800 ANNI 1222 · 2022

UNIVERSITÀ DEGLI STUDI DI PADOVA

Environmental Monitoring By Means of Hyperspectral Cameras on Board The Cubesat

PhD Candidate: Igor Dorgnach - 37th Cycle

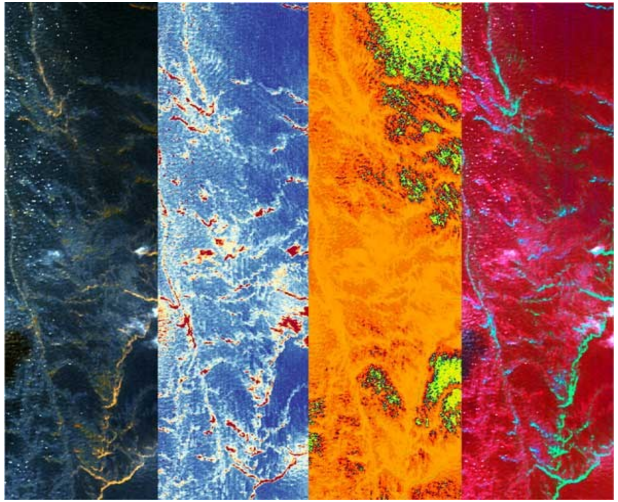
Supervisor: Prof. Giampiero Naletto

PhD Course in Science, Technologies and Measurements for Space

Admission to second year - 15/12/2022

Introduction

- **<u>The aim of the project is to define the design of an innovative instrument for terrestrial remote sensing, that is, for the observation of the Earth from satellite (Possibly extended to solar system application)</u>**
- We will study the feasibility of an instrument of a few units of cubesat to carry out hyperspectral observations, capable of providing spectroscopic information of the observed Earth's surface
- My research proposal focuses on an optical analysis and design methodologies applied to the cubesat missions for environmental monitoring

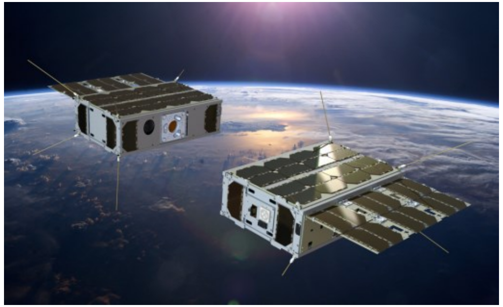


Background CubeSat for Remote Sensing

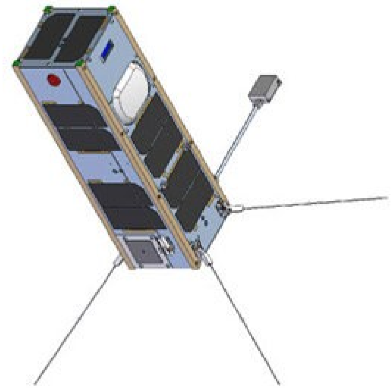
- **Spaceborne-Cubesat Hyperspectral Imaging for Earth Observation**

The use of instrumentation installed within Cubesat is a compactness solution aimed at achieving the "green" objectives of the project.

https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Hand-sized_hyperspectral_camera_to_fly_on_ESA_s_next_CubeSat



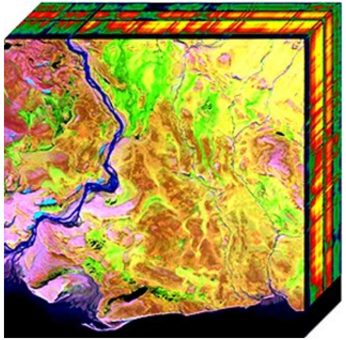
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_CubeSats



https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Hyperspectral_imaging_by_CubeSat_on_the_way

