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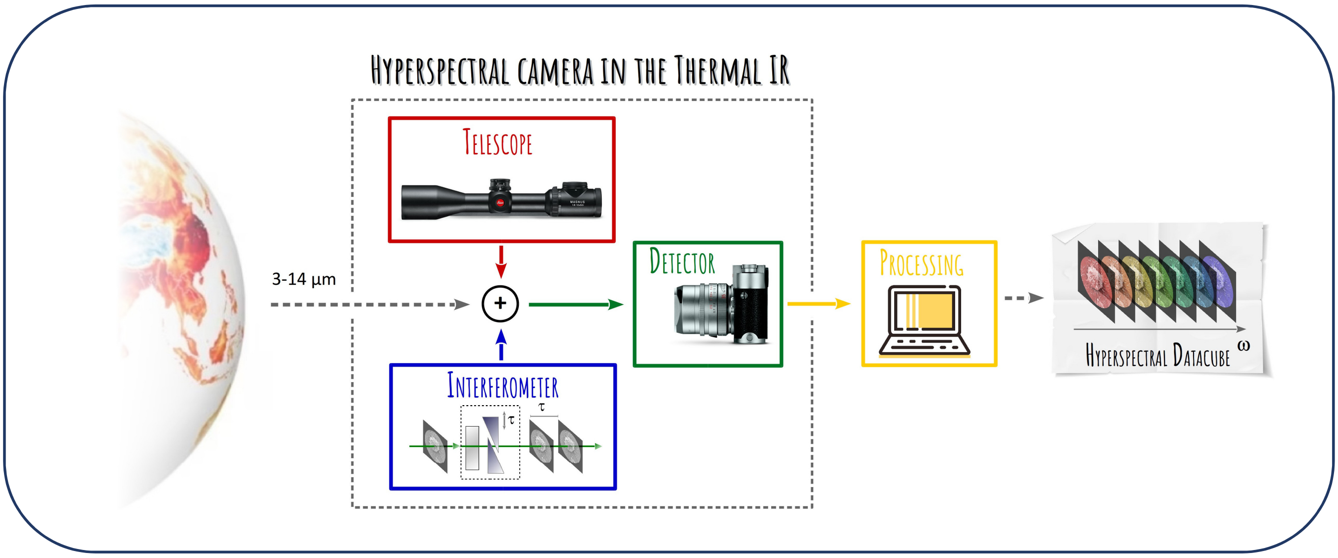

An Ultracompact Hyperspectral imager in the Thermal Infrared
ESA CONTRACT NO. 4000137531/22/NL/GLC/OV

Executive Summary Report

<u>Study</u>

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Affiliations:

Istituto di Fotonica e Nanotecnologie (CNR) – Piazza L. da vinci, 32, 20133 Milan, Italy

NIREOS S.R.L. Via Giovanni Durando, 39, 20158 Milan, Italy

BBT Materials Processing, Ltd., Doubicka 11, 18400 Prague 8, Czech Republic

Activity summary:

We have developed an innovative hyperspectral imaging system for remote sensing applications in the thermal infrared. The camera is compact, lightweight and robust. The activity focused on the development the three modules of the imager, namely the spectrometer, the telescope and the detector. We have designed and manufactured an innovative spectrometer based on Fourier transform spectroscopy, consisting on calomel birefringent crystals, with working range in the thermal infrared. The consortium also designed a telescope and tested the imaging system by using a microbolometer.

Introduction

Many applications in **remote sensing** require measurement of the **light spectrum in the so called thermal infrared (TIR) range, from 3 to 14 μm**, which can be used to uniquely identify molecules. Examples of applications are monitoring of plastic waste in the ocean, tracking of oil spills, identification of fire hazards or detection of atmospheric gases.

The goal of this project is the design and implementation of a **proof-of-concept prototype of a camera which collects the spectrum for each point of the image**. Such a camera could be employed to collect information from space. The proposed system is the combination three components: a detector, a spectrometer and a telescope. The project has been performed by an international team composed by the National Research Council of Italy (CNR, the main contractor), and the companies NIREOS srl (Italy, subcontractor) and BBT (Czech Republic, subcontractor).

