorithm design*

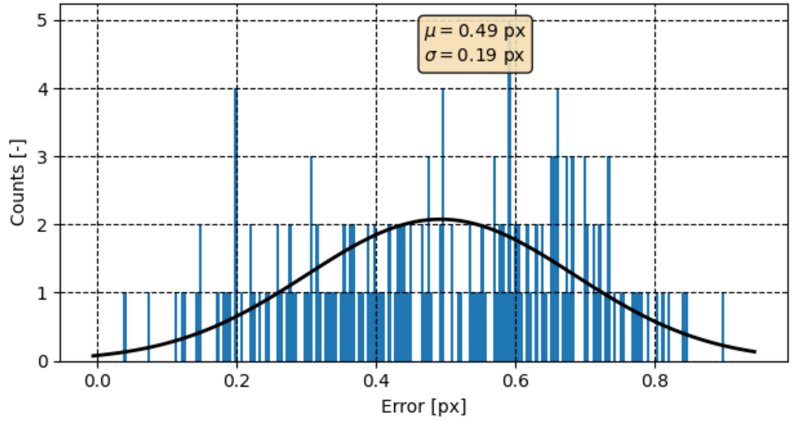




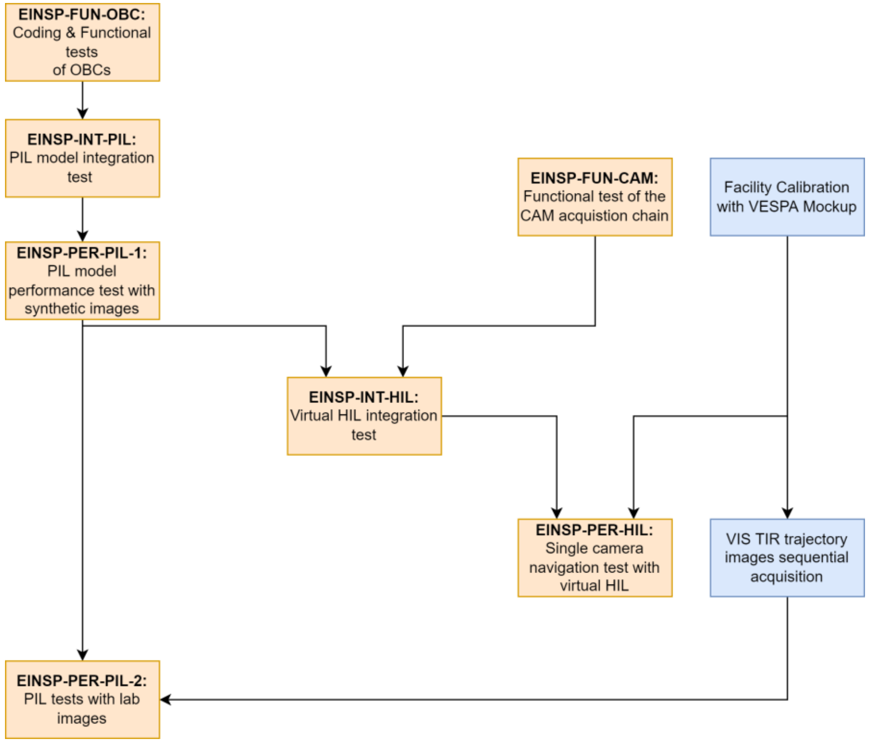
- VIS frame: 2048 x 1024 px
- TIR frame: 640 x 512 px

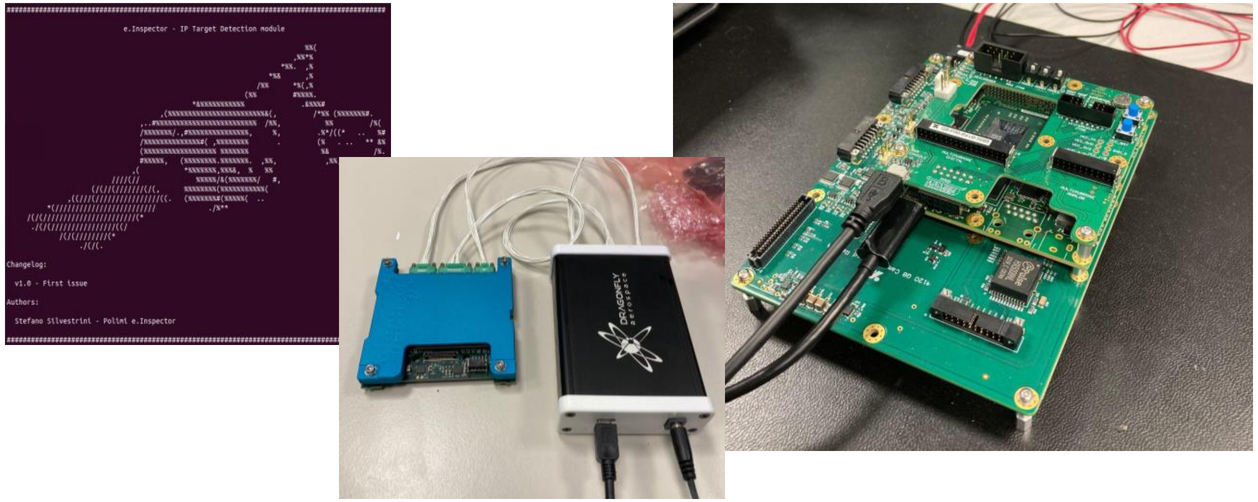
- Frame acquisition: 0.1 Hz





e.Inspector: *PIL test of IP algorithms*

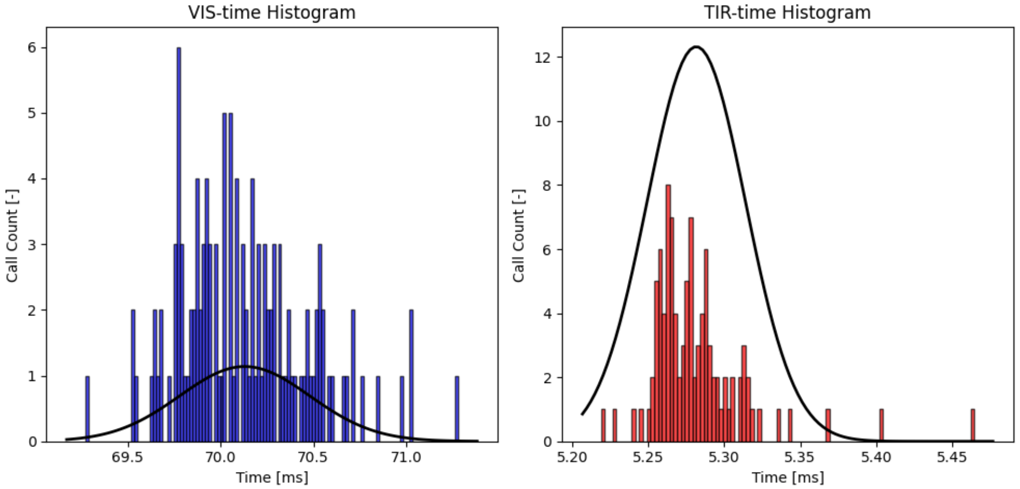




PIL Execution Times

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**.

