

Recent Improvements on the Thermal Infrared Hyperspectral Images of the SIELETTERS Airborne System

O. Gazzano, Y. Ferrec, C. Coudrain and L. Rousset-Rouvière

ONERA – The French Aerospace Lab, BP 80100, F-91123 Palaiseau Cedex France, olivier.gazzano@onera.fr

ABSTRACT

SIELETTERS is an airborne hyperspectral imaging system that covers the mid- and long-wavelength infrared bands. It is part of the SYSIPHE system that covers bands from $0.4\ \mu\text{m}$ to $11.8\ \mu\text{m}$. The ground sampling distance of the SIELETTERS instrument is $0.5\ \text{m}$ (when $2000\ \text{m}$ above the ground) with a spectral resolution between $11\ \text{cm}^{-1}$ and $5\ \text{cm}^{-1}$. In this document, we will introduce the SYSIPHE project, the SIELETTERS system and show the latest results that we have obtained with the system. Our recent studies led to significant improvements on the quality of the hyperspectral images and of the spectra. The hyperspectral images from the previous airborne campaigns are now compatible with atmospheric compensations, data classifications and anomaly detection. The system is opened to external users.

1. INTRODUCTION

SYSIPHE is an airborne hyperspectral imaging system covering all the atmospheric transmission bands between $0.4\ \mu\text{m}$ and $11.8\ \mu\text{m}$: visible (VIS), near-infrared (NIR), short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR). The ground sampling distance is $0.5\ \text{m}$ over a $500\ \text{m}$ swath when the aircraft is $2000\ \text{m}$ above the ground level. A higher resolution is available in the visible and NIR bands. The imaging system, developed by ONERA and Norsk Elektro Optikk, is installed on a Do-228 aircraft operated by the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The SYSIPHE system also includes a real-time processing capability developed by FFI in collaboration with NEO and a ground post-processing chain, the STAD, developed by ONERA. With the SYSIPHE system, we can produce georeferenced hyperspectral images calibrated in spectral radiance, in emissivity and in reflectance. We can also generate surface temperature images.

SYSIPHE is a significant enhancement of airborne sensing capabilities in Europe and it is available to external users. The whole system achieved successfully a first airborne campaign in 2013. Qualification airborne

campaigns took place for Defense applications in summer 2015 and in winter 2019.

In Section 2, we will introduce the SYSIPHE system, its two subsystems – HySpex ODIN-1024 for the VIS, NIR and SWIR bands and SIELETTERS for the MWIR and the LWIR bands –, and the past four campaigns we have made. The SIELETTERS instrument, that is an imaging static Fourier transform spectrometer, and the associated processing chain will be described in Section 3. In Section 4, some hyperspectral data will be presented such as georeferenced false-color RGB images and some SIELETTERS calibrated spectra, compared with ground truth measurements.

2. THE SYSIPHE SYSTEM

2.1 SYSIPHE Project presentation

SYSIPHE (SYstème Spectro-Imageur de mesure des Propriétés Hyperspectrales Embarqué in French ; onboard spectral imaging system for measuring hyperspectral properties) is a system that acquires airborne hyperspectral images from the visible to infrared bands. The system is the result of a collaboration between France and Norway. The objectives of the SYSIPHE project is on the one hand to develop skills, tools and technologies for the design and the manufacturing of an airborne hyperspectral imaging system. On the other hand, the system is aimed to improve knowledge of infrared phenomenology and to be able to specify an operational system.

SYSIPHE is a state-of-the-art system that has a wide spectral coverage (with more than 600 spectral bands from $0.4\ \mu\text{m}$ to $11.5\ \mu\text{m}$), a high spatial resolution ($0.5\ \text{m}$ ground sampling distance) and a swath of $500\ \text{m}$. To achieve this unique performance, SYSIPHE is composed of three instruments, one dispersion-based spectrometer for the visible domain (VIS, $[0.4 - 0.8\ \mu\text{m}]$), near infrared domain (NIR, $[0.8 - 1.4\ \mu\text{m}]$) and short-wavelength infrared domain (SWIR, $[1.4 - 2.5\ \mu\text{m}]$), developed by the Norsk Elektro Optikk, NEO in Norway, and two Fourier transform spectrometers for the mid-wavelength infrared domain (MWIR $[3 - 5.3\ \mu\text{m}]$) and the long-wavelength infrared domain (LWIR $[8 -$