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



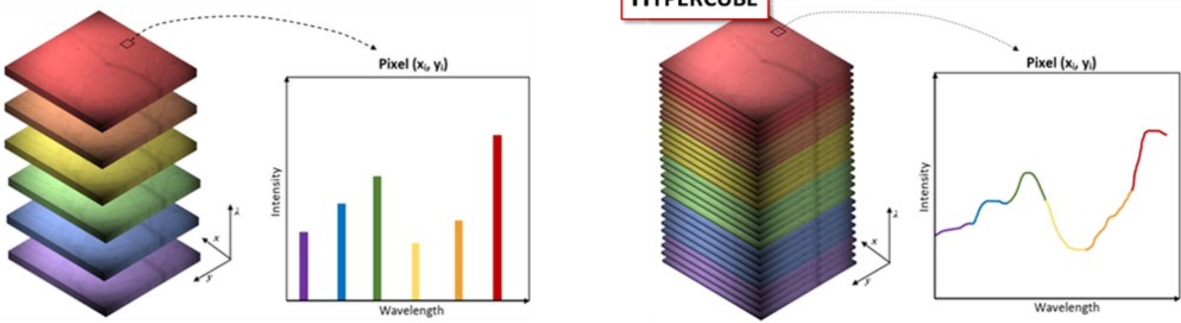
MULTISPECTRAL IMAGING

- N separated bands

HYPERSPECTRAL IMAGING

- Continuous spectrum

HYPERCUBE



Adapted from Luca Giannoni et al 2018 J. Opt. 20 044009

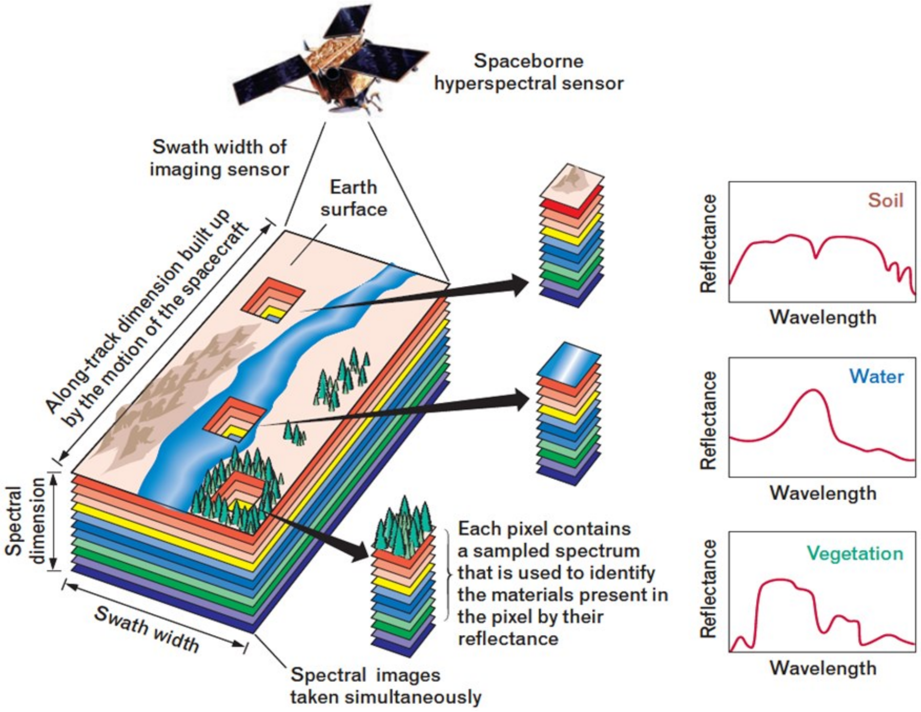
ENABLES SPECTRAL ANALYSIS

- Segmentation
- Spectral unmixing
- Evolution of spectra in time

Hyperspectral Imaging (2)

Domains:

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



http://www.markelowitz.com/Hyperspectral.html

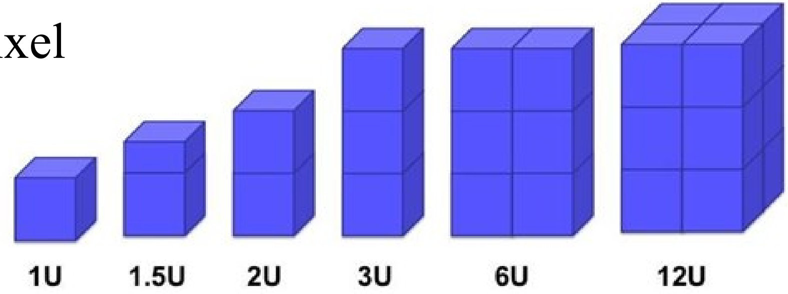
Objectives

The objectives will be achieved through a negotiation and optimization of different payload alternatives, across a vast 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; then you will enter the details of each selected option.

