An Ultra-Compact Hyperspectral Imager in the Thermal Infrared and its application in Earth observation

EPIC Online Technology Meeting on Earth Observation

Fabrizio Preda, CEO at NIREOS SRL | 28th November 2022

NIREOS at a GLANCE

INNOVATIVE

STARTUP COMPANY

SPIN – OFF

OF POLITECNICO di MILANO UNIV.

MAY 2018

INCORPORATION

FACILITIES

BOVISA AREA – MILAN

10 PEOPLE

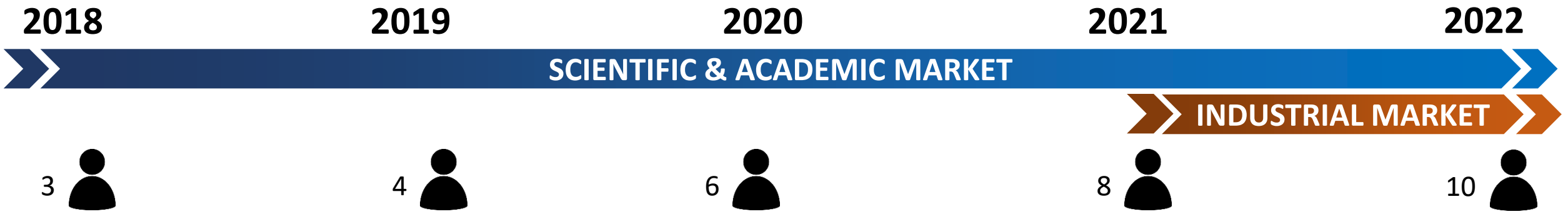
EMPLOYED

> 80 YEARS

CUMULATIVE EXPERIENCE IN PHOTONICS

We develop and manufacture novel devices for SPECTROSCOPY:

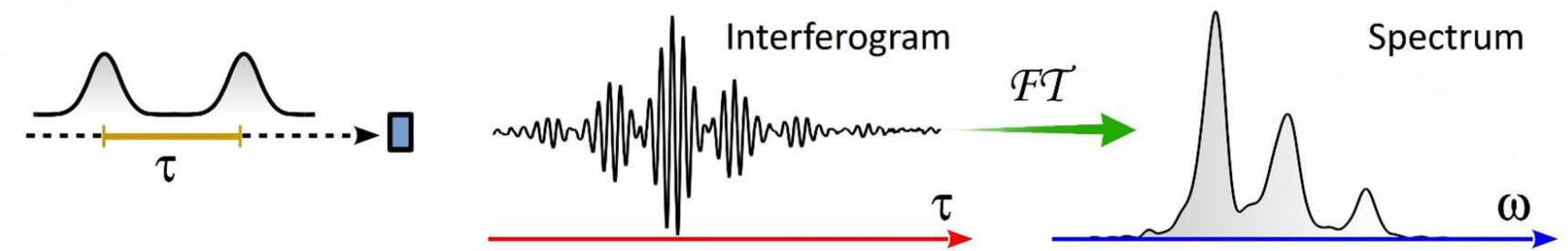
interferometers, spectrometers, multispectral & hyperspectral cameras



HERA *HYPERSPECTRAL CAMERA*

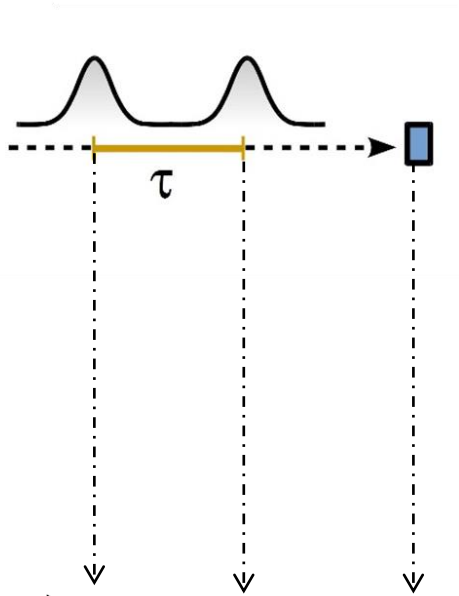
NIREOS

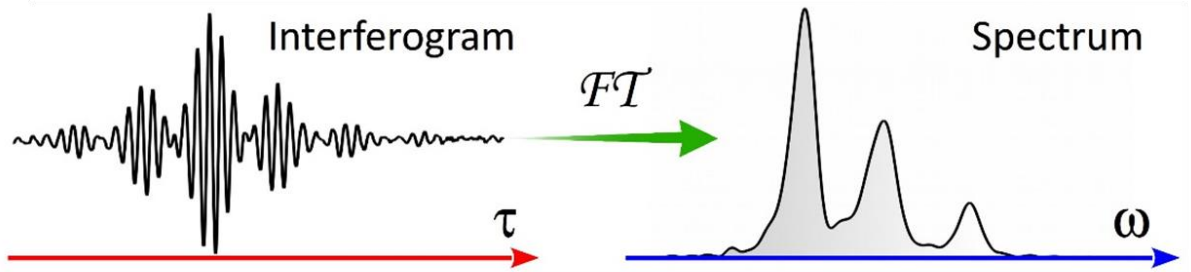
FTIR spectrometer
(single pixel detector)



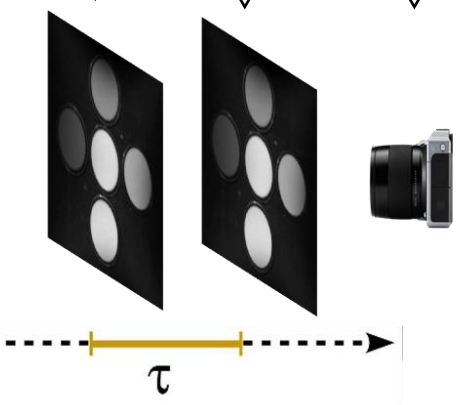
Fourier Transform Hyperspectral Camera

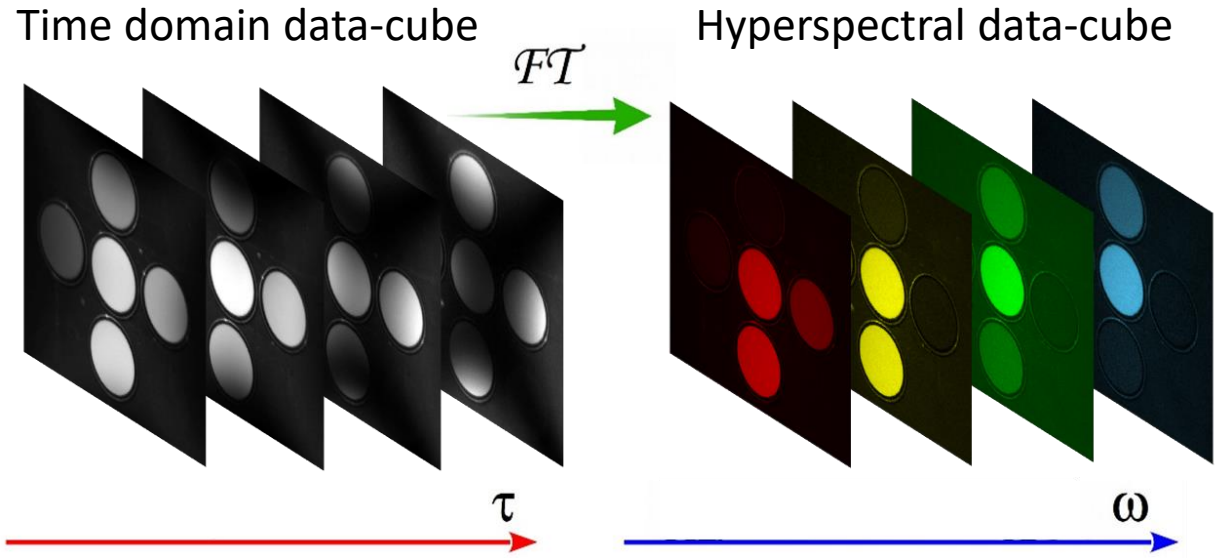
FTIR spectrometer
(single pixel detector)





FTIR Hyperspectral camera
(2D detector)



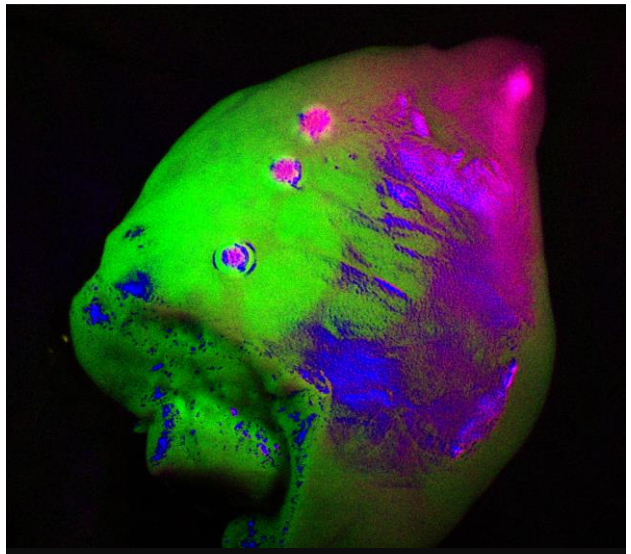


Based on a novel Fourier-Transform approach

- COMPACT & LIGHTWEIGHT
- HIGH SPATIAL & SPECTRAL RESOLUTION
- TUNABLE SPECTRAL RESOLUTION (SELECTABLE VIA SOFTWARE)
- HIGH OPTICAL THROUGHPUT & SENSITIVITY
- HIGHLY STABLE and BROADBAND

HERA *HYPERSPECTRAL CAMERA*

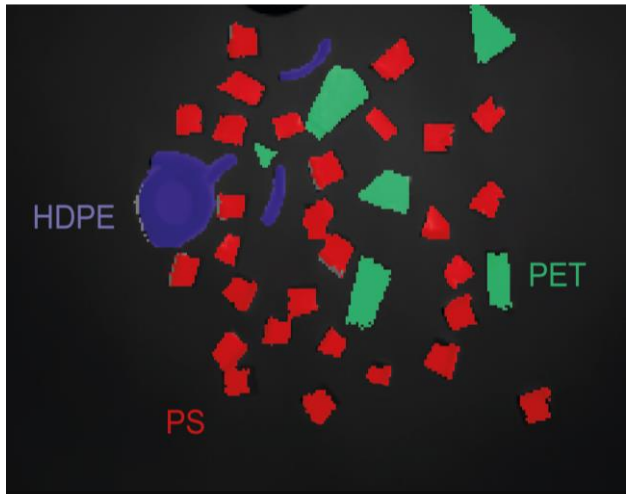
NIREOS



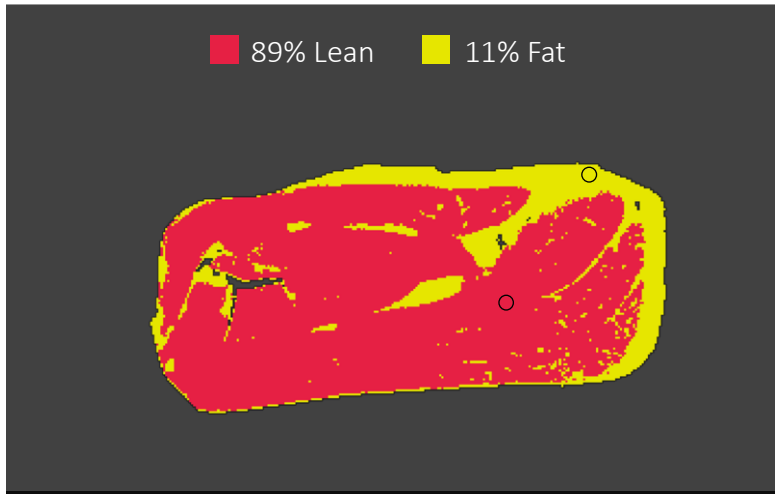
(MICRO)-BIOLOGY

VEGETATION STUDIES

REMOTE SENSING



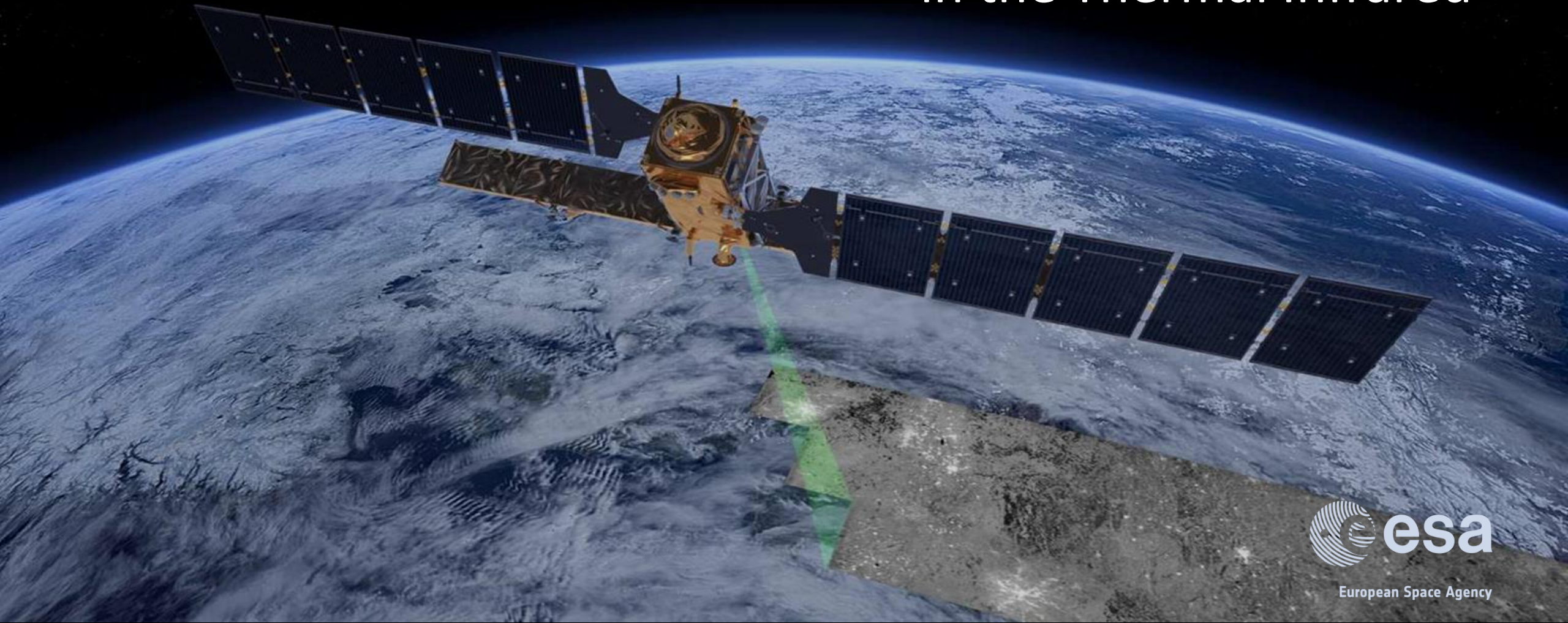
PLASTIC SORTING



FOOD QUALITY CONTROL

CULTURAL HERITAGE

An Ultra-Compact Hyperspectral Imager in the Thermal Infrared



esa
European Space Agency

State of the art: Current NASA imaging missions

TERRA satellite, various spectrometers

- **ASTER**: 14 discrete bands (9 vis/NIR, **5 TIR**)
- **MODIS**: 36 discrete bands (19 vis/NIR, 12 MWIR, **5 TIR**)

