Università degli Studi di Padova

Environmental Monitoring By Means of Hyperspectral Cameras on Board The Cubesat

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Supervisor: Prof. Giampiero Naletto

PhD Course in Science, Technologies and Measurements for Space

Final Exam Admission - 11/12/2024

Working on:

1. PhD Research Project - Environmental Monitoring By Means of Hyperspectral Cameras on Board The Cubesat

2. HYPSOS Project

3. EO-HYPSOS Project [Activities in Industry]

4. In-Orbit Demonstrator Mission (under evaluation)

1. PhD Project

The National Operational Program has provided for the grant that was financed with ESF REACT-EU resources assigned with the MUR decree n. 1061 of 10 August 2021 for doctorates on innovation and green topics.

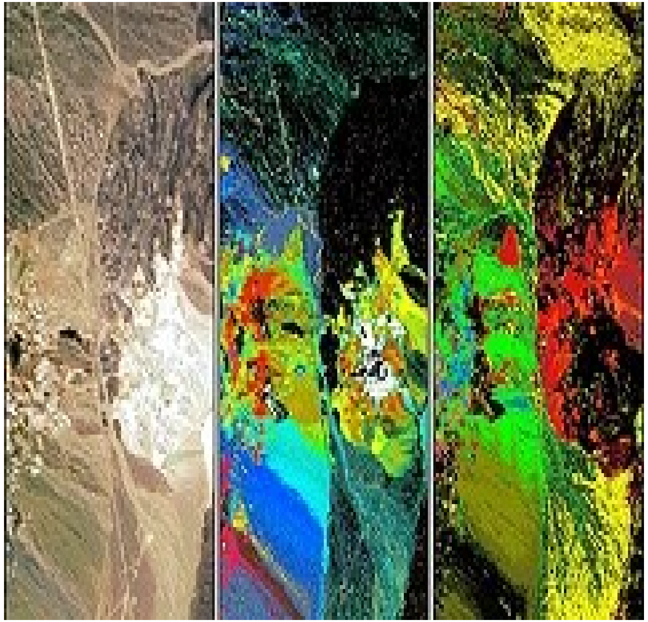
Action IV.5 - Doctorates on green topics of the new Axis IV of the PON (National Operational Program) Research and Innovation 2014-2020.

SNSI Thematic Area 2014-20 - SN_E National Strategy - Aerospace and Defense SN_ E6 Earth observation systems, in the field of missions, instruments and data processing.

Large Research Area 2021-2027– 4. Digital, industry, aerospace.

Introduction

- **The aim of the PhD project is to define the design of an innovative instrument for Satellite-CubeSat (In principle for Earth Observation but possibly extended to Solar System exploration).**
- The feasibility study is carried out of an instrument of a few CubeSat units for hyperspectral observations, capable of providing spectroscopic information of the observed Earth surface.
- The research proposal focuses on an optical analysis and design methodologies applied to the satellite missions for environmental monitoring.



https://www.planetek.it/eng/projects/prisma

The use of instrumentation installed within CubeSat is a compactness solution aimed at achieving the “Green" objectives of the Research Project

PhD Project - Environmental Monitoring By Means of Hyperspectral Cameras on Board The Cubesat

Activities on PhD Project

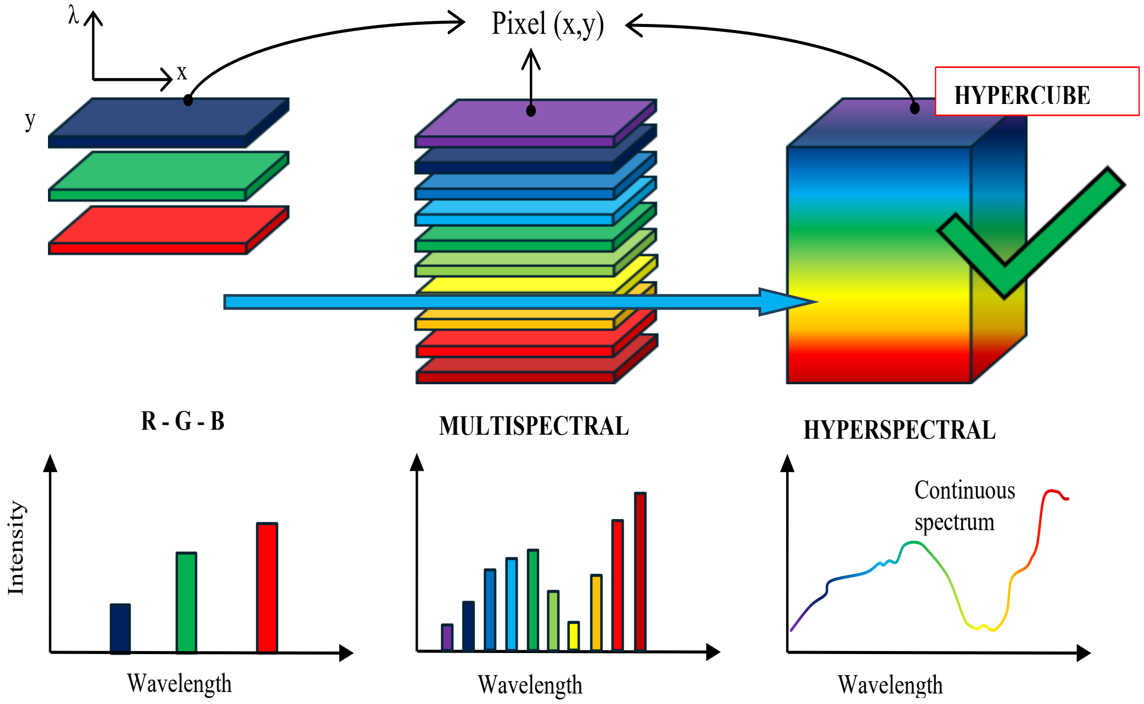
Feasibility Study (Operatinal Research):

- Radiometric Mathematical Model
- General Sub Systems (Opto/Mech) Preliminary Design → Identified
- Optics Layout / Proposed Design → Identified
- Mechanical Layout / Proposed Design → Identified
- Iteration & Optimization Process Designs (Volume, Mass and Thermo-Mech Stress)
- 3D CAD Opto-Mechanic Model Subsystems → Preliminary Realization
- Data Analysis

- **Preliminary design study of opto/mechanical system**
- **Characterization of the optical layout and structural support**
- **Feasibility study aboard a CubeSat & Sat.**

Hyperspectral Imaging (1)

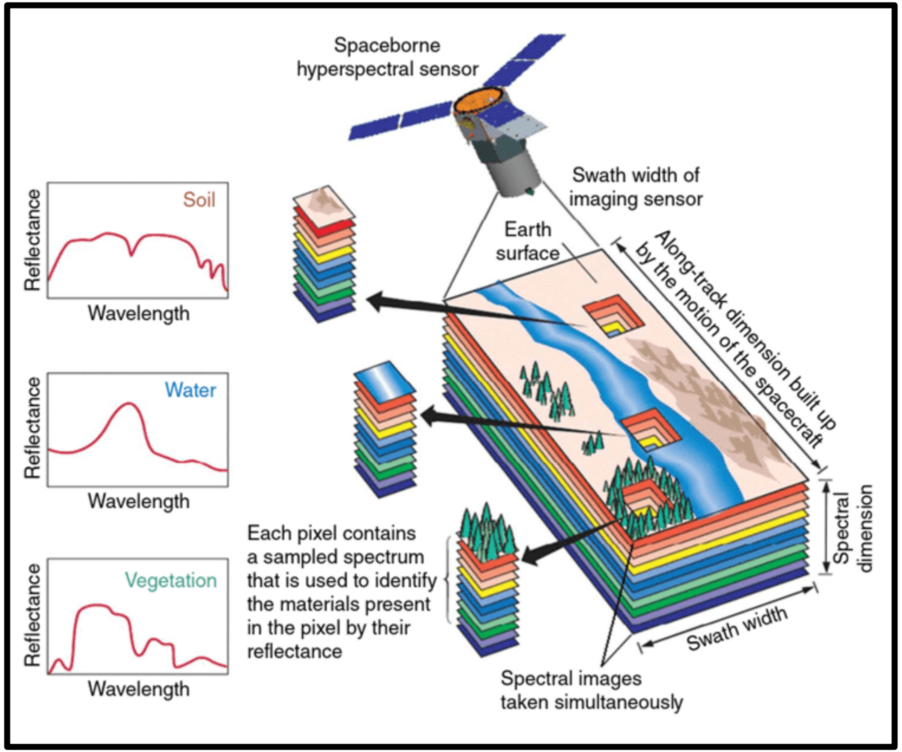
- Hyperspectral imaging, like other spectral images, collects and processes information from across the electromagnetic spectrum
- The goal of hyperspectral imaging is to obtain the spectrum for each pixel in a scene image, in order to find objects, identify materials or detect processes
- In the interest of this research project for environmental control purposes, the hyperspectral solution was preferred



