SYSIPHE SYSTEM: A STATE OF THE ART AIRBORNE HYPERSPECTRAL IMAGING SYSTEM. INITIAL RESULTS FROM THE FIRST AIRBORNE CAMPAIGN

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ABSTRACT

SYSIPHE is an airborne hyperspectral imaging system and the result of a cooperation between France (Onera and DGA – Délégation Générale de l'Armement) and Norway (NEO and FFI (Forsvarets forskningsinstitutt)). It is a unique system by its spatial sampling of 0.5 m with a 500 m swath at a ground height of 2000 m combined with its wide spectral coverage from 0.4 µm to 11.5 µm in the atmospheric transmission bands.

Its infrared component, named SIELETERS, consists in two *high étendue* imaging static Fourier transform spectrometers, one for the midwave infrared and one for the longwave infrared. These two imaging spectrometers are closely similar in design, since both are made of a Michelson interferometer, a refractive imaging system, and a large infrared focal plane array (1016×440 pixels). Moreover, both are cryogenically cooled and mounted on their own stabilization platform which allows the line of sight to be controlled and recorded. These data are useful to reconstruct and to georeference the spectral image from the raw interferometric images.

The visible and shortwave infrared component, named Hyspex ODIN-1024, consists of two spectrographs for VNIR (Visible and Near InfraRed) and SWIR (Short Wave InfraRed) based on transmissive gratings. The latter share a common fore-optics and a common slit to ensure perfect registration between the VNIR and the SWIR images. The spectral resolution varies from 5nm in the visible to 6nm in the shortwave infrared.

In addition, the STAD, the postprocessing and archiving system, is developed to provide spectral reflectance and temperature products (SRT products) from calibrated georeferenced and inter-band registered spectral images at the sensor level acquired and pre-processed by SIELETERS and Hyspex ODIN-1024 systems.

SYSIPHE was flown for the first time in September 2013, over Cazaux, a French military airbase for experiments, and over Fauga-Mauzac in France where Onera has installed ground targets. A description of the experiment and some initial results are presented.

Keywords: Remote sensing, infrared, multispectral, hyperspectral, airborne, SYSIPHE, SIELETERS, thermal infrared, spectroscopy, Fourier transform

INTRODUCTION

SYSIPHE (**SY**stème **S**pectro-**I**mageur de mesure des **P**ropriétés **H**yperspectrales **E**mbarqué) is an airborne hyperspectral imaging sensor system and the result of a cooperation between France (Onera and DGA) and Norway (NEO and FFI). It is a unique system by its spatial sampling of 0.5 m with a 500 m swath at a ground height of 2000 m, combined with its wide spectral coverage

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from 0.4 to 11.8 µm in the atmospheric transmission bands. After a short description of the SYSIPHE system components, we will present a flight campaign held in France in September 2013. Then we will present some first results of the 2013 flight campaign.

THE SYSIPHE SYSTEM

System architecture

SYSIPHE is an airborne hyperspectral imaging system, built in collaboration between France and Norway. It is unique by having a very wide spectral coverage, from 0.4 to 11.5 µm in the atmospheric transmission bands, combined with a high spatial resolution: 0.5 m ground sampling distance over a 500 m swath.

To achieve this unique performance, SYSIPHE is composed of three instruments, one dispersive spectrometer for the visible domain (VIS [0.4-0.8 µm]), Near InfraRed domain (NIR [0.8-1.4 µm]) and ShortWave InfraRed domain (SWIR [1.4-2.5 µm]), developed by Norsk Elektro Optikk in Norway (NEO), and two Fourier transform spectrometers for the MidWave InfraRed domain (MWIR [3-5.3 µm]) and the LongWave InfraRed domain (LWIR [8-11.5 µm]), developed by the French aerospace laboratory Onera. These three instruments are integrated on the same aircraft, a DO-228 operated by DLR in Germany (Figure 1). By having imagers for all bands in the same aircraft, associated to inertial measurement units, SYSIPHE can produce georeferenced images of spectral radiances acquired at the same time in the same environment with more than 500 spectral bands covering the whole spectral domain.

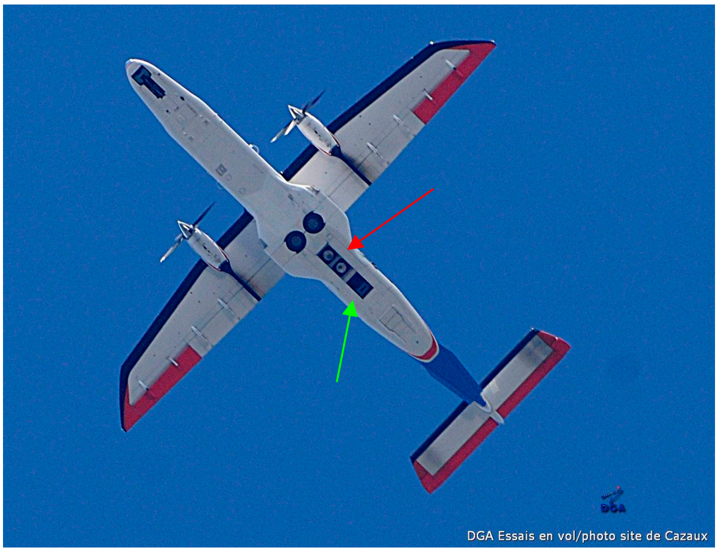

Figure 1: The DO-228 of the DLR with the hatch opened (200 cm × 50 cm). The two circles (red arrow) are the LWIR and MWIR SIELETERS components, the black rectangle (green arrow) is the Hyspex ODIN instrument.