- **The payload must be able to take high quality pictures both in terms of spatial and spectral 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 → Configuration is carried out**

Mission Requirements

- The Instrument shall be capable to perform local characterization of the Earth's surface via a hyperspectral (potentially also hyperspectral-stereo) imager
- Very low IFOV < 0.125 mrad if possible
- The spectral sampling shall be low < 2 nm/pixel
- The mission lifetime shall be > 1yr
- VNIR-SWIR mission wavelength bands
- The CubeSat size <= 12U
- Rad-Hard Tech

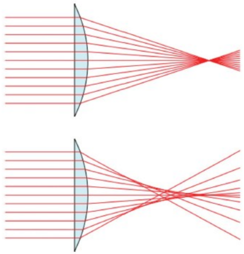


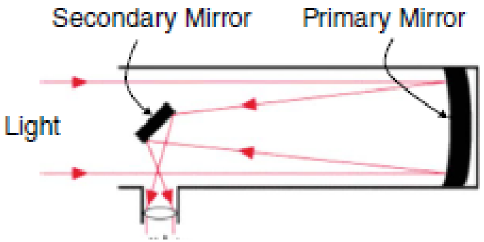
Design Requirements (1)

- ❑ **The CubeSat size <= 12U**
- ❑ **Selected Telescopes Configurations**

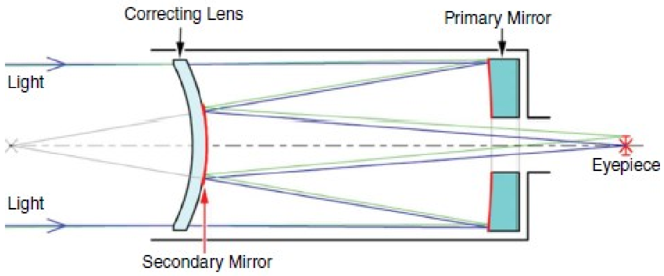
The function of the fore-optics is to use a telescope to image the ground scene onto the slit assembly of each spectrometer (VNIR and SWIR, if the wavelength range needs to be covered by two separate spectrometers). For each detector array, the telescope should meet the requirements for the SNR, the FOV, the spatial resolution, and the wavelength range. Other design requirements are that it meets the modulation transfer function (MTF) requirements, and that the in-field stray light is minimized

- ➢ Selected Refractive Design → Maximum Transmission, Essentially zero TCA, Minimum variation response with wavelength
- ➢ Selected Reflective Design
- ➢ Selected Catadioptric





Internet contents



Design Requirements (2)

- **Spectrometers Configuration (Slit-Scan) → → Prism, R&T Grating, Grism (Under Evaluation)**

A slit-scan imaging spectrometer images an entire line of ground typically (but not necessarily) in the cross-track direction while the spacecraft provides the forward (alo Under-track) scan.
The wider the slit, the more the entry of light, but the lower the resolution. The longer the slit, the better the light flux at the expense of transfer quality and therefore the resolution and image quality

- **Correct Materials for each component (Under Evaluation)**

Design Requirements (3)

❑ 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. In the first analysis, the choices fell on:

- ***Selected CMOS-BI (Complementary Metal-Oxide Semiconductor) for VNIR 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 vs InGaAs Sensors for SWIR range (Under evaluation)***

The *IR sensor will need to be cooled down*

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

- **Selected LEO → Sun-Synchronous 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, etc.

