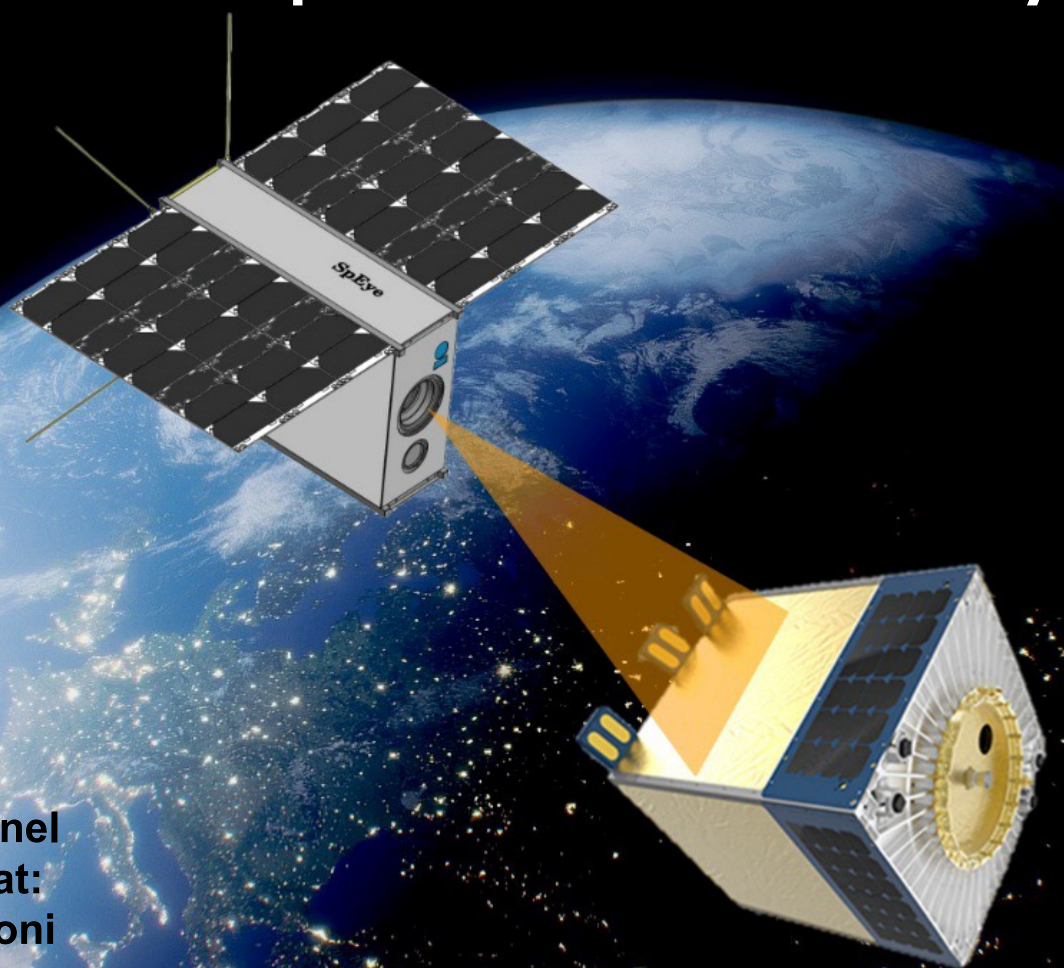
SpEYE: a CubeSat technology demonstration mission for on-orbit inspection and formation-flying



L'impegno Italiano nel settore dei CubeSat: Tecnologie e Missioni Future

July 2nd, 2024

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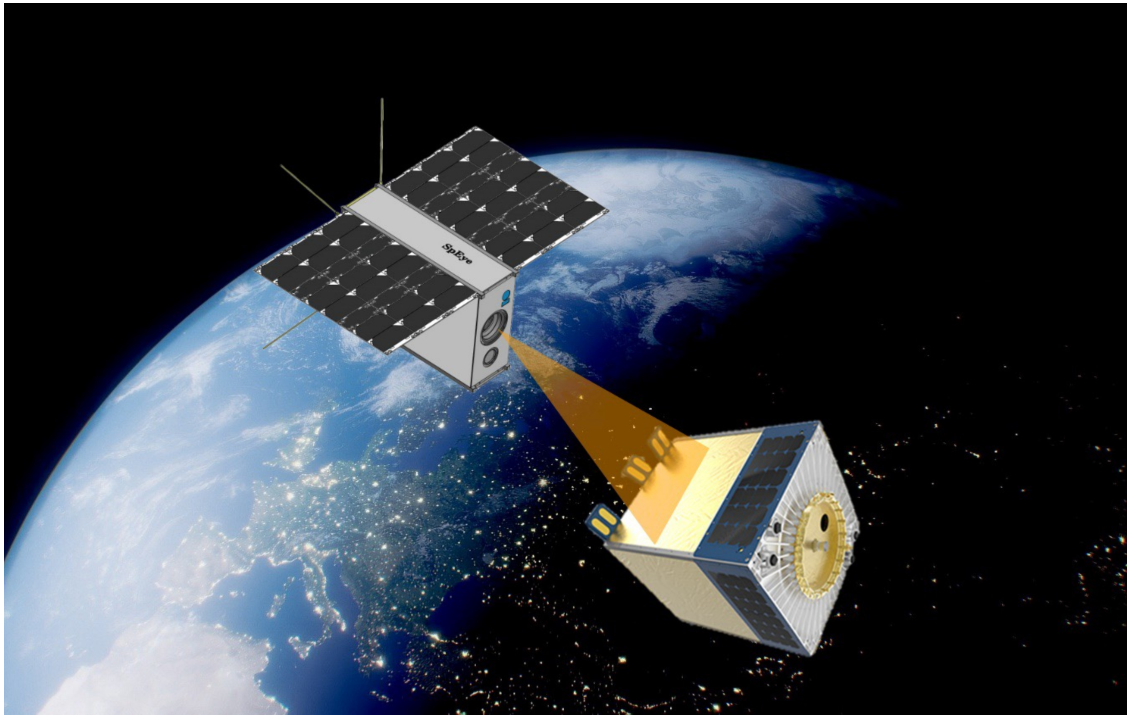
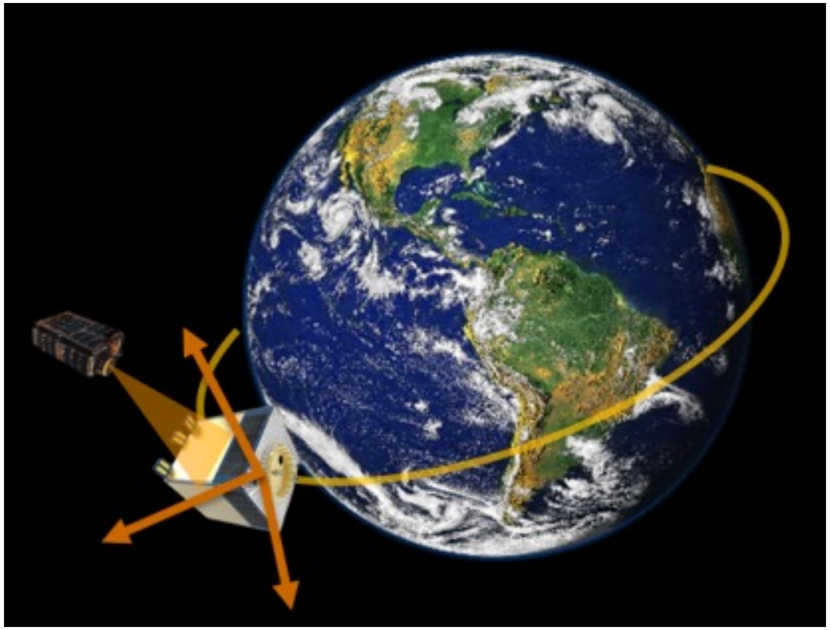
Outline



- Mission Overview
- Mission Design
- Free Flyer (FF)
- Main Satellite
- FF GNC Architecture
- Inspection Tasks
- Ground Segment

Overview



Space Eye (SpEye): a two-satellite technology demonstration mission for the in-flight validation of critical technologies and techniques related to advanced ***on-orbit inspection*** and ***formation-flying***, applicable to future operational nano-satellite capabilities and operations.