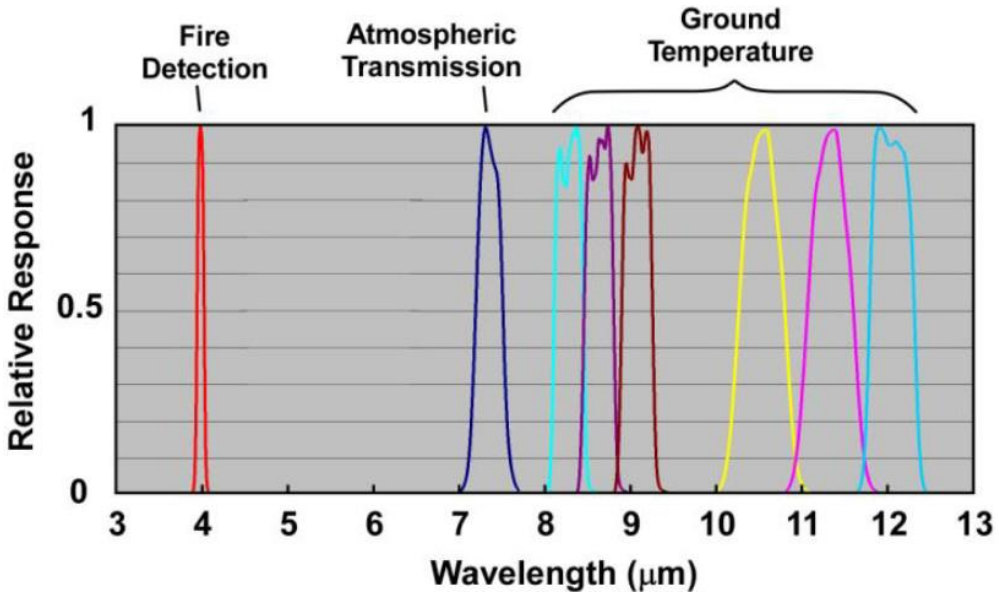
Multispectral

HyspIRI project:

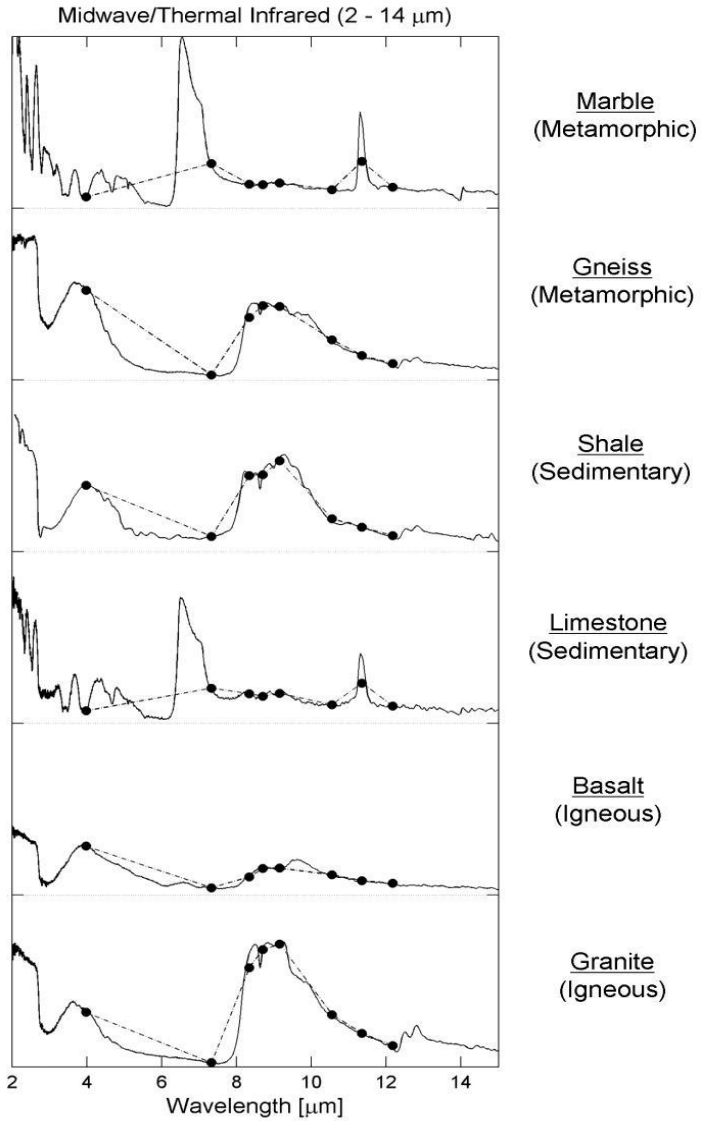
- visible shortwave infrared (VSWIR) imaging spectrometer (380 and 2500 nm in 10-nm contiguous bands)
- a thermal infrared (TIR) multispectral scanner**: 8 spectral bands in the TIR**.

Multispectral

Discrete Detection bands of **HyspIRI project**

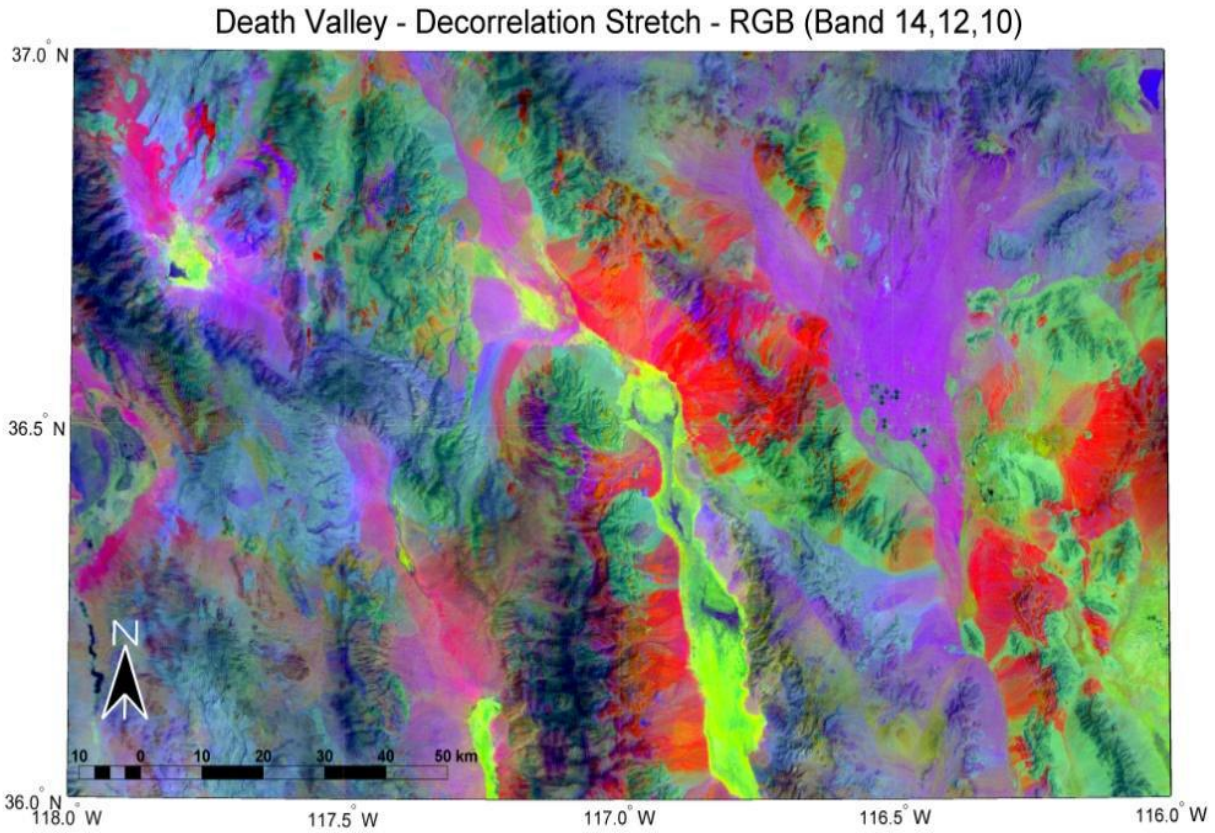


State of the art: Spectral Limitations of Current Missions



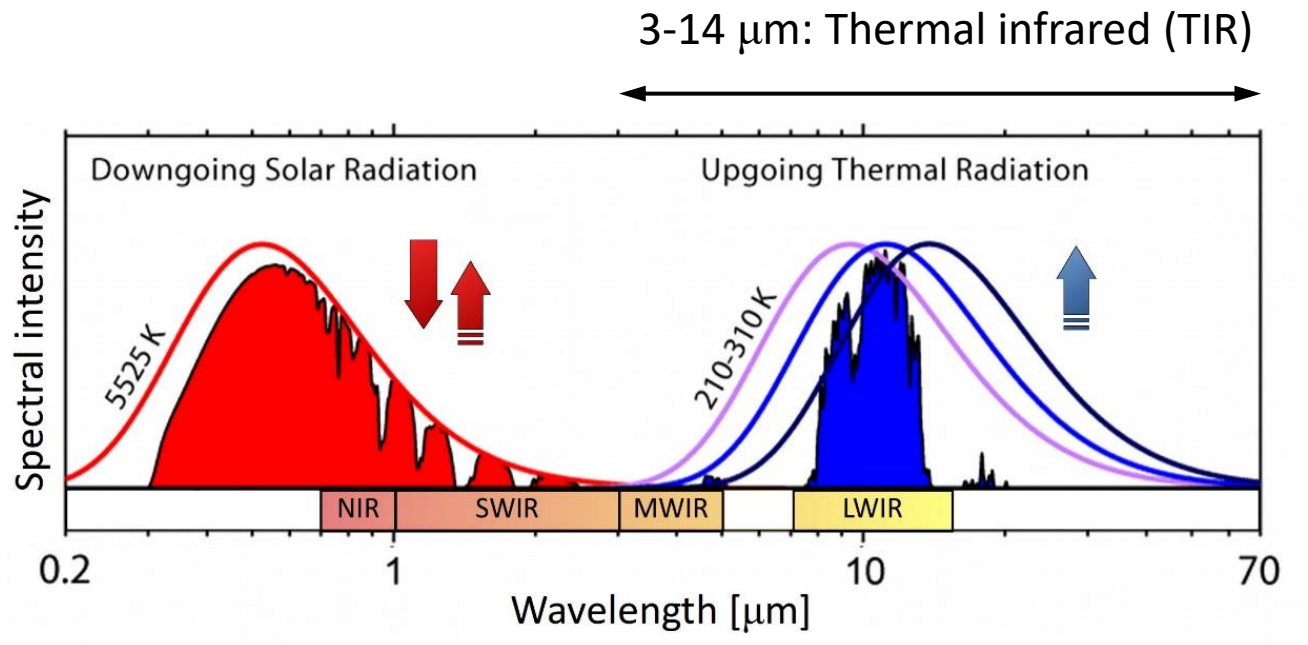
Detection of mineral types (ASTER)

quartz features - **Carbonates** - **quartz-poor regions**



HyspIRI Thermal Infrared (TIR) Band Study Report

WHY the Thermal Infrared?