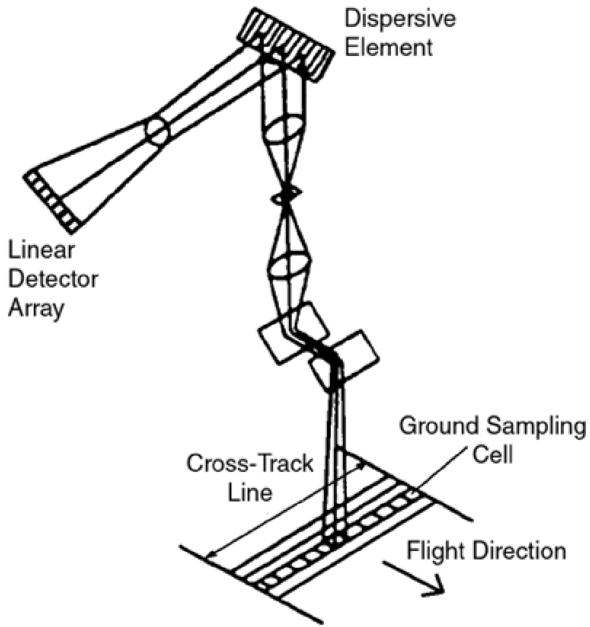
Trade-Off Parameters

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

System & Sub-Systems Parameter – Mission Concept (2)

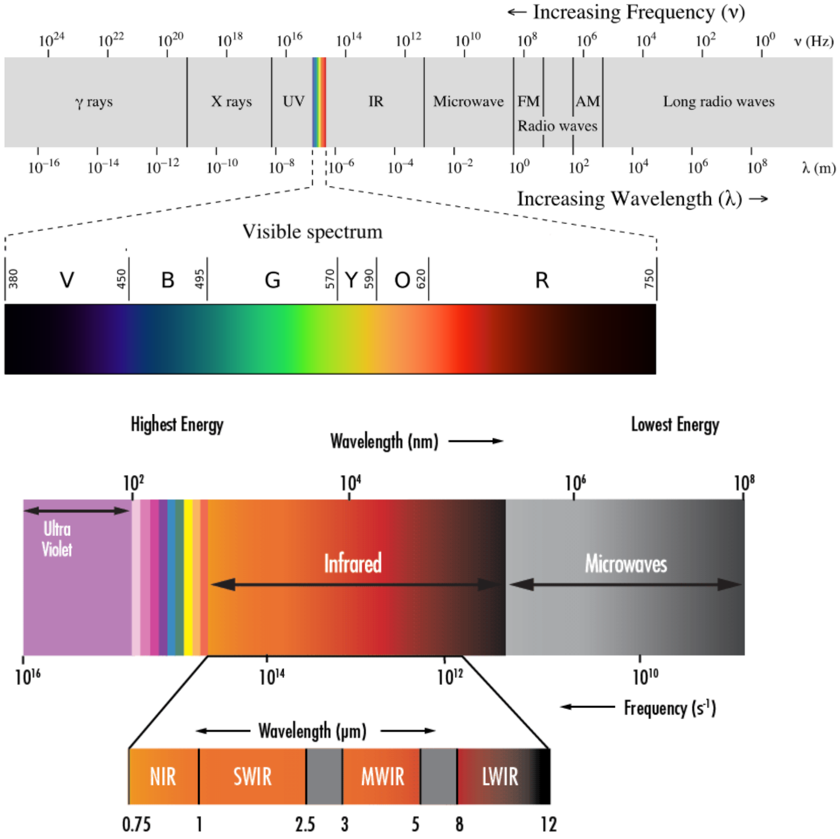
- **Selected Pushbroom Scanning mode**

A "Pushbroom" (along track) sensor consists of a line of sensors arranged perpendicular to the flight direction of the spacecraft. Different areas of the surface are imaged as the spacecraft flies forward. Pushbroom sensors are generally lighter and less expensive



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

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.