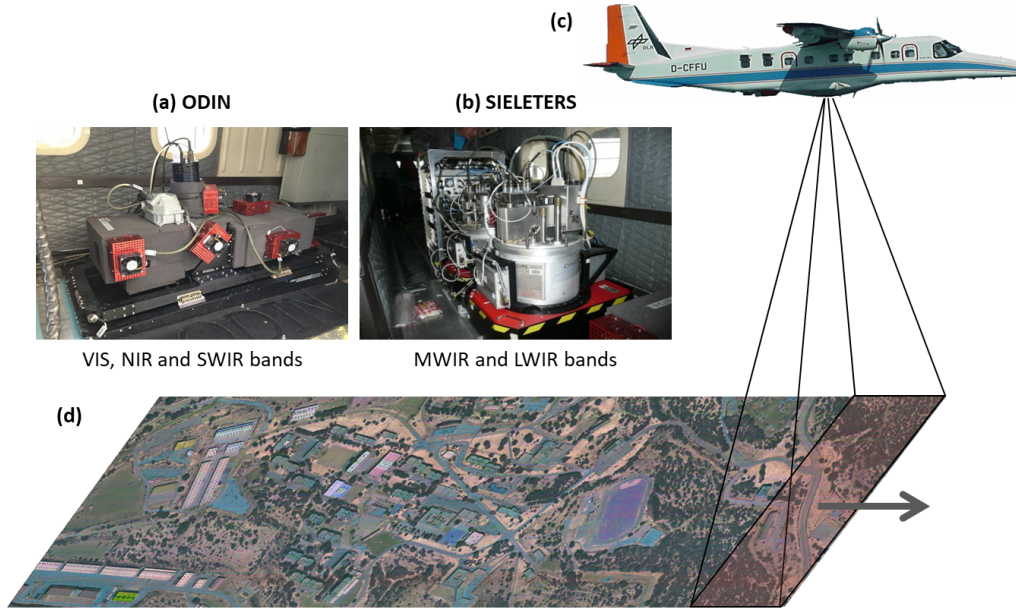


Figure 1: **The SYSIPHE system.** (a,b,c) Photos of the HySpex ODIN-1024 instrument (a) and of the SIELETTERS instrument (b) installed inside a Do-228 operated by the DLR (c). (d) Example of a false-color RGB image in the LWIR band ($R = 9.13 \mu\text{m}$, $G = 9.52 \mu\text{m}$ and $B = 10.75 \mu\text{m}$).

11.5 μm]), developed by the French aerospace laboratory, ONERA. These three instruments are integrated on the same aircraft, a Do-228 operated by the DLR in Germany (figure 1).

With those hyperspectral imaging systems and inertial measurement units installed on the same aircraft, we can produce up to 600 georeferenced and calibrated spectral images acquired simultaneously and in the same environment. Some technical specifications of the system are written in Table 1. Using several lines of flights, we evaluated the quality of the registration between bands, and we found that the registration error is smaller than 0.3 pixels [12].

2.2 HySpex ODIN-1024, the VIS, NIR and SWIR component

HySpex ODIN-1024 [2] is the visible, near infrared and short-wavelength infrared part of the SYSIPHE system. It consists of two pushbroom imaging spectrographs based on diffraction gratings (Figure 1(a)). These two modules share a common fore-optics and a common slit, to ensure perfect registration between the VIS-NIR and the SWIR images. The spectral sampling is 3.0 nm in the VIS-NIR bands and 6.1 nm in the SWIR band (Table 1). The HySpex ODIN-1024 has an onboard spectral and radiometric calibration source. More details about the instrument can be found in [2].

2.3 SIELETTERS, the MWIR and LWIR component

SIELETTERS [5] is the infrared component of SYSIPHE. It is composed of two distinct static-Fourier transform spectrometers [7, 10], one for the MWIR band and one for the LWIR band. The spectral resolution, defined as the full width at half maximum of the spectrum of a monochromatic source and that we measured using a laser, is 11 cm^{-1} in the MWIR and 5 cm^{-1} in the LWIR (Table 1). Each instrument is cooled to cryogenic temperatures ($\approx 90 \text{ K}$) to achieve high performance and absolute measurements.