Validation of the following technologies:

- the **free flying nanosatellite** inspector, capable of autonomously flying around and imaging the main satellite from which it is deployed
- a multispectral **vision-based sensor system**, for autonomous navigation and inspection
- a **GNC processing unit** that integrates code-phase and carrier-phase GNSS, EO and INS observations, for robust and accurate absolute and relative navigation
- a **CubeSat propulsion system** that enables formation keeping and proximity operations

At the same time, such technologies will be also used to demonstrate:

- **autonomous formation flying of a 6U CubeSat** with its carrier
- **autonomous rendezvous of a 6U CubeSat** with a resident space object

Project Status and Team

SpEye, funded and managed by ASI in the framework of the *ALCOR* program has successfully completed the B1 phase after passing the System Requirements Review (SRR) in Q4 2023 and is now under contract signature for the upcoming B2 phase, targeting the preliminary design completion

Team:

- **Techno System developments (TSD Space)** srl (Prime) – Free Flyer, GNSS Navigation, Project Management
- **D-Orbit spa** (PMI) - Main Satellite, Mission Control
- **Technology for Propulsion and Innovation** S.p.A - Free Flyer Propulsion System
- **Planetek Italia** s.r.l – Free Flyer Inspection Data Processing, Free Flyer Control
- **Department of Aerospace Science and Technology del Politecnico di Milano** - Mission Design, Guidance & Control
- **Dipartimento di Ingegneria Industriale dell'Università di Napoli Federico II** - Electro-Optical Navigation

Mission Description and ConOps

① Absolute operational orbit transfer

② Release operations

③ Coarse station keeping

④ Nominal approach relative parking orbit

⑤ Relative parking orbit (RPO)

⑥ **GATE I**: Collaborative inspection phase

Demo 1.1: ION rotationally collaborative

⑦ **GATE II**: Non collaborative inspection phase

Demo 2.1: ION stable in RTN (i.e. Earth pointing)

Demo 2.2: ION flat spin one axis rotation

Demo 2.3: ION rotating/tumbling

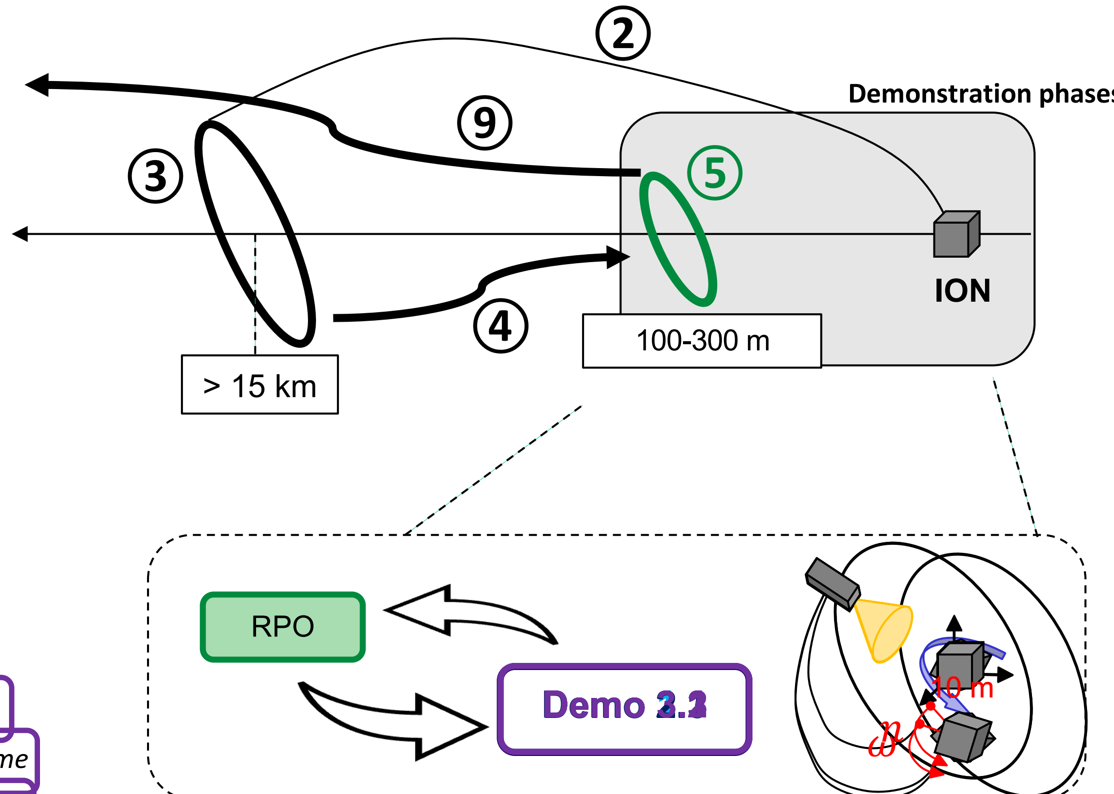
⑧ **GATE III:** Rendezvous demonstrations

Demo 3.1: approach to stable point in RTN frame

Demo 3.2: approach to stable point in inertial frame

Demo 3.3: approach to rotating point in RTN frame

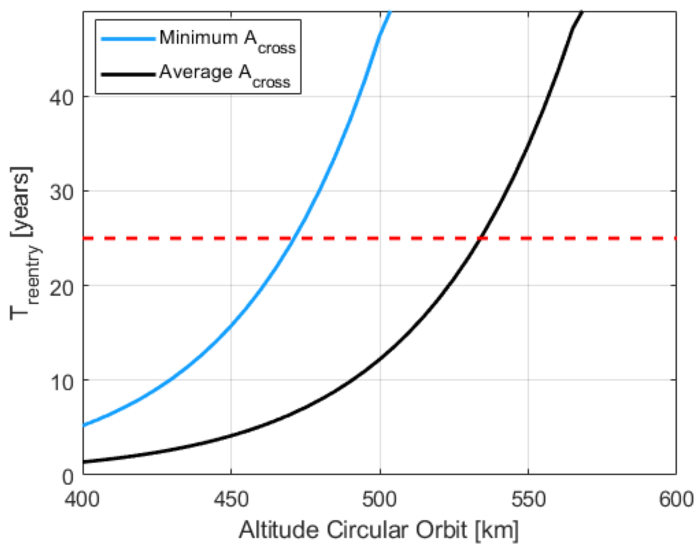
⑨ **Disposal operations**



Key objectives and drivers:

- Approach ION target using a forced motion using Visual Based navigation
- Rendezvous to a rotating hold point in the RTN frame
- **Relative navigation mode 4: EO-only**

Operational Orbit Analysis

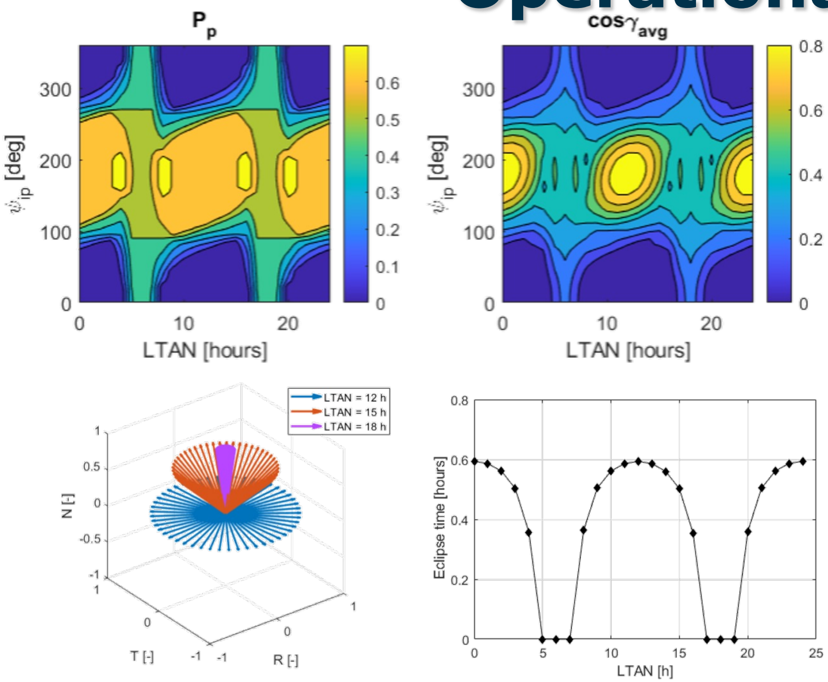


Absolute Motion

The SpEye mission operational orbit for proximity operations demonstration shall have an altitude of **535 km**:

- A/m considered of a tumbling object (free-flyer with the current configuration and highest mass).
- Drag coefficient considered as 2.1,
- Solar flux considered constant and equivalent to an exoteric temperature T_∞ = 750 K **(worst-case scenario).**