The novelty of the prototype is the use of a very challenging technique, called "Fourier-transform spectroscopy" (synthetically, Fourier-transform will be called FT hereafter). This method is schematically depicted in Figure 1(a,b): the light is split by an interferometer in two delayed replicas, whose interference pattern is measured by one detector as a function of their delay. This produces an interferogram, whose FT yields the intensity spectrum of light. The amplitude of the spectrum obtained by this method depends on the contrast of the interferogram: in practice, the contrast accounts for the depth of the interferometric oscillations, which must be optimized. The FT approach is also the method of choice for imaging: as shown in Figure 1(c,d) the FT method enables **collecting in parallel the information from all the points of the image**, which is a great advantage when taking images from space.

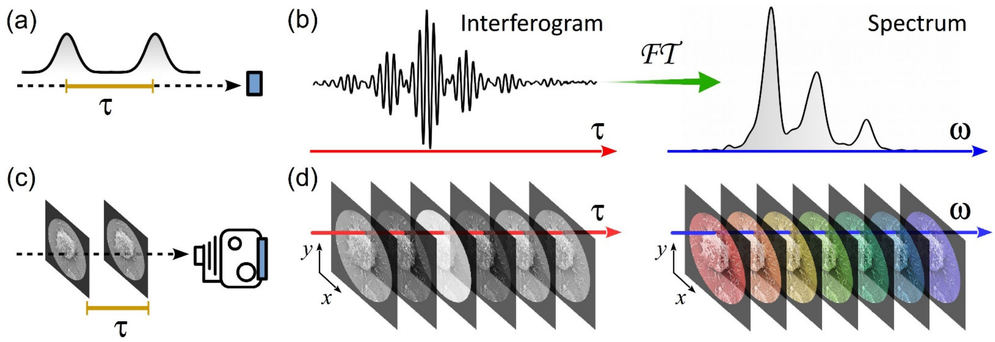

Figure 1: Schematic of Fourier-transform spectroscopy for a single light beam (a,b) and for an image (c,d). (a) The light under test is split into two replicas delayed by time τ and collected by a single-point detector. (b) The light intensity as a function of delay (interferogram) and the intensity spectrum after Fourier transform (FT). (c) The same as (a), but for an image, collected by a 2D matrix detector. (d) Stack of images acquired by changing τ. Each pixel of the image carries an interferogram. By taking the FT for each pixel, one gets an intensity spectrum.

Technically, the time-domain spectroscopy is performed by means of an **interferometer**, a high-precision optical assembly that in the following will also be called "spectrometer".

The **camera** consists of the following **building blocks** (see Figure 2):

- An optical imaging system, i.e. a **telescope**: this will be helpful to image an area on the Earth surface from a satellite;
- An interferometer, acting as a spectrometer;
- A detector, which records the images.

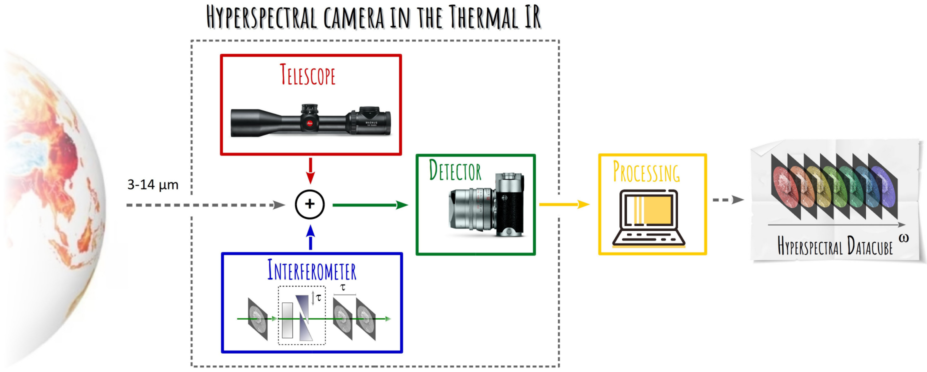

Figure 2: general scheme of a hyperspectral imager operating in the Thermal infrared.

After the acquisition, the data must be processed. The development of the analysis software is beyond the scope of the project. Here, our work focussed on:

- the **implementation of an innovative interferometer:** The interferometer is based on calomel –an unrivaled material- and employs a novel layout, which improves the signal detection **with respect to current birefringent interferometers**.