The SYSIPHE system also integrates a real-time processing capability dedicated for target detection (1) developed by FFI, and a ground processing chain, the STAD, developed by Onera to register the georeferenced hyperspectral images provided by each instrument and to produce outputs as spectral radiance, ground spectral reflectance, and surface temperature maps. All these products are georeferenced.

The visible-near infrared instrument (HySpex ODIN-1024)

HySpex ODIN-1024 (2) is the visible and shortwave infrared part of the SYSIPHE system. It has been developed by NEO. It consists of two pushbroom imaging spectrographs based on transmissive gratings. These two modules share a common fore-optics and a common slit to ensure perfect registration between the VNIR (Visible-NIR) and the SWIR images. The spectral resolution varies from 5.0 nm in the VNIR to 6.1 nm in the SWIR.

The HySpex ODIN-1024 has an onboard spectral and radiometric calibration source. The VNIR channel is capable of higher spatial resolution than the other SYSIPHE bands by sampling 2048 cross-track pixels. A picture of HySpex ODIN-1024 is shown in Figure 2. Hyspex ODIN-1024 will also be offered as a commercial product by NEO. Figure 3 shows a false colour georeferenced image extracted from the airborne hyperspectral cube acquired by HySpex ODIN-1024.

Figure 2: The HySpex ODIN-1024 spectral imager installed into the aircraft.

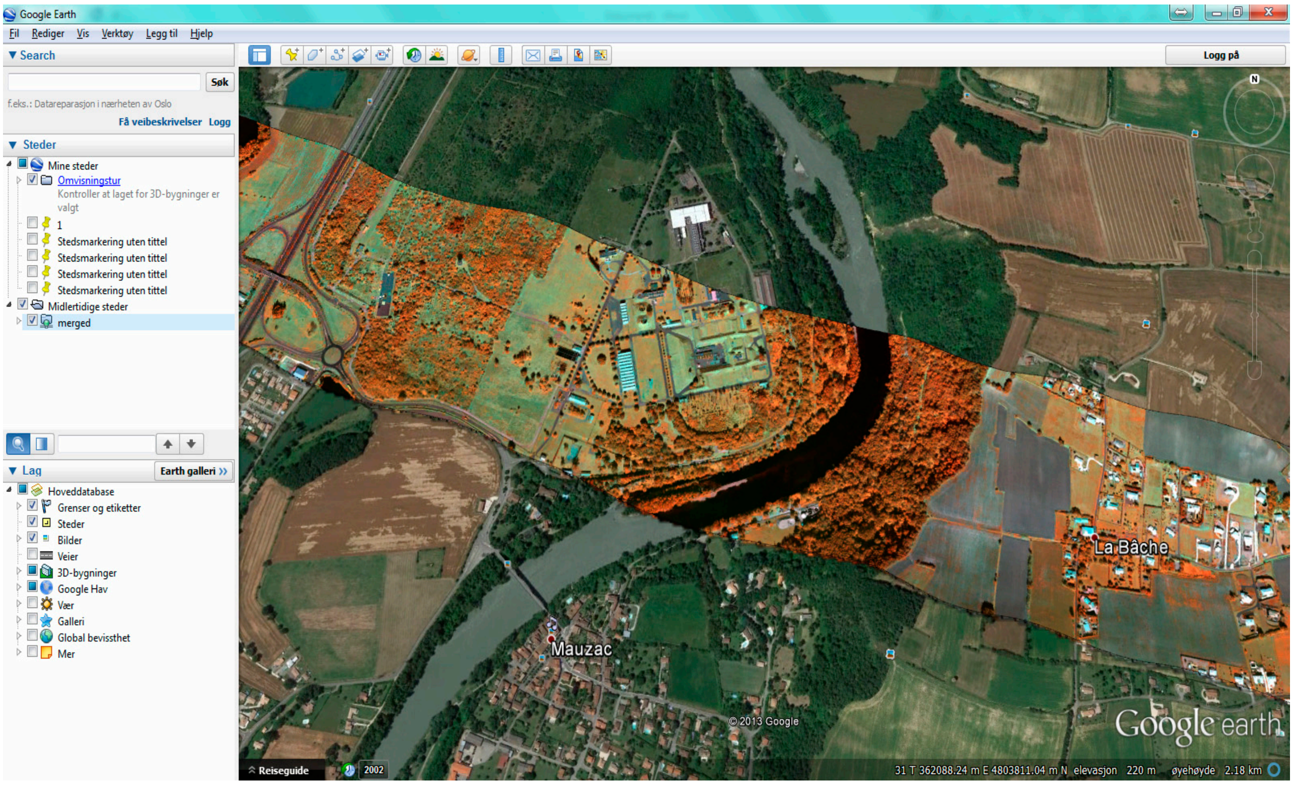

Figure 3: RGB georeferenced image acquired by HySpex ODIN-1024 represented on the GoogleEarth© map.