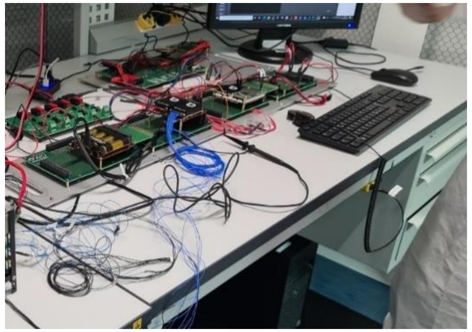


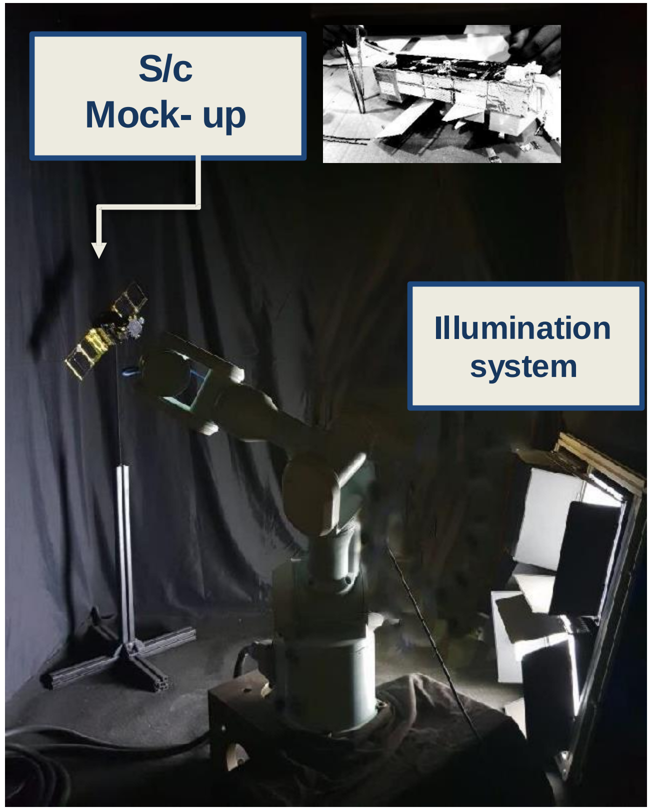
e.Inspector – *IP-GNC HIL testing*

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

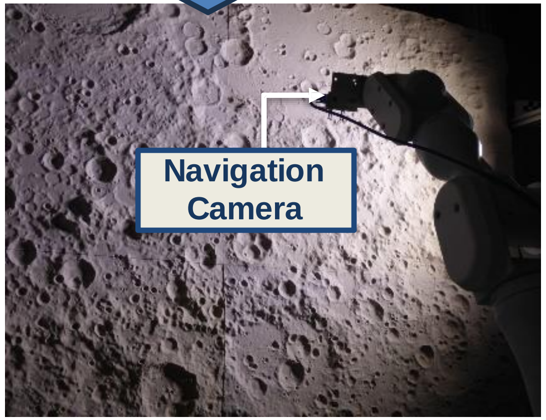
- *1:50 satellite mockup*
- *5700 K tuneable illumination*
- *VIS camera – IR camera upcoming*
- *6 dof Robotic arm*
- *3x2,4m calibrated Moon diorama*

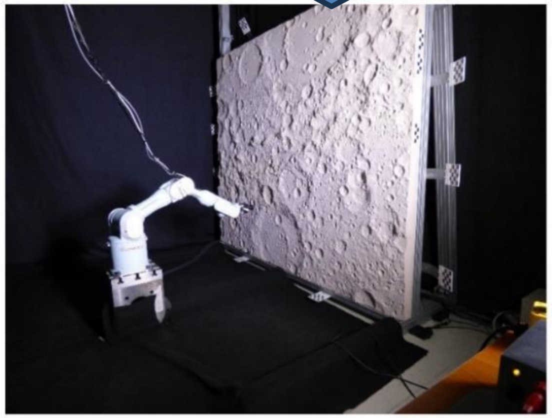
AVIONIC testbench



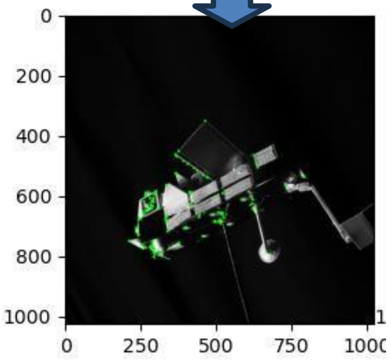


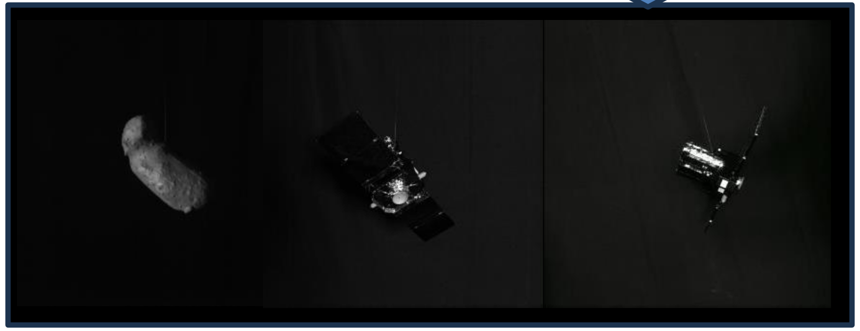
Dark room calibrated facility (8mx5m)





Real in lab images

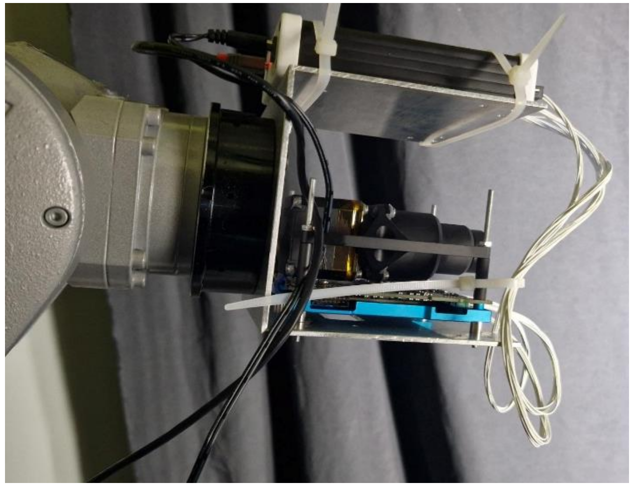




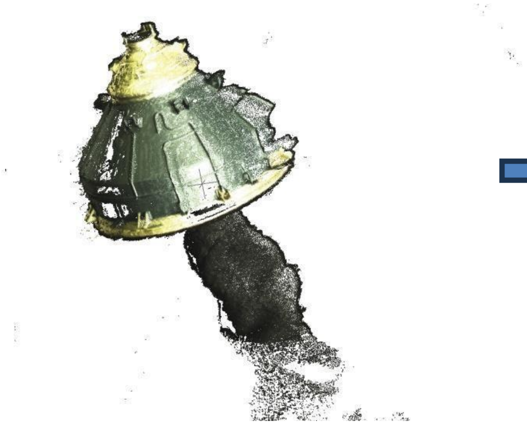
e.Inspector: *HIL - VIS camera-mockup calibration*

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

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.