- the **design of the model telescope:** we devised for the first time a telescope tailored to host our interferometer.

- the **test of the Interferometer**, which demonstrate that it constitutes a relevant improvement with respect to existing systems.

The interferometer

Standard FT spectrometers are based on an optical scheme known as Michelson interferometer; however these schemes are heavy, cumbersome and too unstable to be deployed for space applications. In this project, we have developed an **FT spectrometer** which is **ultrastable, compact and lightweight**, and is hence suited for space applications.

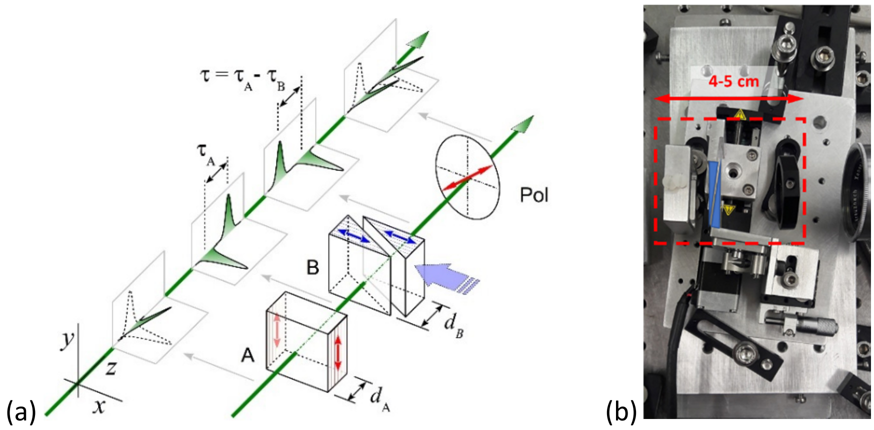

Figure 3: (a) Conceptual scheme of the birefringent interferometer. A is the birefringent plate with optical axis along y (red double arrow); B is the block with the birefringent wedges pair with optical axis along x (blue double arrows). The overall delay between x and y projections depends on the difference between the thickness of A and B; the thickness is changed by moving one of the wedges B. Pol: polarizer at 45°, which projects the two delayed replicas to the same polarization. In the project, the material of the birefringent plates and wedges is calomel. (b) One implementation of the birefringent interferometer in the visible spectral range. The lateral size of the interferometer is less than 10 cm.

For the project, as birefringent material we have used **Calomel** (Hg_2Cl_2), an innovative material which is highly birefringent ($\Delta n \approx 0.55$) and works in the TIR. The interferometer basic scheme is sketched in Figure 3. It's made of two crystal blocks, A and B. Their role is to generate two replicas of the input image and to delay them.

When the system uses crystals such as Calomel, characterized by large birefringence ($\Delta n \approx 0.55$), care must be taken to design a proper interferometer. Designing a **novel layout** was one important tasks of the project; CNR designed the novel system, BBT manufactured the calomel crystals (see Figure 4) and NIREOS implemented the optomechanical assembly in **anodized duraluminum**.

(a) (b) (c)

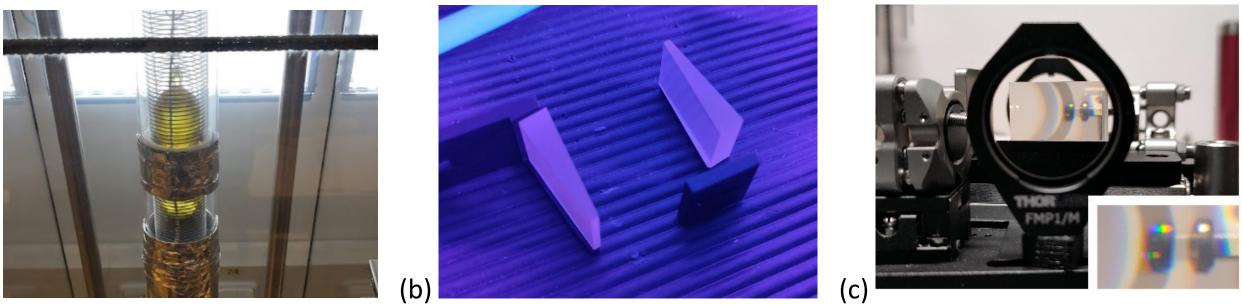

Figure 4: (a) Furnace during crystal growth. (b) A pair of wedges under UV illumination. (c) One wedge of Calomel, mounted in the interferometer; note the chromatic aberration due to the prism-shape of the crystal, and the double image of the screw, due to its birefringence.