Operational Orbit Analysis



Illumination Conditions

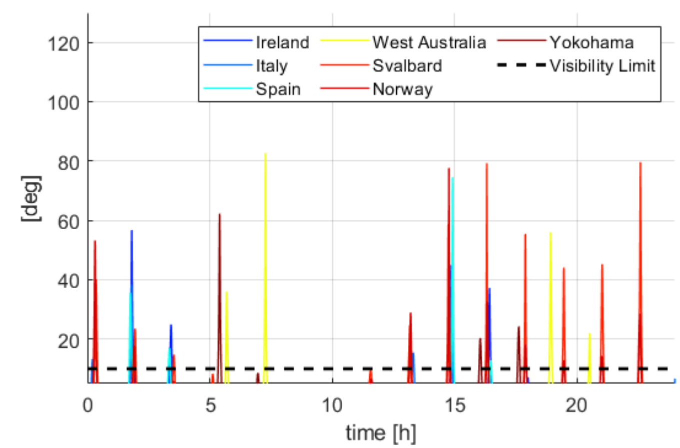
The SpEye mission operational orbit nominal LTAN value is **0 h or 12 h**. Tolerance based on launch availability and ION transfer capability is plus and minus 2 hours around the nominal values:

- LTAN 6 h (18 h) during demo 2.1 causes only limited ION faces to be illuminated.
- LTAN 6 h (18 h) provide bad illumination conditions for Gate III visual based navigation.
- In LTAN 0 h (12 h) values power generation facilitated in certain mission operations with attitude constraints (i.e., inspection pointing).
- LTAN 0 h (12h) provides long eclipse period.

Ground Coverage Analysis

The SpEye mission shall allocate for at least 1 downlink/uplink ground-contact **every 12 hours**, and a passage over the ground network every **8 hours** during the inspection demonstrations:

- **LeafSpace** network considered as the baseline solution for the ground segment.
- Augmentation of LeafSpace UHF with other providers
  - *K-SAT-lite*: Svalbard and Norway
  - *Infostellar*: Yokohoma

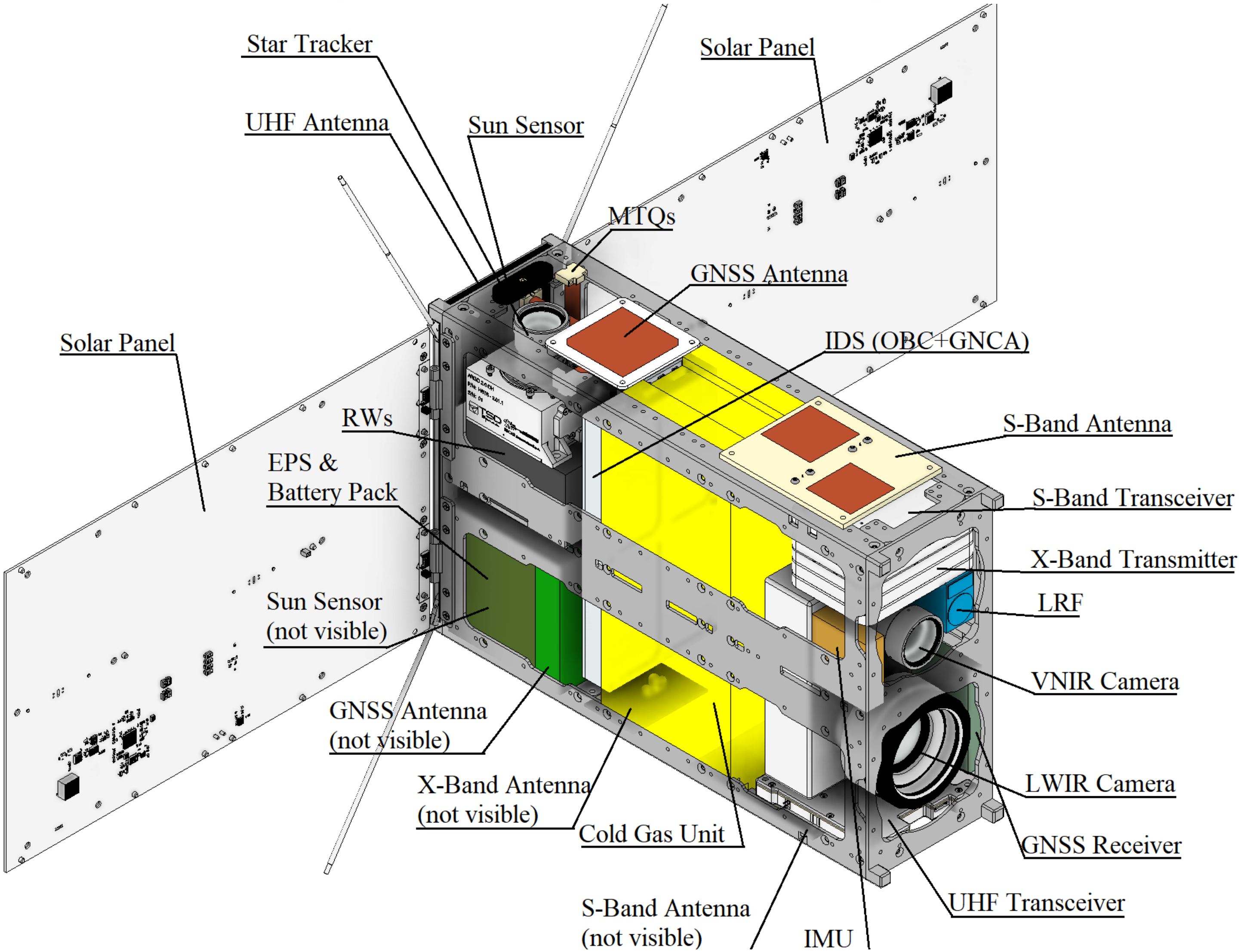


Mission Budgets

Phase/demo	Time	SpEye delta-v	ION delta-v
P.01 – Transfer	N/A	N/A	N/A
P.02 – Release	0.3 days	N/A	2.34 m/s
P.03 – Coarse formation keeping	7 days	0.2 m/s	2.24 m/s
P.04 – Far&Mid-range RdV	~7.85 days	N/A	0.95 m/s
P.05 – Relative parking orbit	7 days	0.83 m/s	N/A
P.06.01 – Demo 1.1			
Demo 1.1 preparation	3 days	0.356 m/s	N/A
Demo 1.1	1.4 days	0.423 m/s	N/A
P.07.01 – Demo 2.1			
Demo 2.1 preparation	3 days	0.328 m/s	N/A
Demo 2.1	5.5 days	1.49 m/s	N/A
P.07.02 – Demo 2.2*			
Demo 2.2 preparation	3 days	0.310 m/s	N/A
Demo 2.2	5.5 days	1.485 m/s	N/A
P.07.03 – Demo 2.3			
Demo 2.3 preparation	3 days	0.310 m/s	N/A
Demo 2.3	3.8 days	1.242 m/s	N/A
P.08.01 – Demo 3.1			
Demo 3.1 preparation	3 days	0.328 m/s	N/A
Demo 3.1	0.27 days	0.908 m/s	N/A
P.08.02 – Demo 3.2			
Demo 3.2 preparation	3 days	0.310 m/s	N/A
Demo 3.2	0.27 days	1.226 m/s	N/A
P.08.03 – Demo 3.3			
Demo 3.3 preparation	3 days	0.310 m/s	N/A
Demo 3.3	0.27 days	2.46 m/s	N/A
P.09 – Disposal operation	N/A	N/A	0.66 m/s
Total budget	61.6 days	12.49 m/s	6.15 m/s
Wheel desaturation	All mission	3.34 m/s	N/A
Total overall	61.6 days	15.83 m/s	6.15 m/s
Additional formation keeping available (worst relative configuration DD)	11.55 days	4.2 m/s	

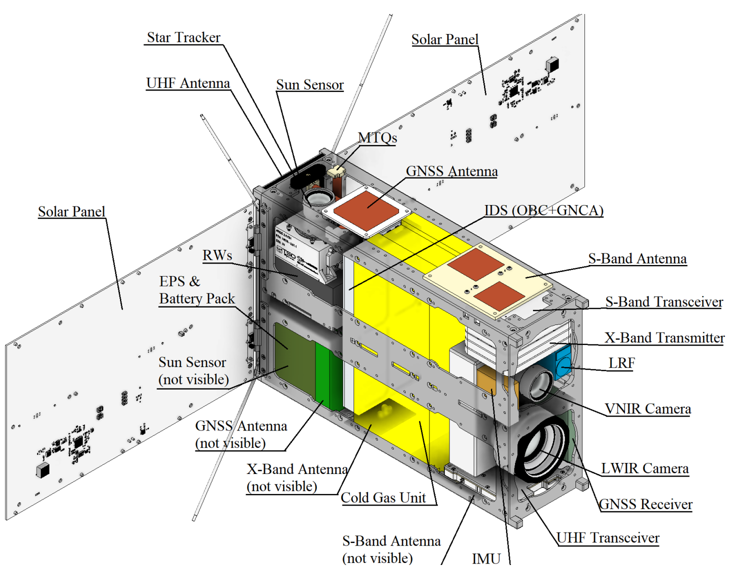
Source: Borelli G, Gaias G, Nakajima Y, Colombo C, Capuano V, Saggiomo F, Leccese G, Natalucci S. Mission analysis and guidance and control for the SpEye inspection CubeSat. Acta Astronautica. 2024 Jul 1;220:75-87.