Hyperspectral Imaging (2)

Domains:

- ✓ Environment (Earth)
- ✓ Coastal and inland waters
- ✓ Precision Agriculture
- ✓ Natural resources, including forestry, lithology, geology, …
- ✓ Defense and security
- ✓ Solar system application (Moon, Mars, …)



https://ebrary.net/205101/engineering/introduction_hyperspectral_satellites

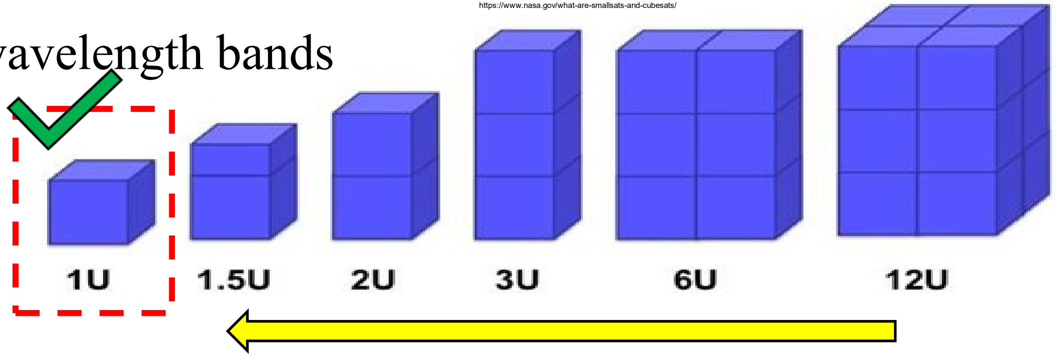
Objectives

- The payload must be able to take high quality data both in terms of spatial and spectral resolution (Low- Mid-High resolution)
- To evaluate the feasibility of the mission, it is necessary to study how the different variables influence the instrument performances
- To design an appropriate configuration for the detector as simple as possible
- To proof that the proposed configuration fits the requirements of the CubeSat (in terms of available space and desired performance of the cameras)
- Iterative and Optimization Process Systems Design → Configurations are carried out

Mission Requirements

- The Instrument shall be capable to perform local characterization of the Earth's surface targets via a hyperspectral instrument, in final doing a hyperspectral-stereo instrument.
- Low IFOV
- The spectral sampling shall be low < 10 nm/pixel (if possible < 2 nm/pixel)
- The mission lifetime shall be > 1yr
- VNIR-SWIR mission windows wavelength bands
- The CubeSat size <= 12U
- Rad-Hard Tech

https://www.nasa.gov/what-are-smallsats-and-cubesats/



Design Requirements (1)

❑ **Selected Hyperspectral Space Optics Instrumentation Configurations**

FORE OPTICS + TELESCOPE + CORRECTOR LENSES & FOLDING MIRRORS + SLIT/S + SPECTROMETER (VNIR & SWIR separated or not-separated spectrometers).

- Selected Refractive Design
- Selected Reflective Design
- Hybrid, Selected Catadioptric Design ✓

System & Sub-Systems Parameters – Mission Concept (1)

- **Selected LEO → Sun-Synchronous Polar Orbit**
- **Selected Pushbroom Scan**

- Instrument development for high signal-to-noise ratio, high spatial and spectral resolution, broad wavelength range, wide spatial coverage, low distortion, low self-polarization, …
- Processing, new parallel or grid processing schemes for large hyperspectral data volumes
- Calibration, uniformity, sensor stability, accuracies, ecc…

Trade-Off Parameters

There are a lot of parameters for Design and Optimization the apparatus:

- H - Orbit Altitude
- AOI -Area of interest
- SW - SwathWidth
- GSD - Ground Sampling Distance
- …..

Multi variable Optimization Problem (Dedicated Algorithms) – Operational Research

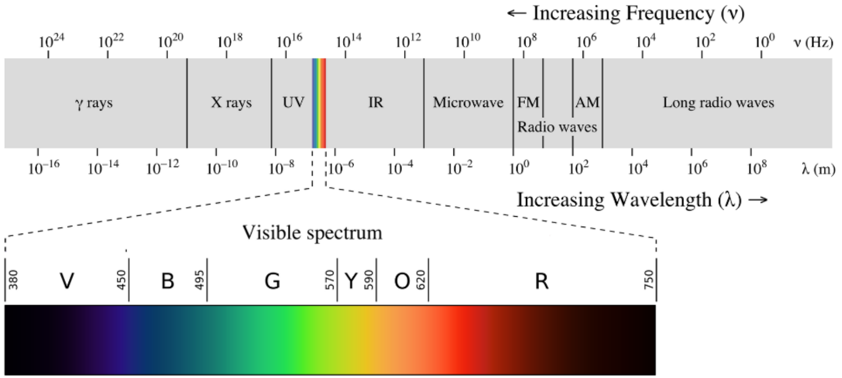
Radiometric Analysis (1)

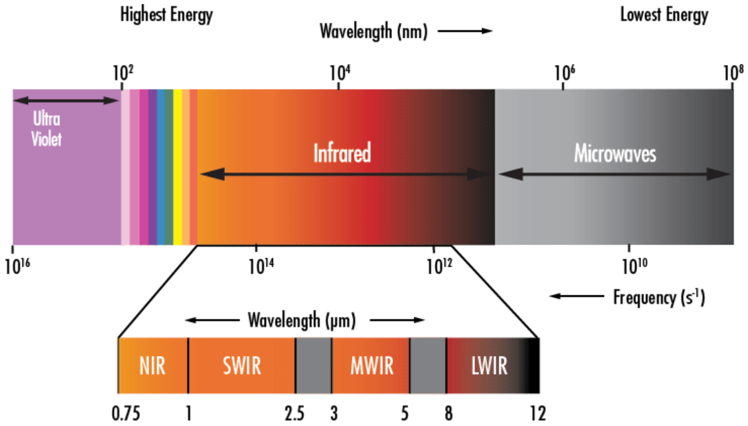
Selected Operative Windows

- To predict the radiometric budget in the VNIR-SWIR windows, first of all, it is necessary to model the atmospheric transmission window. Then, the Sun Reflected and the Ground Thermal Emitted radiances can be evaluated.
- Windows with high enough and almost constant transmission coefficient:

@ VNIR, from > 0.38-0.4 μm to 1 μm

@ SWIR, from > 1 μm to 2.5 μm

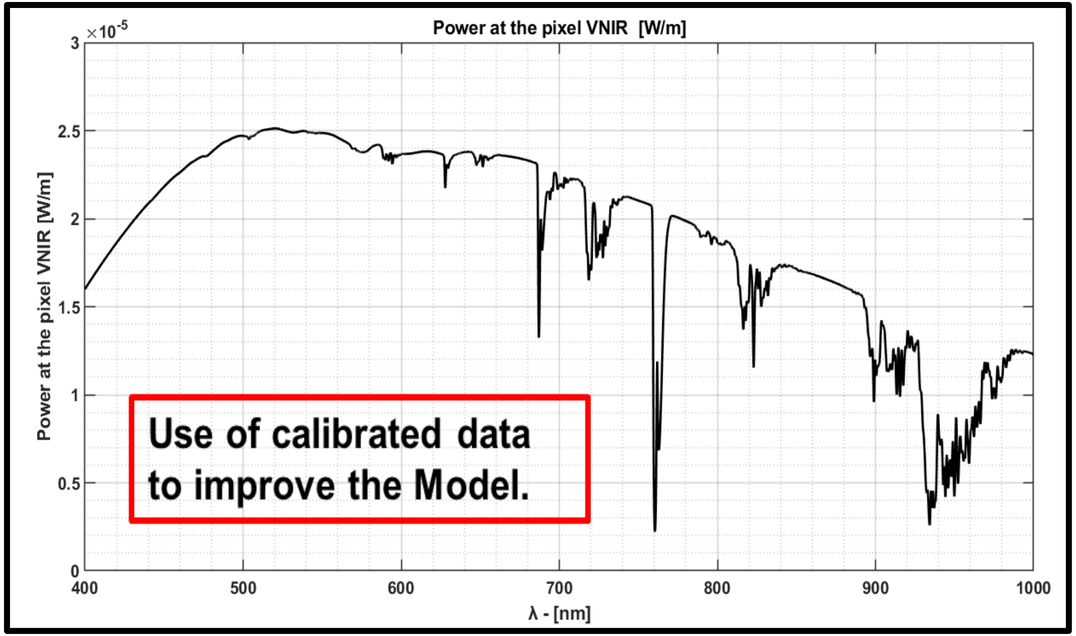




https://www.edmundoptics.com/knowledge-center/application-notes/imaging/what-is-swir/