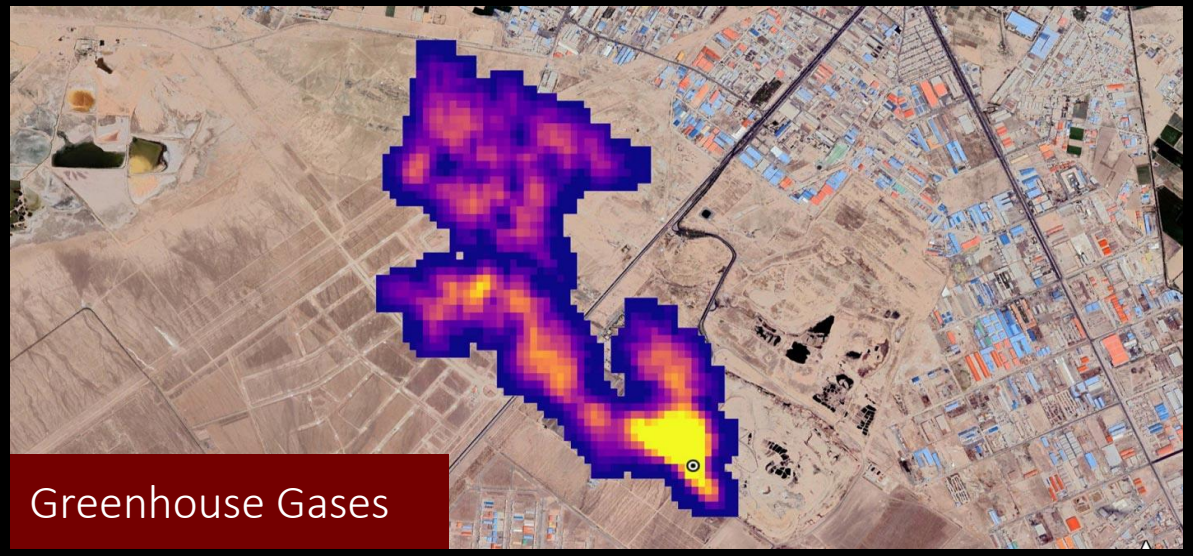
VISIBLE / NIR

- scattered solar radiation
- spectral information about **absorption**, **reflection** and **scattering** of molecules and particles
- *land*, *water* and *atmosphere* environments;

MWIR / LWIR

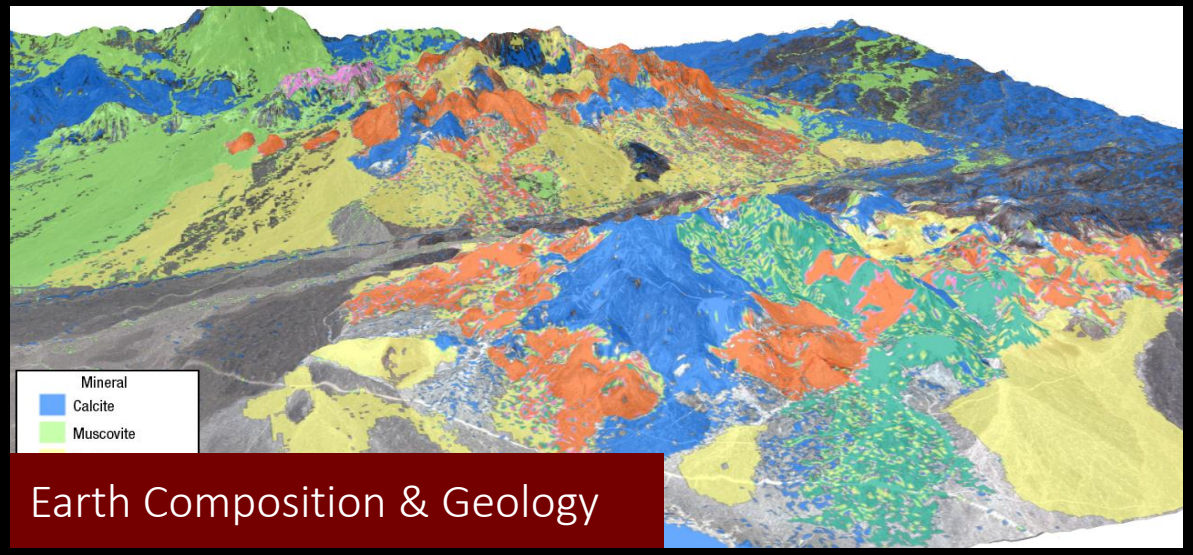
- thermal radiation from Earth surface and atmosphere
- spectrum reveals **temperature**, **albedo**, **radiance** and **emissivity**, composition of the surface
- Bands due to absorption lines from **vibrational modes**
- fingerprinting of chemical compounds on surface and in atmosphere.

HYPERSPECTRAL CAMERA IN THE THERMAL INFRARED APPLICATIONS



Greenhouse Gases

Earthquakes, Volcanoes, Wildfires



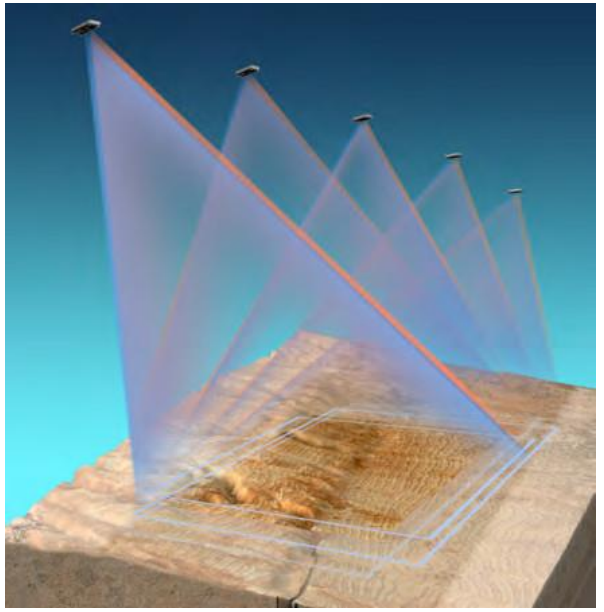
Earth Composition & Geology

Water Pollution

Hypothesis on Orbit and Parameters

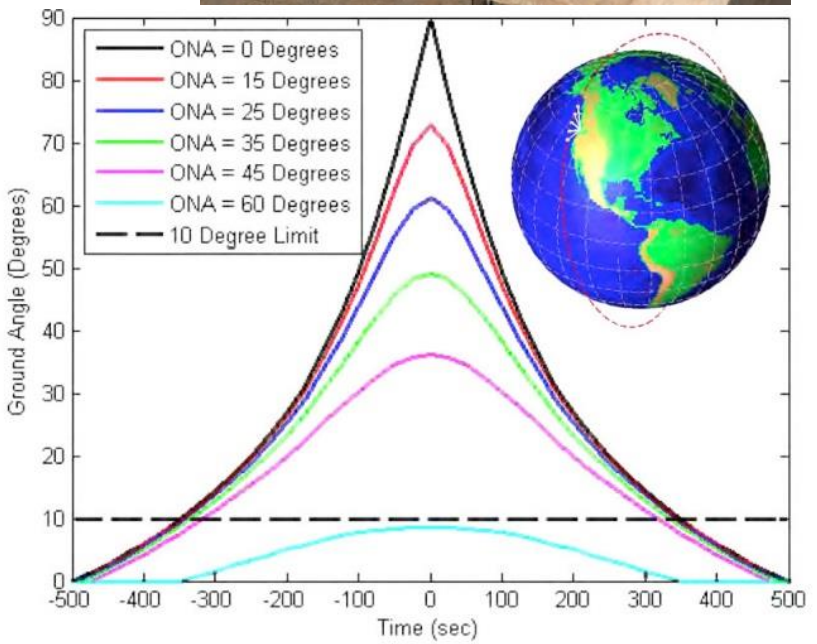
REQUIREMENTS OF OUR CAMERA:

- Staring imaging: each frame acquired as a whole
- Integration time per frame: **1ms-1000ms**
- 1 hypercube = 150-400 frames
- Acquisition time per hypercube: **from few seconds to few minutes**



SUGGESTED ORBIT PARAMETERS:

- Low-Earth Orbit (600-800 km)
- **Fixed-point staring approach**:
  Vehicle rotates to maintain a fixed aim point during pass



Orbit and imaging technique used by:
ISS, weather satellites, SkySat satellites ...

Data from: Joseph Green, Jet Propulsion Laboratory, «Staring Imaging Overview», KISS Workshop 2014, *June 16 – 20, 2014 California Institute of Technology*

NIREOS

Meeting at ESTEC - European Space Agency (the Netherlands, 24 Nov 2022)

Phone: +39 327.67.18.100

Website: www.nireos.com

Email: info@nireos.com

NIREOS SRL – Follow us!

Products on the Market

GEMINI

Common-Path Interferometer

GEMINI-2D

Common-Path Interferometer,
(advanced version of GEMINI)

SPIDER

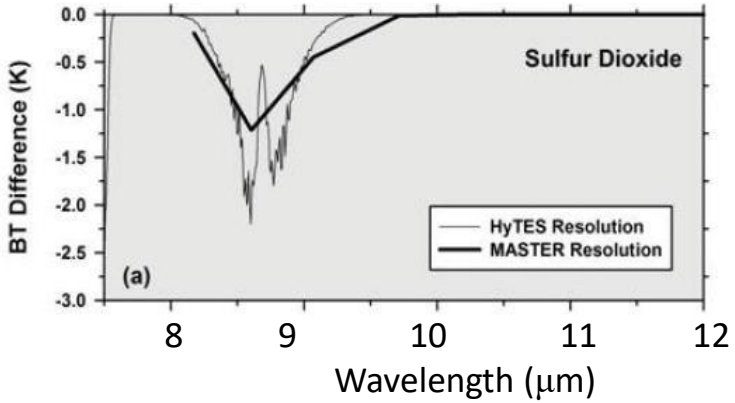
Broadband Photodetector
Amplified
ADC embedded

HERA

Hyperspectral Camera

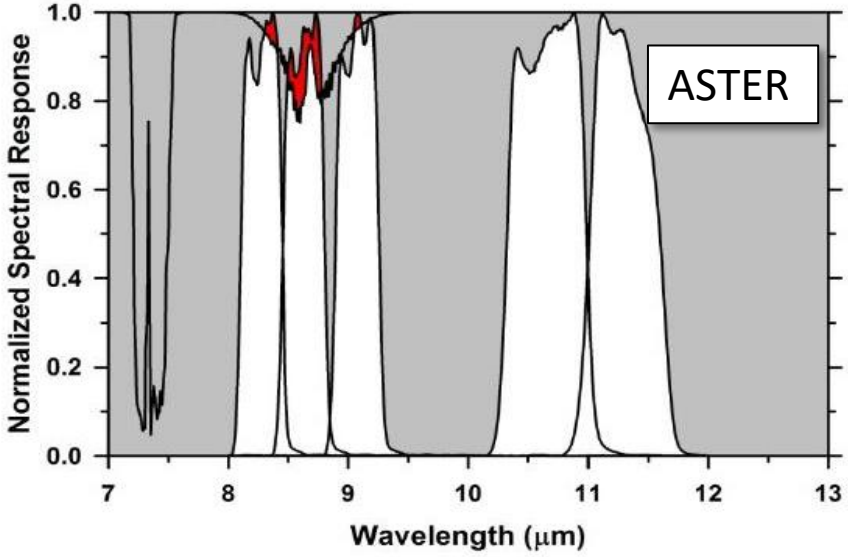
State of the art: Spectral Limitations of Current Missions

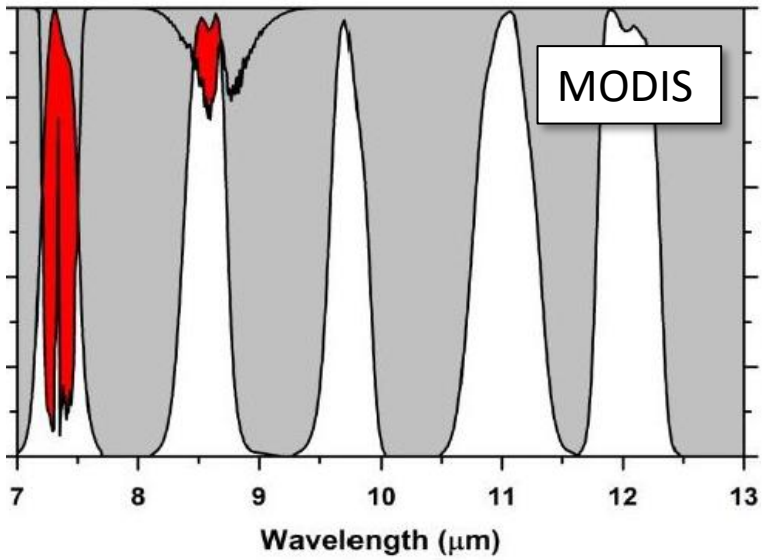
EXAMPLE. Spectrometer response *vs* SiO_2 transmission (volcanic plumes)

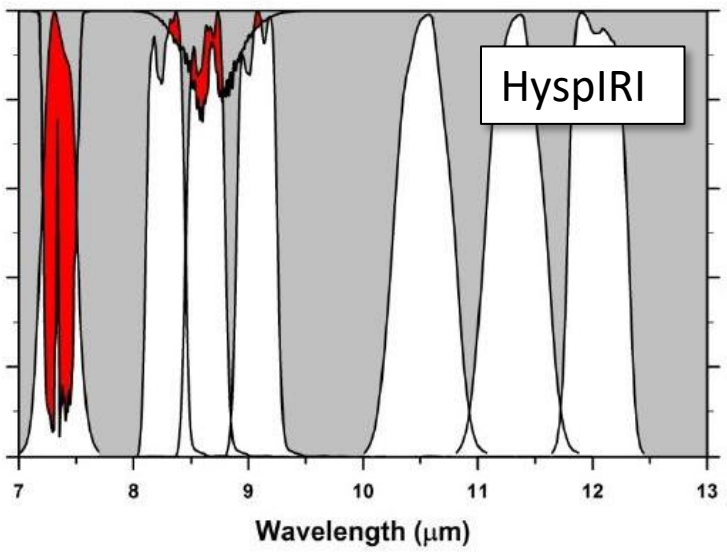


High-resolution band models [*Berk et al.*, 2005] are required to retrieve spectra from multispectral TIR data.