Free Flyer Mechanical Configuration



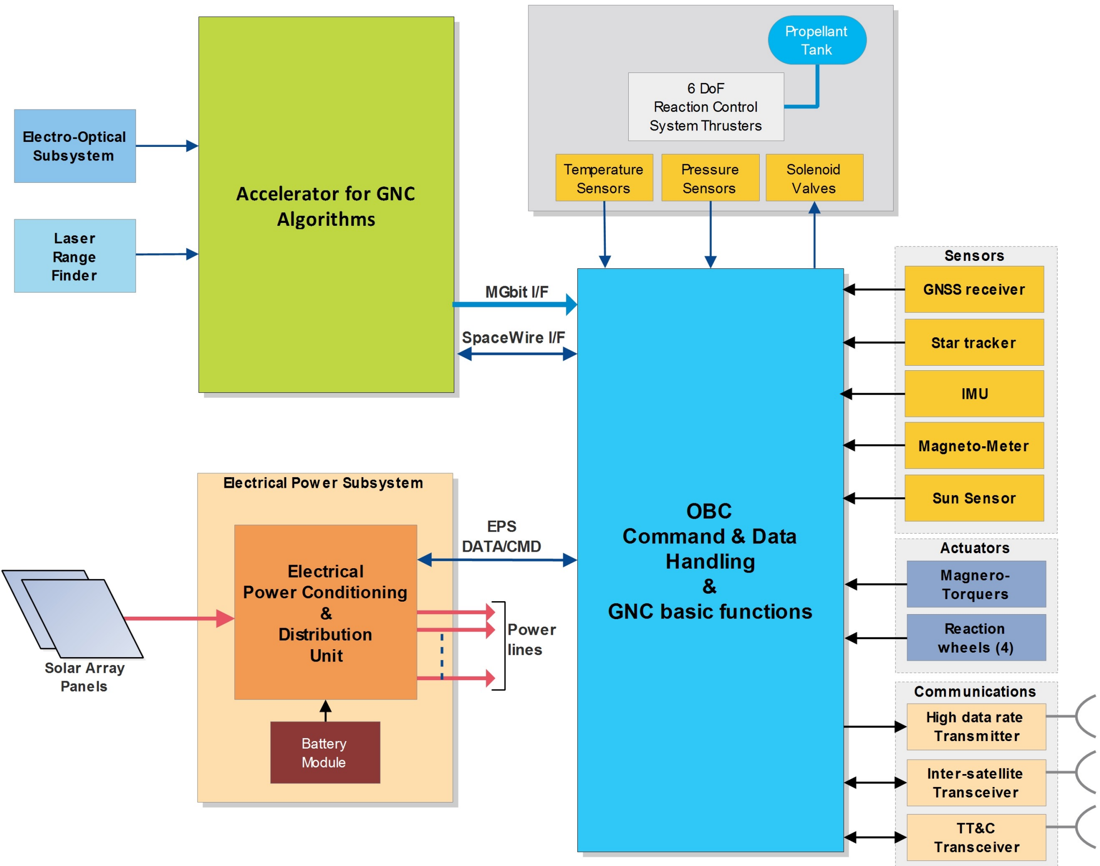
Free Flyer Mass and Volume Budget

Component	Subtotal [g]
Structure Subtotal	1139.3
TCS	180
Communications Subtotal	890
EPS Subtotal	2007
ADCS Subtotal	1251.1
Propulsion Subtotal	3202
Electro-Optical Subtotal	1116
OBC Subtotal	495
Total w/o System level margin	**10281.3**
Total w/ System level margin	**12337.6**



Component	L [mm]	H [mm]	W [mm]	Qty	Subtotal [cm³]
Structure Subsystem					
6UXL Structure	366	226.3	100	1	(8282.58)
Harness	(27k)	(0,71)	(0,71)		13.81
Structure Subtotal					**13.81**
Communications Subsystem					
TT&C Transceiver	95	89	23.2	1	196.16
TT&C Antenna	225.3	99	6.3	1	140.52
ISL Transceiver	90	65	25.3	1	148.01
ISL Antenna	80	100	3.4	2	54.4
Radio Transmitter	90	65	25.3	1	148.01
Radio Antenna	60	40	1.8	1	4.32
Communications Subtotal					**691.42**
EPS					
EPS Electronics	90	96	20	1	172.8
Battery Pack (3 strings, 150Wh)	90	96	70	1	604.8
Solar Array (6U)	342	209.3	10	2	(1431.61)
EPS Subtotal					**777.6**
ADCS					
Star Tracker	79	61	82	1	395.16
IMU + magnetometer	47	44	14	1	28.95
Sun Sensor	27.4	14	5.9	2	4.5
GNSS Receiver	71	46	11	1	35.93
GNSS Antenna	96	80	5	2	76.8
Reaction Wheel tetrahedral configuration	92.5	92.5	51.3	1	438.94
Magnetorquer	72	15	13	3	42.12
ADCS Subtotal					**1022.4**
Propulsion Subsystem Subtotal*	**105**	**226.3**	**100**		**2376.15**
Electro-Optical Subsystem					
VNIR camera	81	89	58	1	418.12
LWIR camera	81	89	80	1	576.72
Laser Range Finder	50	34	22	1	37.4
Electro-Optical Subtotal					**1032.24**
OBC Subsystem					
OBC (CDH & GNC basic functions)	88	92	21	1	170.02
GNC Accelerator	88	92	21	1	170.02
OBC Subtotal					**340.03**
Total					**6253.4**

Free Flyer Functional Architecture



In the figure it is shown the Architecture of the Free Flyer **Data System** defined following an optimization phase aimed at minimizing the power consumption.

The Data System is based on two main functional blocks:

- **OBC Command & Data Handling** (OBC C&DH) module
- **GNC Accelerator**

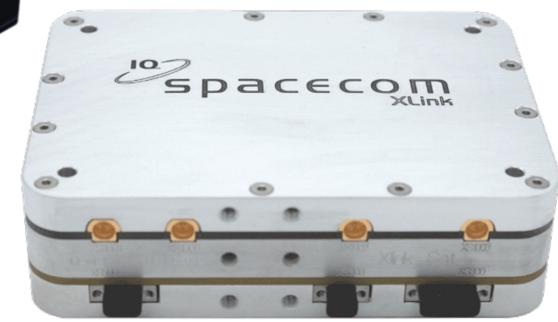
The Electro-Optical subsystems and the Laser range Finder only are directly interfaced to the GNC Accelerator.

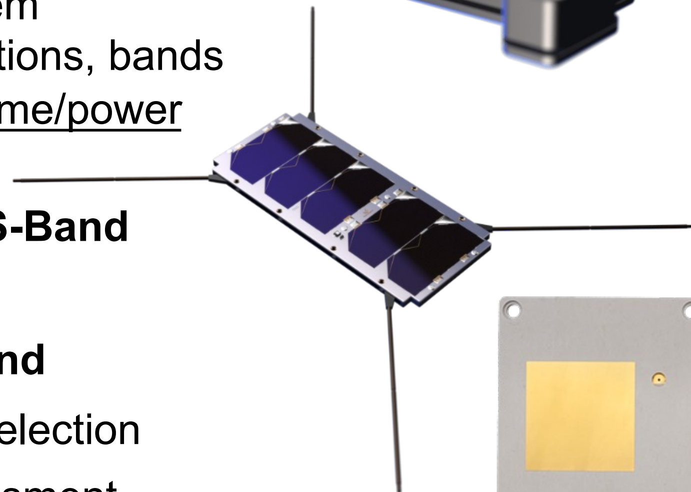
The GNC/ADC sensors and actuators and the sensor and solenoid valves of the propulsion subsystem are all interfaced to the OBC C&DH.

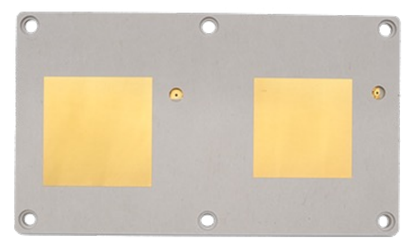
It is needed to power the accelerator only in operating modes that require the execution of **demanding algorithms** (like image processing and data fusion), thus significantly reducing the average power consumption.