Radiometric Analysis (6)

Mathematical Radiometric Analysis – Power at the pixel → SNR



Complex Model: **SNR**, **S**, **N**, Pi(λ), Φ(λ), L, n(λ), Ad, ΩSE, Ω_EO, Ω_OD, τ, atm(λ), η_opt(n,λ), η_Qeff(λ), ε, g(λ), ti, ρ(λ), k, c, dλ, h, f, D, F/#, RE, T_Sun, T_ground, r, a, d_Sun-Earth, R_Sun, A_s, dω_2, dω_1, T_(1→2), T_(2→1), qp, N_s, N_RO, N_DC, …

❑Focal Plane Arrays –FPA

Different types of technology have been identified for the FPAs of the spectral range of interest, 2D sensor with high gain and low noise.

➢ ***Selected CMOS-BI (Complementary Metal-Oxide Semiconductor) for VNIR range:***

- SONY, Teledyne, ams, HAMAMATSU,… (Shutter type, Spectral Range, Pixel size [µm], Dim [px], QE [%], Dynamic range, …)

BSI, or Back Side Illuminated sensors are also known as 'Back Illuminated'-BI sensors. They are a revision of traditional sensor designs which increases the light gathering efficiency of the sensor to deliver higher sensitivity, less noise and better all-round image quality

➢ ***HgCdTe Sensors for SWIR range***

- Teledyne, FLIR, , …(Shutter type, Spectral Range, Pixel size [µm], Dim [px], QE [%], Dynamic range, NETD, …)

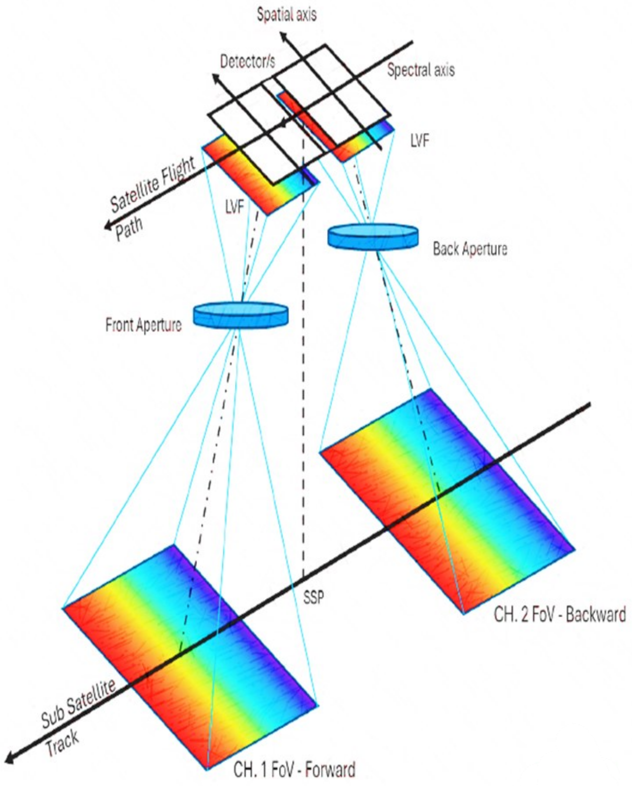
The IR sensor should have a dedicated cooling system.

➢ ***Microbolometers for Extended LWIR & FIR range (Amorphous silicon, Vanadium oxide, Ti, YBaCuO, GeSiO, poly SiGe, BiLaSrMnO) (Under evaluation)***

- Teledyne, FLIR, Honeywell, BAE Systems, DRS Technologies, … (NETD, …)

Preliminary Solutions – System & Subsystems (1)

Instrument Environment	**LEO-Orbit (400 km)**
System structures	Metal panel concept with internal shear frame. Turned and milled elements.
System size	Payload compartment: From 1U to 12U
Thermal Control Subsystem	Passive/Active cooling electronics
Spectral Range	VIS / Extendable in IR
Telescope	Three-Mirror Anastigmat / TMA with two symmetric entrance pupils Focal Length: ~ 100 mm Aperture (Pupil Diameter-D): < 20 mm F-number: ~ 10 - 5
Spectrometer	Linear Variable Filter (LVF) Resolving spectral element (double sampling): ~< 10 nm
Spatial Resolution	< 50 m
FoV	Two Channels (2 apertures) tilted by ±15° with respect to nadir pointing



Preliminary Solutions – System & Subsystems (2)

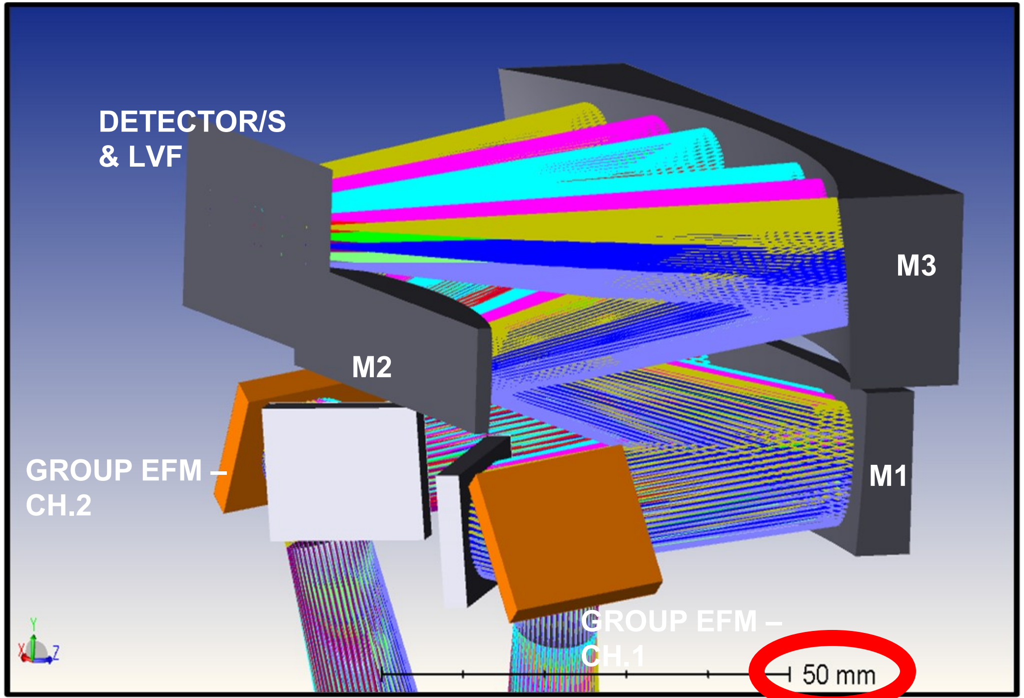
Hyperspectral-Stereo Space Optics Instrumentation
Hyperspectral-Stereo Camera for CubeSat (HSCC)

FORE-OPTICS

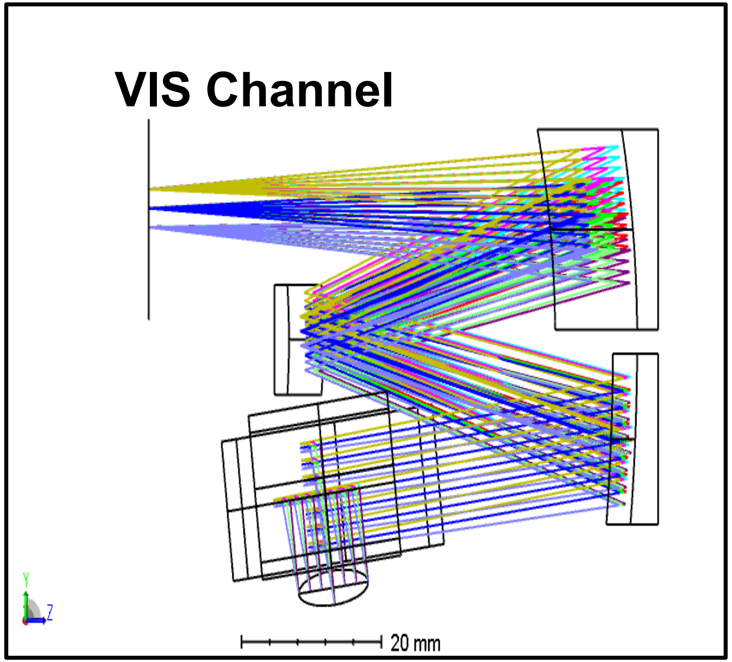
Two groups of quadrangular/circular entrance flat mirrors. Mirrors for reorienting the light beam and rotating the image plane.