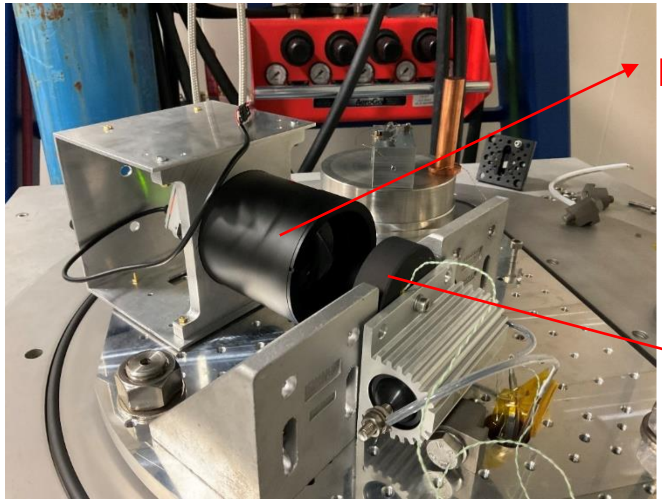
- Convex hull identification tends to move the momentum towards the golden plates
- Diffusive light makes the **background (black curtains) more illuminated** than the deep space of the rendered images, making VESPA body less recognizable

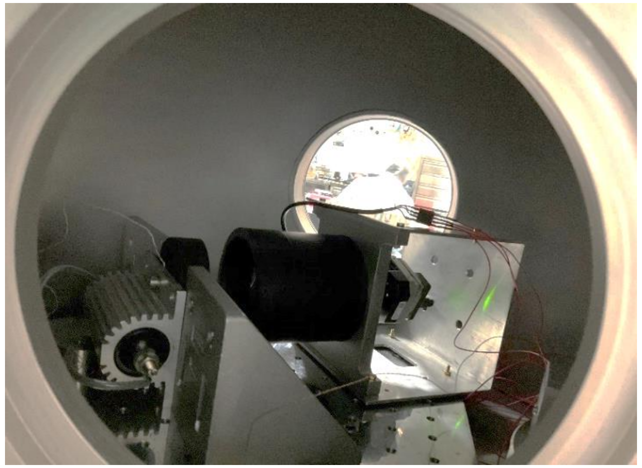
An important remark is that the acquisition time through LVDS can reach up to 1s.

e.Inspector: *TIR camera calibration setup*

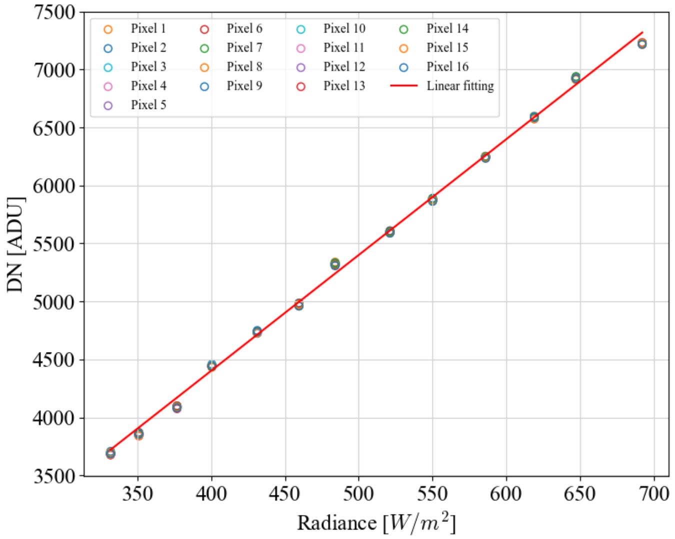
POLITECNICO MILANO 1863 LEONARDO LEAF SPACE T4i TECHNOLOGY FOR PROPULSION AND INNOVATION

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

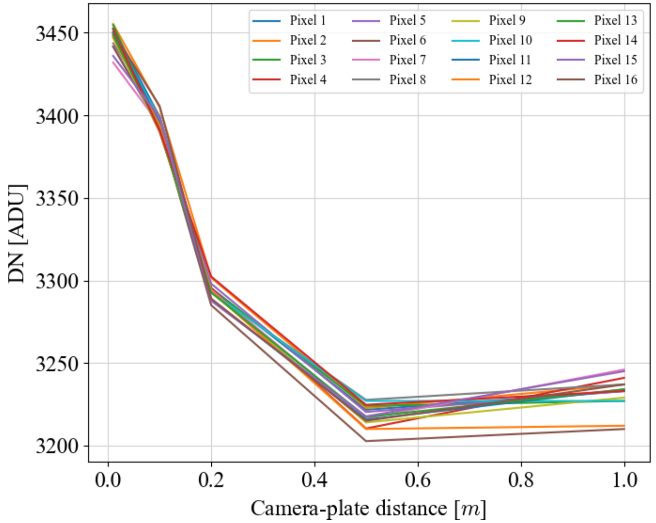




Camera response function: $DN = A \cdot q_{fc} + B$



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



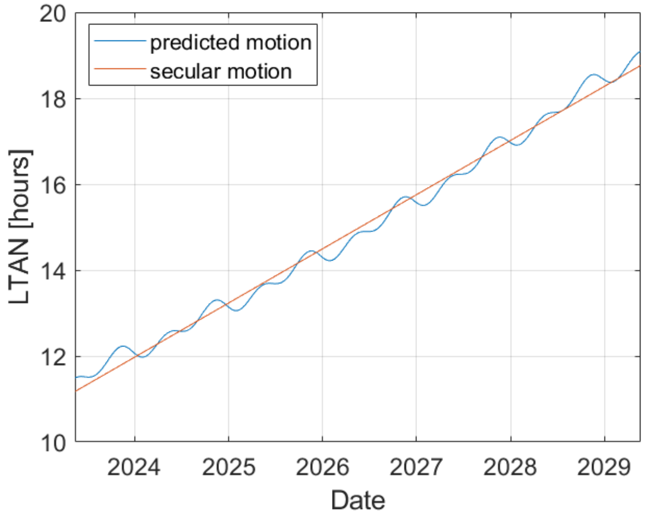
Vacuum conditions: 1e-4 mbar

Two thermal scenarios:

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

e.Inspector - *Mission Design*

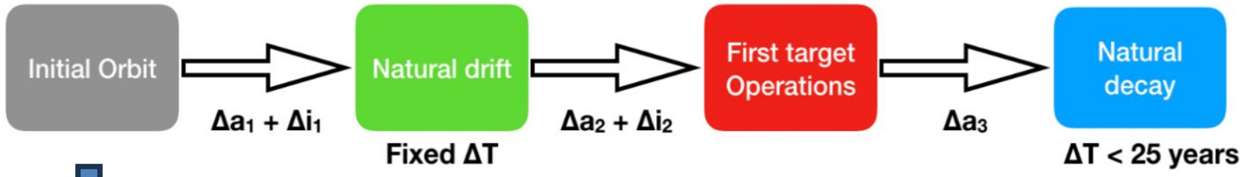
Baseline target debris motion

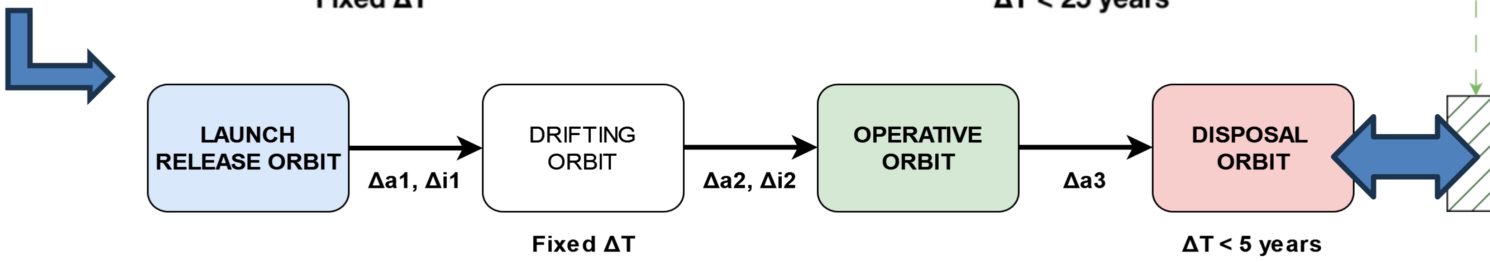


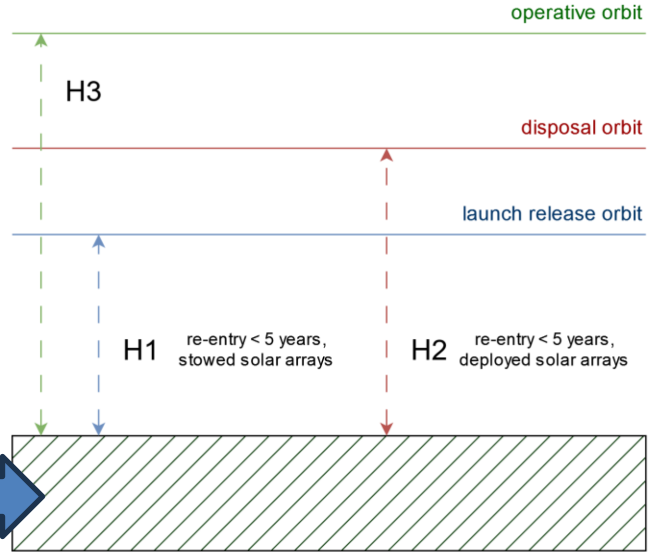
Semi-major axis [km]	7103.86
Eccentricity [-]	0.009185
Inclination [deg]	98.72
RAAN [deg]	219.19
Arg. Of perigee [deg]	41.96

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

Transfer strategy

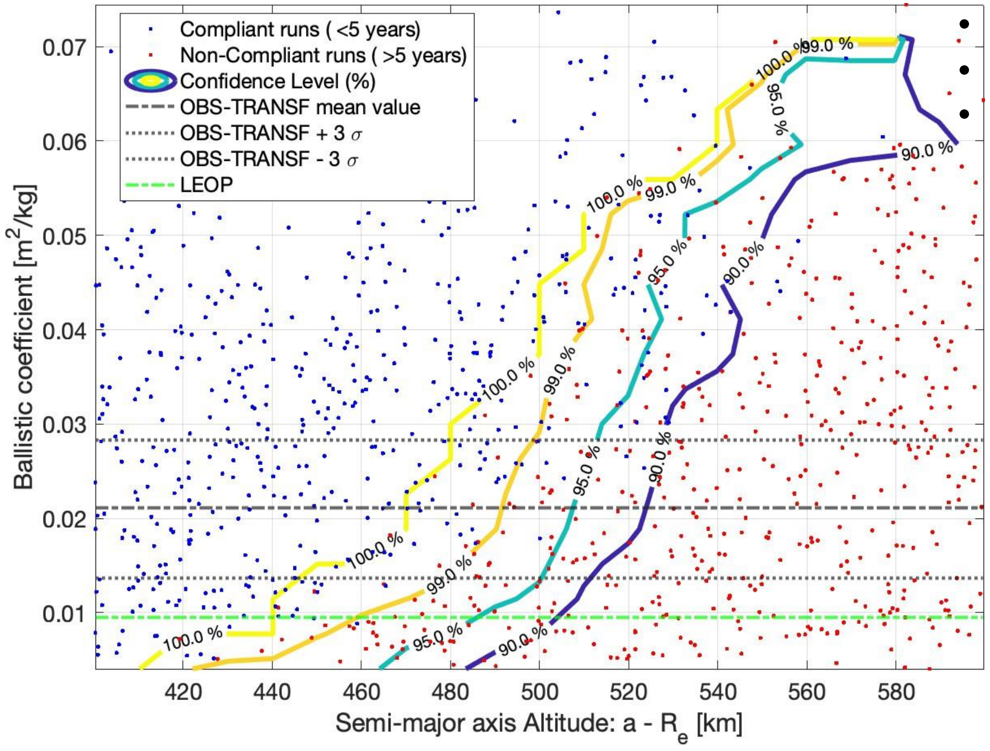






e.Inspector - *disposal new regulations effects*

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



- **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

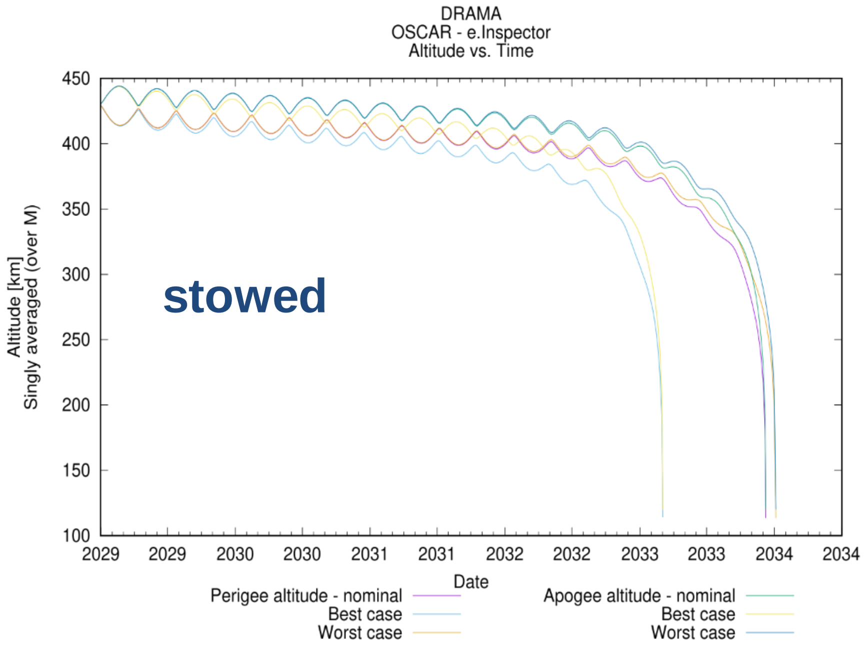
Natural reentry time	25 years (h<575km)	5 years (h<500km)
All debris	777	394
All debris (European)	**11**	**3**
Rocket bodies	146	71
Rocket bodies (European)	**4**	**0**