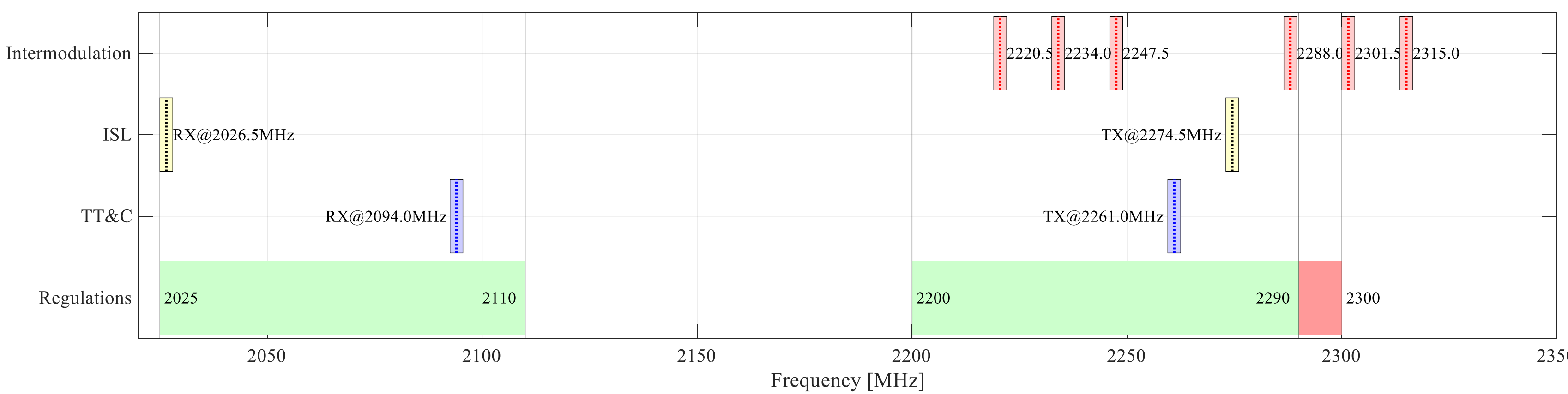
Communications

- Architectural design of communication subsystem
- Preliminary definition of communication subsystem specifications (configurations, bands and <u>data-rate/mass/volume/power budgets</u>)
  - Inter Satellite Link: **S-Band**
  - TT&C: **UHF**
  - Payload Data: **X-Band**
- COTS part preliminary selection
- Risk and criticality assessment



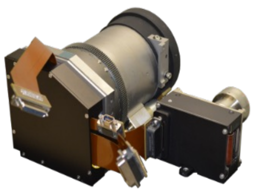


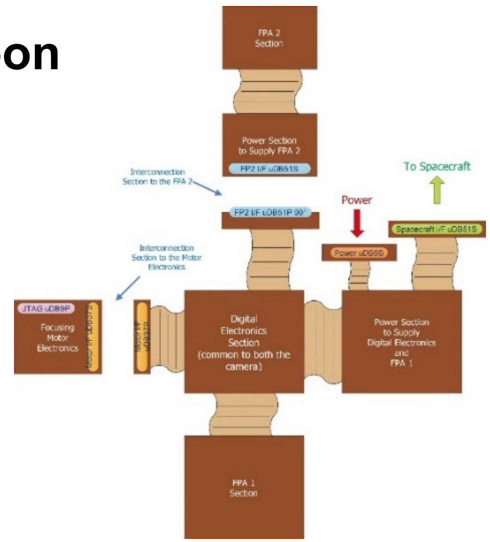


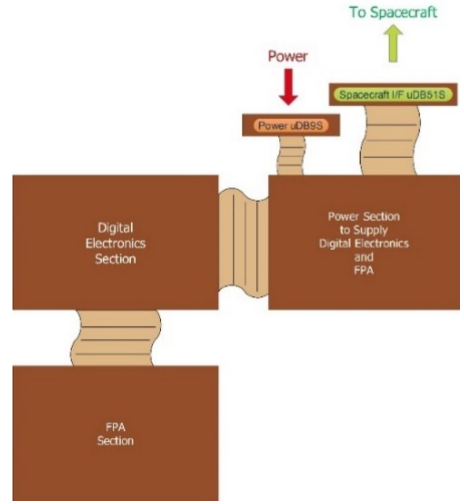


Electro-Optical System

Argomoon





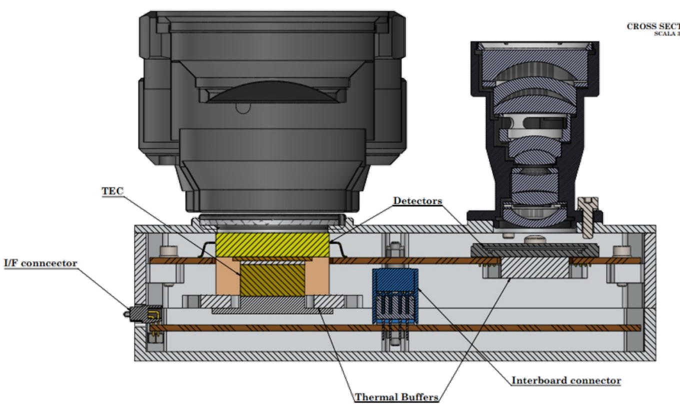


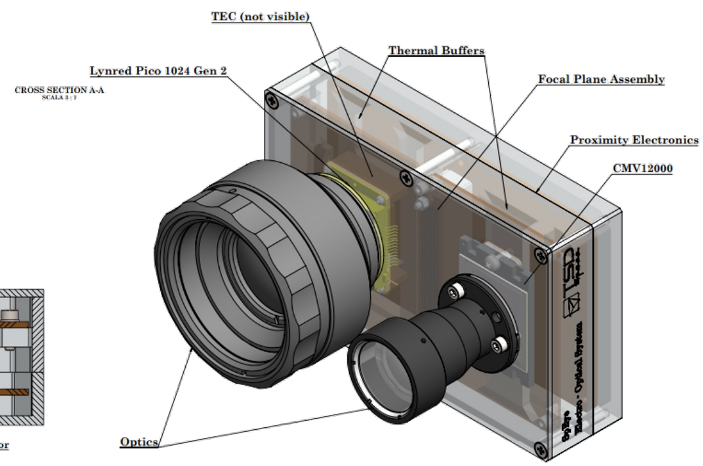
Due to the constraint in volume, the Argomoon Imager has to be modified in form factor.

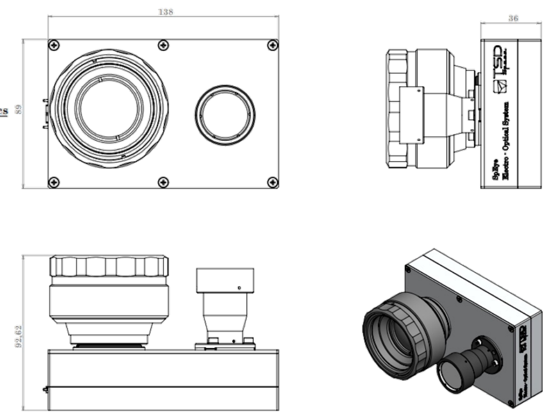
The number of the rigid sections of the PCB will be decreased and the area of each of them will be increased.

Two separated PCB of the FPAs will be substituted by <u>one larger PCB hosting the FPAs for both the detectors</u>.