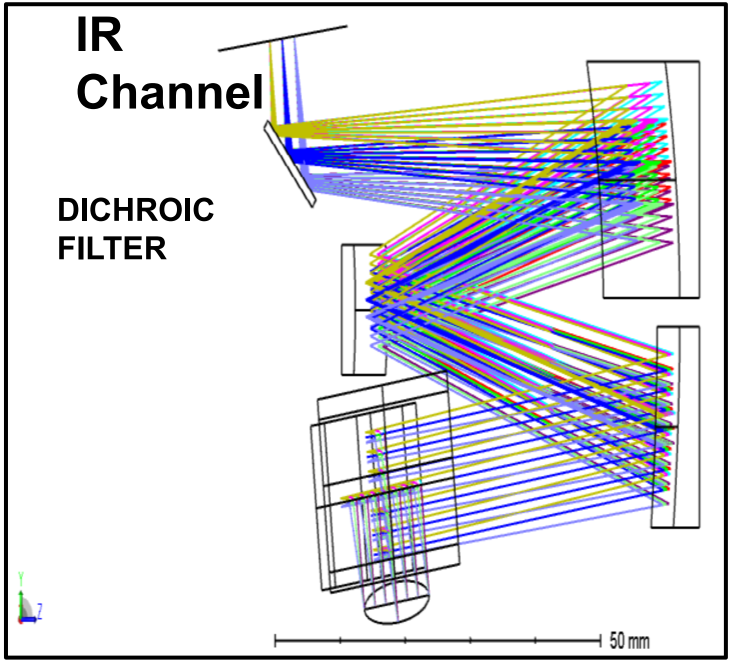
TELESCOPE

Mirror	Shape & Curvature
M1	Concave hyperbolic surface Radius curvature Conic constant
M2	Convex prolate ellipsoidal surface Radius curvature Conic constant
M3	Concave oblate ellipsoidal surface Radius curvature Conic constant

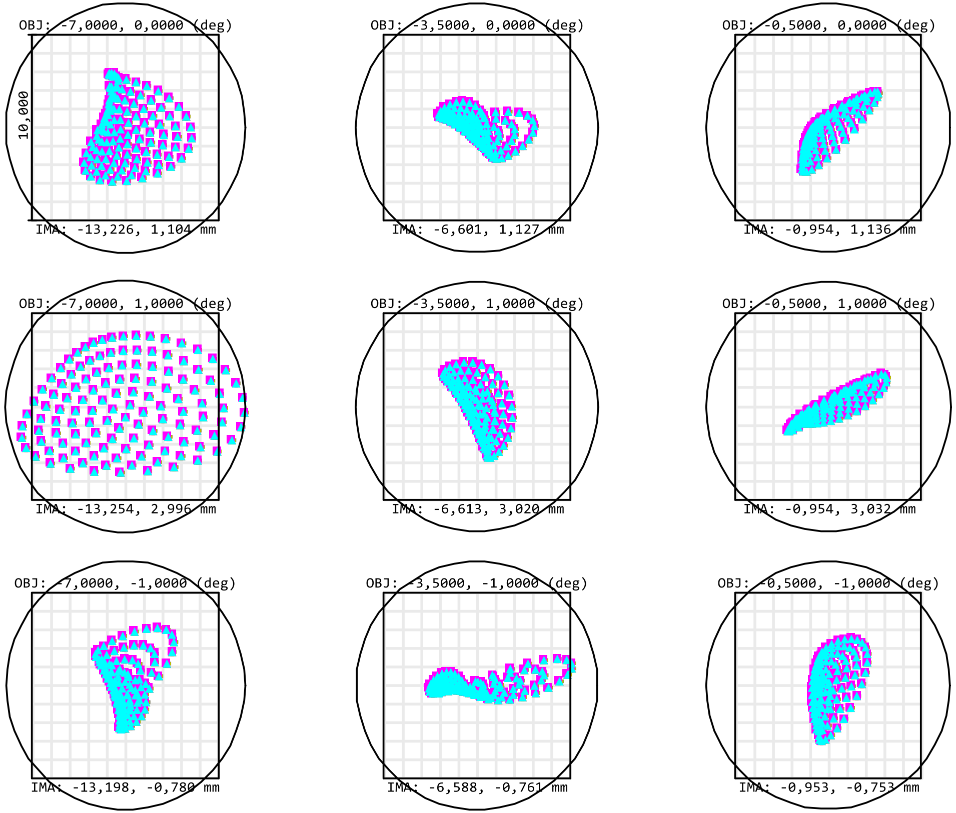


Preliminary Solutions – System & Subsystems (3)





HSCC Optical Performance. Spot Diagrams [1]

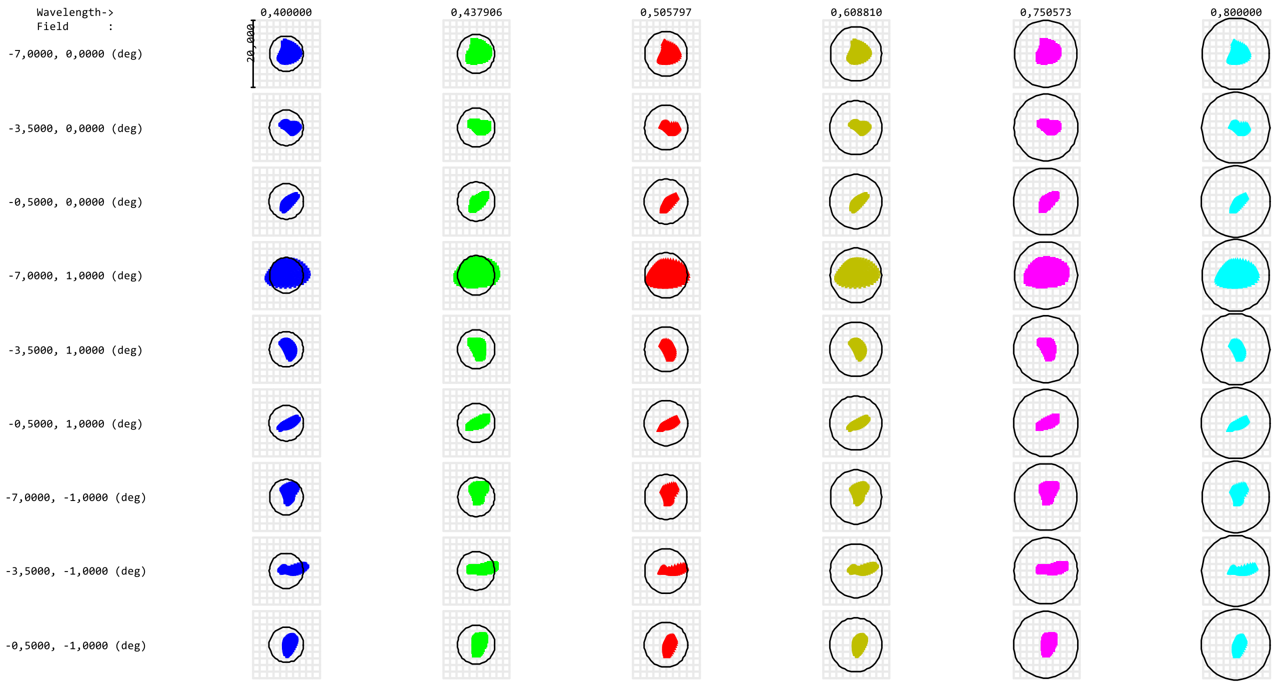


SPOT DIAGRAMS

Nominal spot diagram showing performance of the very compact TMA. The circles represent the size of the Airy disk.

Figure also show that the instrument is substantially diffraction limited in visible range over the whole field of view.