Table 1: Main technical specifications for HySpex ODIN-1024 (values are subject to change due to on-going development)

Parameter	VNIR	SWIR
Spectral range	400-1000 nm	950-2500 nm
Spectral resolution	5.0 nm	6.1 nm
Pixel FOV	0.25 mrad	0.25 mrad
Total across track FOV	15°	15°
Spatial resolution	1024 px	1024 px
F-number	F1.5	F2.0

The MWIR/LWIR instrument (SIELETERS)

SIELETERS (3) is the infrared component of SYSIPHE. It is composed of two distinct Fourier transform spectrometers, one for the MWIR and one for the LWIR. The spectral resolution (where the definition used is 1.2/(2·MPD), where MPD is the Maximum Path Difference of the interferometer) is 11 cm^{-1} in the MWIR and 5 cm^{-1} in the LWIR.

Figure 4, left: MWIR interferometric image from SIELETERS (note the interference fringes on the left). Right: LWIR panchromatic image for MTF estimation. This image was acquired during another flight in different flight conditions.

Both instruments are cryogenically cooled to achieve high performance absolute measurements and both are imaging static Fourier transform spectrometers (ISFTS) (4,5): An imaging system is combined with a lateral shearing interferometer. Thanks to this interferometer, linear interference fringes are superimposed on the image of the scene (Figure 4): When flying over the scene, a ground point is seen through the various optical path differences. After optical path difference registration, we can thus reconstruct the interferogram (and therefore the spectrum) of each ground pixel.

Table 2: Main technical specifications for SIELETERS (values are subject to change due to on-going development)

Parameter	MWIR	LWIR
Spectral range	3.0-5.4 µm	8.1-11.8 µm
Spectral MWIR resolution	11 cm^{-1}	5 cm^{-1}
Pixel Fov	0.25 mrad	0.25 mrad
Total across track FOV	15°	15°
Spatial resolution	1016 px	1016 px
F-number	F4.0	F3.0

Each instrument is installed on a specific gyro-stabilized platform based on the Leica Geosystems (PAV80) to control the line of sight (LOS), normally in the Nadir direction during recording. The control loop system commands the different phases of the flight (take-off, landing, transit flight, and recording) and the coupling between the two stabilized platforms. On one stabilized platform, an independent high precision IMU (Inertial Measurement Unit PosPac 610 from Applanix) was installed, working in open-loop mode, to check the quality of the LOS control. Figure 5 shows the two SIELETERS instruments, each on their own stabilization platform unit.

Figure 1: The SIELETERS spectral imagers.

Each stabilization platform unit integrates several components, for a large part developed by Onera:

- a motorized gimbal based on PAV80 from Leica Geosystem,
- an integrated new generation inertial motion unit based on the µPos AP from Applanix,
- a control electronic system based on a DSP (Digital Signal Processing) based on the µAutobox II from dSPACE
- a mechanical structure allowing a rigid integration of the optical systems of SIELETERS that enables the centre of gravity, inertial moment and mechanical deformation to be tuned.

In addition, the SIELETERS stabilization system integrates the "harmonization" between the two instruments in the close-loop control, the flight plan control and the attitude measurements (PosPac 610 from Applanix).

Some important features of the stabilization system are:

- Mass of one instrument : 110 kg (with 65 kg for instrument itself and 45 kg for the stabilization solution)
- Stabilization : < 90 µrad (during all the line)
- Position accuracy (in WGS84) : <15 cm (with post-processing).

The processing and archiving system (STAD)

The last component of SYSIPHE is the processing and archiving system. It collects the products from ODIN and SIELETERS and verifies their completeness (presence or absence of files in the product and the presence or absence of specific information in the file headers like, for example, the definition of the projection system). The inter-instrument registration module of the STAD provides a single georeferenced hyperspectral radiance image covering the whole spectral domain. The STAD then performs atmospheric correction in order to produce an estimation of spectral reflectance, emissivity and temperature of the scene.

Atmospheric correction is based on two modules, one to estimate the spectral reflectance in the VNIR and SWIR spectral domain and the other one to assess the spectral reflectance and temperature of the surface in the thermal infrared spectral domain.

- For the VNIR-SWIR domain, this module uses the Cochise software (6,7) supported by ONERA/DOTA
- For the MWIR-LWIR domain, two dedicated autonomous methods (without need of additional atmospheric measurement) have been developed. The first one is based on a neural network (8,9) used to estimate the atmospheric thermodynamic parameters from the hypercubes acquired by the SIELETERS system. The radiative atmospheric terms are then assessed with the radiative transfer code MODTRAN (10) and the emissivity/temperature separation is done by a spectral smoothness algorithm.