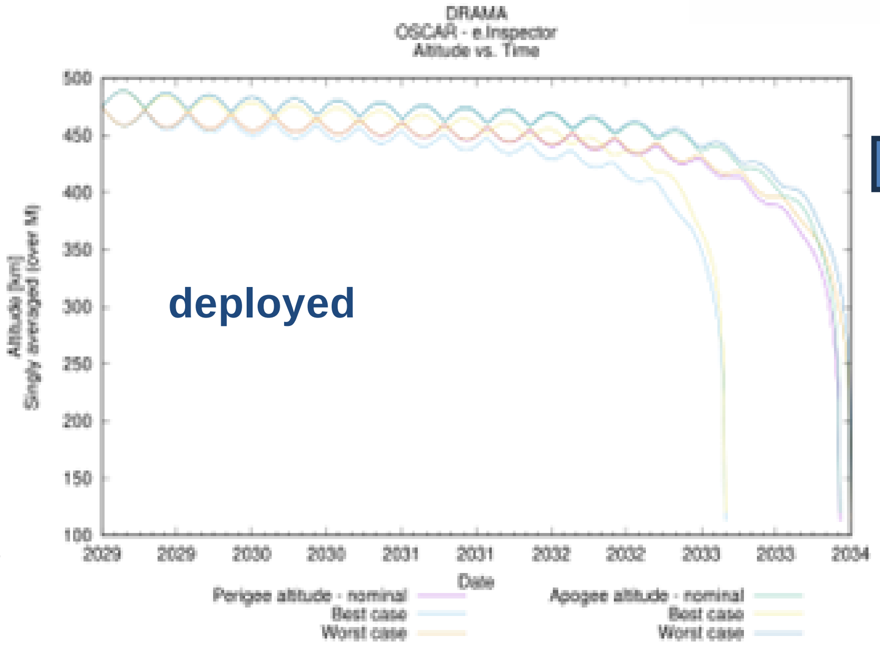
Natural reentry time	25 years (h<575km)	5 years (h<500km)
All debris	67	22
All debris (European)	**5**	**1**
Rocket bodies	54	16
Rocket bodies (European)	**3**	**0**

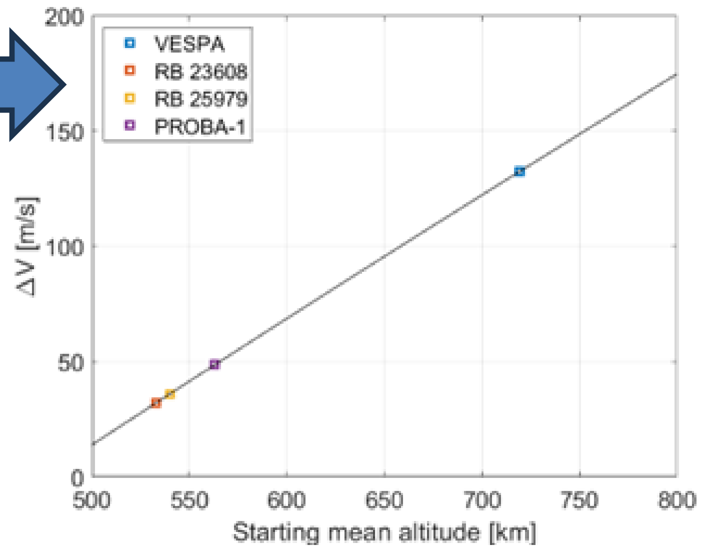
H<575 km accepted →

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

e.Inspector - *disposal new regulations effects*

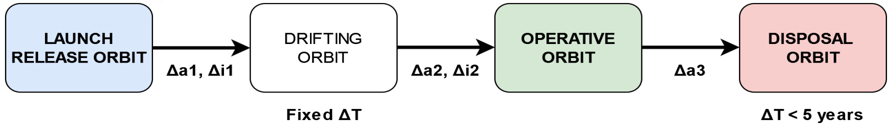






Target ID	ΔV [m/s]	Time of flight [days]
39162 (VESPA)	132.25	95.24
23608	32.07	23.09
25979	35.91	25.86
26958 (PROBA-1)	48.50	34.93

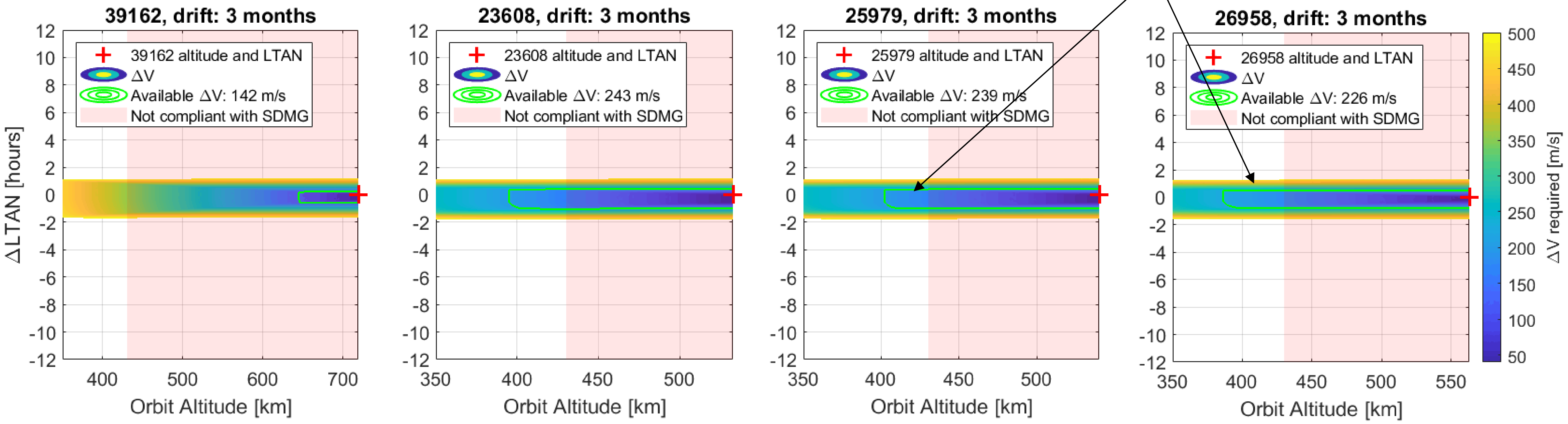
e.Inspector target selection: *Mission Analysis*