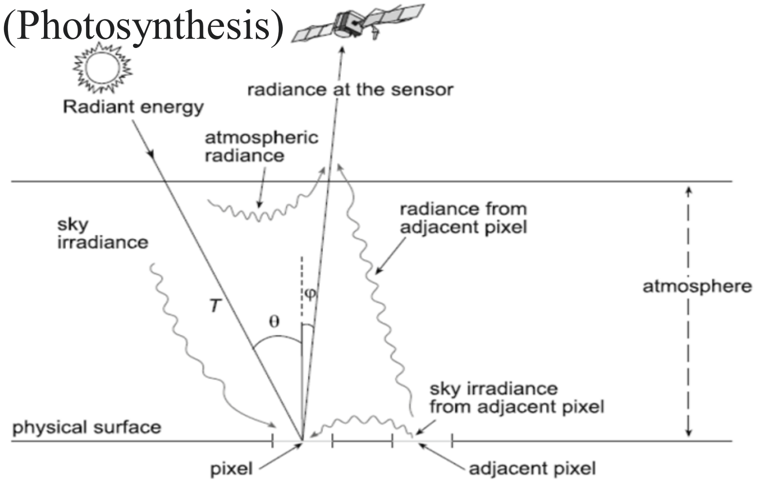
- Windows with high enough and almost constant transmission coefficient:

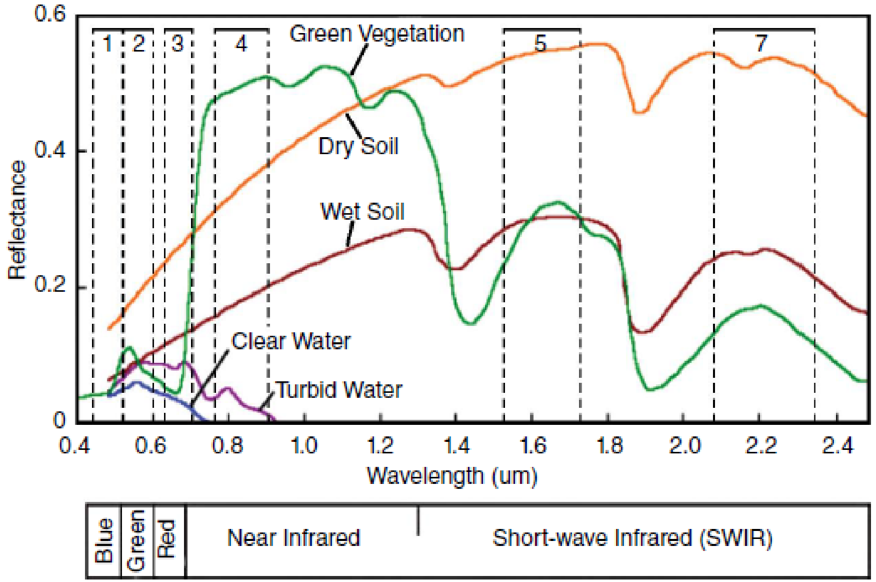
@ VNIR, from > 0.3-0.4 µm to 1 µm

@ SWIR, from > 1 µm to 2.5 µm

Radiometric Analysis (2)

- Leaf cells have evolved to re-emit solar radiation in the near-infrared spectral region (which carries approximately half of the total incoming solar energy), because the photon energy at wavelengths longer than about 700 nanometers is too small to synthesize organic molecules (Photosynthesis)





∑ Normalized difference vegetation index (NDVI)