All the data are collected in a database searchable by a dedicated GUI based on GeoNetwork.

The SYSIPHE system offers two product levels for the users:

- Georeferenced spectral radiance images at the sensor level covering the whole spectral range (from visible to LWIR- band);
- Target spectral reflectance/emissivity after atmospheric correction and the related temperature image.

The STAD products include hyperspectral image, quality matrix image and optional temperature image. Each image is informed by a header file in the ENVI (Environment for Visualizing Images) format and an ASCII header file containing information supplemented by each module (version, data input, intrinsic parameter values, …). The image format is the BSQ (Band SeQuential) format.

Figure 6 illustrates the SYSIPHE post-processing scheme and the different product levels which could be offered to the users depending on their applications.

AIRBORNE MEASUREMENT

The September 2013 first airborne campaign

A flight campaign was led on the French air base of Cazaux in September 2013. This site was chosen, because the DGA-EV (French military flight test center) has a large active infrared target which enables in-flight radiometric and imaging performances of airborne infrared systems to be measured. This "Cobra" target is composed of independent panels to create controlled temperature patterns (Figure 7).

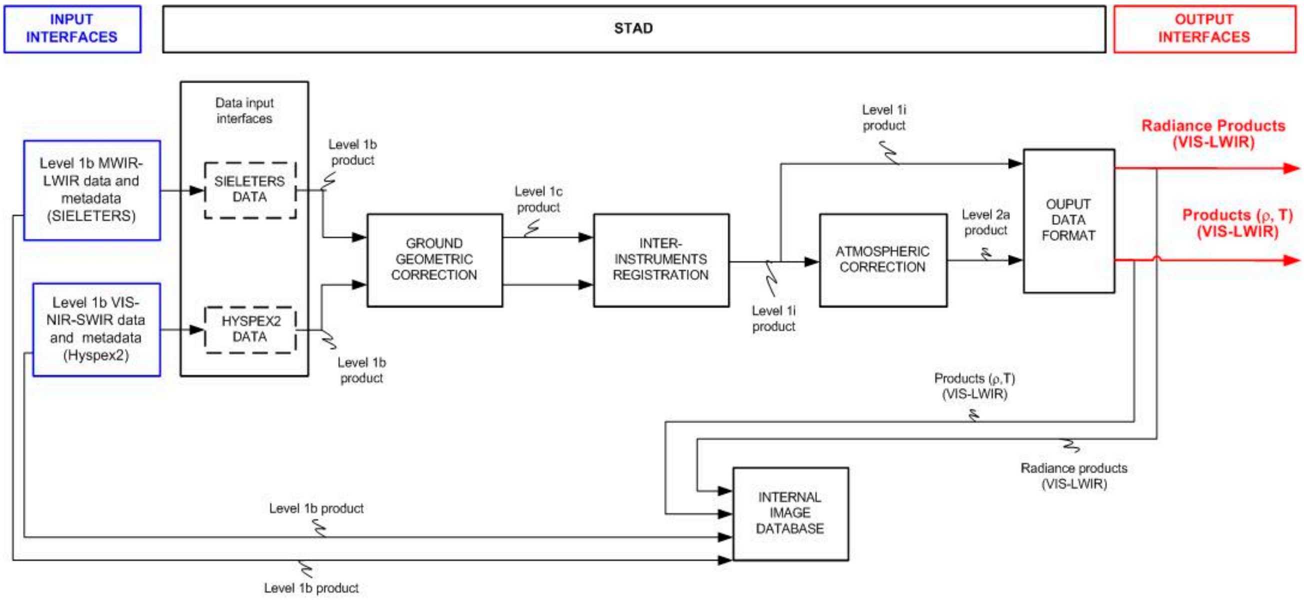

Figure 6: SYSIPHE post-processing scheme and products levels.

Figure 7: The Cobra target at Cazaux on the right (active infrared target), Black and white target reflective target on the left, different kind of material target in the middle.

The performance of the stabilization platform is illustrated in Figure 8**.** The acquisition time is 45 seconds (3 km length). The beginning of this graph (roll attitude) shows the platform alignment (with the first and second zero crossings) followed by the measurement phase. The stabilization accuracy is better than the requirements (<125 µrad over all the line) and we note a small static misalignment of about 30 to 35 µrad between the instrument and the platform. The other axes (pitch and yaw) present a performance similar to the roll attitude correction.

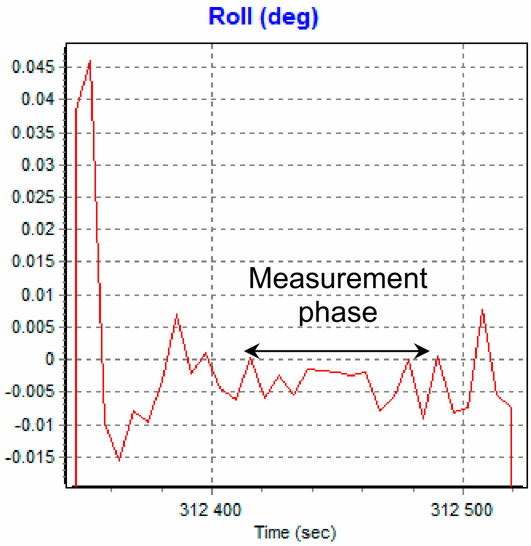

Figure 8: Correction of the Roll axis with the SIELETERS stabilization platform.