SpEye

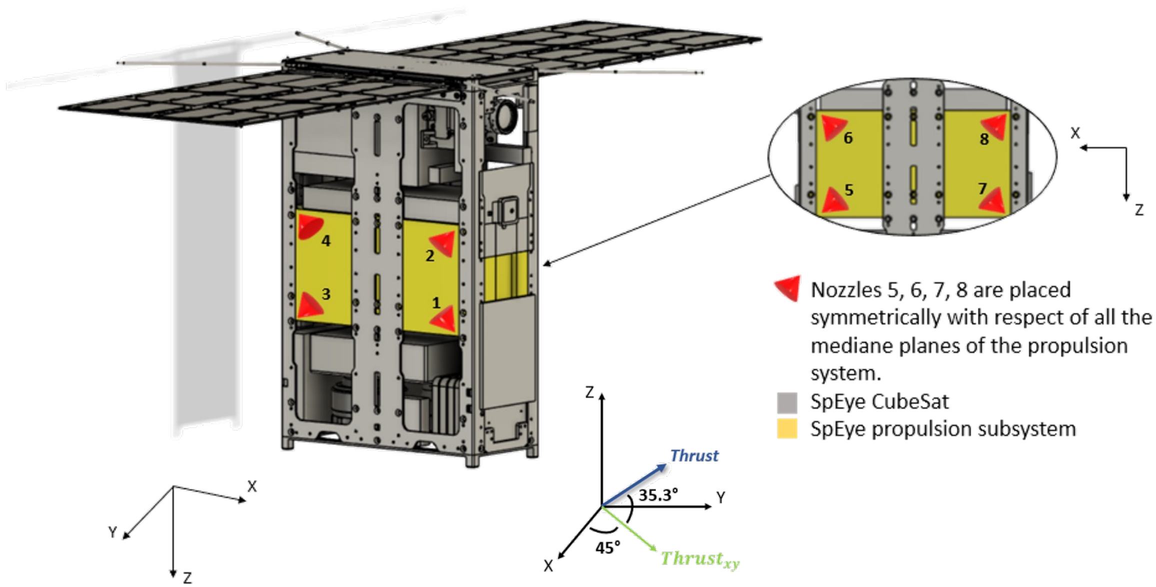






Propulsion Subsystem

A **Cold gas propulsion system** has been selected as best architecture for the mission.



The hybrid propulsion system configuration (monopropellant + cold gas) has been discarded as it is not suitable for 6U Cubesats and not necessary for mission scientific goals.

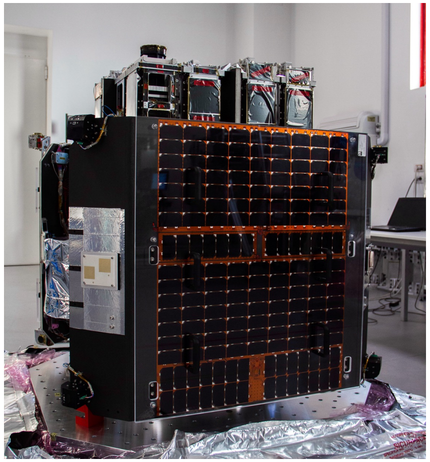
Deployer Target - D-Orbit

The spacecraft for the SPEYE mission takes advantage of D-Orbit heritage acquired through several InOrbit NOW (ION) missions. N°8 ION have been already launched and are still operative.

The following subsystems have been added for the SpEye mission:

- **Inter-satellite Link:**
  ION platform will be adapted to allow inter-satellite link communication with the target. Development will focus mainly on on-board Software, with minor updates on mechanical accommodation.

- **Propulsion system**:
  Propulsion system has been engineered and assembled by D-Orbit, and it is currently at TRL 9. A trade-off will be performed to analyze the compliance with mission requirements.



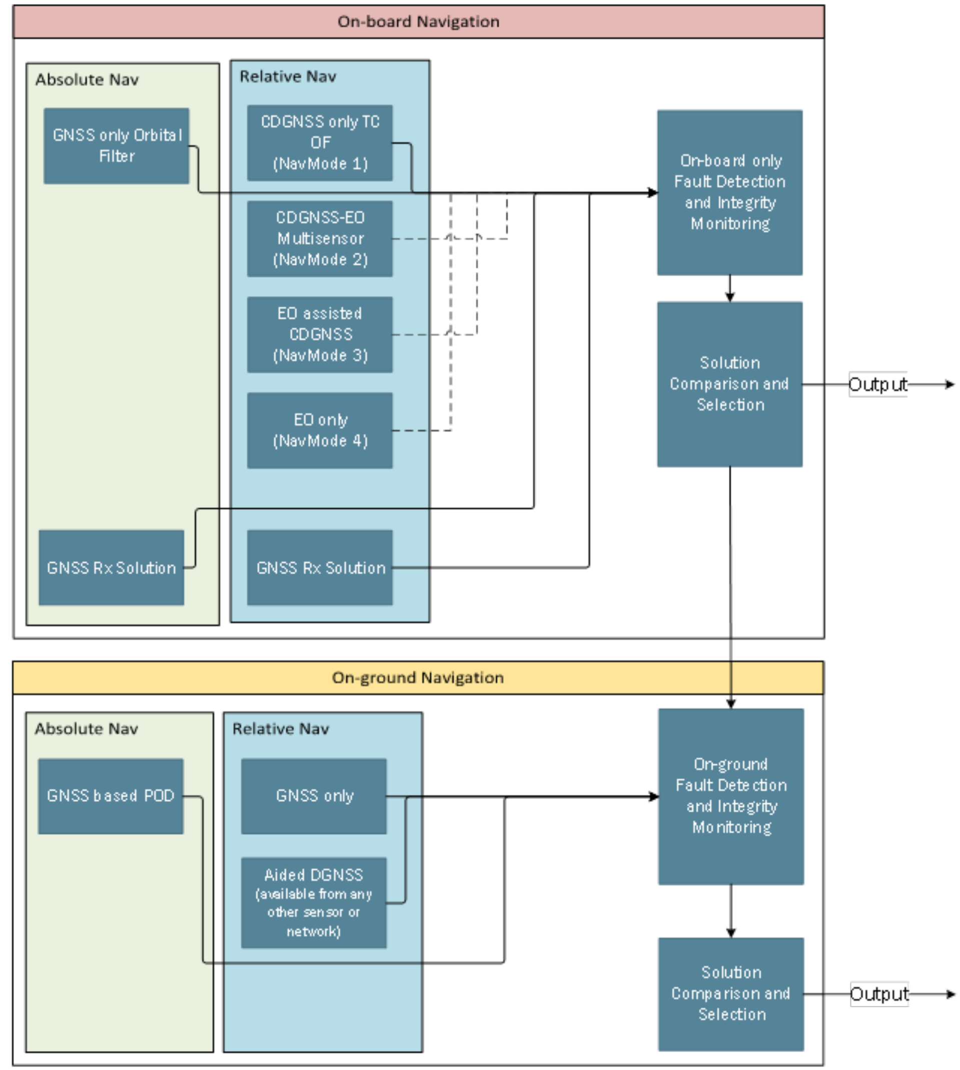
Credit: D-Orbit

Navigation Modes and Architecture

	CDGNSS	Visual Camera	LRF	Loose Coupling	Tight Coupling
Nav Mode 1 - CDGNSS only	✓				✓
Nav Mode 2 - CDGNSS-EO Multisensor	✓	✓	✓	✓	
Nav Mode 3 - EO Assisted CDGNSS	✓	✓	✓		✓
Nav Mode 4 - EO only		✓	✓	✓	

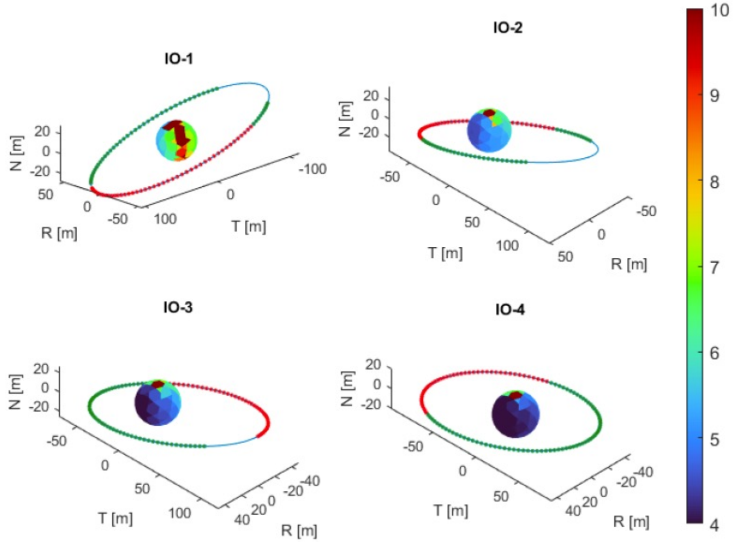
- Different navigation modes in different demos

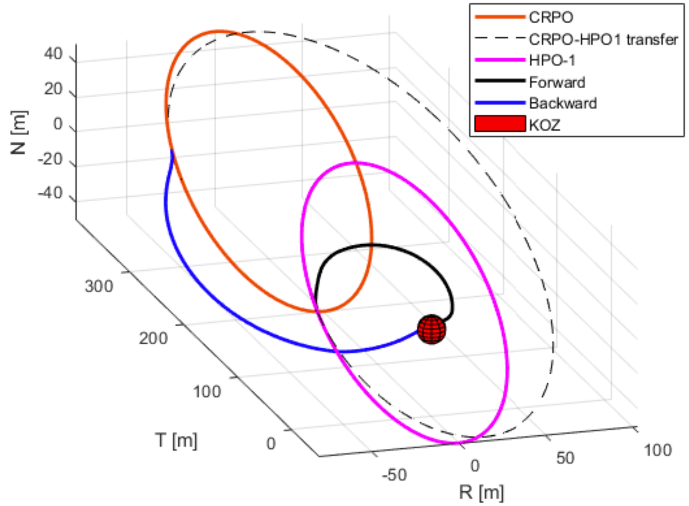
- In the SpEye mission, a <u>hybrid approach</u> shall be used, where the spacecraft performs initial navigation computations on-board and periodically sends collected raw GNSS data to ground stations for more precise processing and error correction. This approach balances autonomy with the benefits of ground-based processing.