A. Berk et al., *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XI*, edited by S. S. Sylvia and P. E. Lewis, Proceedings of SPIE, Bellingham, WA. (2005)







Towards the Space

"An Ultracompact Hyperspectral imager in the Thermal Infrared"
(3 – 14 μm)

The Open Space Innovation Platform (OSIP)

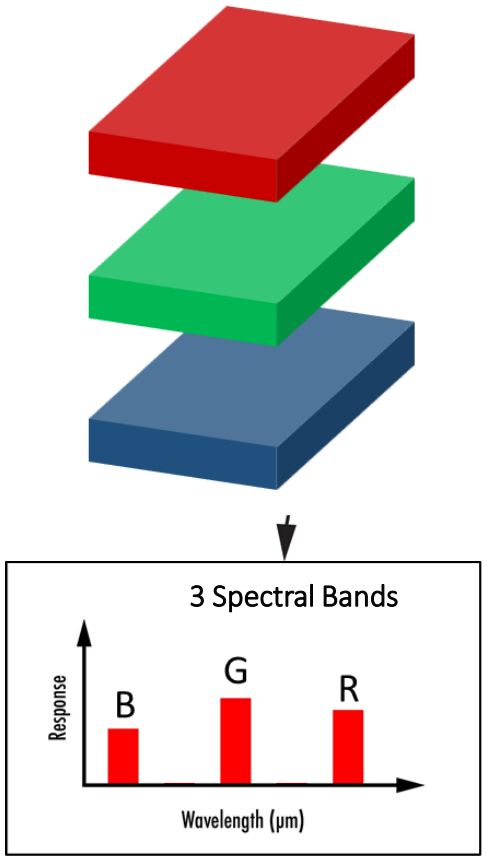
Consiglio Nazionale delle Ricerche Istituto di Fotonica e Nanotecnologie - Milan, Italy

NIREOS S.R.L. - Official Spin-Off company of Politecnico di Milano, Milan, Italy

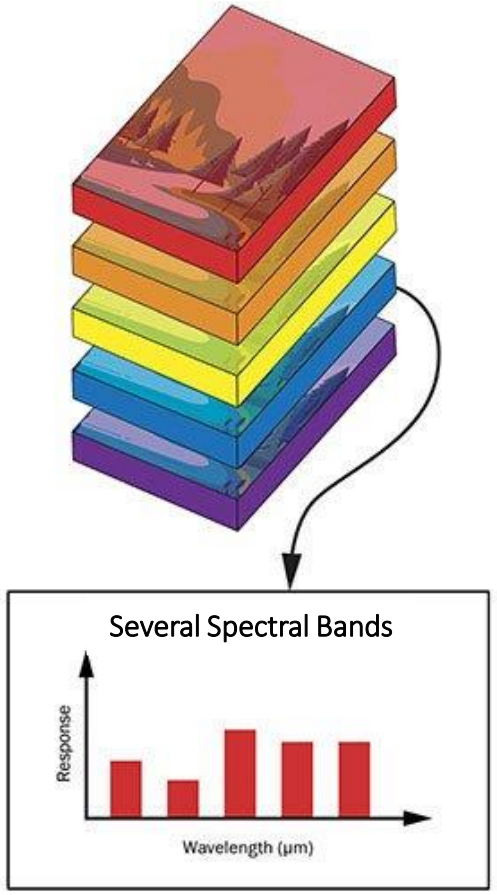
BBT Materials Processing, Ltd., Prague, Czech Republic

From RGB to Hyperspectral

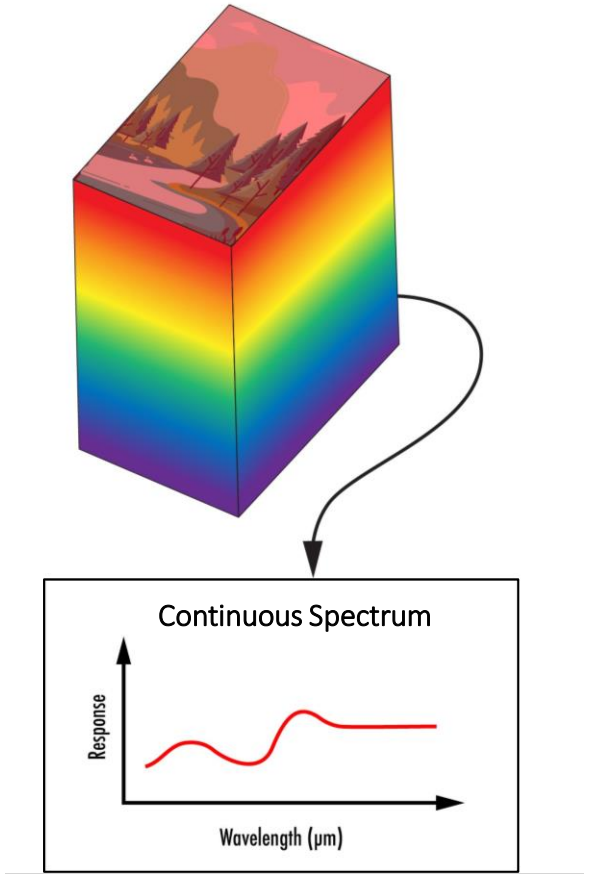
RGB



Multi-spectral Imaging



Hyper-spectral Imaging



Motivation

Spectral imaging of Earth surface and atmosphere:
enables monitoring various ecosystem and natural aspects, such as

VOLCANOES AND EARTHQUAKES

- transient thermal anomalies preceding eruptions
- Atmospheric gases (SO_2, ash and water ice in the eruptive plumes)

WILDFIRES

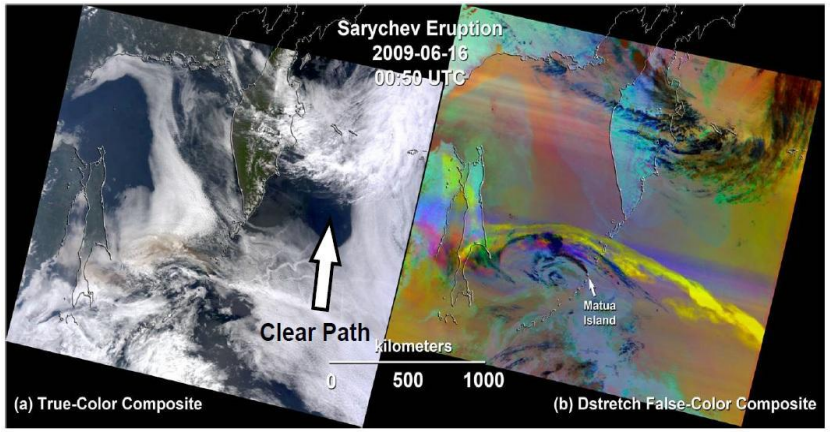
- burning biomass

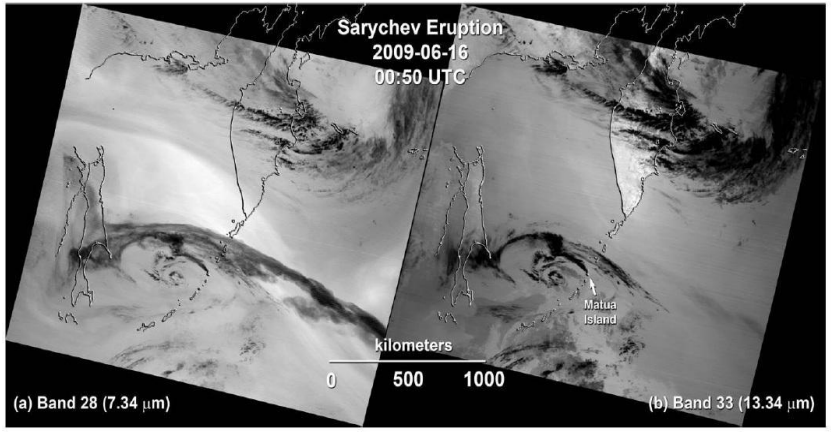
WATER USE AND AVAILABILITY

- global freshwater supplies
- Water resources
- Ice

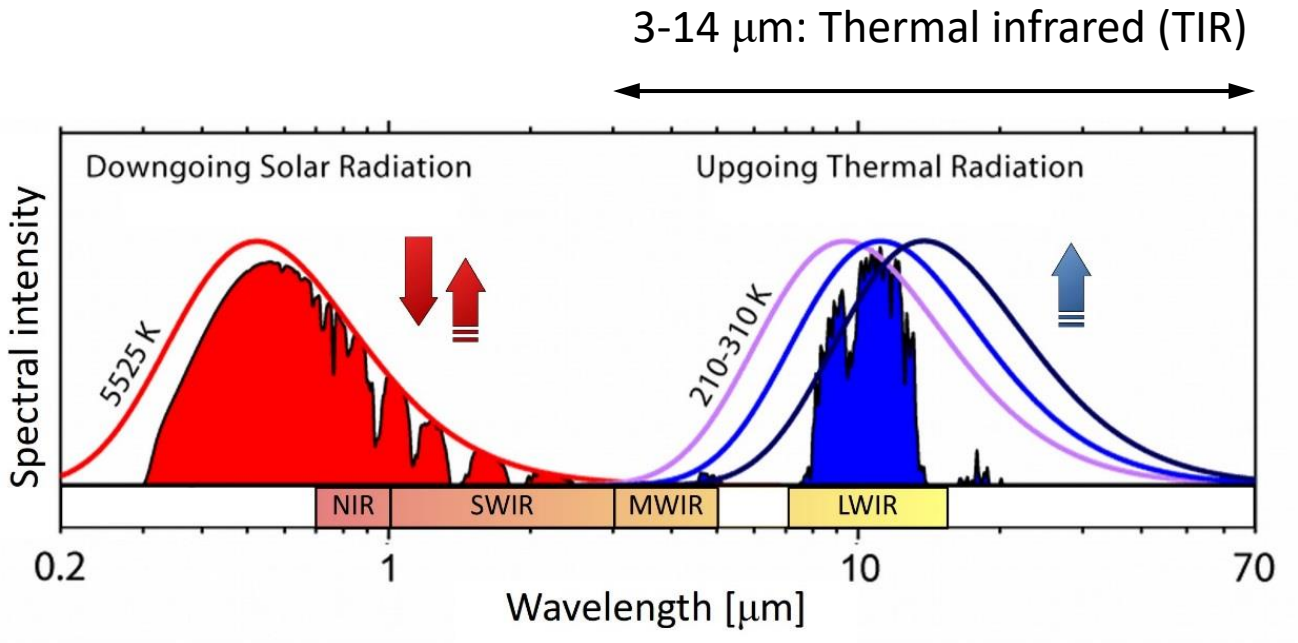
EARTH SURFACE COMPOSITION AND CHANGE:

- composition and thermal properties of the surface of the Earth





Motivation: Spectral bands of interest



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Example: Volcanoes and Earthquakes

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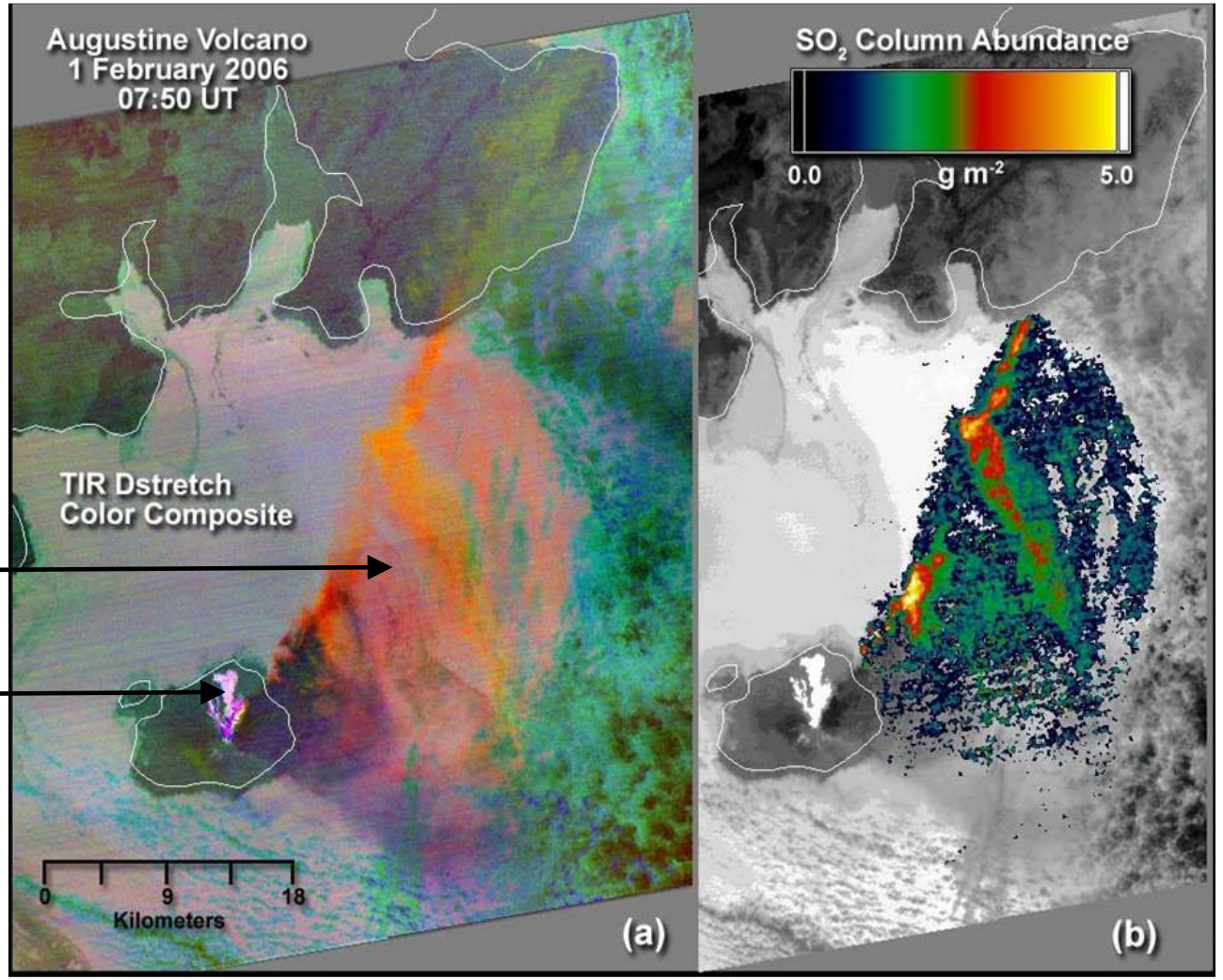
- Atmospheric gases (SO_2, ash and water ice in the eruptive plumes)