HSCC Optical Performance. Spot Diagrams [2]

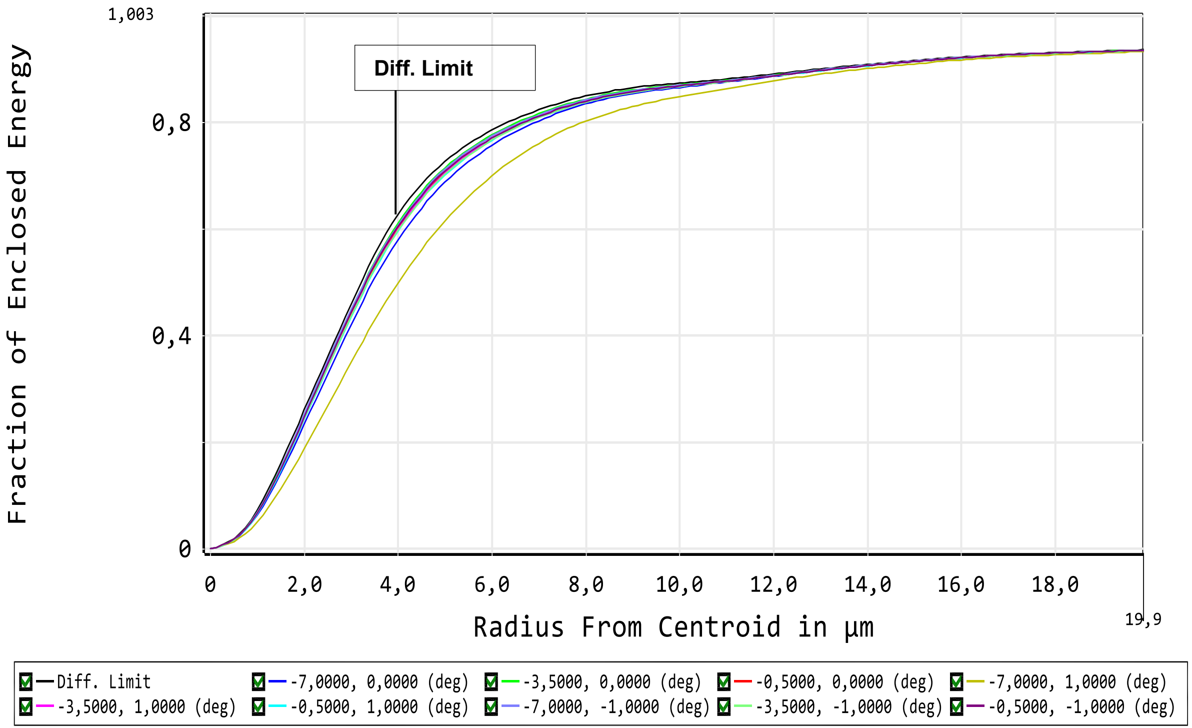


SPOT MATRIX DIAGRAMS

Distribution of spots on the focal plane of the telescope as a function of the analyzed wavelengths and fields of view.

It can be seen that for all cases of FoV < 7° the system is diffraction limited. In fact, in most cases spots are well shaped and concentrated at the center.

HSCC Optical Performance. FFT Diffraction Encircled Energy



FFT DIFFRACTION ENCLOSED ENERGY

Plot illustrating the calculated diffraction-limited encircled energy performance

At 84% fraction of enclosed energy the calculated focused spot radius is approximately under 10 µm.

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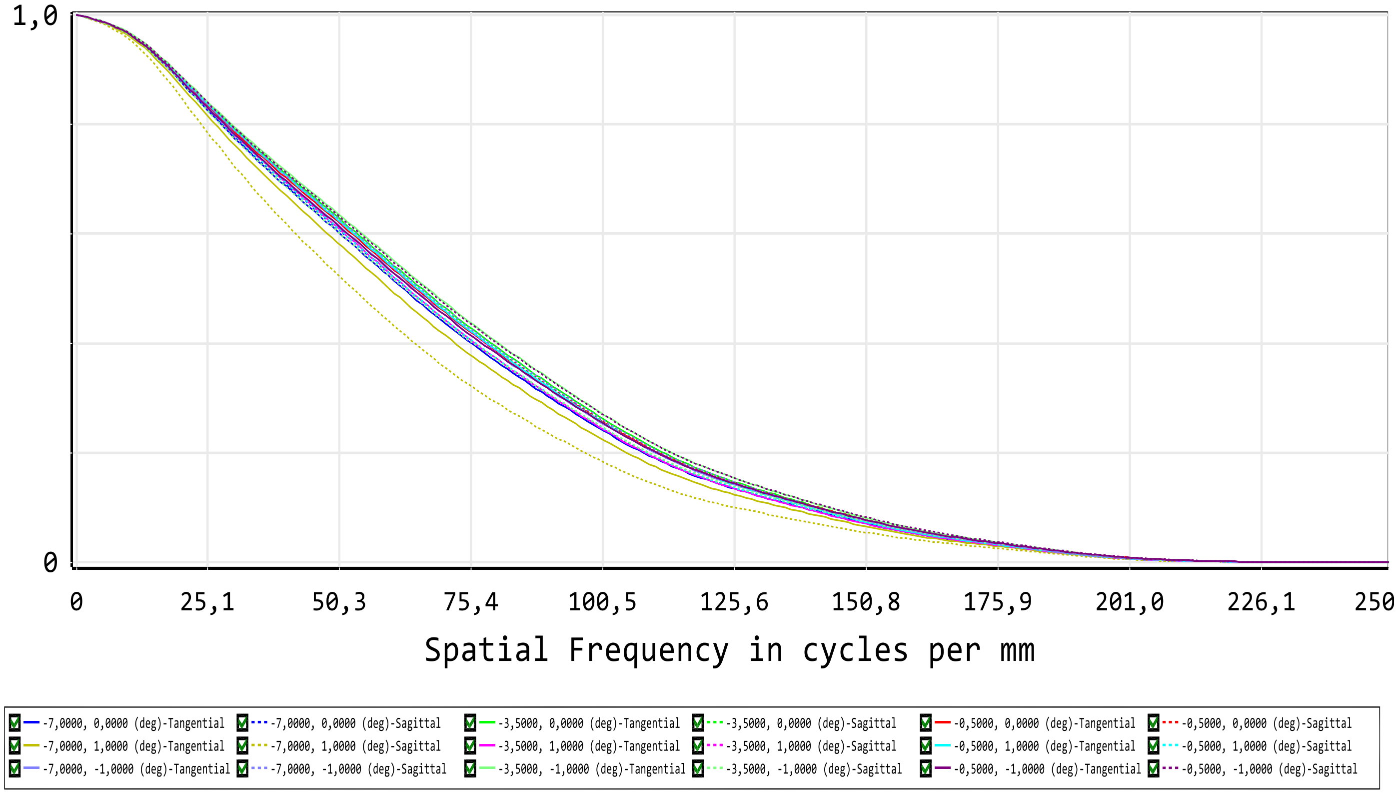
HSCC Optical Performance. Modulation Transfer Function – MTF



Polychromatic Diffraction MTF

POLYCHROMATIC MTF

The MTF is more or less linearly decreasing up to the cutoff frequency around 220 lp/mm.

HSCC for EO-HYPSOS System

Hyperspectral-Stereo Space Optics Instrumentation
Hyperspectral-Stereo Camera for CubeSat (HSCC)

FORE-OPTICS

Two groups of quadrangular/circular entrance flat mirrors. Mirrors for reorienting the light beam and rotating the image plane.