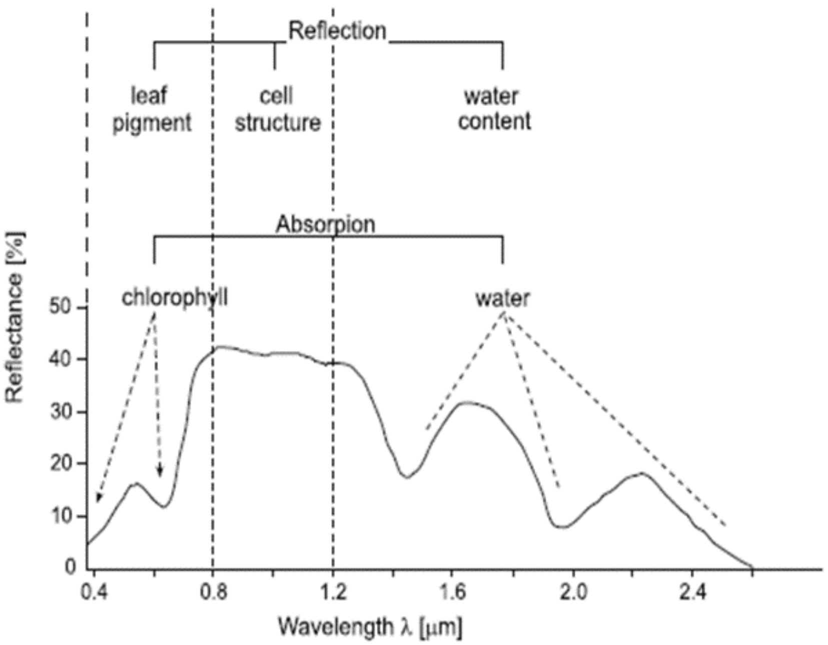
$$NDVI = \frac{NIR - R}{NIR + R}$$

R and NIR are spectral reflectance measurements acquired in the red (visible) and near-infrared regions respectively.

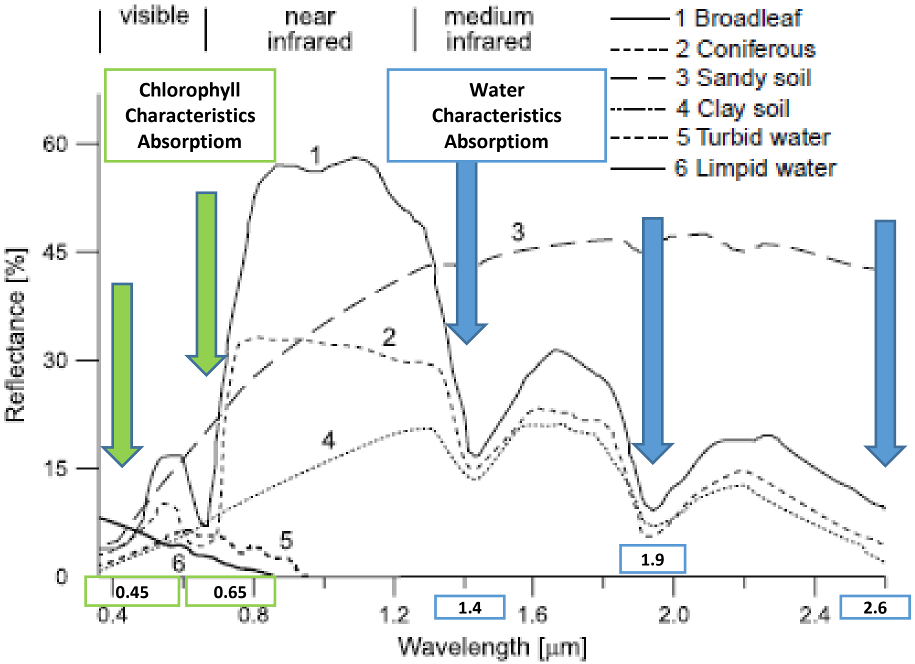
$NDVI$ is just one of the many parameters which will then be analyzed for the extrapolation of the useful data

Radiometric Analysis (3)