HyspIRI Thermal Infrared (TIR) Band Study Report

State of the art: PRISMA mission

PRISMA
PRecursore IperSpettrale della Missione Applicativa

3 cameras onboard:

- VNIR
- SWIR
- Pan channel (panchromatic, no spectral resolution)
- No TIR detection

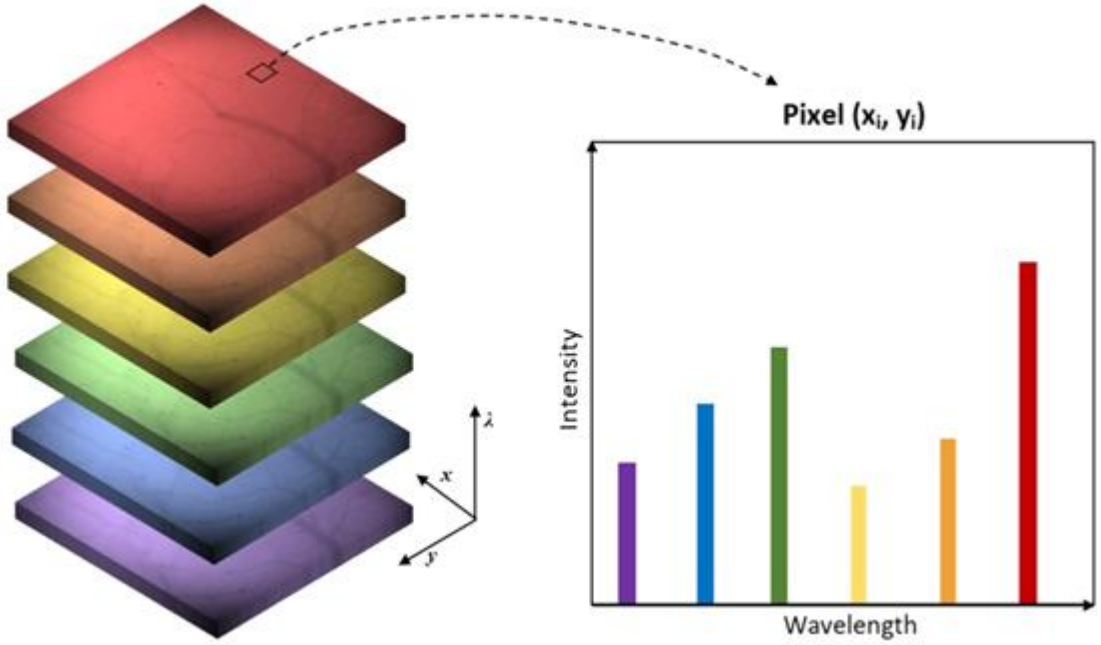
Parameter	VNIR channel	SWIR channel	Pan channel
Spectral range	400-1010 nm	920-2505 nm	400-700 nm
Spectral resolution (FWHM)	≤ 12 nm	≤ 12 nm	Collects all light
Spectral bands	66	171	1

From: https://earth.esa.int/web/eoportal/satellite-missions/p/prisma-hyperspectral

Types of spectral imaging

MULTISPECTRAL IMAGING

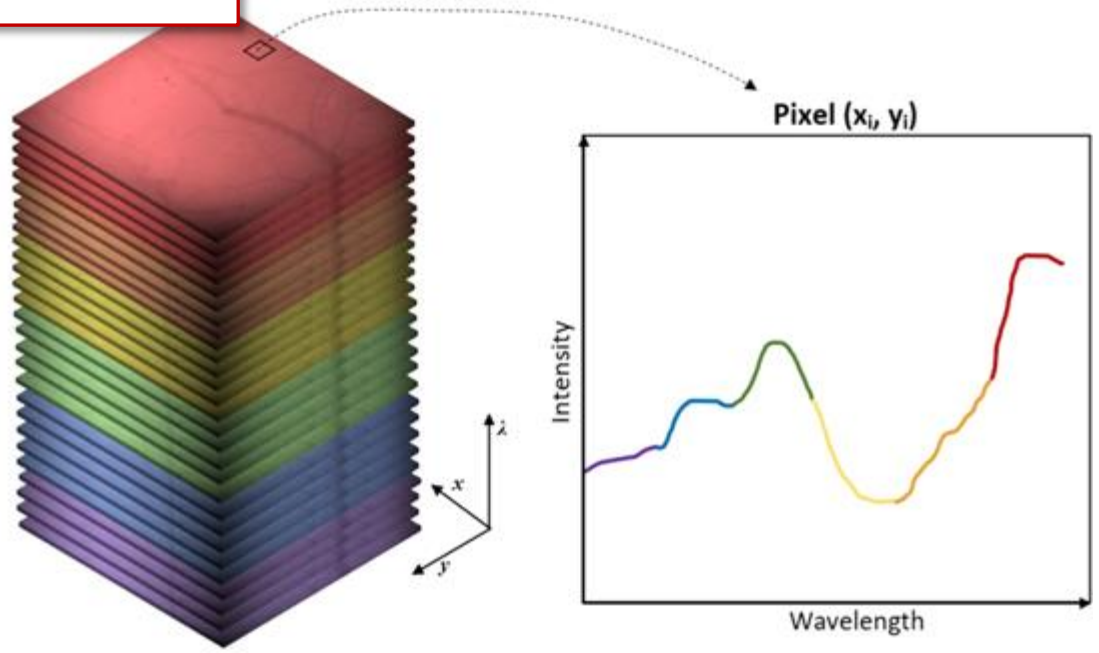
- N separated bands



HYPERSPECTRAL IMAGING

- Continuous spectrum

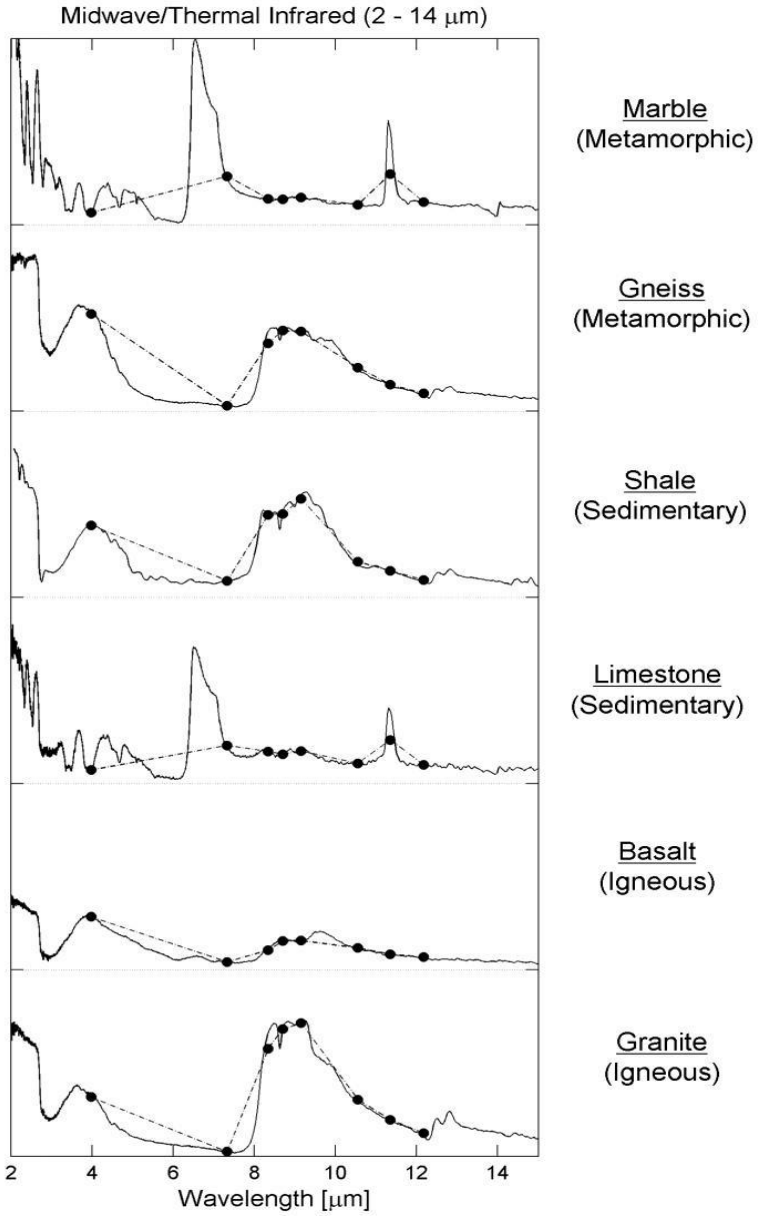
HYPERCUBE



ENABLES SPECTRAL ANALYSIS

- Segmentation
- Spectral unmixing
- Evolution of spectra in time

Importance of Thermal Infrared



Detection of mineral types (ASTER)

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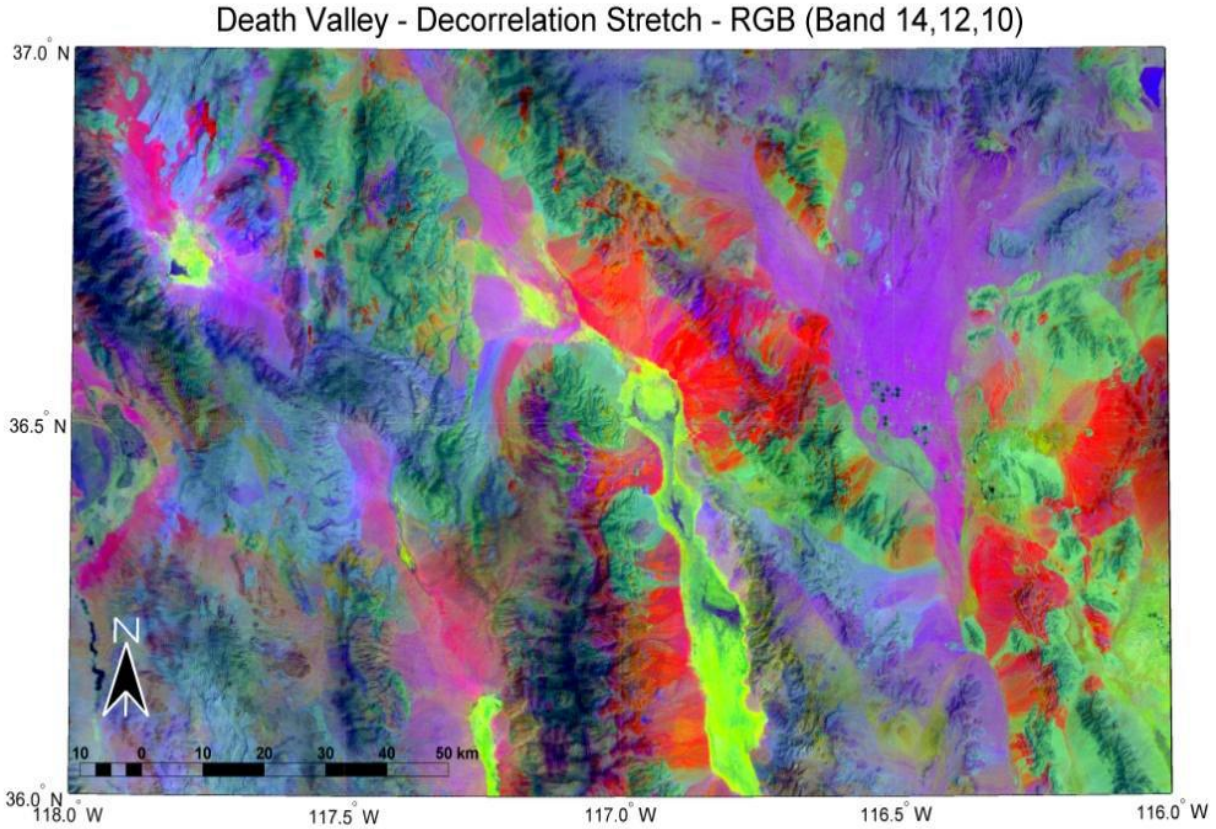
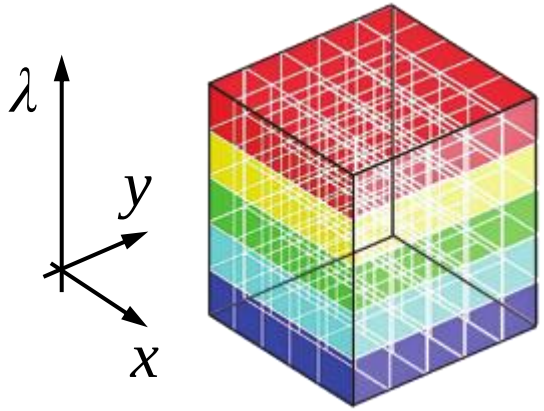
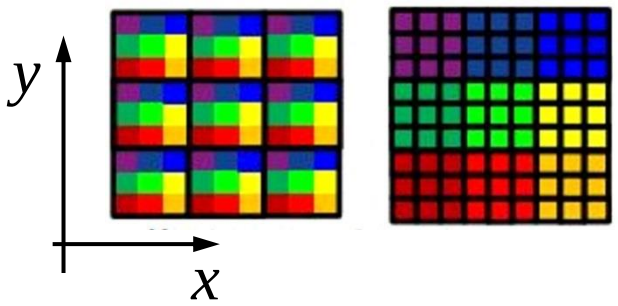