During this campaign, imagery was also recorded over the Onera site of *Le Fauga-Mauzac*, near Toulouse city, where passive targets had been deployed along with ground spectroradiometers in order to measure the ground truth. Only one flight was done over this site.

Figure 9 depicts this flight with the georeferenced image of the LWIR band. Figure 10 illustrates the ground truth area with the different patterns on the ground. Table 3 gives the nature and the dimension of the ground patterns.

Figure 9: Illustration of the SIELETERS georeferenced image on the Fauga line over the Google Earth© map

Table 3: Calibration patterns installed at Le Fauga centre.

Pattern	Dimension
Concrete FERMAT	30×30 m^2
Asphalt FERMAT	30×80 m^2
White “Lima” pattern	4.5×4.5 m^2
Black “Lima” pattern	4.5×4.5 m^2
Sand	4.5×4.5 m^2
Linoleum dark grey	8×8 m^2
Linoleum light grey	8×8 m^2

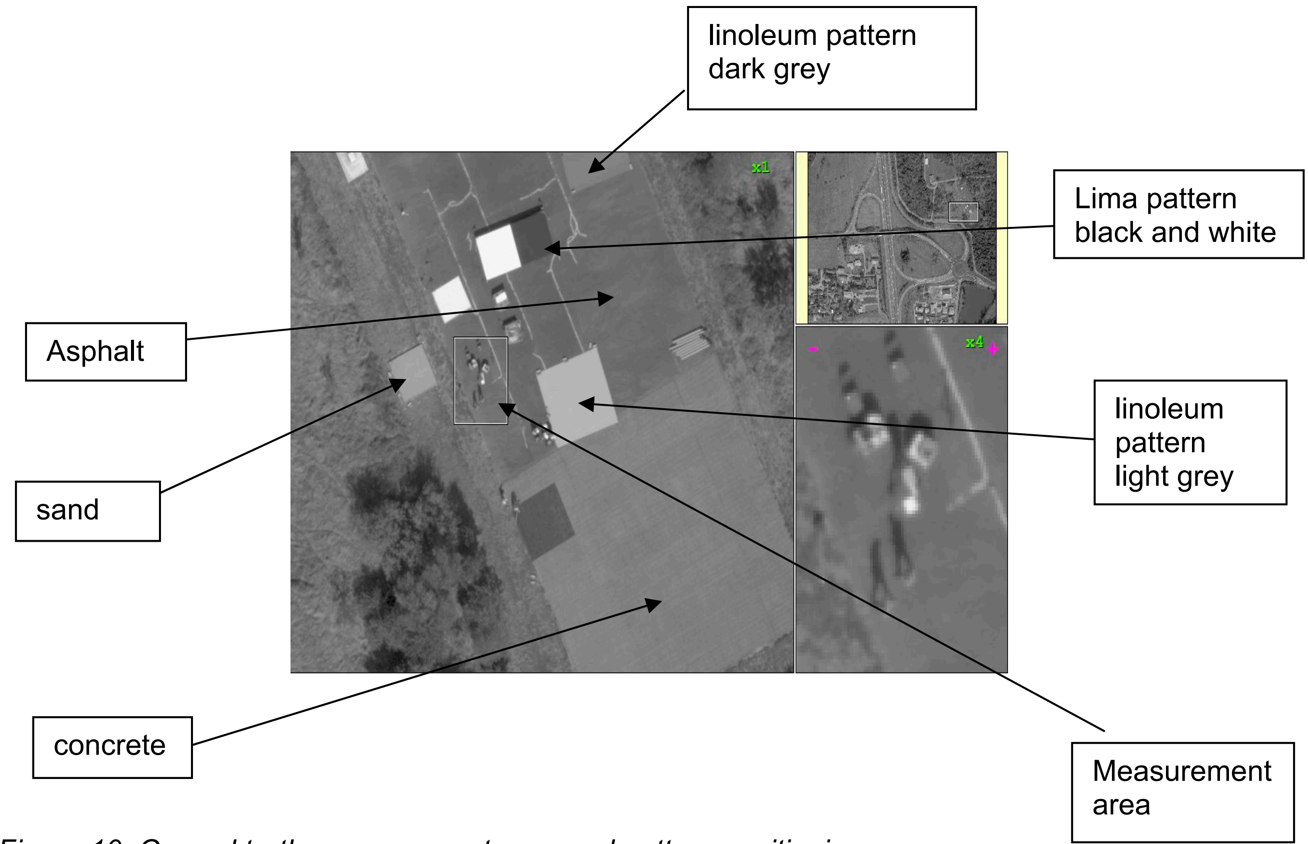

Figure 10: Ground truth measurement area and pattern positioning

ODIN and SIELETERS image registration

The spectral images acquired over the Fauga-Mauzac center by the ODIN and SIELETERS systems are used to test the inter-instrument registration and to build the full wavelength hyperspectral product. Figure 11 shows the quicklook images of the ODIN and the SIELETERS flight lines. The image orientations are different: the Geographic North orientation for ODIN image and the flight line orientation for SIELETERS image.