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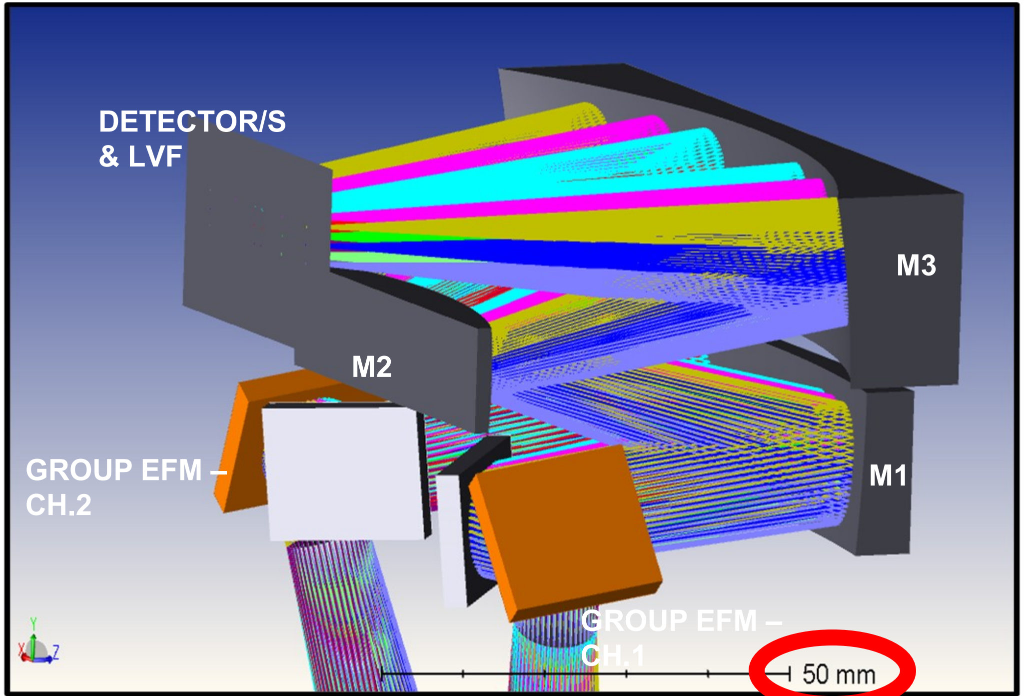


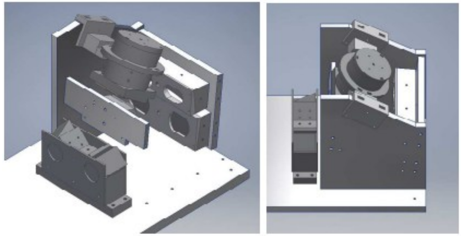
2. HYPSOS Project

Team Activities on HYPSOS Project (With INAF)

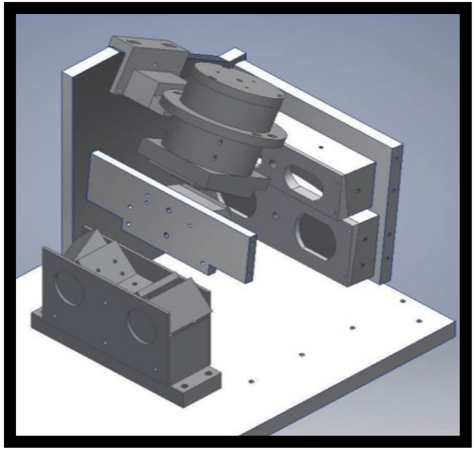
- HYPSOS - HYPerspectral Stereo Observing System. A remote sensing pushbroom instrument able to give simultaneously both 4D information, spatial and spectral, of the observed features

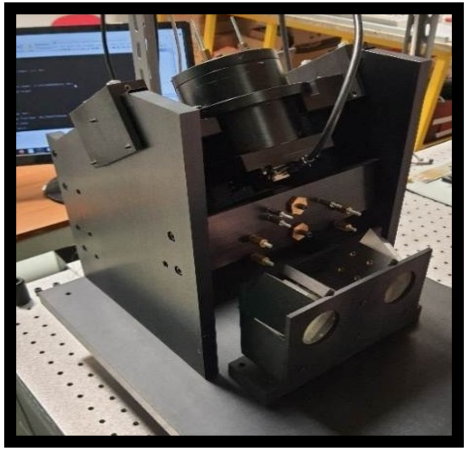
- In-lab characterization of HYPSOS, a novel stereo hyperspectral observing system: first results

- In-lab Characterization of HYPSOS, a Novel Stereo Hyperspectral Observing System: Latest Results



HYPSOS





<u>Carried out & Optimization activities:</u>

- Optical Bench
- Assembly
- Integration
- Alignment
- System Calibration
- Data Collection & Analysis

HYPSOS

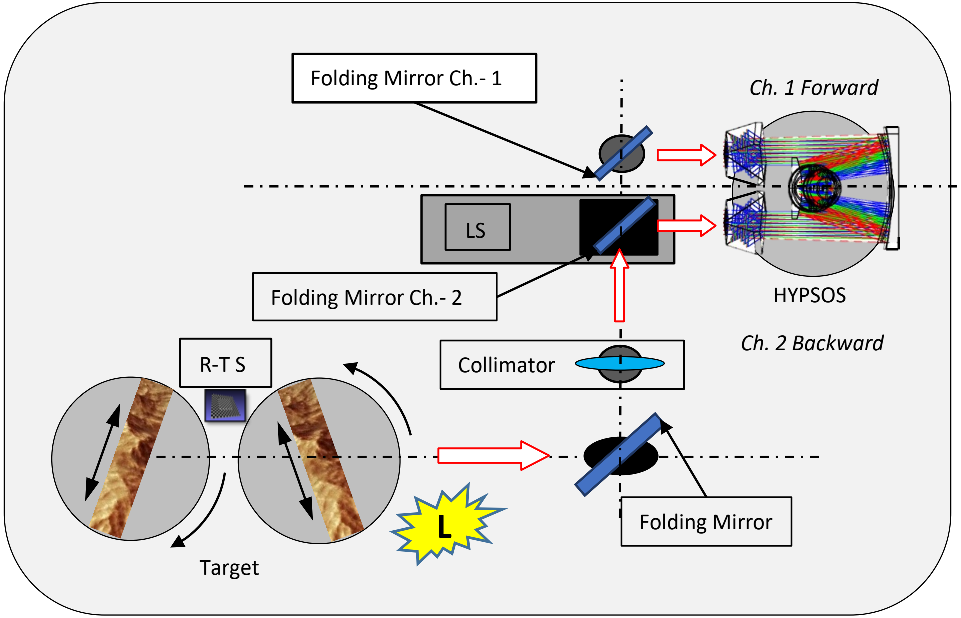
Team Activities on HYPSOS Project (With INAF)

Carried out & Optimization activities:

- HYPSOS Optical Bench + Assembly

- **A new chessboard type 4×4 cm^2 biplane calibration gauge which allows to estimate the components of the projection matrix M (Photogrammetric calibration)**
- **Targets like rocks of different compositions**
- **A halogen lamp light source**
- **A rotational stage capable of reproducing the stereo angle of HYPSOS similar to the flight model**
- **A translational stage capable of reproducing the push-broom modality**
- **A 1010 mm focal length collimator**
- **A linear stage that selects one of the two acquisition channels.**

Final acquisition configuration scheme



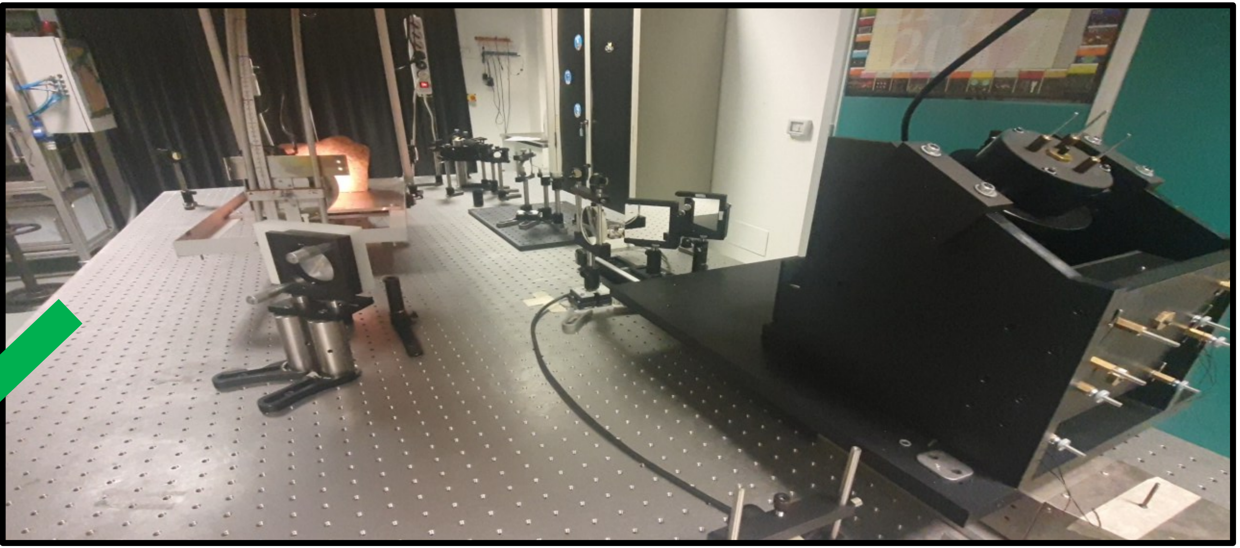
The acquisition system is automatically controlled and synchronizes the speed of the translation stage simulating the pushbroom scan with the acquisition frame rate of the sensor; moreover, it automatically switches between the two HYPSOS channels