HyspIRI Thermal Infrared (TIR) Band Study Report

Canonical Spectral imaging approaches

SNAPSHOT



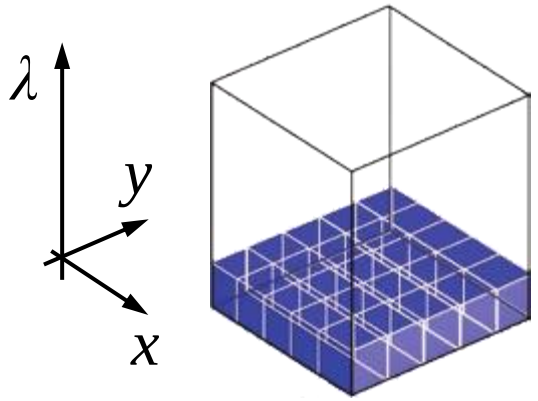


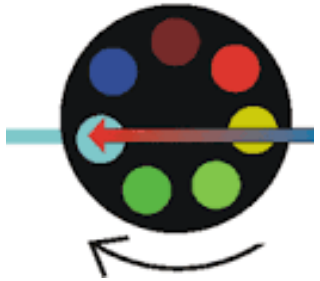
Mosaic 2D sensor

e.g.: Bayer filter in RGB sensors

Discrete number of bands

STARING



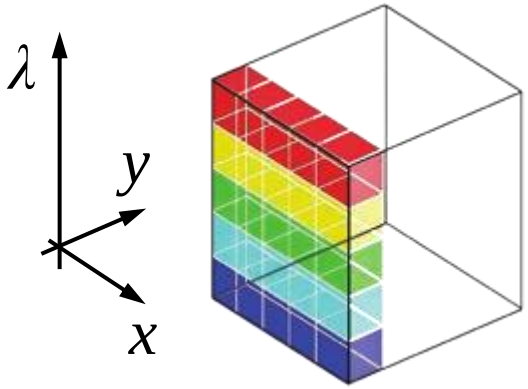


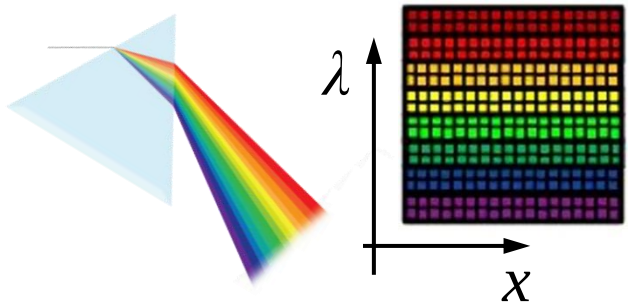
Tunable filter

Spectral scanning

Discrete number of bands

PUSHBROOM





Dispersion + 2D sensor

Spatial scanning

Continuous spectrum

Canonical Acquisition: Method and Orbit

SPECTRAL ACQUISITION TECHNIQUE:

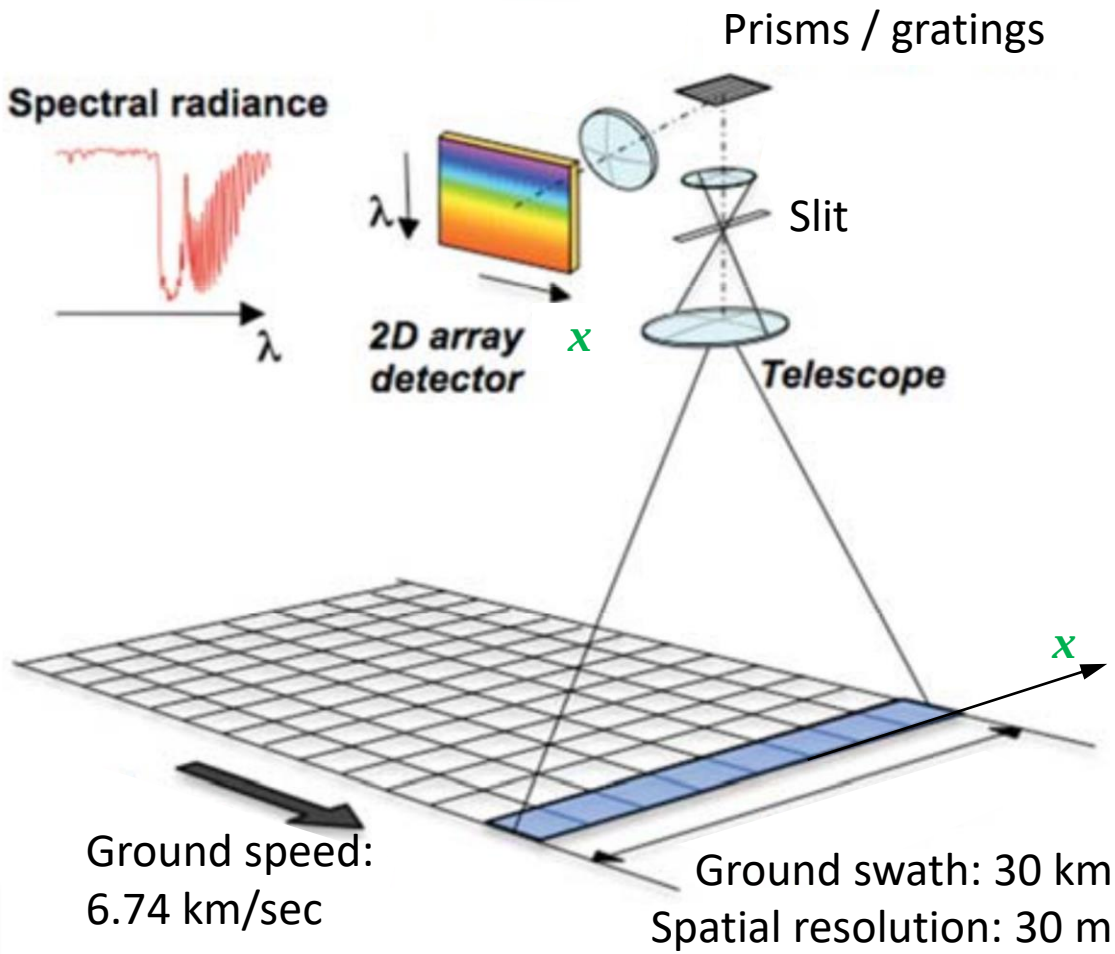
- **Pushbroom**
  target continuously moving, spectrum from one image line
- Employs slit + prism/grating

ORBIT TYPE:

- **Sun-synchronous circular**
  the satellite always passes over a location at the same local solar time Imaging at the same solar illumination condition
- Altitude = 600–800 km [Prisma: 614 km]
- Period = 96-100 min [Prisma: ~99 minutes]
- orbit repeat cycle = 29 days
- Ground speed: 6-7km/sec [Prisma: 6.74 km/sec]

Orbit and imaging technique used by:
TERRA (ASTER, MODIS), PRISMA, MISR, LANDSAT, WORLDVIEW, ...

Pushbroom acquisition scheme



Data: PRISMA mission
[https://earth.esa.int/web/eoportal/satellite-missions/p/prisma-hyperspectral]

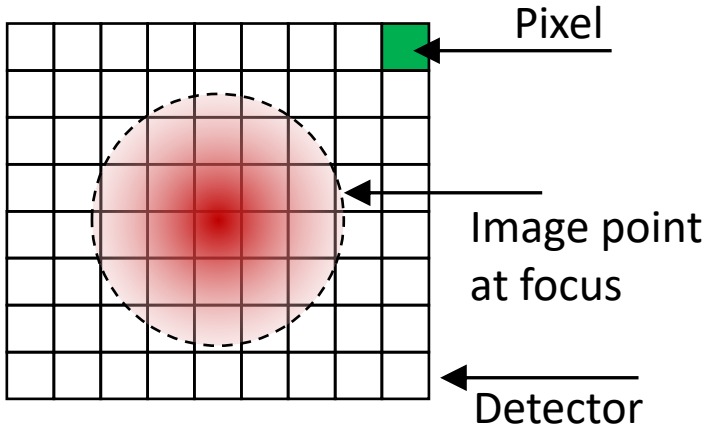
Image from doi: 10.1117/12.2309086

Canonical Acquisition: Imaging properties

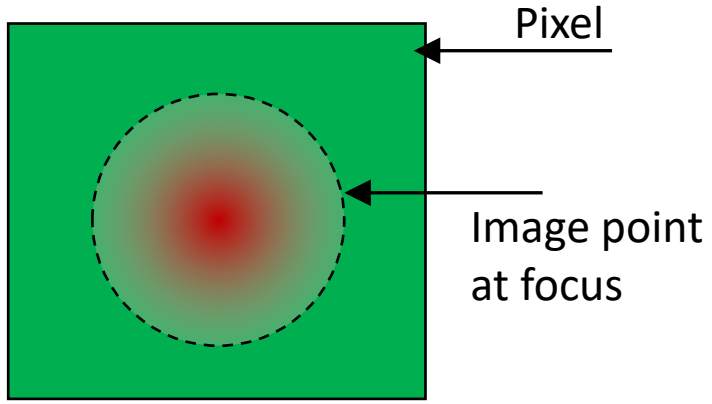
ACQUISITION CONSTRAINTS POSED BY LARGE GROUND SPEED (6-7KM/SEC)

- Integration time: **0.1 – 3 msec**
- Imaging Q*: poor (0.25-1)
- Pixel resolution: 30-50 m
- Field of view: 30-50 km
- Aperture diameter: Large to overcome low Q
- Frames per pass: 1–10's

* Imaging Q:



Pixel < image focus
High Q (Q > 2)

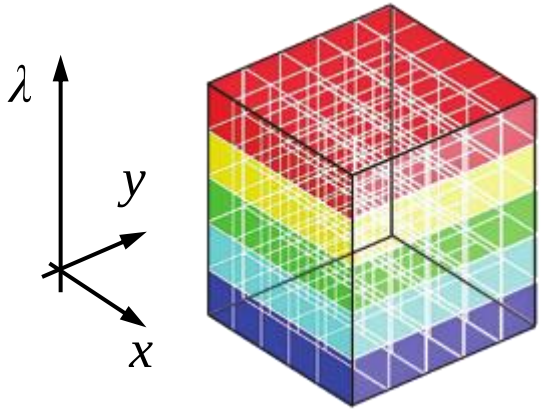


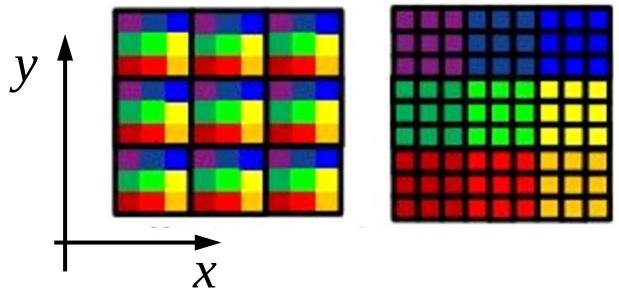
Pixel > image focus
Low Q (Q < 1)
Spatial resolution is limited by *pixel resolution*

Common Spectral Imaging Approaches

NIREOS

SNAPSHOT

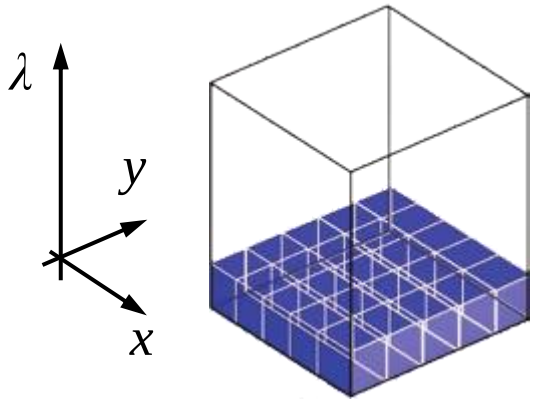


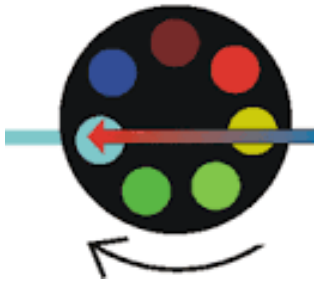


Mosaic 2D sensor

Discrete number of bands

STARING

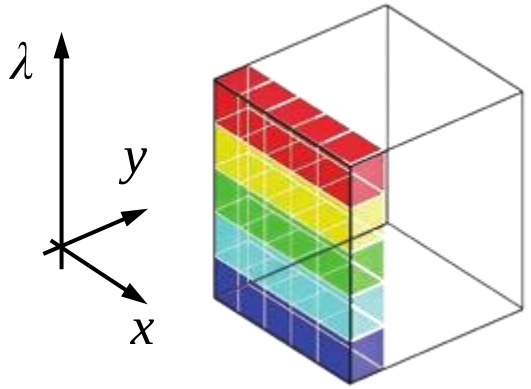


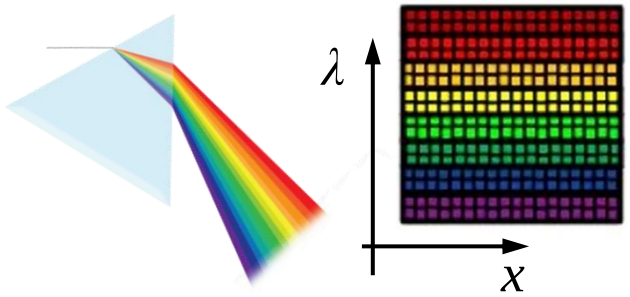


Tunable filter
Spectral scanning

Discrete number of bands

PUSH-BROOM





Dispersion + 2D sensor
Spatial scanning

Continuous spectrum


NIREOS
GEMINI
INTERFEROMETER
NIREOS

Importance of Thermal Infrared

Spectral imaging of Earth surface and atmosphere:
enables monitoring various ecosystem and natural aspects, such as