Both SIELETTERS instrument are installed on a specific gyro-stabilized platform based on the Leica Geosystems PAV80 to control the line of sight. The line of sight is stabilized in real time to be as close as possible to the Nadir direction during recording. The control loop system monitors the whole flight (including take-off and landing) and the coupling between the two stabilized platforms. An independent high precision Inertial Measurement Unit (IMU, PosPac 610 from Applanix) is installed on one stabilized platform. It is configured in open-loop mode in order to check the quality of the line of sight in real-time and to allow for further, post-processing, registration (Section 3). Figure 1(b) shows a picture of the SIELETTERS instrument, where both cryostats are installed on their stabilization platform unit (in red) inside the Do-228 aircraft.

System	HySpex Odin-1024		SIELETERS	
Band name	VIS-NIR	SWIR	MWIR	LWIR
Spectral range	0.4 – 1.0 μm	0.95 – 2.5 μm	3.0 – 5.4 μm	8.1 – 11.8 μm
Spectral sampling	3.0 nm	6.1 nm	11 cm^{-1} (17 nm at 4 μm)	5 cm^{-1} (50 nm at 10 μm)
Number of spectral bands	≈ 197	≈ 256	≈ 130	≈ 75
Pixel field of view	0.25/0.125 mrad	0.25 mrad	0.25 mrad	0.25 mrad
Across track field of view	15°	15°	15°	15°
Ground sampling at 2000 m	0.25 m or 0.5 m	0.25 m or 0.5 m	0.5 m	0.5 m
F-number	F1.64	F2.0	F4.0	F3.0

Table 1: Main technical characteristics of the SYSIPHE system.

2.4 Airborne campaigns

The first airborne campaign occurred in 2013 on the French air base of Cazaux. This place was chosen because the DGA-EV (French military flight test center) has a large active infrared target (Cobra) which allows measuring in-flight radiometric and imaging performances of airborne infrared systems. The target is composed with independent panels to create controlled temperature patterns. For instance, we characterized the modulation transfer function using the Cobra target. Most parameters of HySpex ODIN-1024 and SIELETERS instruments were measured during this campaign, and similar results were obtained during the later campaigns (Table 1). During this first campaign, the system has been tested and validated.

Another airborne campaign took place in August 2015 where we performed measurements in clear sky and partially cloudy sky conditions. This campaign was located in the South of France, over the military base of Canjuers and the aircraft was located on the French Navy-Air base of Hyères. One of the objective was to address all the verification needed to qualify the SYSIPHE system and that were not performed during the 2013 airborne campaign. In particular, this includes the verification of the spectro-radiometric calibration of the instruments and the atmospheric compensation programs.

A ground truth target array was deployed consisting of many surfaces (Figures 2(a-f)) such as gray linoleum, black and white targets, polystyrene, sand, painted concrete, etc. In parallel, military scenarios were deployed in the Canjuers base to acquire full bandwidth hyperspectral images with the SYSIPHE system. Figure 2(g) illustrates some military targets that were present on the scene during the acquisitions.

The 2015 campaign, that involved about 50 persons, was successful. The SYSIPHE system flew 7 times, without failure, including a night flight. Several weather conditions were encountered, including clear sky, partially cloudy and windy, allowing for new studies related to

the robustness of the hyperspectral products regarding the weather conditions.

In 2016, we successfully tested the LWIR instrument of SIELETERS system in another aircraft, a Piper PA31 operated by the French company IMAO. One of the goal of this campaign was to prove the ability of the system to work in a different environment and aircraft.

The more recent SYSIPHE campaign, with only the two SIELETERS subsystems, occurred in January 2019 over Canjuers, Hyères and Salon-de-Provence (where the ground truth targets were installed). One goal of this campaign was to acquire data and spectral images with winter scenarios. The system flew 7 times without failures, including one night flight, and more than 80 lines of measurements. More than 50 people were involved, mostly on the ground to prepare the civilian and military targets and to perform the ground truth measurements.

3. SIELETERS INSTRUMENT: AN IMAGING STATIC FOURIER TRANSFORM SPECTROMETER

This section and the followings are dedicated to the SIELETERS instruments. We will describe into more detail the instrument in this section. In Section 4, we will show some results obtained from the airborne campaign. The SIELETERS instrument is made of two imaging static Fourier transform spectrometers. A high étendue static Fourier transform spectrometer for spectral imaging was proposed in 1987 [13] and, to the best of our knowledge, demonstrated experimentally in 1996 [4]. Since then, several systems have been developed for laboratory [9, 14, 6], ground [3, 1, 8] or airborne demonstrations [11, 7, 10].