HYPSOS

STEREO & PUSHBROOM SETUP SIMULATION

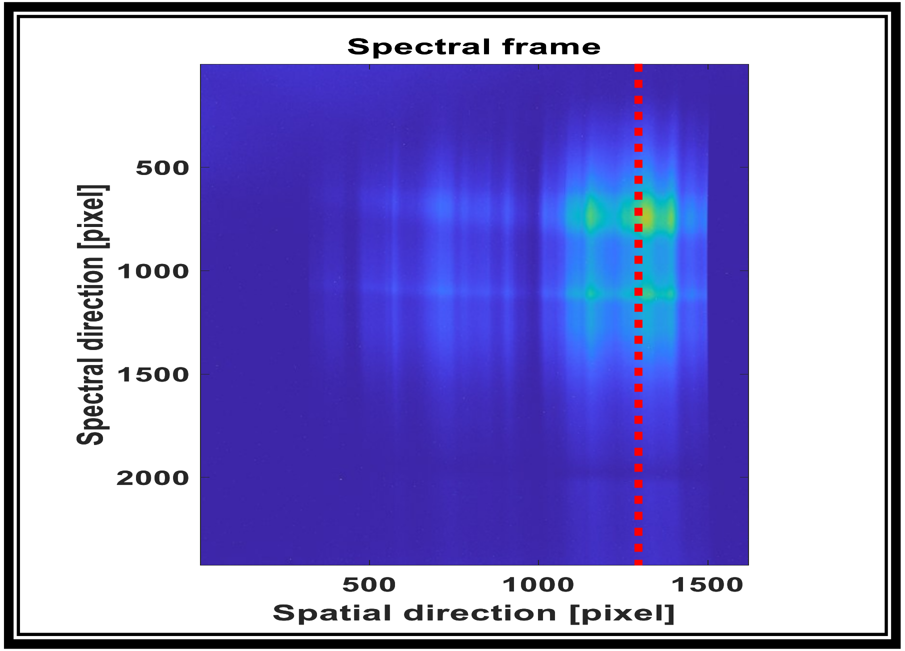
Team Activities on HYPSOS Project (with INAF)
<u>Carried out & Optimization activities:</u>

- ➢ Full Assembly
- ➢ Full Integration
- ➢ Data Acquisition
- ➢ Post Processing

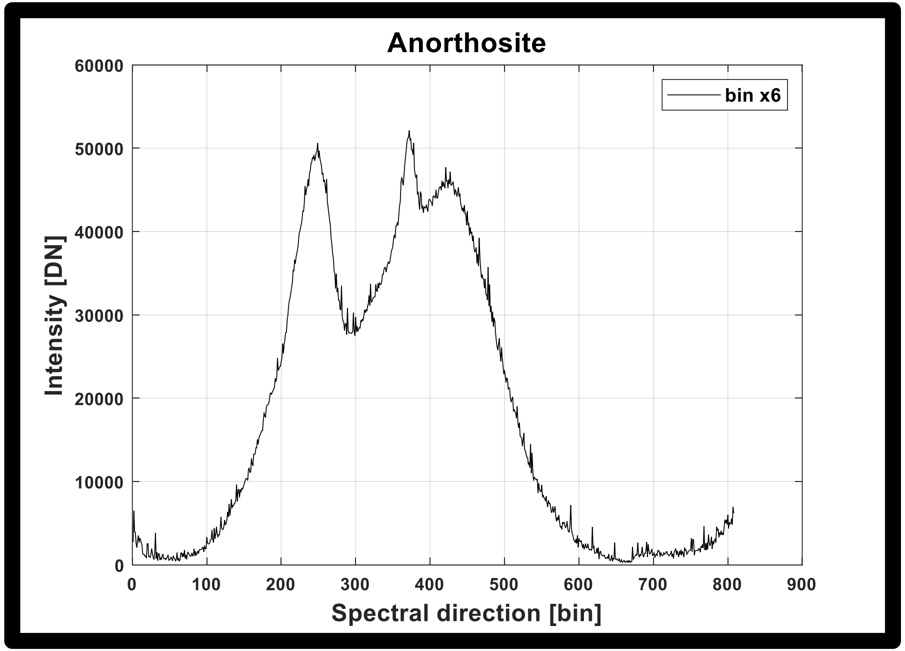


HYPSOS

FPA



Target Spectrum



Team Activities on HYPSOS Project (with INAF)

HYPSOS

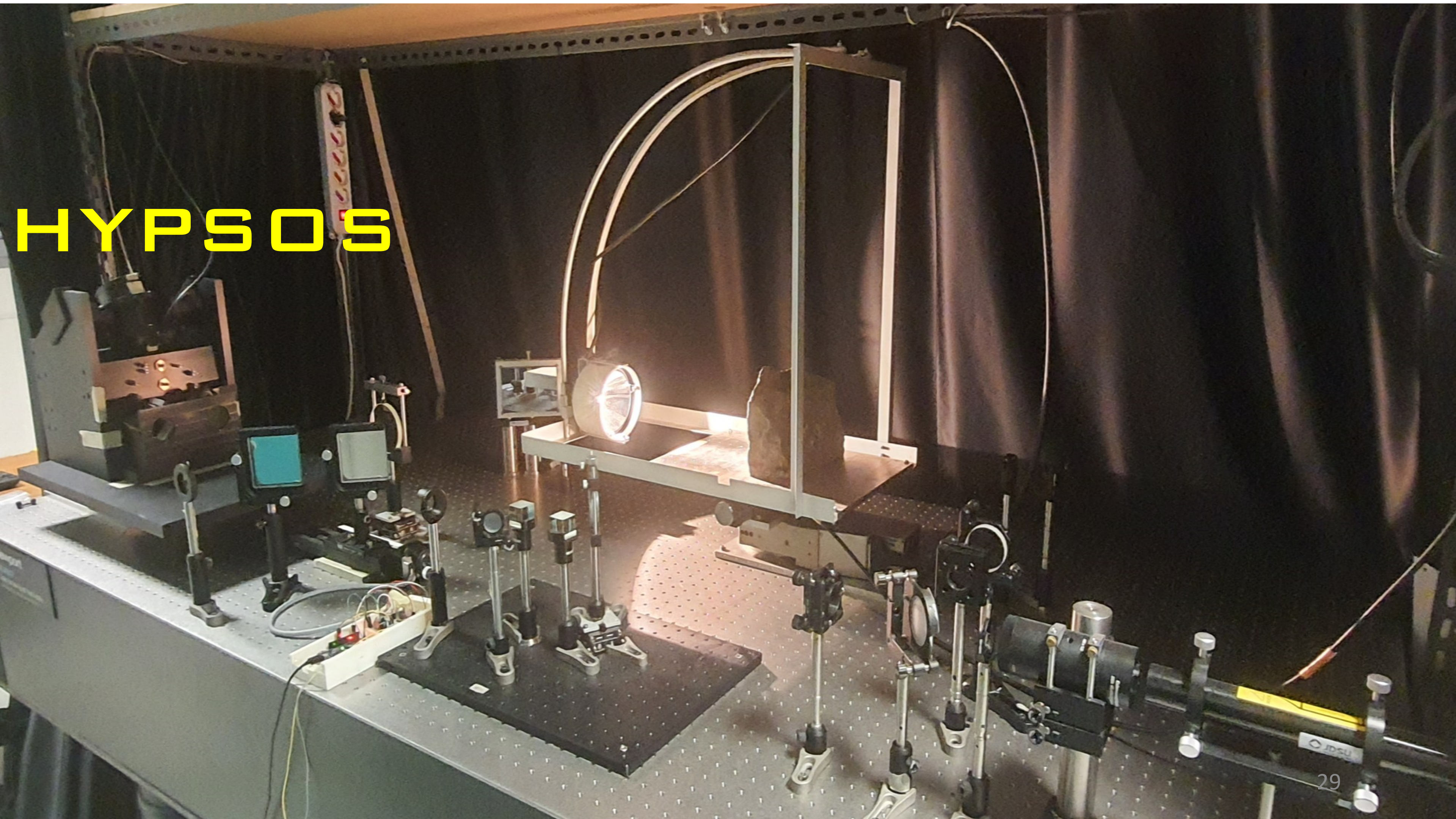
Carried out & Optimization activities:

- Data Collection & Analysis

We have HYPSOS 4D final product data to validate the system performance

- **The extraction of 3D information from the spectral pairs of stereo images acquired with HYPSOS is performed following a specific photogrammetric pipeline**
- **With the information about the two channels obtained by the calibration process it is possible to analyse the disparity and derive the 3D coordinates in the form of a sparse point cloud or grid DTM**
- **Comparison methodology will be used: all the targets under measurement by HYPSOS are rock samples whose surface has been previously measured by means of a high precision laser scan system (20 µm resolution) and with known spectral characteristics**

HYPSOS



3. EO-HYPSOS (Earth Observator) Project Activities in Industry

EO-HYPSOS Project (Earth Observator)

Activity in Industry: EIE Group Company

- ❑ Collaboration in EIE Group – 6 Months

The HYPSOS instrument provides stereo-hyperspectral data for mapping planetary surfaces. The project developed at EIE Group Company by the PhD candidate will consist in the identification and development of an opto-mechanical solution suitable for use on board CubeSats, and aimed at mapping the Earth's targets surface (EO-HYPSOS)

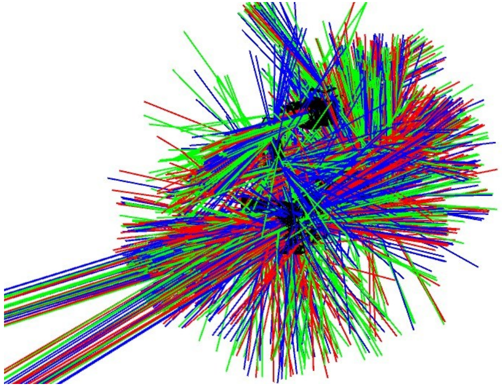
Task 1. General review of the conceptual design in EIE Group company on HYPSOS, identifying possible improvements or alternative solutions to the existing opto-mechanical configuration. Global review of the conceptual study → Review of the opto-mechanical requirements of the system.

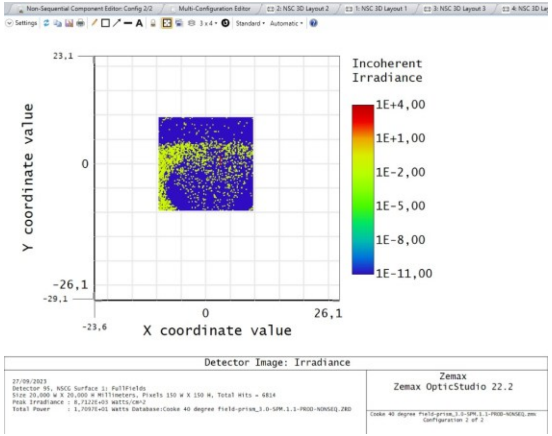
Task 2. Subsequently, alternative opto-mechanical solutions will be identified and studied, which will be compared on the basis of semi-qualitative evaluations.

Task 3. The opto-mechanical solutions identified in the previous phase as the best candidate will be developed by optimizing its optical performance. As part of the same activity, a preliminary study will also be carried out on the stray-light of the instrument.

EO-HYPSOS Project - Objectives

Straylight Analysis FRED - Zemax





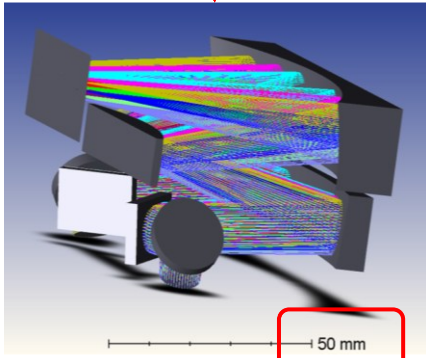
The objectives will be achieved through the negotiation of different payload alternatives, across a large number of potential candidates. In the early stages of the analysis process it is important to be able to evaluate different options without going into detail about each one; subsequently you will enter the details of each selected option.

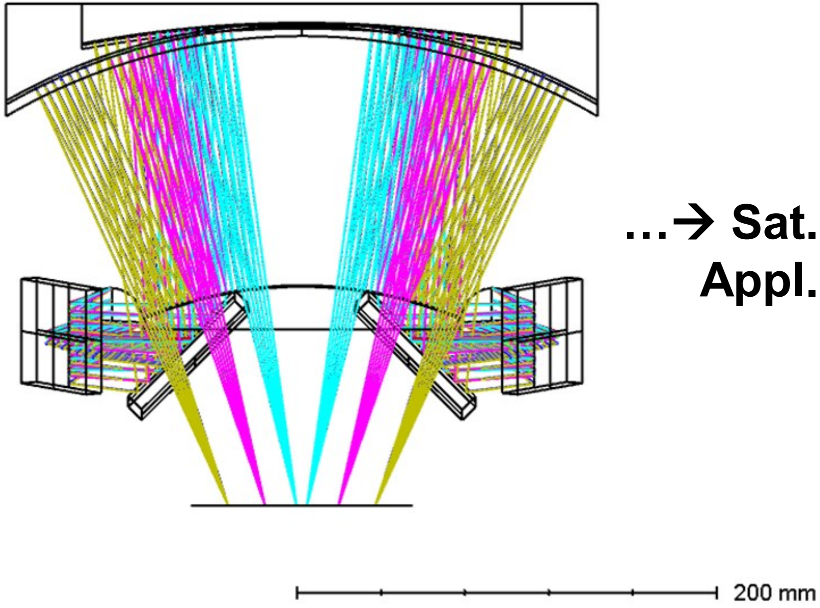
EO-HYPSOS (Earth Observator) Optical Design Layouts

(1)

From 1U → To 12U CubeSat Instrument Compartment

First compact layout configuration (1U), considering as proposal for an In-Orbit Demonstrator



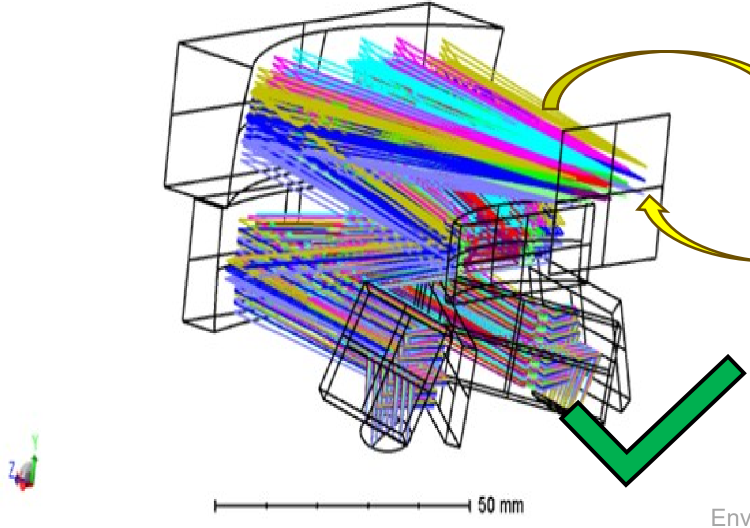


…→ Sat. Appl.

EO-HYPSOS (Earth Observator)

(2)

Evolutions of Optical Layout as a function of preferential optimizations. Iterative process. From the first solutions to the current ones. We expect that the datasets that EO-HYPSOS will be able to provide could have a strong impact in a perspective of stereo-remote sensing, both for Earth observation and Solar system exploration.



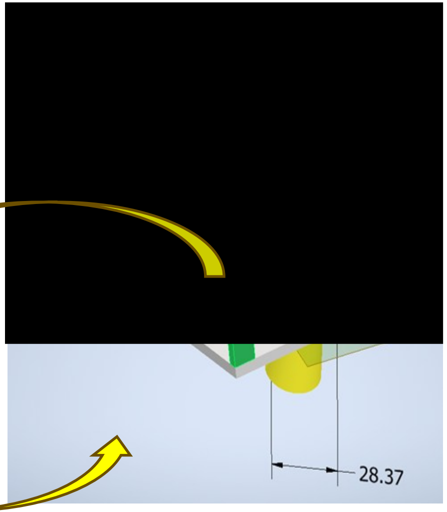
Zemax Ansys

OpticStudio Zemax

python

MATLAB

OPERATIONAL RESEARCH (Dedicated Algorithms & Software Strategies for optimization models)



ACKNOWLEDGEMENTS

The HYPSOS Project has been realized thanks to the contributions of the Italian Space Agency (ASI) and the Italian National Institute of AstroPhysics (INAF) under the ASI-INAF agreement 2018-16.HH.0

Thanks to all the Project Teams members who participated.

Thanks for the attention

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