After assembling the system and performing complex optical tests, we verified that the innovative calomel-based interferometer successfully fulfilled the expectations. The performances of the interferometer are summarized in Figure 5. Panel (a) shows that the interferometer reproduces remarkably well the spectra measured by a commercial, bulky spectrometer.

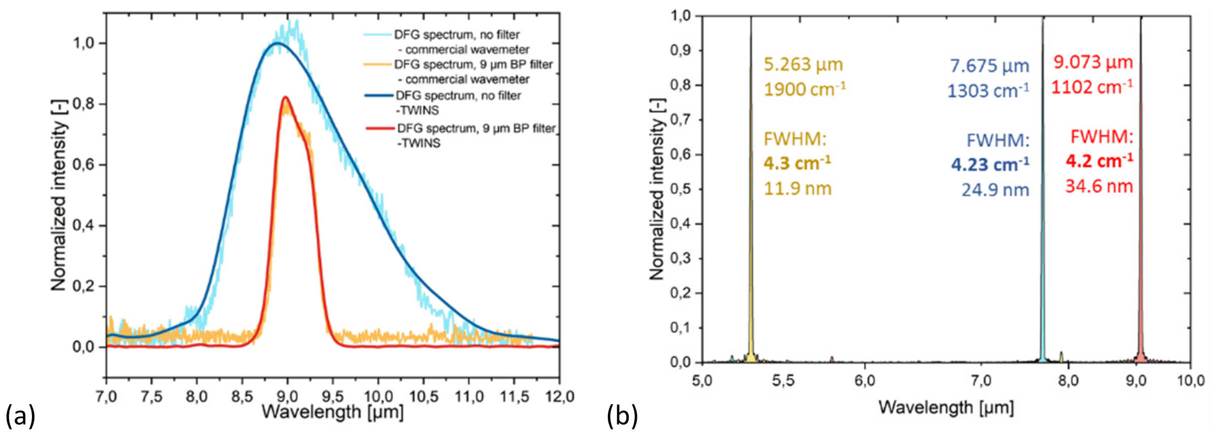

Figure 5: Spectral characterization of our interferometer. (a) Measurement tests of a light beam. Thick lines: spectra obtained with our novel interferometer. Thin lines: spectra obtained with a commercial spectrometer. (b) Spectra of monochromatic lasers.

Another exceptional result is the ability to precisely measure the wavelength of light, witnessed by the remarkably thin spectral lines shown in Figure 5(b). The thickness of the spectral lines is the so-called **spectral resolution** of the interferometer, which is much smaller than the devices developed so far by the team members.

In order to perform Earth observation from a satellite, a telescope is required. Such device was specifically designed and tested by NIREOS. Figure 6 shows a schematically layout of the telescope, which is composed by a sequence of at least 3 lenses.

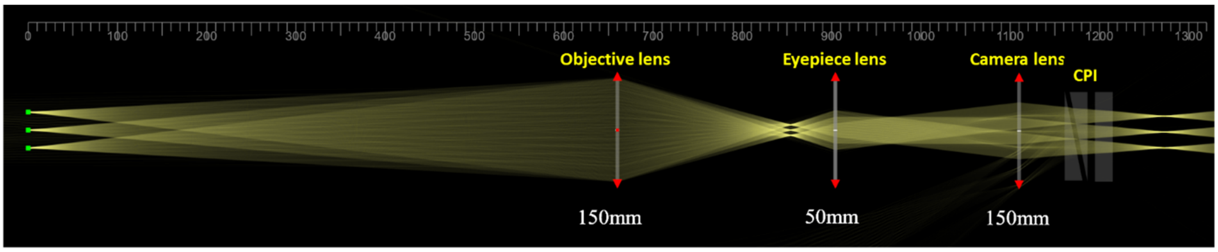

Figure 6: Design of the optical scheme of the telescope. CPI: our interferometer.