The two images are georeferenced in the WGS84 - UTM 31 North system coordinate, with a spatial resolution of 0.5 m $\times$ 0.5 m for ODIN and 0.52 m $\times$ 0.489 m for SIELETERS.

In order to globally assess the georeferencing precision, the images are compared to a reference georeferenced mosaic image based on BD ORTHO imagery provided by IGN, the French mapping agency. The BD ORTHO® includes colour orthophoto with spatial resolution of 0.5 m covering

France in the Lambert 93 projection system. The georeferencing precision of ODIN is about 1 to 2 pixels. The georeferencing precision of SIELETERS is about 10 pixels, essentially because SIELETERS images are not yet orthorectified and the line of sight measurement was not yet used. The misregistration between ODIN and SIELETERS is illustrated in Figure 12.

Figure 11: Quicklooks of ODIN image (left – north orientation) and SIELETERS image (right: flight orientation).

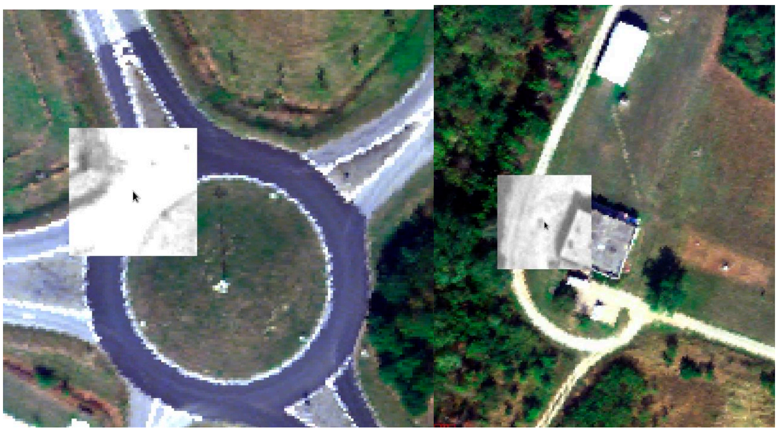

Figure12: Misregistration illustration between the ODIN product and the SIELETERS product. The RGB (Red-Green-Blue) image is constructed with the corresponding spectral bands of the ODIN hypercube and the grayscale SIELETERS image representing a given spectral band is superposed on the RGB image.

The first stage of the STAD consists in the reorientation of the SIELETERS product according to the Geographical North and resampling at a spatial resolution of 0.5 m × 0.5 m which is the spatial resolution of the ODIN product.

Then, the inter-instrument registration is done taking the ODIN product as reference. The registration process is applied on the 1.55 µm spectral image for ODIN and the 4.7 µm spectral image for SIELETERS. This method includes two stages: Estimation of the deformation model between the two products based on geometric correlation and application of the deformation model on the SIELETERS product with a resampling tool. The result is illustrated in Figure 13 and detailed results are given in Figure 14.

The global evaluation of the inter-instrument registration performance on this data set indicates a precision better than one pixel, showing the good quality of the inter-instrument STAD registration.

Figure 13: STAD registration result illustration by superimposition of the 4.7 µm spectral band over RGB composition obtained with three spectral bands of the ODIN image

Figure14: Zoom on the STAD registration results.

Reflectance data first results from ODIN data

The ODIN spectral image acquired on 25th September 2013 over the Fauga-Mauzac Onera center has been processed with the COCHISE tool (6) integrated in the STAD for atmospheric correction in the reflective domain.

The first results are shown in Figure 15 for some parts of the ground truth measurement area shown in Figure 10. The black curves are the reflectance given by the COCHISE software (mean and standard deviation), compared with the red curve measured on the ground with an ASD Field-Spec. Here, it must be noted that the measurements taken with the ASD were done a clear day before the SYSIPHE flight, which was lightly cloudy (cirrus). Due to this cloudy day, the calibration of the ODIN instrument could not be verified with this experiment. The COMANCHE propagation model (6) was validated only for clean sky conditions. Nevertheless, the ODIN data were performed by the STAD to process the atmospheric correction. As for the COMANCHE model, the COCHISE code is validated only for clean sky conditions. The only thing to be outlined is that ODIN data could be processed by the STAD. The differences on reflectance between the COCHISE output and ASD fieldspec spectrometer output cannot be explained today, mainly due to the cloudy day and the inflight calibration of ODIN data verification. Further investigations have to be carried out in order to assess the inflight radiometric calibration before giving a complete error budget for the reflectance product. Those investigations will be based on a clean sky measurement during a new airborne campaign scheduled for August 2015.