Radiometric Analysis of the Spectral Signature of Natural Elements



%Reflectance vs Wavelength
Natural Elements + Waters + Soil



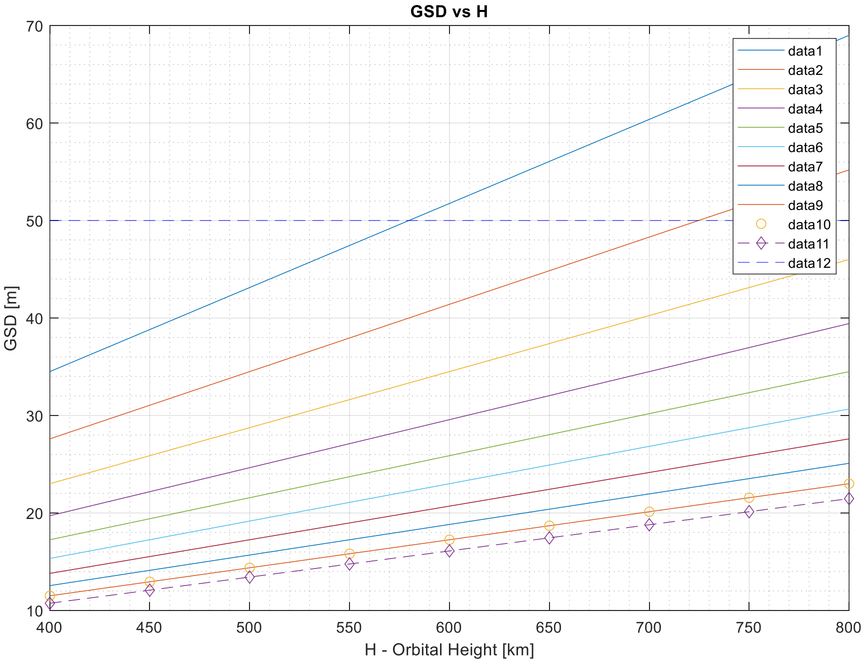
System & Sub-Systems Opto-Mechanical Parametric Studies (1)

- **Trade-Off Parametric Analysis Hyperspectral Camera**
- **Multi variable Optimization Problem (Algorithms)**

➢ GSD vs H (Parametric variable)

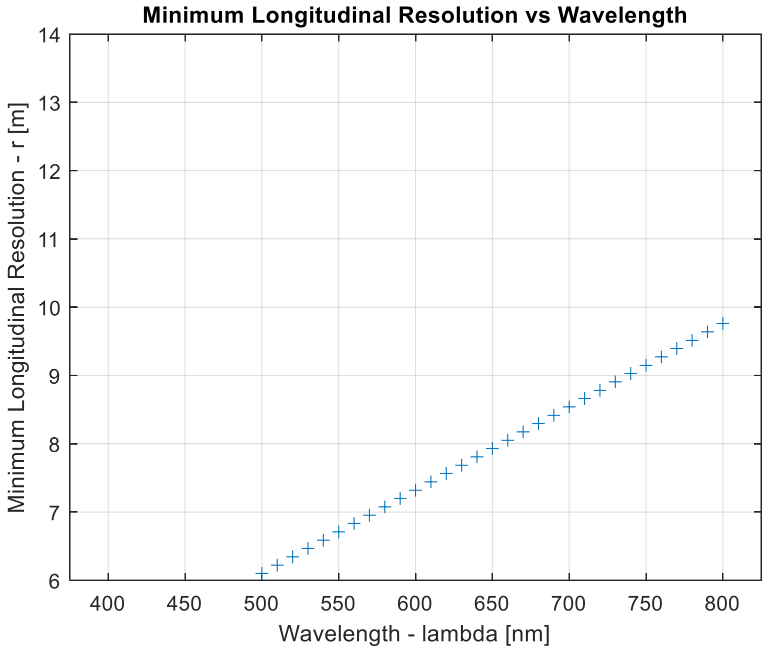
➢ … vs ps (Parametric variable)

➢ EFL vs … (Parametric variable)



System & Sub-Systems Opto-Mechanical Parametric Studies (2)

- **Trade-Off Parametric Analysis Hyperspectral Camera**
- **Multi variable Optimization (Algorithms)**
  - **r vs λ (Parametric variable)**
  - **SNR vs …(Parametric variable)**
  - **… vs H (Parametric variable)**