Guidance and Control

- Guidance and control algorithm selection for inspection
  - **Optimised motion planning** based on information cost
  - Optimal transfer between fly-arounds
- Guidance and control algorithm selection for close range rendezvous
  - **Sequential Convex Programming (SCP)** algorithm for optimal rendezvous with improved safety
- Preliminary implementation of **inspection motion planning algorithms**
- Preliminary implementation for **close range rendezvous algorithm**
- Preliminary definition of attitude modes during mission demonstrations
- Guidance and control development of formation keeping and far range rendezvous phases.

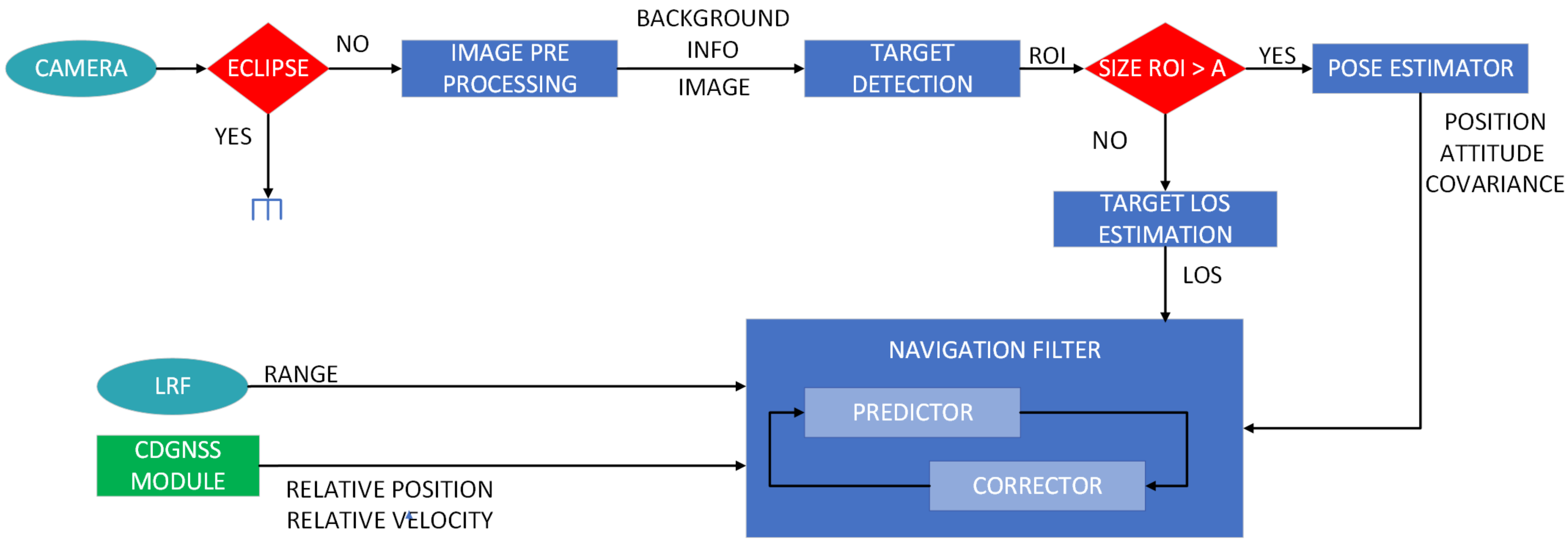




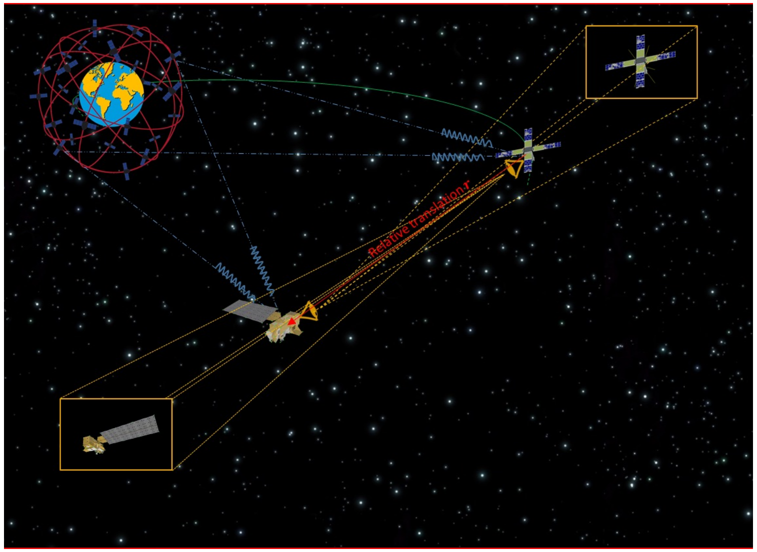
Electro-optical based relative navigation

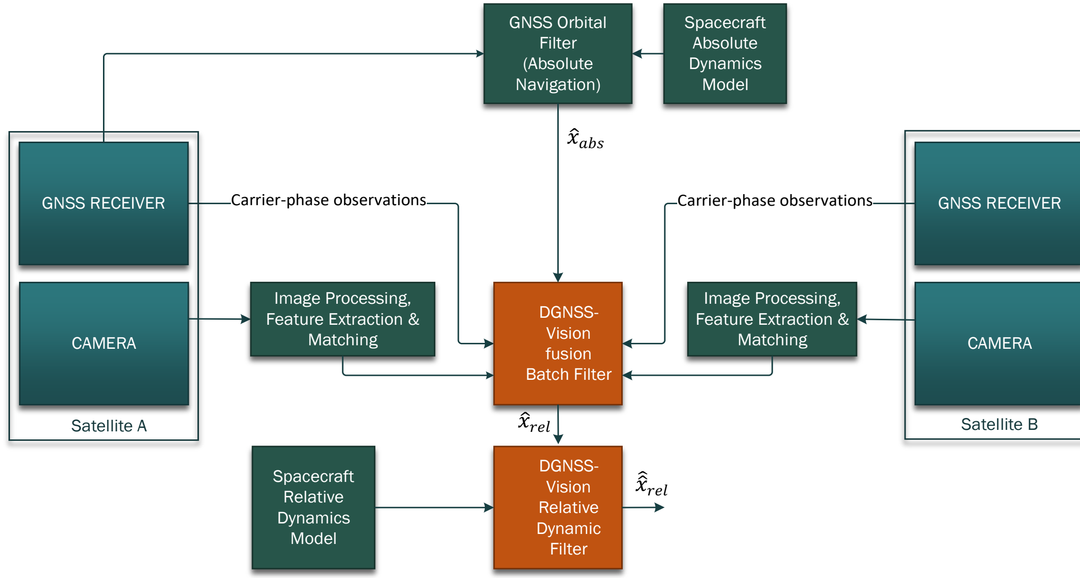
Relative navigation architecture

- Images from the monocular camera are employed for pose/line-of-sight estimation, depending on the target distance
- A relative navigation filter fuses the measurements obtained from the monocular camera, the laser range finder and the GNSS receivers (loosely-coupled architecture)
- Safety checks are performed on range and pose measurements, and on the output of the navigation filter