Volcanoes and Earthquakes

- transient thermal anomalies preceding eruptions
- Atmospheric gases (SO_2, ash and water ice in the eruptive plumes)

Wildfires

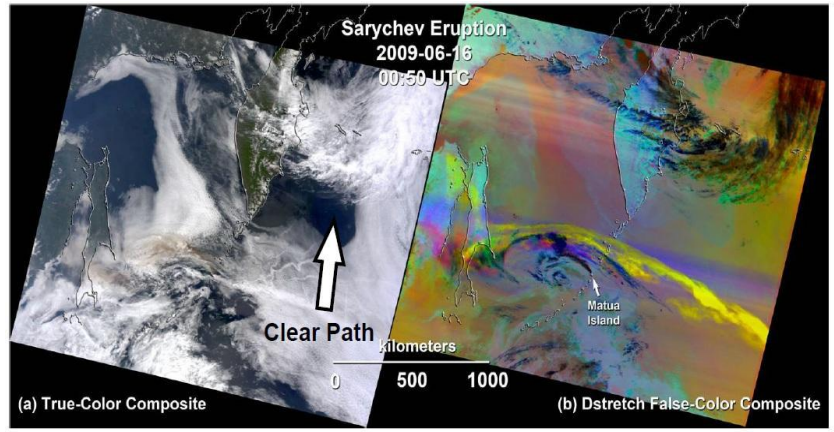
- burning biomass

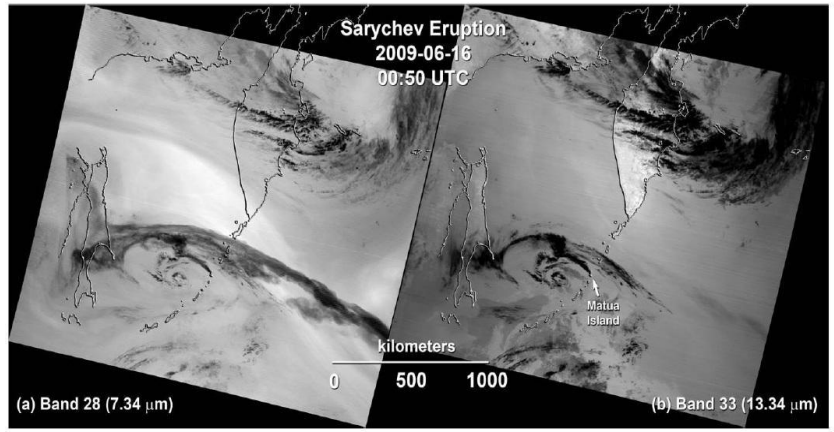
Water Use and Availability

- global freshwater supplies
- Water resources
- Ice

Earth Surface Composition and Change:

- Composition and thermal properties of the surface of the Earth
- Monitoring of Mining Areas
- Plastic patches, ghost nets, marine pollution



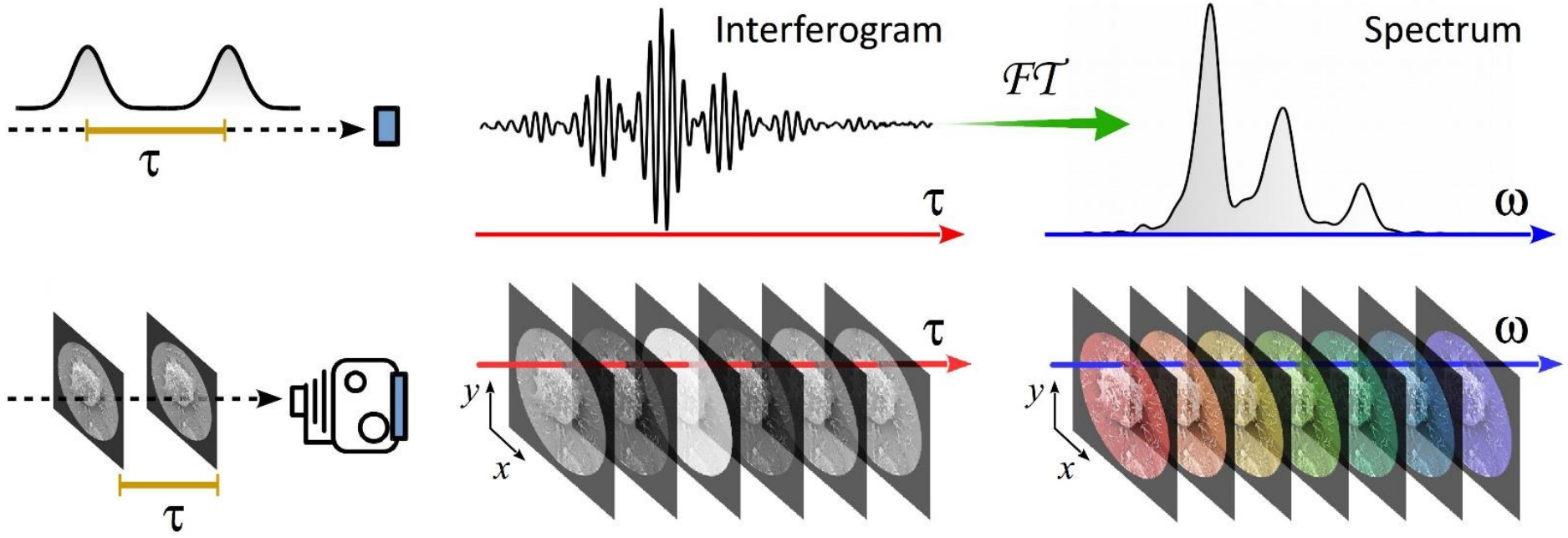


Alternative approach: Fourier Transform spectroscopy

- Interferometry + Fourier-transform

From 1 beam...

...to a 2D field



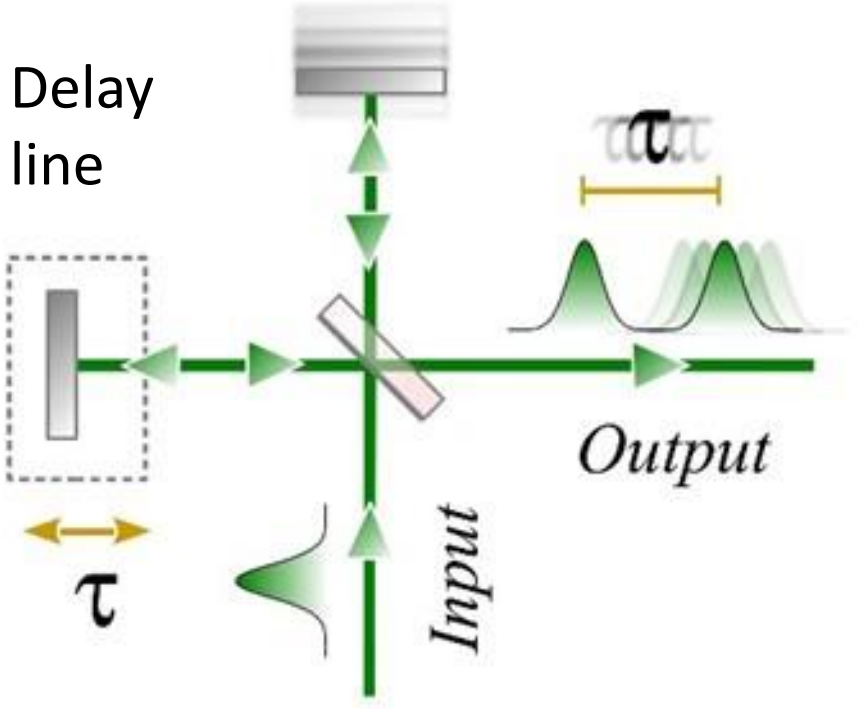
HYPERCUBE

REQUIREMENTS :

- Accuracy of delay: **< 1/100** optical cycle (Phase locking)
- Collinear replicas

Fourier-Transform Spectrometer

STANDARD FT SPECTROMETER: MICHELSON INTERFEROMETER



REQUIREMENTS :

- Accuracy of delay: **< 1/100** optical cycle
- Collinear replicas

LIMITATIONS OF MICHELSON INTERFEROMETER :

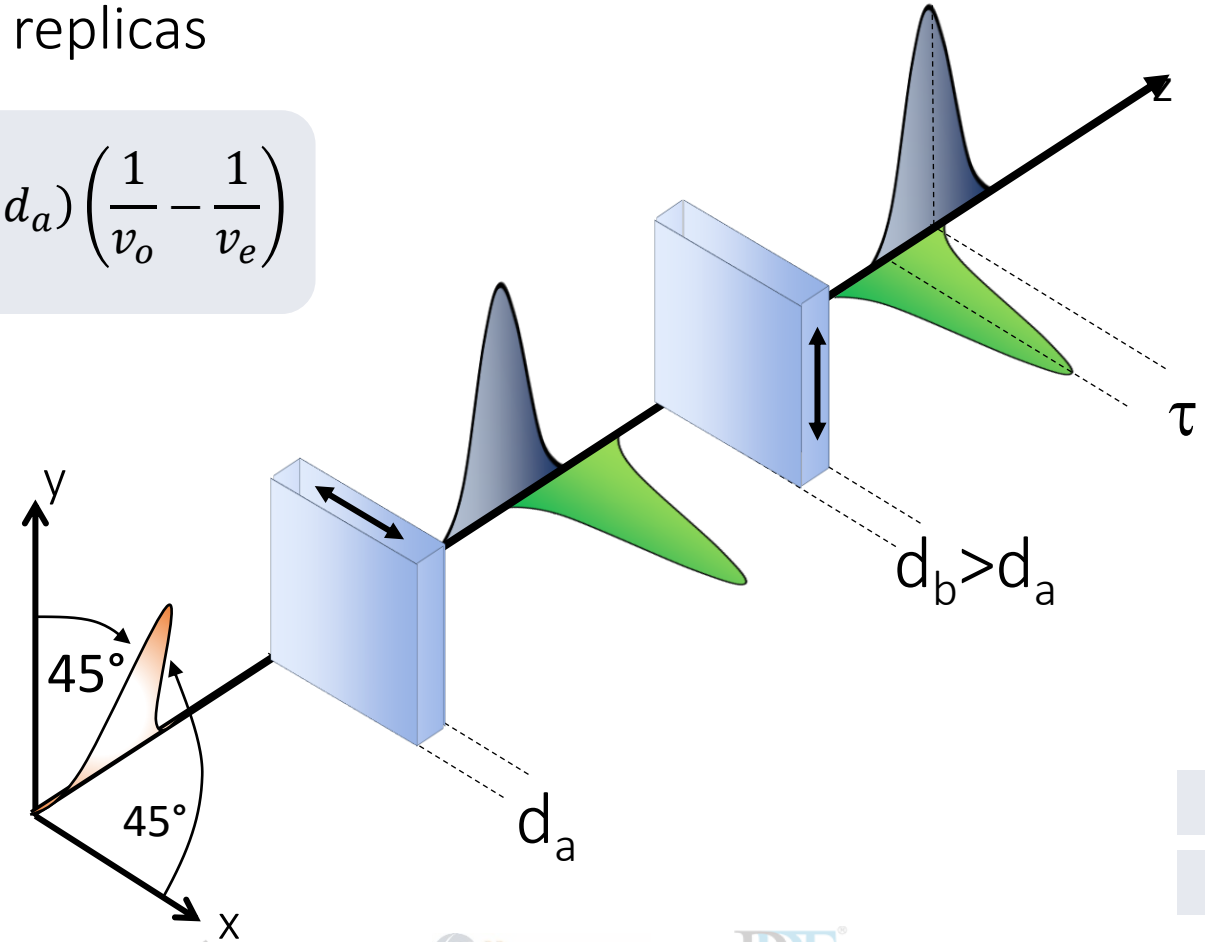
- Vibrations destroy phase-locking
- Need of stabilization strategies
  - ✓ Bulky devices
  - ✓ Active feedback

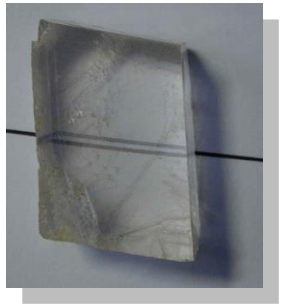
Standard FT spectrometers are cumbersome, heavy and too sensitive for portable devices or for deployment in space applications