Next Step

❖ **Preliminary design study of opto/mechanical system follows**

❖ **Characterization of the optical layout and structural support follows**

❖ **Feasibility study aboard a CubeSat**

❑ **Collaborative activities in EIE GROUP – 6 Months**

EIE GROUP   EIE Engineering & Design

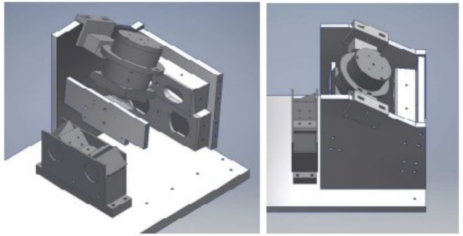
Activity on HYPSOS Project

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

<u>Optimization activities:</u>

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

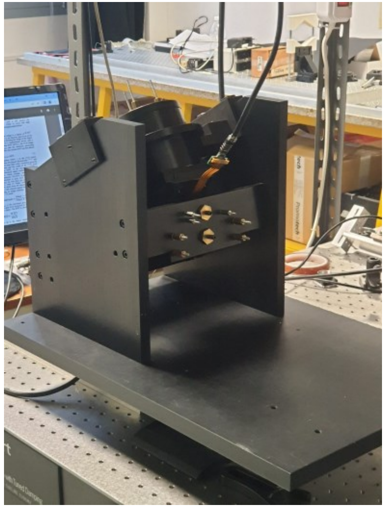
Agenzia Spaziale Italiana

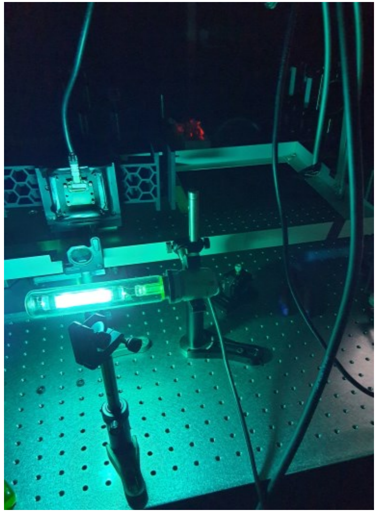


Osservatorio Astronomico di Padova

HYPSOS

CNR IFN Istituto di Fotonica e Nanotecnologie





Conclusions

- Project Objectives: The identifiable objectives are represented by the actual design and implementation of the correct optical and mechanical layout of the Spectrograph that will be installed on Cubesat according to specific system requirements. Feasibility studies
- Methodology: The development methodology consists in obtaining, through the various phases of analysis and design, a process of continuous multivariable optimization of the system and of the related subsystems of the hyperspectral instrumentation. Trying to adopt innovative solutions that allow the housing of the instrumentation inside a Cubesat
- Personal Objective: To improve the set of knowledge and competencies to contribute and realize a novel type of optical instrumentation that meets the research objectives

Università degli Studi di Padova

800 anni 1222·2022

Gantt Chart of Activities

CISAS G. Colombo

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE
1	Hyperspectral instrumentation on Cubesat	
1.1	Bibliography research. State of the Art - Study of the Hyperspectral instrumentation on Cubesat	100%
1.2	Methods of Analysis. General and Specific System Requirements	100%
1.3	Methods of Experimental Design	100%
2	Optics Layout charaterization & Structural Support - Numerical Investigation	
2.1	Preliminary Designs	80%
2.3	Sub Systems (Opto/Mech) Preliminary Design	70%
2.5	Optics Layout / Validation	40%
2.6	Mechanical Layout	10%
2.7	Iteration & Optimization Process Designs (Volume, Mass & Stress)	0%
2.8	3D CAD Model Realization	0%
2.9	Data Analysis	0%
3	Feasibility Study - Spectrograph on Cubesat	
3.1	Interface definition	0%
3.2	Optimization of dimensions and masses	0%
3.3	Thermal analysis	0%
3.4	Structural analysis	0%
3.5	Validation	0%
3.6	3D CAD Model of the Spectrograph on Cubesat Final Design	0%
3.7	Data Analysis	0%
4	Validation	
4.1	Exploitation	0%
4	Analysis for Space Applications	0%
5	PhD Thesis Development	
5.1	Report	0%
5.2	PhD Thesis Writing and Documentation	0%

FIRST YEAR				SECOND YEAR				THIRD YEAR			
T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D

Thanks for the attention

1222 · 2022
800 ANNI

UNIVERSITÀ
DEGLI STUDI
DI PADOVA