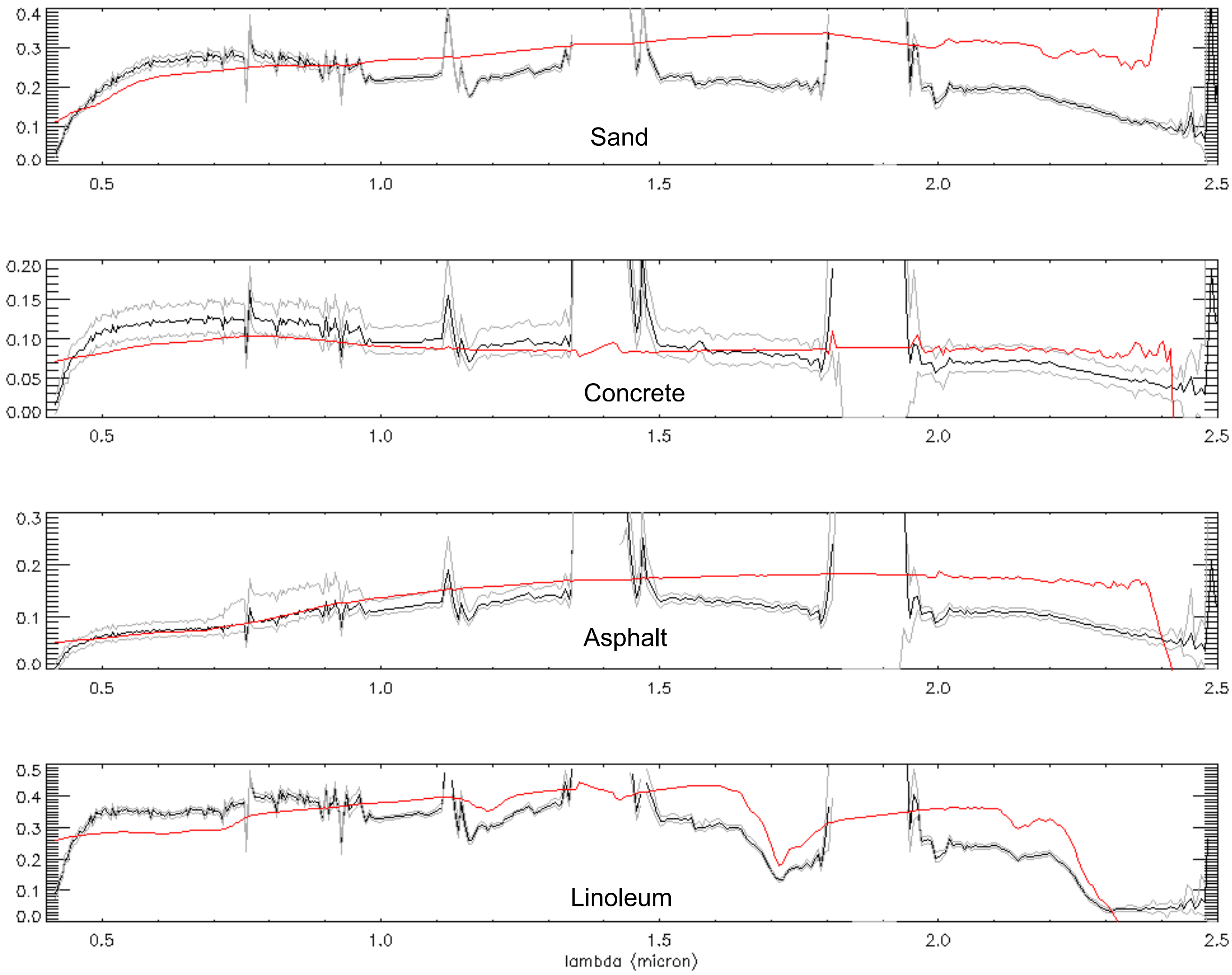

Figure 15: First reflectance results on ODIN image with the COCHISE software. Red: ASD Field-Spec measures, dark : COCHISE output reflectance (mean and standard deviation).

Spectral radiance first results on SIELETERS data

The SIELETERS spectral image acquired on 25th September 2013 over the Fauga-Mauzac Onera centre has been processed and compared to spectral radiance measurements done on ground. The spectral radiance ground measurements were done as the Sieleters acquisition. The spectral radiance measurements are propagated to the entrance window of the Sieleters instrument through the atmosphere and convolved with the Sieleters instrument shape response. It has to be noted that this day was slightly cloudy (cirrus).

Figure 16 presents monochromatic images obtained from the MWIR instrument at 4.8 µm and from the LWIR instrument at 10.2 µm. The images illustrate the ground truth area at Onera-Fauga centre where the patterns were deployed. The ground size of those images is 500 × 200 m². The spatial quality of the images is good, which was confirmed by MTF in-flight measurements (3).