CPI: A Common-Path Interferometer

- **Generation of** phase-locked replicas by birefringence
- ordinary and extraordinary polarizations: different propagation speeds
- Total delay: proportional only to thickness
- Collinear replicas

$$\tau = (d_b - d_a)\left(\frac{1}{v_o} - \frac{1}{v_e}\right)$$





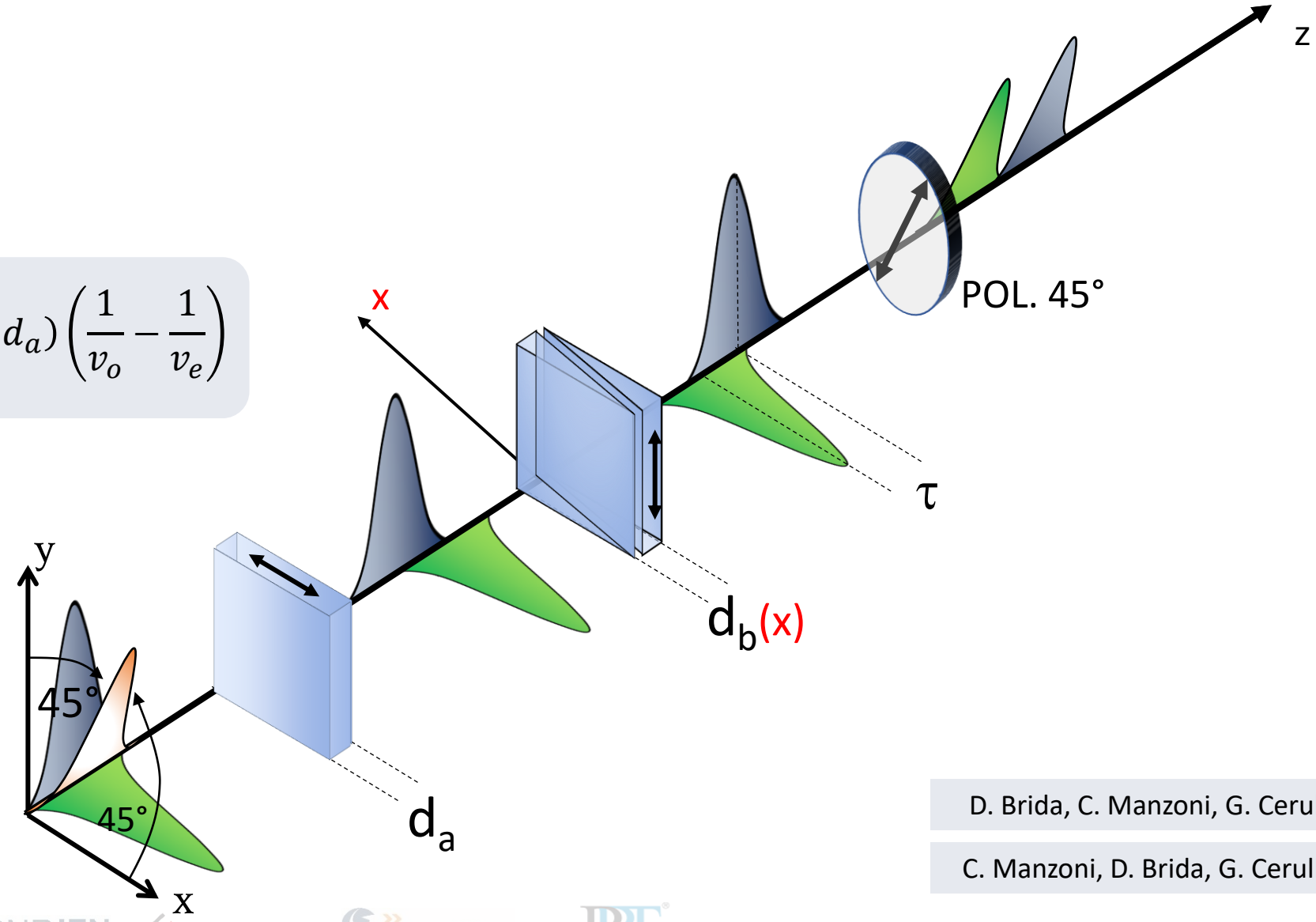
Crystal	Range (micron)
Alpha-BBO	0.2-3.5
Yttrium Vanadate	0.4-5
Lithium Niobate	0.4-5.2
Calomel	0.4-20

D. Brida, C. Manzoni, G. Cerullo, Opt. Lett. **37**, 3027 (2012)

C. Manzoni, D. Brida, G. Cerullo, US Patent: 9182284 (2015)

CPI: A Common-Path Interferometer

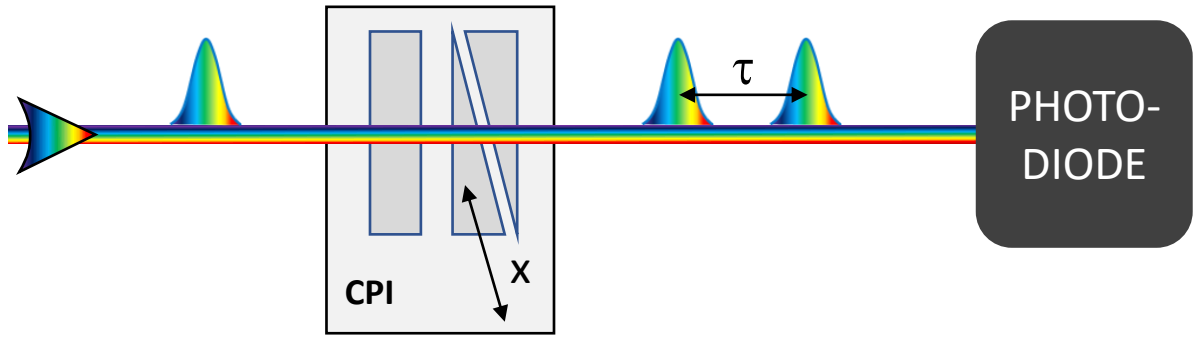
$$\tau = (d_b - d_a)\left(\frac{1}{v_o} - \frac{1}{v_e}\right)$$

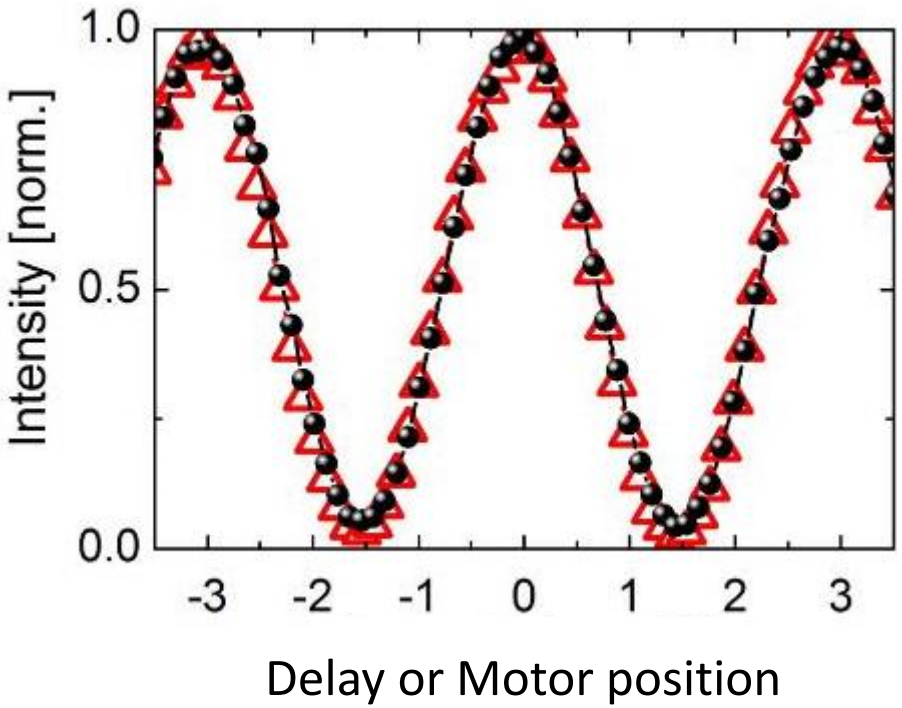


D. Brida, C. Manzoni, G. Cerullo, Opt. Lett. **37**, 3027 (2012)

C. Manzoni, D. Brida, G. Cerullo, US Patent: 9182284 (2015)

CPI characterization – Dynamic Reproducibility



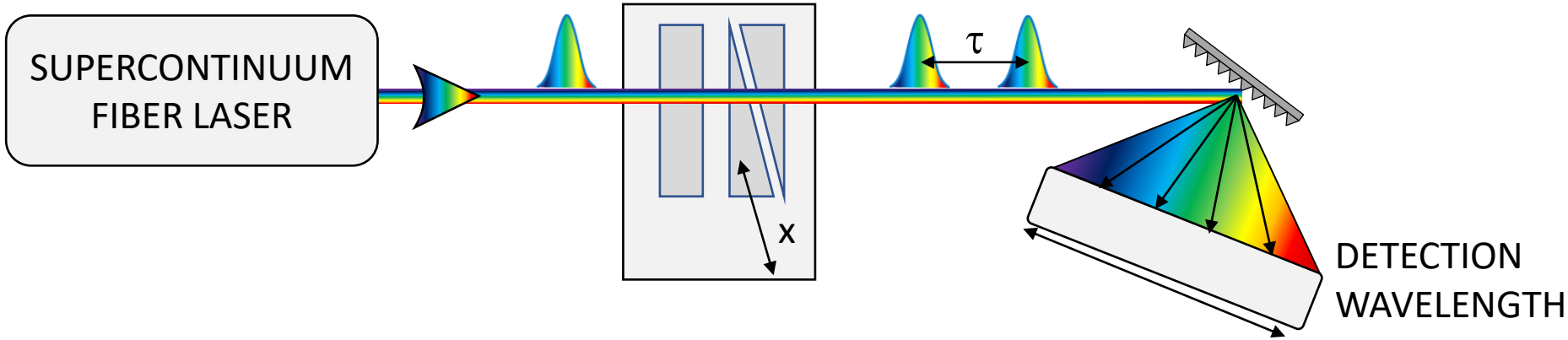


DYNAMIC REPRODUCIBILITY

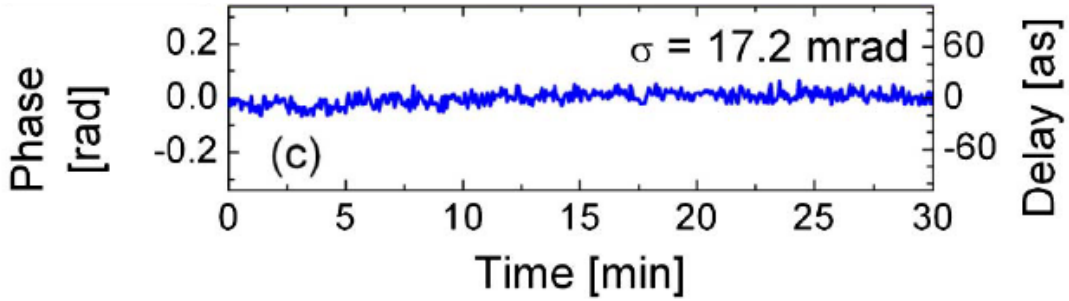
- Interferograms acquired after 30 minutes
- **perfect reproducibility**

D. Brida, C. Manzoni, G. Cerullo, Opt. Lett. **37**, 3027 (2012)

CPI characterization – Static Stability



@ Fixed position of the wedge



STATIC STABILITY

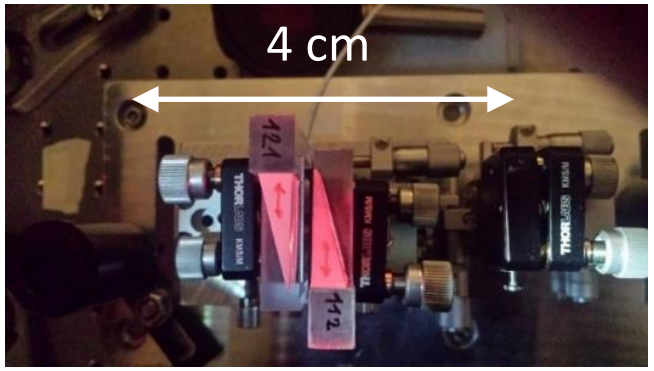
- delay fluctuations:

λ / 360 (~5 as at 600 nm)

D. Brida, C. Manzoni, G. Cerullo, Opt. Lett. **37**, 3027 (2012)

CPI characterization – Dimensions and Weight

- **SMALL FOOTPRINT**
  Few centimeters



- **POWER CONSUMPTION**
  < 50 W

- **OPTICAL ALIGNEMENT**
  No realignment required

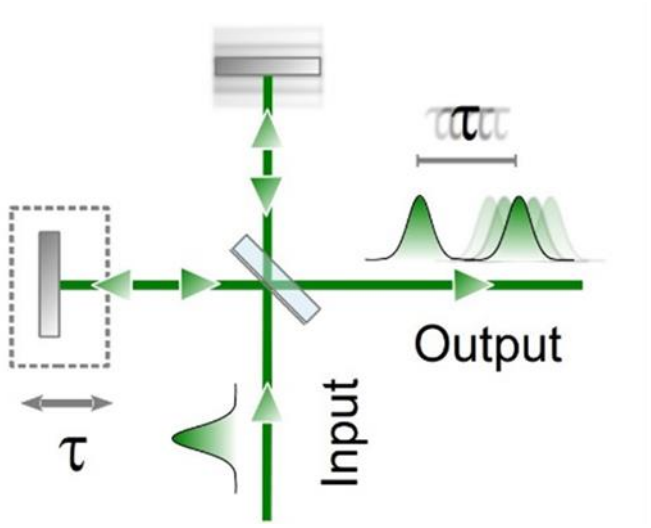
- **LIGHTWEIGHT**
  < 1 kg

- **NO ACTIVE CONTROL REQUIRED**

Ideal device for portable, on field and spaceborne applications

Comparison: Michelson VS CPI interferometers

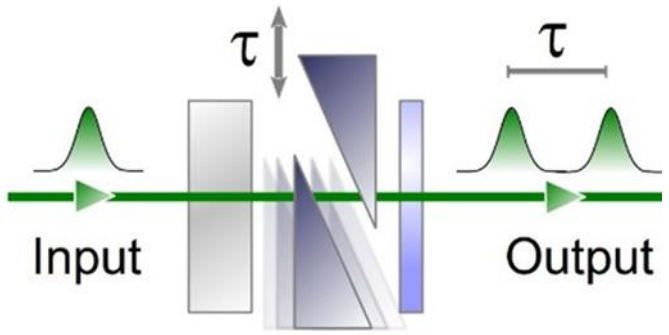
Michelson Interferometer



>50 cm

Cumbersome and heavy!

CPI



2-3 cm

Compact!