The specificity of the SIELETERS instrument is that it operates in thermal infrared bands, up to 11.5 μm . Moreover, the interferometer and the imaging optics are cooled to liquid nitrogen temperatures ($\approx 90\text{ K}$) to reduce the background noise on the signal. Both instruments are in-



Figure 2: **Airborne campaigns.** (a-f) Targets and reference ground surfaces for ground truth measurements: (a) black and white panels, (b) linoleum panels, (c) polystyrene panel, (d) painted concrete, (e) sand, (f) clay. (g) Examples of targets used during the campaign.

stalled on stabilization platforms to minimize the effect of the pitch, roll and yaw of the aircraft on the images (figure 1(b)).

The interferometer is a Michelson-like interferometer made of two dihedrons, a beam splitter, and a compensating plate, all made of ZnSe to avoid stress during the cooling of the instrument (Figure 3(a)) [5]. The dihedrons are translated longitudinally, t_{\parallel} in Figure 3(a), to tune the position of the central fringe (corresponding to the zero optical path difference) in the field. A transversal translation of one dihedron regarding the other, t_{\perp} is performed to adjust the fringe pitch [7]. When t_{\perp} is large enough the fringes appear mostly rectilinear on the camera. Figure 3(b) shows an example of a raw image of the LWIR SIELETTERS instrument after a correction of the non-uniformity of the detector and of the bad pixels. Interference fringes are along the long axis of the images, and they are located on the whole image. The interference fringes are mostly visible around the zero optical path difference, in the lower part of the image (Figure 3(c)).

On our system, the Michelson interferometer is static, meaning that no mechanical part of the interferometer is moving during an acquisition. The optical path difference is not time-dependent and the optical path difference for a ground point seen by the camera is changed by the aircraft displacement. For instance, as shown in Figure 4(a), the corner of the building indicated by the yellow dot moves towards the left when the time t increases. Thus, this ground point will be seen through many optical path differences (about 440 different optical path differences).

After the data acquisition, we register the images such that ground points correspond to the same pixel on all the registered images: the scene appears to be static on the image and the interference fringes are moving across the images. This is schematically shown in Figure 4(b). With our newest data analysis program, the registration is performed by a two-step method. First we preregister the images using the light of sight data recorded during the flight (pitch, roll, yaw and $x-y-z$ position of the instrument on its stabilization platform) and ground elevation models. The error on the registration is on the order of 0.1 pixels, which corresponds to only 5 cm on the ground when the aircraft is 2000 m above the ground. As a second step, we perform image correlations on the registered images using spatial Fourier transform between the images. As a result, the registration error will be smaller than 0.1 pixels.

Once the image registration is performed, we can extract the interferogram of every pixel from the registered images. Then, by knowing the map of the optical path differences (that we measured using a laser) and other laboratory-estimated parameters, we can apply a Fourier transform on every interferogram. As a result, we will obtain a three-dimensional array of data where two dimensions correspond to the position on the ground and the third dimension corresponds to the spectral information. An example of three spectral images are shown in Figure 4(c). As indicated in Table 1, we have ≈ 130 spectral images in the MWIR band and ≈ 75 images in the MWIR band.