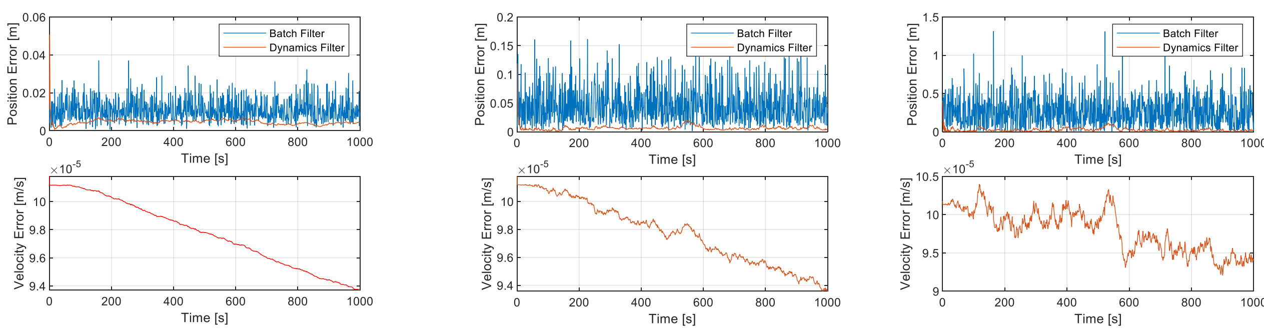


GNSS based relative navigation



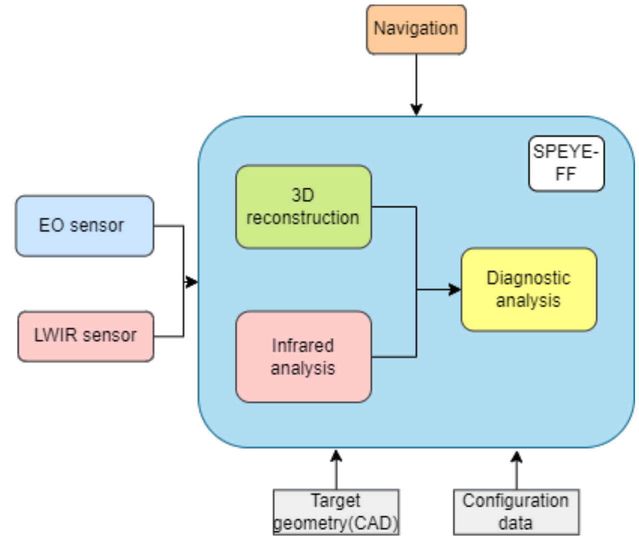


GNSS-Vision	GNSS only	Vision only (FOV 90 deg)
1.8 mm	5 mm	2.5 cm



Source:
1. Capuano, V., Harvard, A., & Chung, S. J. (2023). *U.S. Patent No. 11,733,399*. Washington, DC: U.S. Patent and Trademark Office.
2. Capuano, V., Harvard, A., & Chung, S. J. (2022). On-board cooperative spacecraft relative navigation fusing GNSS with vision. *Progress in Aerospace Sciences*, *128*, 100761.

Inspection Tasks

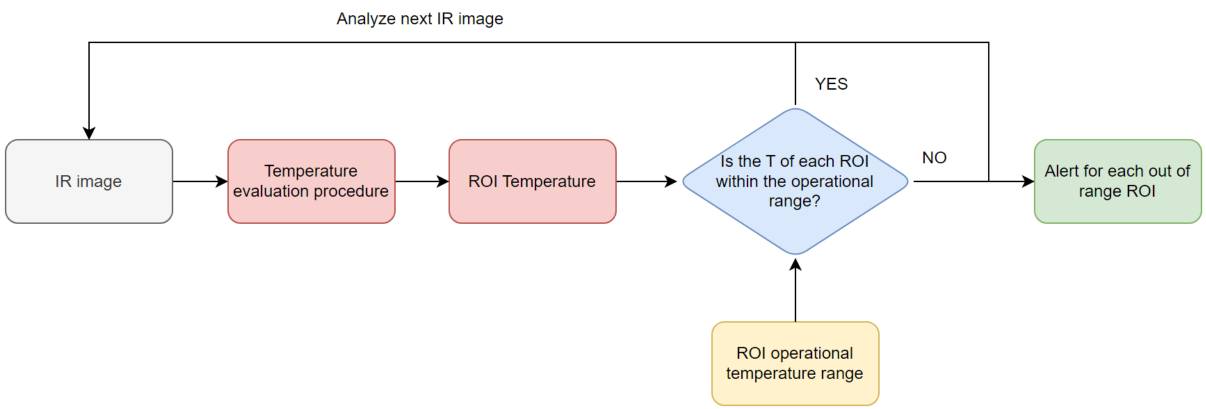


DIAGNOSTIC ANALYSIS 3D RECONSTRUCTION

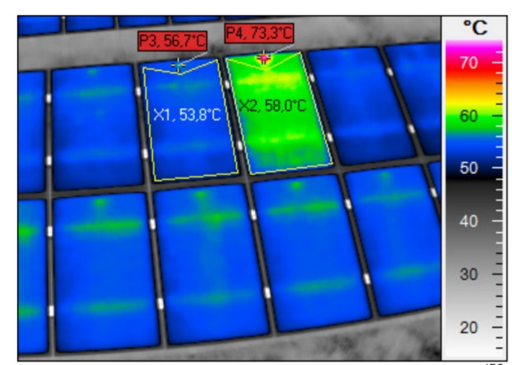
- A preliminary version of the 3D reconstruction algorithm workflow was selected
- Requirements for performing the 3D reconstruction, including preliminary data size, memory capacity, and data acquisition conditions, were defined

IR DIAGNOSTIC ANALYSIS

- A preliminary version of thermal inspection algorithm workflow was defined
- Requirements in order to perform thermal inspection (GSD, illumination conditions, calibration parameters, etc.) were defined



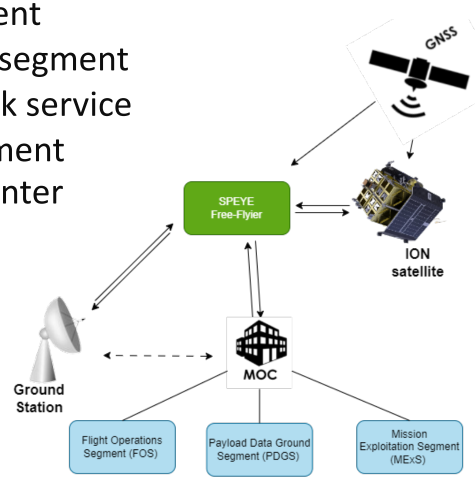
Mean ΔT of + 4,2 K. This is the expectation in case of **open circuit**. Additionally the spot ΔT of 16,6 K (- 4,2 K) at the junction box indicates active bypass diodes. Probably all substrings are in **open circuit**

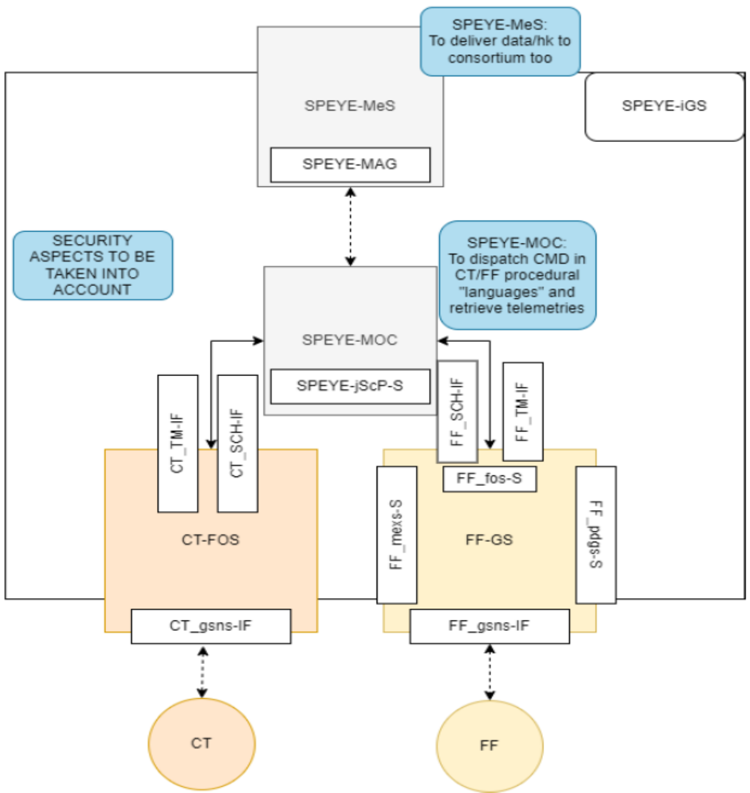


Ground Segment

- **ION/Target Control** by D-Orbit trough the D-Orbit FOS (Flight Operations Segment) based on the Aurora SW
- **Free Flyer Control** by Planetek trough a Ground Control Segment based on a customized version of Planetek's ERMES product
- **Formation Control** trough SpEye MOC (Mission Operation Center)

MAG: Mission advisory group
jSCP: joint Spacecrafts Planner
SCH: scheduling
TM: Telemetry
MeS/mexS: mission exploitation segment
FOS: flight operations segment
PDGS: payload data ground segment
gsns: ground station network service
iGS: integrated Ground Segment
MOC: mission operations center
FF: free flyer
CT: carrier/target
-S: subsystem
-IF: interface





Thank you for your attention!