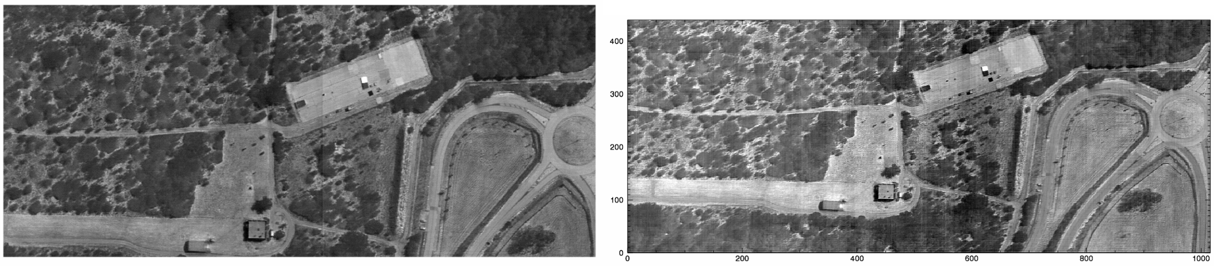

Figure 16: Monochromatic images from Sieleters hyperspectral cube (left: λ=4.8µm, right: λ=10.2 µm).

Another way to display the information is to consider the spectrum obtained for one point of the scene. So, the spectra of two individual pixels are drawn in Figure 17. They correspond to a pixel lying inside a large polystyrene target which was set on the ground (green curve), to a pixel lying on a white target (blue curve), and to a pixel lying on a dark target (red curve). The bold curves are the spectra from the SIELETERS measurement and the normal curves are the ground truth measurement propagated to the entrance window of the SIELETERS instrument. From these spectra, it appears that the signal-to-noise ratio remains to be improved. Various avenues are currently explored to enhance the SNR. Nevertheless, these spectra show a good agreement in terms of both spectral and radiometric calibration. Quantitative comparison, including an exhaustive error budget, is ongoing especially with a new airborne campaign scheduled for August 2015 where measurements with clean sky will be done.

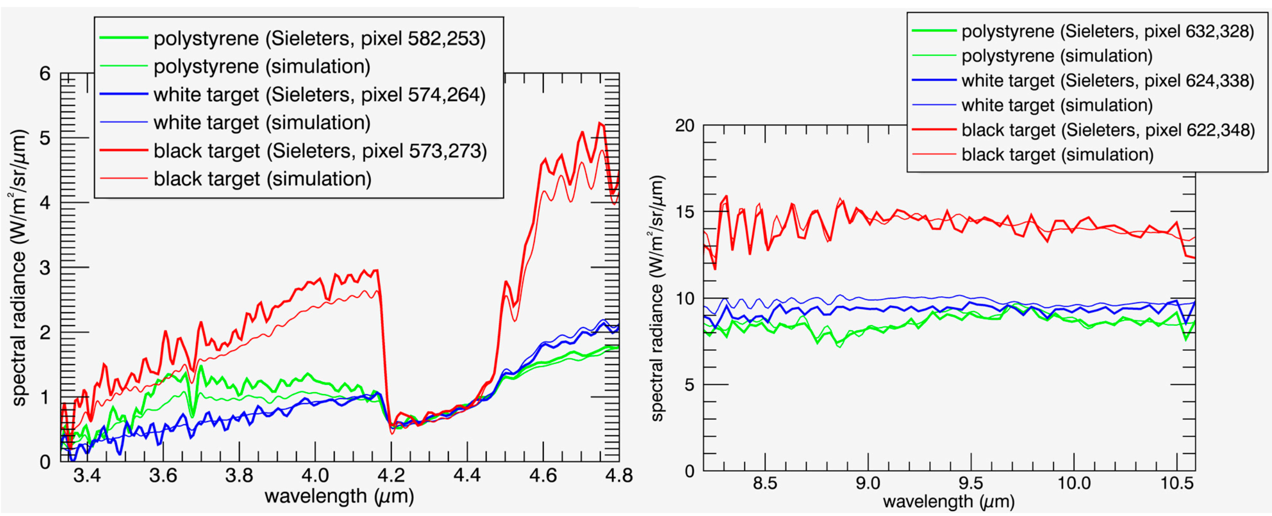

Figure 2: Spectra of three individual pixels, respectively, placed in the polystyrene target (green), the white target (blue) and the dark target (red) compared to the ground spectral radiance measure propagated to the pupil of the SIELETERS instrument

CONCLUSION

The SYSIPHE development programme has been completed. The two instruments have been successfully developed, together with the ground processing and archiving system (STAD), forming a system with unparalleled capability and performance. The two instruments are flight certified and completed the acceptance campaign in September 2013. First results are encouraging and in accordance with the requirements. Some improvements are currently in progress, especially related to the SIELETERS data processing.

The SYSIPHE programme is continuing with a new airborne campaign done in August 2015 in the south of France for French and Norwegian defence needs. The data acquired during this campaign will improve the knowledge of the calibration of the instruments and will test the atmospheric correction in the reflective and emissive domain. SYSIPHE will be open soon to the wider defence and scientific community as a unique tool for airborne data collection campaigns.

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