We tested the performances of the hyperspectral telescope system by imaging a mountain ("Pizzo dei Tre Signori") at distance of 60 km from the lab (Figure 7). By adding a birefringent interferometer to the telescope, we could acquire a hyperspectral image in the visible spectral range of the mountain. The inset of the figure shows the RGB image synthesized from the hyperspectral datacube.

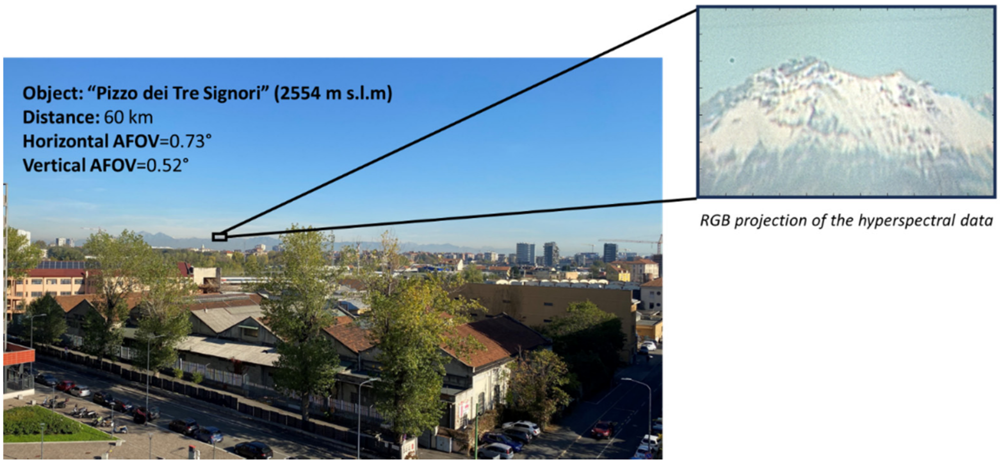

Figure 7. Picture of the landscape and zoom-in of the imaged mountain. The zoom-in is the RGB projection of the hyperspectral data.

Finally, for the first time we tested the potentiality of a commercial detector, called **microbolometer**, to perform spectral imaging with our birefringent interferometer. We measured the thermal image of the minerals and glasses, shown in Figure 8. Our camera was able to identify the presence of 3 different materials, namely pure monocrystalline quartz, defected mineral quartz and polycrystalline fused silica glass. Panel (b) shows the image of the sample in which we have enhanced in different colours the various materials. Panel (c) shows the scientific information provided by the camera in various sample points, namely the emissivity spectra used to identify the materials.

Figure 8: thermal imaging of a sample heated at 200°C. (a) The sample in the visible spectral range. (b) False-RGB image in the thermal infrared, obtained with the innovative hyperspectral camera developed in the project. (c) Emissivity spectra at selected points.

Conclusions

In the current project we have developed an innovative system for the acquisition of hyperspectral images in the thermal infrared. The activity was performed by CNR (contractor), NIREOS (subcontractor) and BBT (subcontractor).

We manufactured a birefringent interferometer based on the innovative calomel crystal. The final outcome of the project is a **prototype hyperspectral camera** fulfilling all the promised requirements. In particular the camera has **spectral coverage of 3-16 um**; **spectral resolution of 4.2 cm^{-1}**, and **interferometric contrast larger than 91.8%**. These performances constitute a relevant improvement with respect to existing systems. The performance of the interferometer are summarized in the following Table 1.

Requirement	Threshold	Target	Obtained	
Spectral range	7 – 15 um	2 – 20 um	3 – 16 um	**Threshold**
Spectral resolution	20cm^{-1}	5cm^{-1}	4.2 cm^{-1}	**Target**
Footprint	< 150 x 150 mm (225 cm^2)	< 100 x 100 mm (100 cm^2)	120 x 90mm (108 cm^2)	**Target**
Interferogram Contrast	50%	70%	> 91.8%	**Target**

Table 1: requirement table with the expected and pursued performances of the interferometer

The results of the tests demonstrate that all the objectives of the study have been achieved. Further development will call for optimization of the interferometer throughput by the deposition of antireflection coating, selection of a suitable detector (micro-bolometer or MCT), realisation of a final imaging telescope, design of the calibration unit.