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

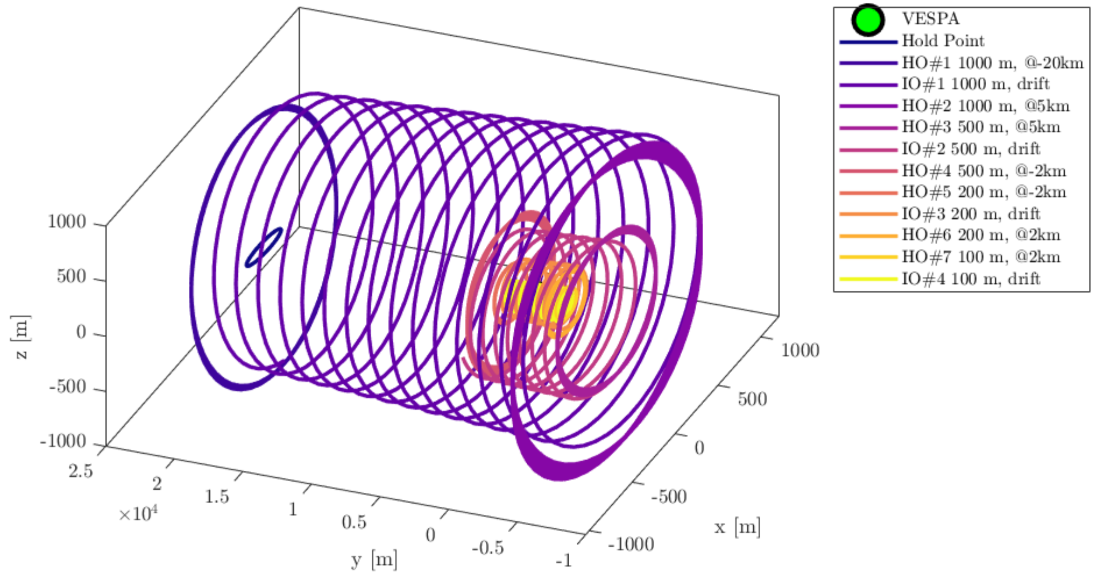
Minimum altitude
398 km

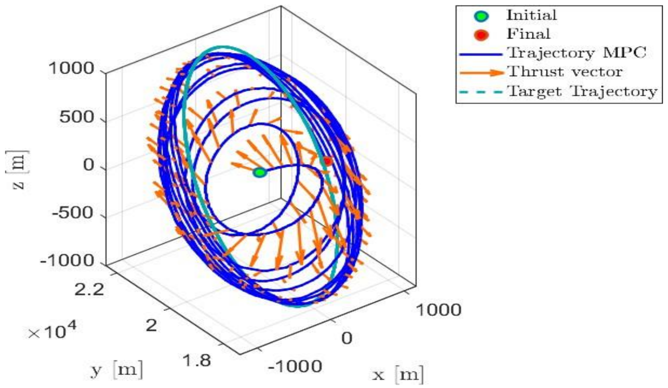
Minimum altitude
405 km

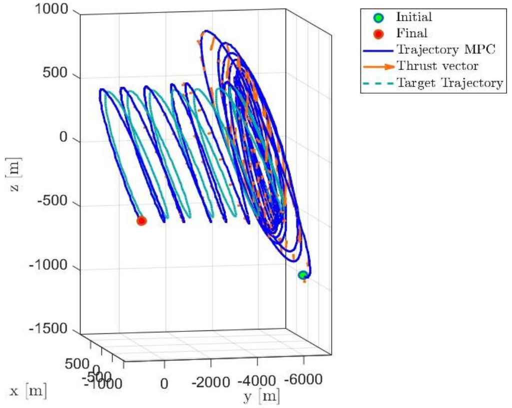
Minimum altitude
388 km

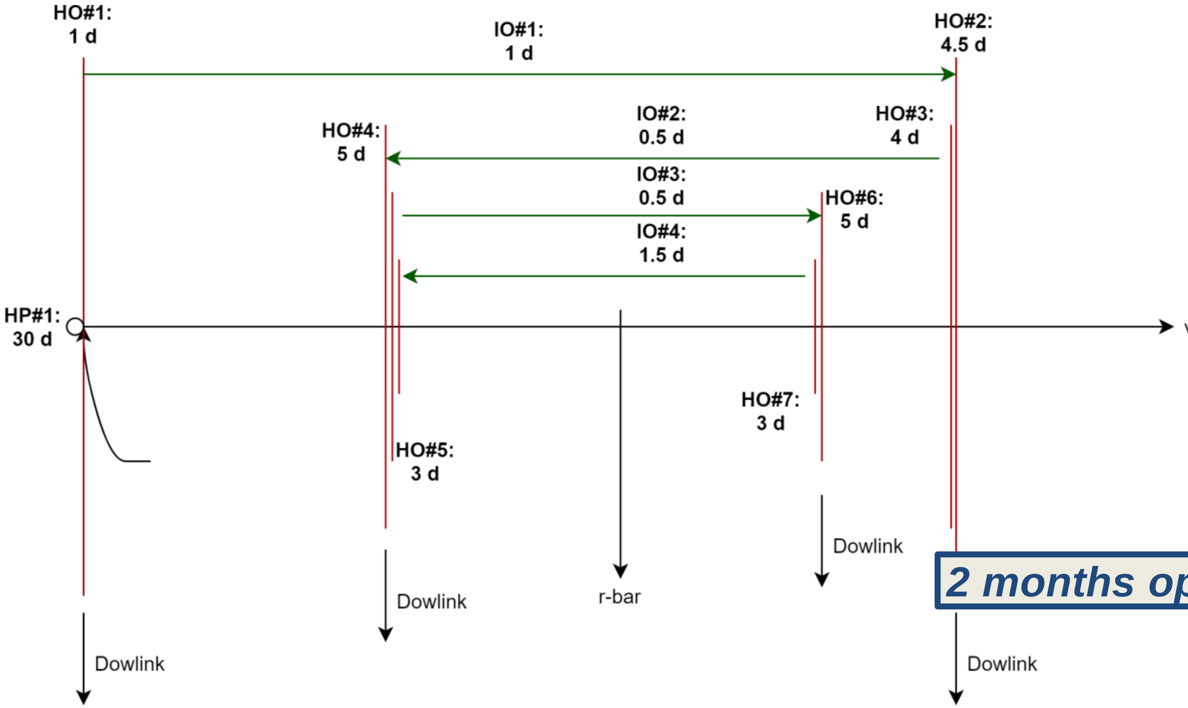
e.Inspector - *Mission Design*

Imaging orbits







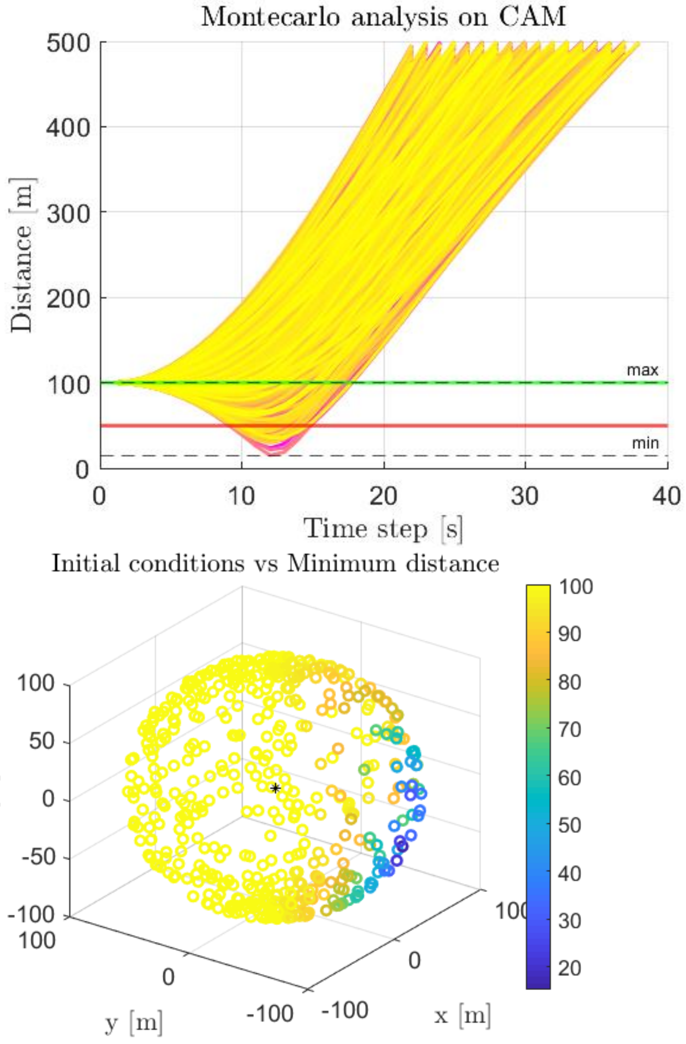


2 months ops

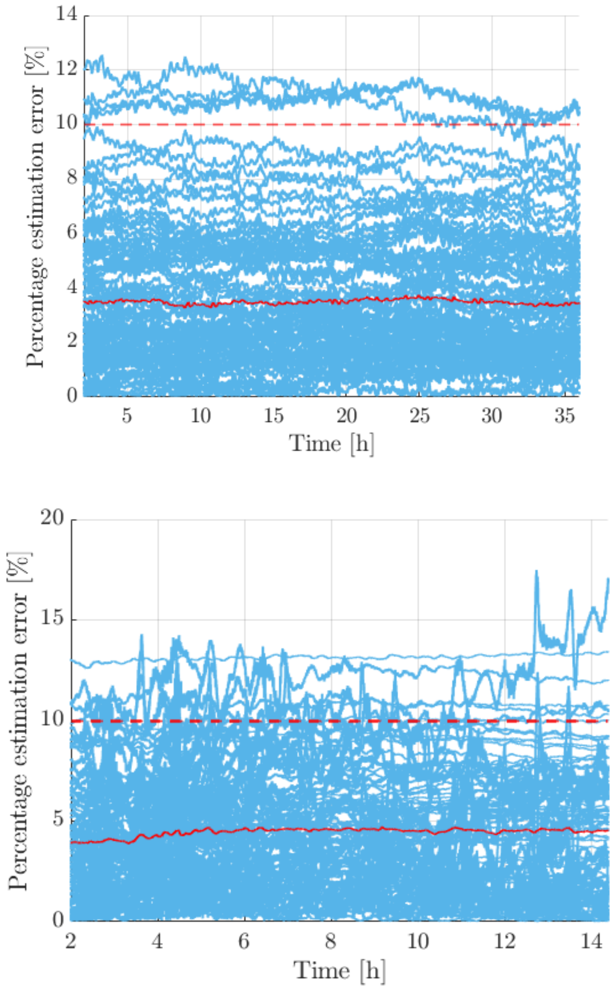
GS contact is established during the hold orbits, in the Communication phase, to **downlink data** and to **check the spacecraft conditions** before re-entering in the Inspection phase.