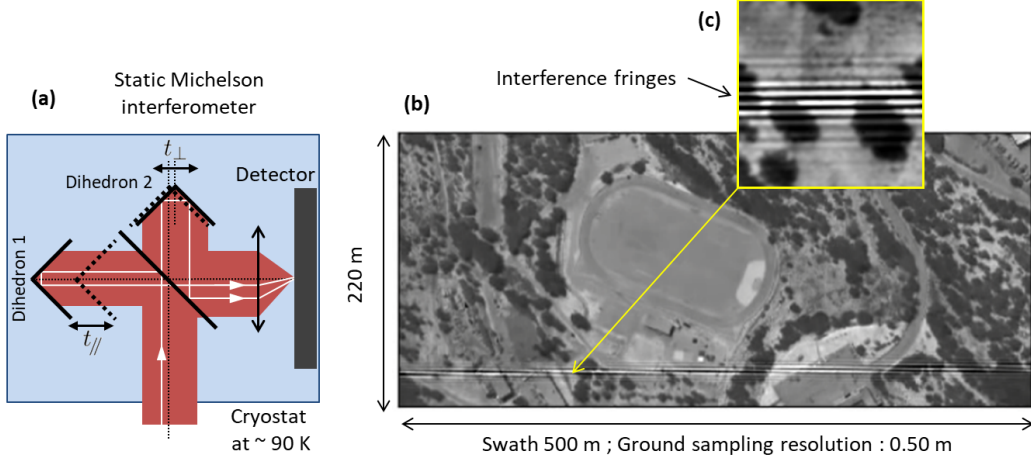


Figure 3: **SIELETTERS, an imaging static Fourier transform spectrometer.** (a) Simplified schematic of the SIELETTERS system. It is composed of a static Michelson interferometer made of two dihedrons [7]. All the optics are cooled to about 90 K. (b) Example of an interferometric image taken by the LWIR instrument. The interference fringes are mostly visible near the zero optical path difference, in the bottom of the image. (c) Detail of the interference fringes.

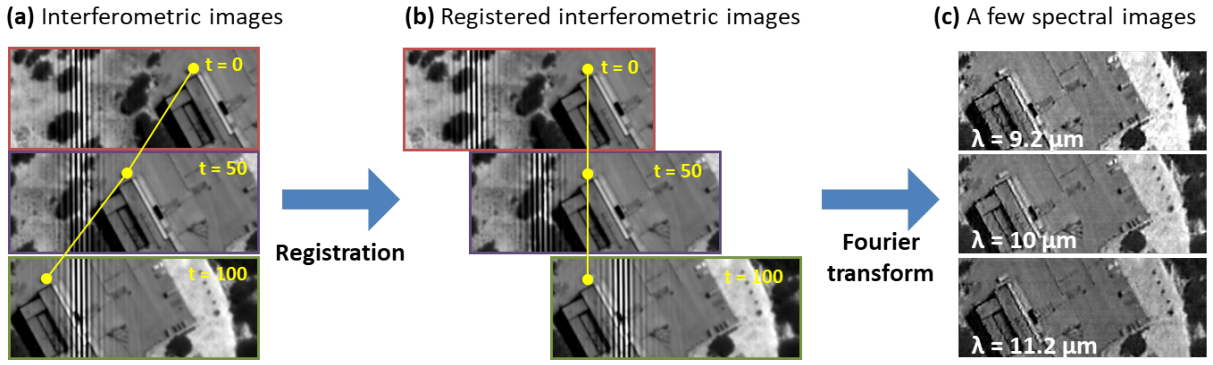


Figure 4: **Conversion of raw images to spectral images.** (a) Some cropped raw images taken by the LWIR instrument illustrating how the acquisition is performed. (b) A data registration step is done such that interferograms can be extracted from the images. (c) A last step that includes Fourier transforms convert interferograms into spectra. By repeating this step to every pixel, we obtain spectral images. Three out of ≈ 200 spectral images are shown here.

4. RESULTS

From the spectral data, we can plot false-color RGB images, *i.e.* where the red, the green and the blue colors correspond to user-defined wavelengths. Figures 5(a) and (b) show some georeferenced RGB images where $R = 4.1 \mu\text{m}$, $G = 4.6 \mu\text{m}$ and $B = 5.0 \mu\text{m}$ (Figures 5(a)) and $R = 9.1 \mu\text{m}$, $G = 9.5 \mu\text{m}$ and $B = 10.7 \mu\text{m}$ (Figures 5(b)). The flight direction is from the bottom to the top and the North is toward the left.

Several colors are visible on those false-color RGB images in the thermal infrared (Figures 5(a,b)). For instance the trees appears mostly green and roof buildings can be red, green, pink, yellow, blue, violet depending on the

material they are made of. More colors are visible in LWIR band indicating that more spectral signatures are in the LWIR band, or at least for the wavelengths we selected. With those two images, data from only six spectral bands are used, suggesting that some more information should be extracted from the images by doing data classification or anomaly detection, methods for which all the 600 spectral images of the SYSIPHE system can be used.

During the summer 2015 and winter 2019 airborne campaign, targets were installed on the ground as mentioned in Section 2.4 and shown in Figure 2(a-f). The targets were monitored and their spectral radiance was measured. Properties of the atmosphere were also mea-

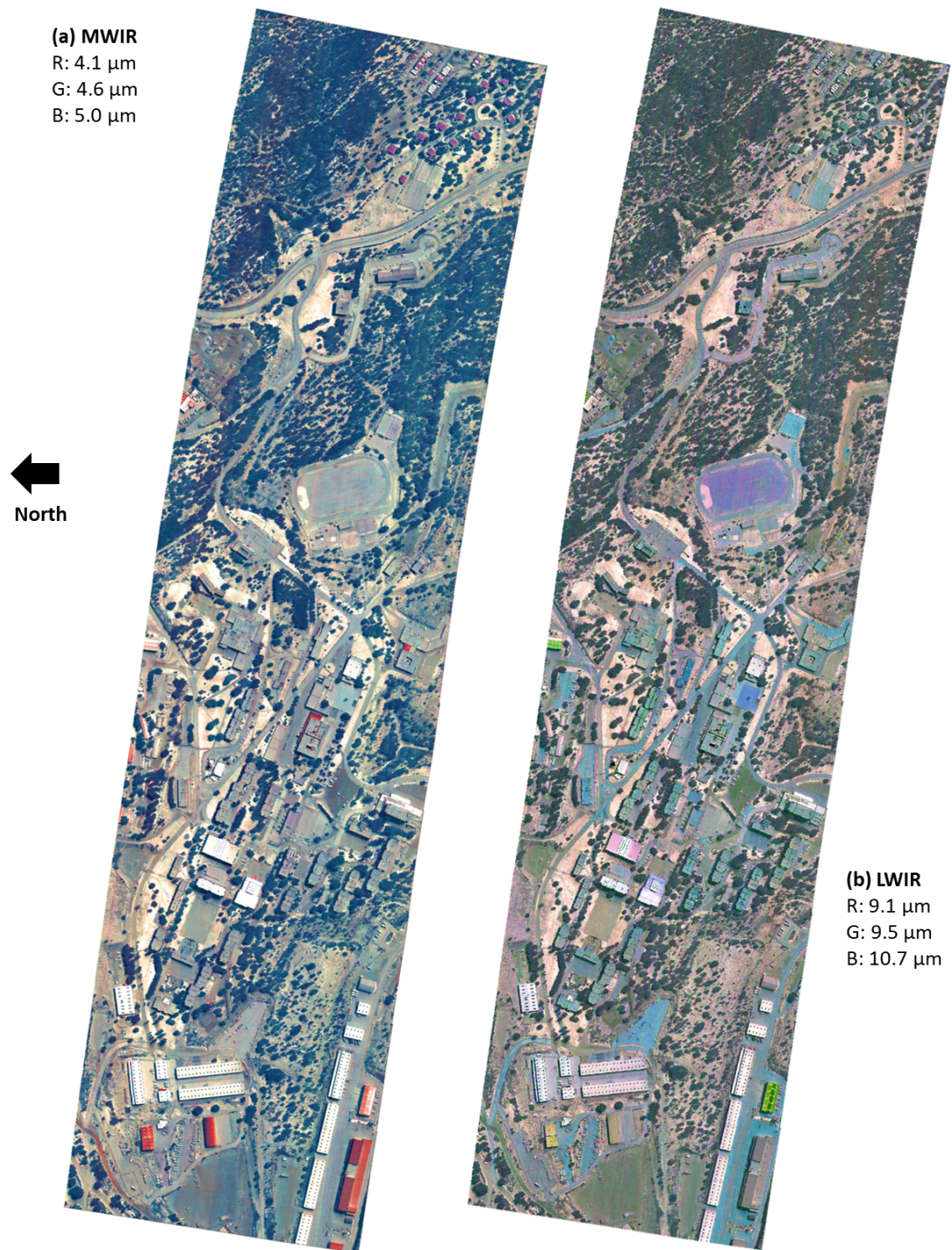


Figure 5: **False-color RGB images in the MWIR (a) and LWIR (b).** Although spectra are more uniform in the thermal infrared band than in the visible wavelengths, some colors appear on the images, especially for the LWIR band (b). Those two images, where only three bands are represented for each, show that information can be extracted from thermal infrared spectral images. Further information can be extracted from the hyperspectral images by performing data classification for instance.

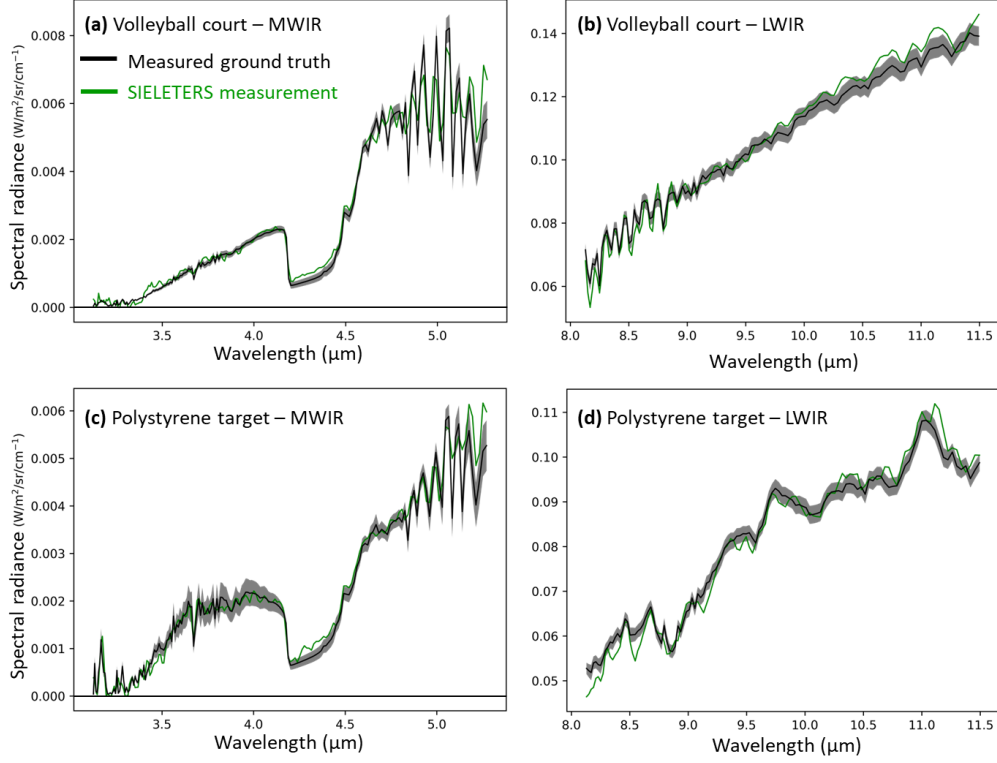


Figure 6: **SIELETTERS spectra and ground truth spectra.** (a-d) Spectral radiance of the ground targets measured by the SIELETTERS instrument (green lines) and the ground truth spectra estimated at the entrance pupil of SIELETTERS (black lines, error bars in gray). SIELETTERS spectra are averaged over 3×3 pixels. Measurements shown here are performed on a volleyball court (a,b) and on a target made of polystyrene (c,d).

sured so that the ground spectra could be estimated at the entrance pupil of the SIELETTERS instruments. Example of such spectra are plotted in black in Figure 6 (error bars in gray). We note that the region of lower radiance around $4.3 \mu\text{m}$ is because of the CO_2 absorption in the atmosphere and that the oscillations visible in the ranges $[5.0 \mu\text{m} - 5.5 \mu\text{m}]$ and $[8 \mu\text{m} - 9 \mu\text{m}]$ by the absorption of the atmosphere's water molecules.

From the hyperspectral data of the SIELETTERS instruments, we also extracted the spectral radiance of the targets. Example spectra are plotted in Figure 6. The spectral information are averaged over 3×3 pixels which correspond to a ground surface of 2.25 m^2 . The large fidelity of the SIELETTERS spectra compared to the ground truth ones shows the good quality of the overall SIELETTERS system.

5. CONCLUSION

The recent developments on the SIELETTERS data analysis program improved the quality of the hyperspectral images and of the spectra. We have good quality images and spectra as we have shown in this paper. Data classification, atmosphere compensations and anomaly detection are undergoing with the SIELETTERS data acquired

during the past campaigns.

The SIELETTERS instrument, the SYSIPHE project and the data and expertise acquired during our several campaigns are making a robust framework for hyperspectral imaging, data collection (on both civilian and military targets) and the project is going toward deep scientific understandings on, in particular, Fourier transform imaging spectroscopy and on thermal infrared phenomenology. To further develop this knowledge and to increase the scope of applications of the system, we are developing a ground version of the SIELETTERS instrument. We are planning to perform high spatial and spectral resolutions imaging spectroscopy and also gas identifications.

The SIELETTERS / SYSIPHE system is opened to external users such as NATO, EDA or bi-lateral arrangement but also to the European Facility for Airborne Research and to national and international communities (scientific, industrial or institutional)

6. ACKNOWLEDGMENTS

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