e.Inspector - *Mission Design robustness*

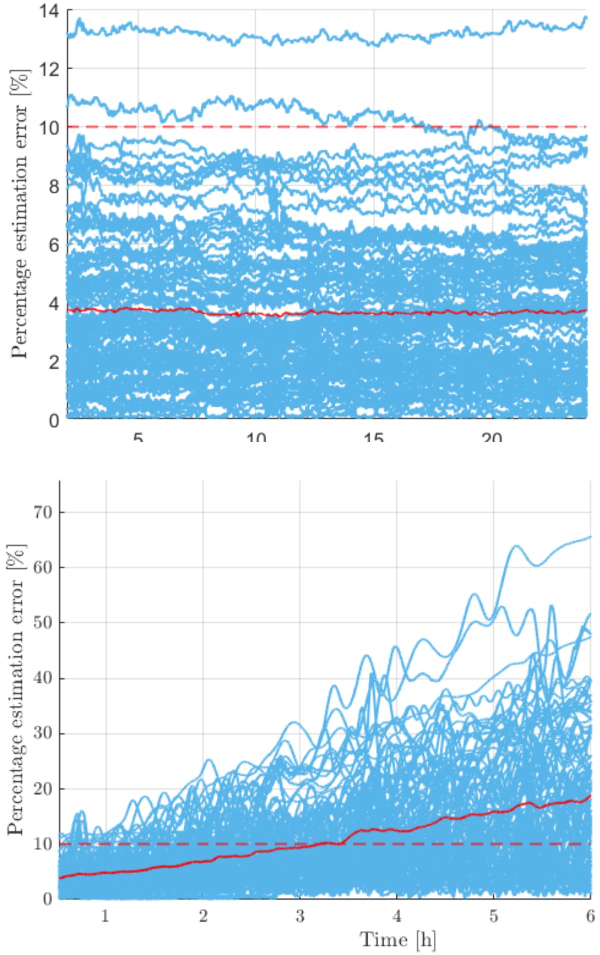
- CAM robustness at KOZ



- HO\IO robustness



- Loss of target\loss of STR

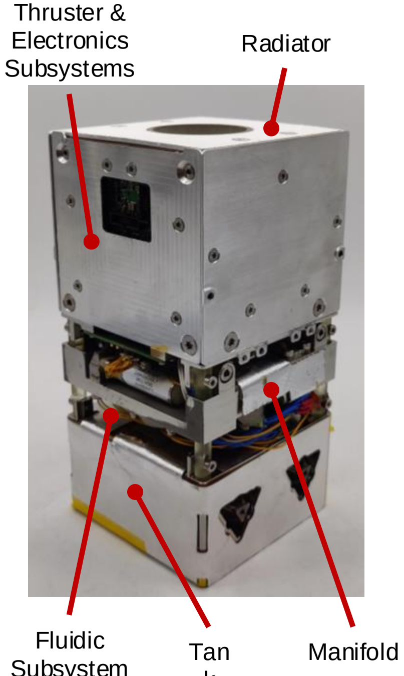


Propulsion→ low thrust for CubeSat to mature in endurance

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

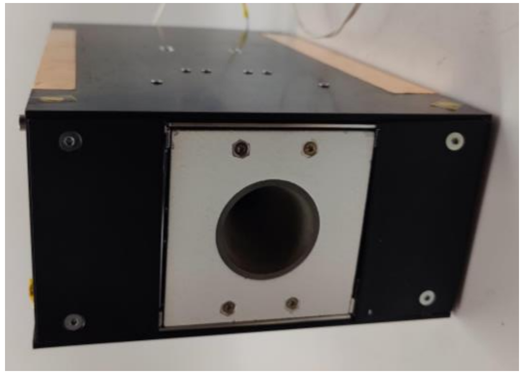
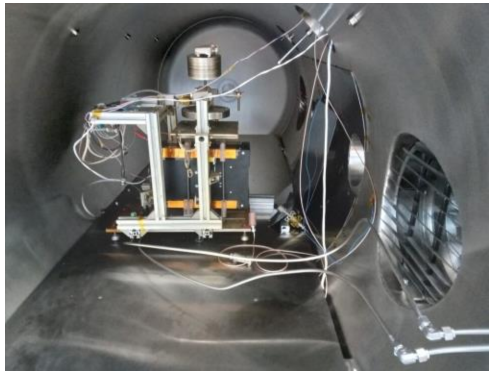
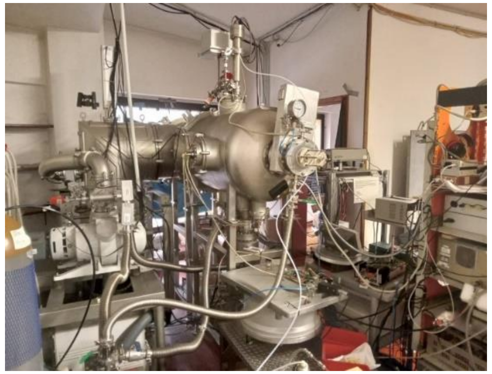
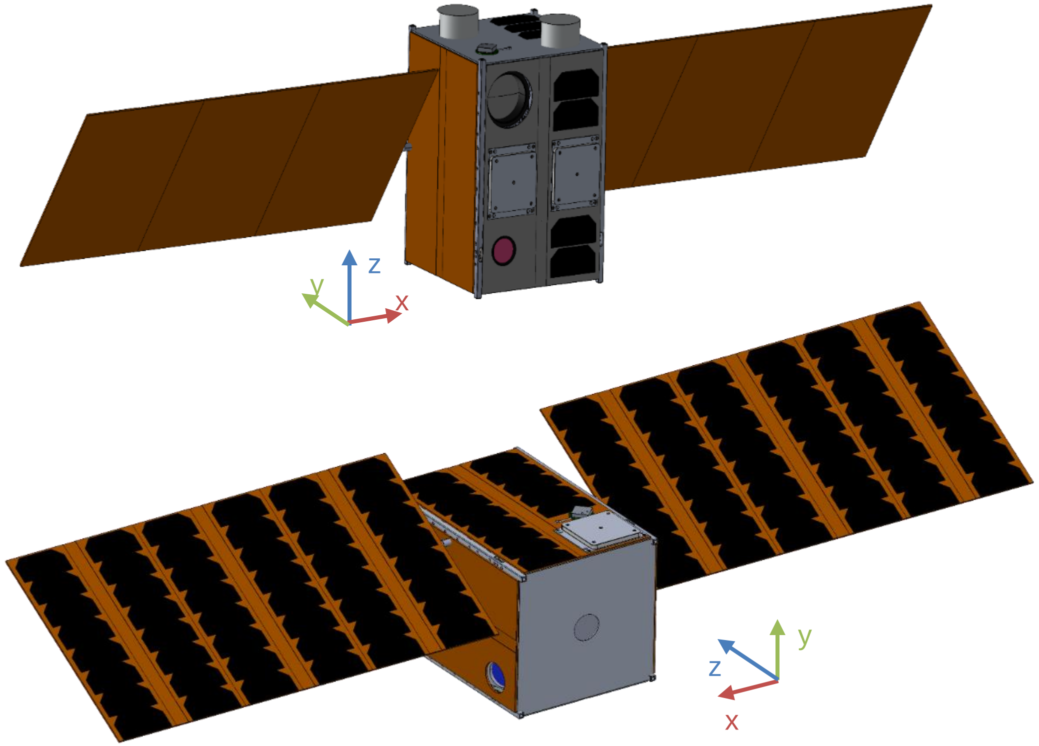


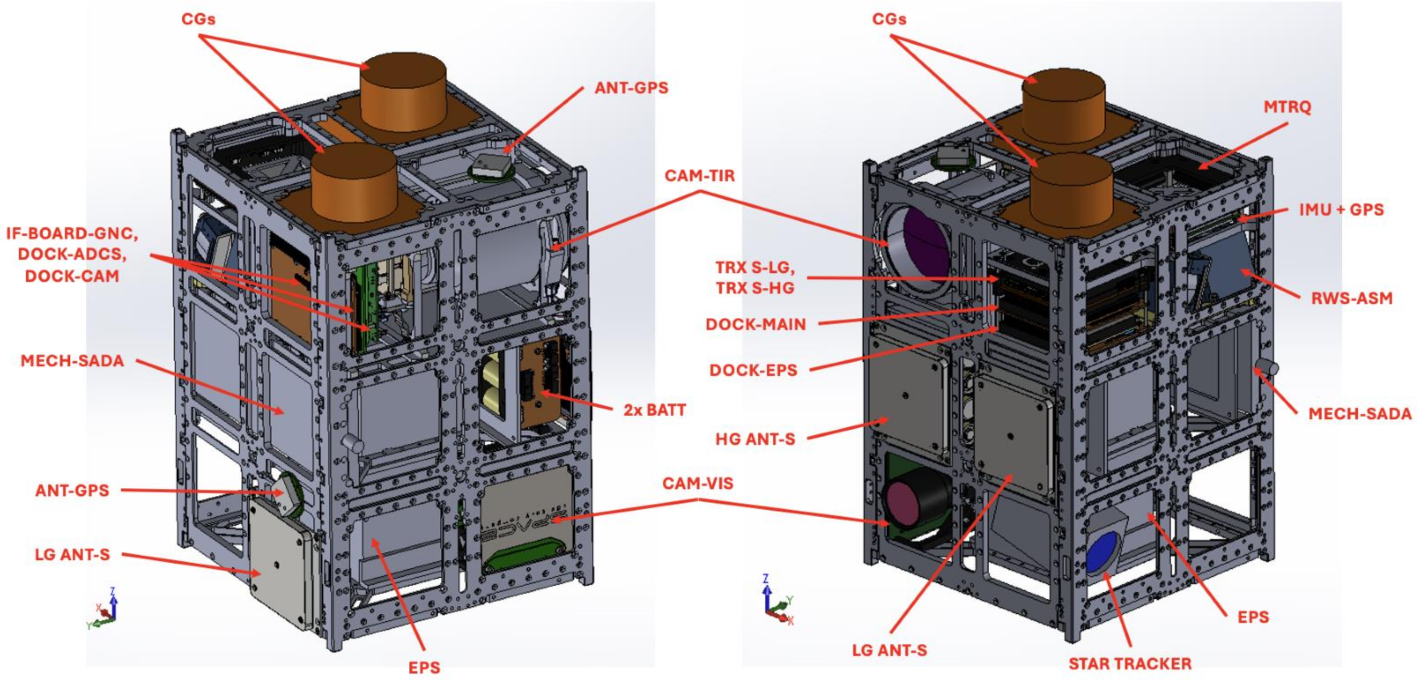
Photo of REGULUS-50-I2-M integrated in the 6U module (right).


Test setup in vacuum chamber.


Vacuum chamber at CISAS.

Configuration 12U CubeSat





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

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

Clean Space Days 2024: Towards a Sustainable Future in Space

e.Inspector

a 12U microsat to support future IOS missions by VIS-IR imaging Proba I

October 9, 2024

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

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI