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## SYSIPHE system: a state of the art airborne hyperspectral imaging system: initial results from the first airborne campaign

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# 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, result of a cooperation between France (Onera and DGA) and Norway (NEO and FFI). It is a unique system by its spatial sampling -0.5m with a 500m swath at a ground height of 2000m- combined with its wide spectral coverage -from 0.4 $\mu$ m to 11.5 $\mu$ m in the atmospheric transmission bands.

Its infrared component, named SIELETTERS, 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 IRFPA (1016x440 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 Hypsux ODIN-1024, consists of two spectrographs for VNIR and SWIR based on transmissive gratings. These 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 post processing 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 SIELETTERS and Hypsux ODIN-1024 systems.

SYSIPHE was flown for the first time in September, 2013. Initial results are shown.

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

## 1. INTRODUCTION

SYSIPHE is an airborne hyperspectral imaging sensor system, result of a cooperation between France (Onera and DGA) and Norway (NEO and FFI). It is a unique system by its spatial sampling -0.5m with a 500m swath at a ground height of 2000m- combined with its wide spectral coverage -from 0.4 $\mu$ m to 11.5 $\mu$ m in the atmospheric transmission bands. After a short description of the SYSIPHE system components, we will present the flight campaign held in France in September 2013. Then we will present some first results of the 2013 flight campaign.

## 2. THE SYSIPHE SYSTEM

### 2.1 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  $0.4\mu\text{m}$  to  $11.5\mu\text{m}$  in the atmospheric transmission bands, combined with a high spatial resolution:  $0.5\text{m}$  ground sampling distance over a  $500\text{m}$  swath.

To achieve this unique performance, SYSIPHE is composed of three instruments, one dispersive spectrometer for the visible domain (VIS [ $0.4\text{-}0.8\ \mu\text{m}$ ]), Near InfraRed domain (NIR [ $0.8\text{-}1.4\ \mu\text{m}$ ]) and ShortWave InfraRed domain (SWIR [ $1.4\text{-}2.5\ \mu\text{m}$ ]), developed by the Norsk Elektro Optikk in Norway (NEO), and two Fourier transform spectrometers for the MidWave InfraRed domain (MWIR [ $3\text{-}5.3\ \mu\text{m}$ ]) and the LongWave InfraRed domain (LWIR [ $8\text{-}11.5\ \mu\text{m}$ ]), developed by the French aerospace laboratory Onera. These three instruments are integrated on the same aircraft, a DO-228 operated by DLR in Germany. (See **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 ( $200\text{cm} \times 50\text{cm}$ ). The 2 circles (red arrow) are the LWIR and MWIR SIELETTERS 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 (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.

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

HySpex ODIN-1024 is the visible and shortwave infrared part of the SYSIPHE system [1]. It is 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  $5\text{nm}$  in the VIS to  $6\text{nm}$  in the SWIR.



Figure 2. The HySpex ODIN-1024 spectral imager prototype.

The HySpex ODIN-1024 has an onboard spectral and radiometric calibration source. The inflight radiometric and spectral stability was found to be of good quality. 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**. This imager 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 3. RGB georeferenced image acquired by HySpex ODIN-1024 represented on the GoogleEarth map.

### 2.3 The MWIR/LWIR instrument (SIELETTERS)

SIELETTERS is the infrared component of SYSIPHE. It is composed of two distinct instruments, one for the MWIR and one for the LWIR. The spectral resolution (where the definition used is  $1.2/(2 \cdot \text{MPD})$ , with MPD the maximum path

difference) is better than  $13\text{cm}^{-1}$  in the MWIR and  $6\text{cm}^{-1}$  in the LWIR. Both instruments are cryogenically cooled to achieve high performance absolute measurements, and both are imaging static Fourier transform spectrometers (ISFTS) [2, 3]: 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. Thus, after optical path difference registration, we can reconstruct the interferogram (and therefore the spectrum) of each ground pixel.



*Figure 4. left: MWIR interferometric image from SIELETTERS (note the interference fringes on the left). Right: LWIR panchromatic image for MTF estimation (see section 3.2). This image is acquired during another flight in different conditions.*

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. The *Figure 5* shows the two SIELETTERS instruments, each on their own stabilization platform unit.



*Figure 5. The SIELETTERS spectral imagers*

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

- a motorized gimbal from Leica Geosystem,
- a "mini" control attitude system based on the  $\mu$ PosAv Applanix (for the sensors),
- a custom Digital Signal Processor based on the  $\mu$ Autobox from dSPACE to command the stabilization (connected to the aircraft network),
- a control loop optimized over a gliding window of 440 images (residual error < 1 pixel)
- a custom geometric calibration.

In addition, the SIELETTERS 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:

- Weight of one instrument : 110 kg (with 65 kg for instrument himself and 45 kg for the stabilization solution)
- Stabilization : < 90  $\mu$ rad (during all the line)
- Position accuracy (in WGS84) : < 15 cm (with post-processing)

#### **2.4 The processing and archiving system (STAD)**

The last component of SYSIPHE is the processing and archiving system. It collects the data from ODIN and SIELETTERS and it verifies the data completeness (the file headers are indicated and all the data files needed are present) to provide a single georeferenced hyperspectral radiance image covering the whole spectral domain. The STAD then performs atmospheric compensation, in order to produce an estimation of spectral reflectance, emissivity and temperature of the scene. All the data are collected in a database searchable by a dedicated GUI.

The SYSIPHE system offers two product levels for the users:

- The spectral radiance images at the sensor level covering the whole spectral range (from visible to LWIR- band) and georeferenced;
- The 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. Metadata are provided in the form of an ENVI (Environment for Visualizing Images) header file. The image format is the BSQ (Band SeQuential interleave) format.

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

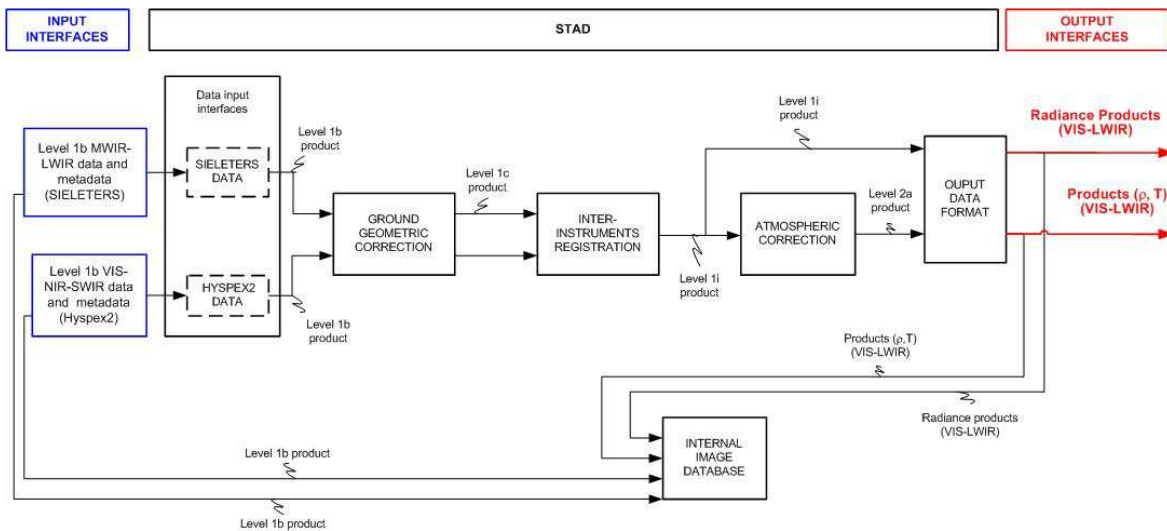


Figure 6 : SYSIPHE post-processing scheme and products levels

### 3. AIRBORNE MEASUREMENT

#### 3.1 The September 2013 first airborne campaign

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



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.

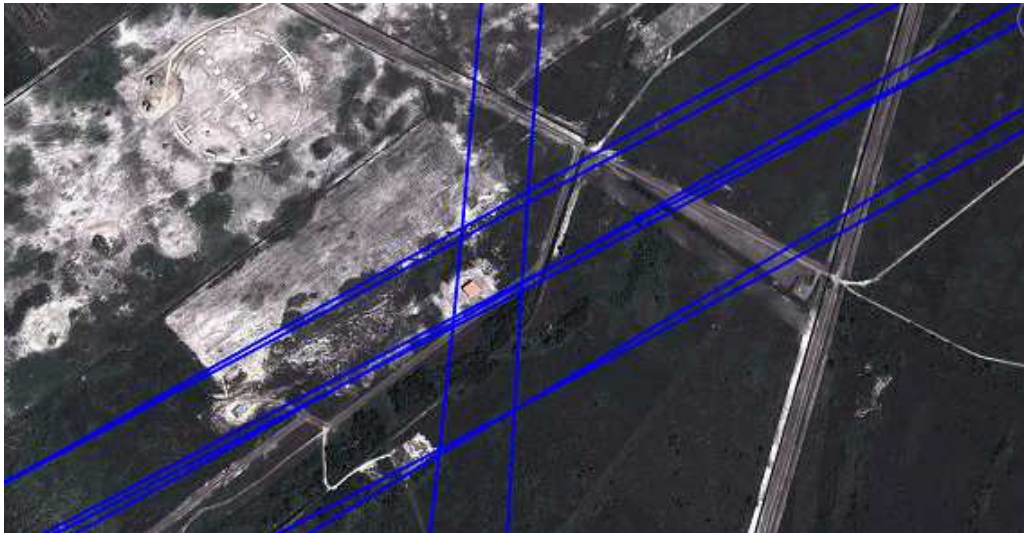


Figure 8. sept 25, 2013 - several lines over the Cobra target (active thermal pattern) for MTF and radiometric characterization (the pattern is imaged on different areas of the IR FPAs) .

The **Figure 8** show examples of flight track on the French air base of Cazaux over the Cobra target.

The performance of the stabilization platform is illustrated in **Figure 9**. 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 crossing) followed by the measurement phase. The stabilization accuracy is better than the requirements ( $<125 \mu\text{rad}$  over all the line) and we note a small static misalignment between the instrument and the platform about 30 to 35  $\mu\text{rad}$ . The other axes (pitch and yaw) present similar performance as the roll attitude correction. **Figure 10** shows the raw image acquired in one SIELETTERS band without any geometric correction or compensation by post-processing.



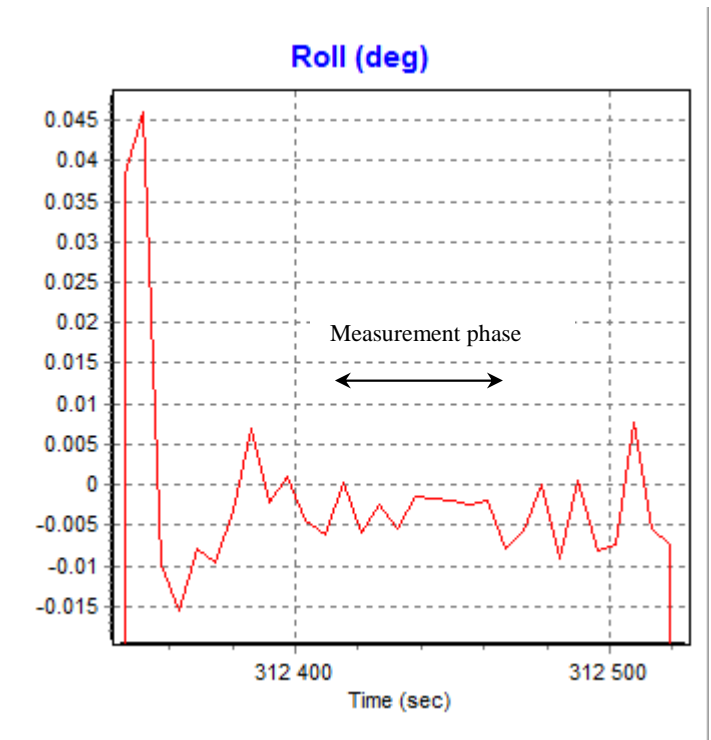
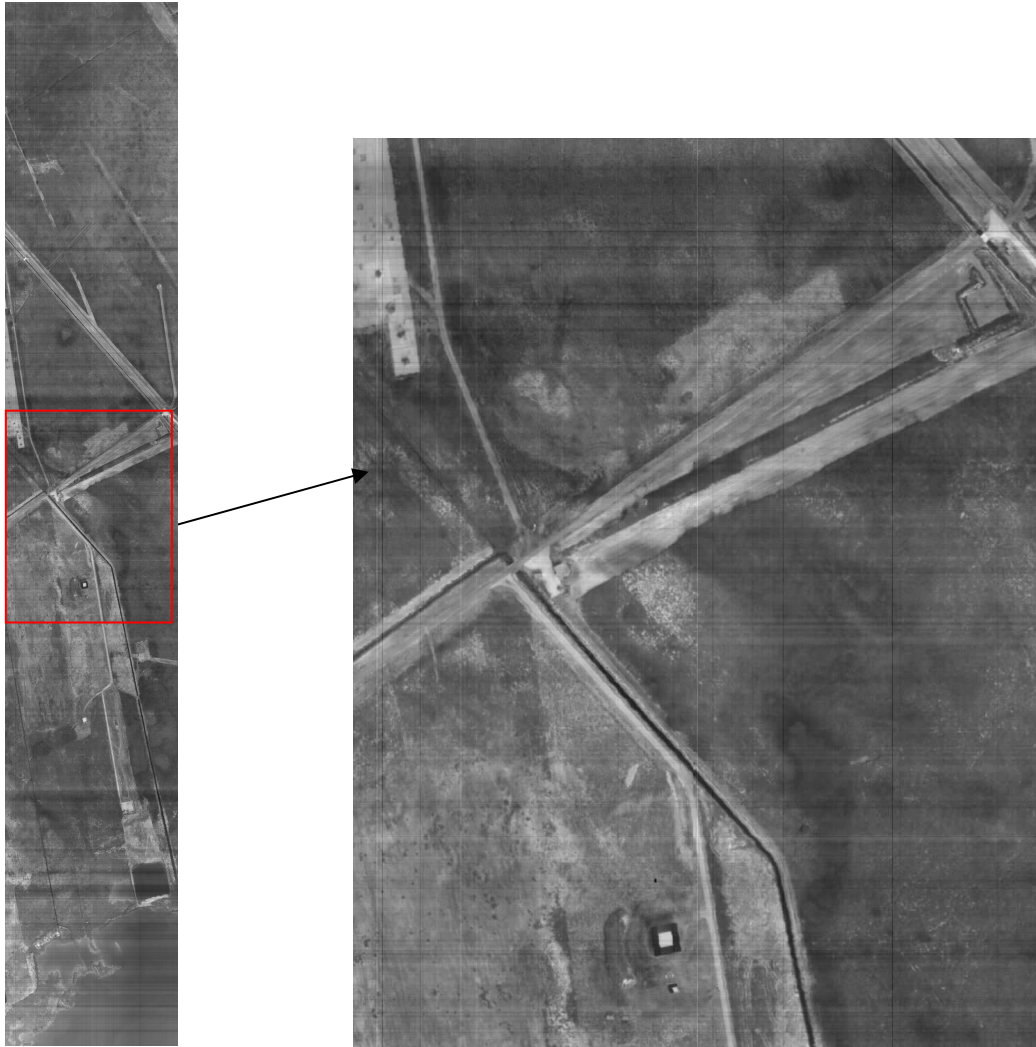


Figure 9. Correction of the Roll axis with the SIELETTERS stabilization platform.



*Figure 10 : Left : Full 3 km Sieleters line (using only one line of the IR FPA) – 6195 raw images with a 50 cm ground sampling pitch (flight at 2000m over the ground). Right: Zoom on the Cobra target area.*

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.

The *Figure 11* illustrates this flight with the georeferenced image of the LWIR band.

The *Figure 12* illustrates the ground truth area with the different patterns on the ground. The *Table 1* gives the nature and the dimension of the ground patterns



Figure 11. Illustration of the SIELETTERS georeferenced image on the Fauga line over the Google Earth map

Pattern	Dimension
Concrete FERMAT	30x30m
Asphalt FERMAT	30 x 80m
White "Lima" pattern	4,5x4,5m
Black "Lima" pattern	4,5x4,5m
Sand	4.5x4.5m
Linoleum dark grey	8x8m
Linoleum light grey	8x8m

Table 1: Calibration patterns installed at Le Fauga center

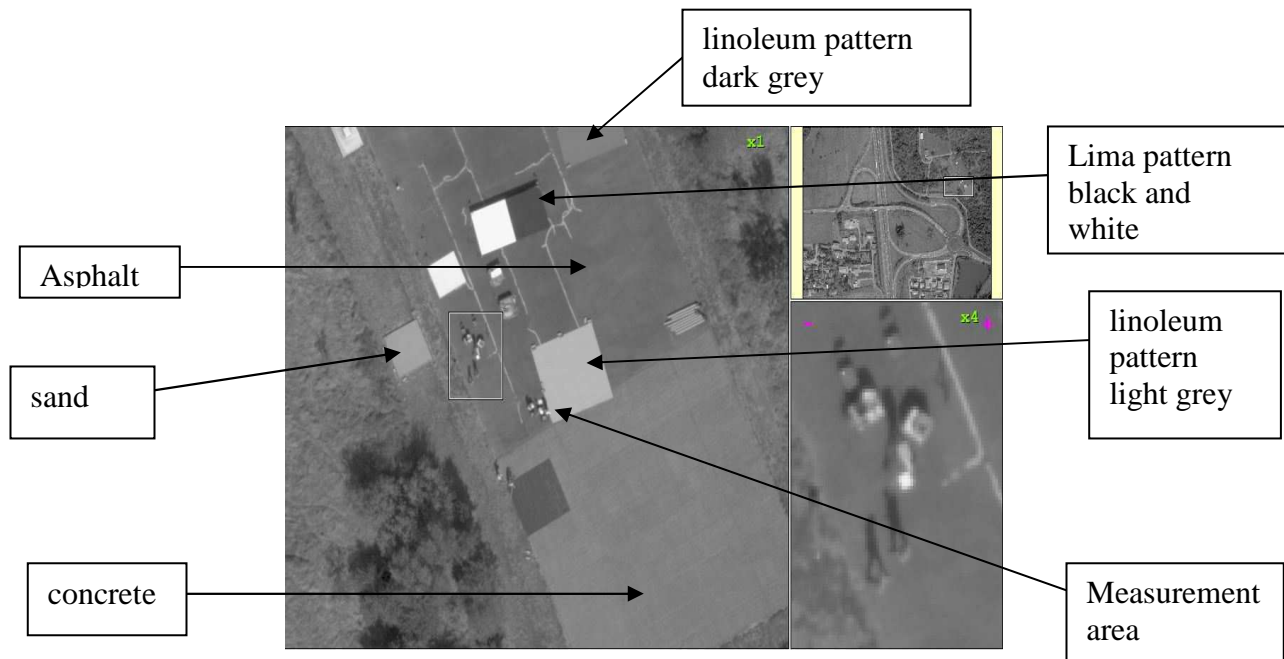


Figure 12: ground truth measurement area and pattern positioning

### 3.2 SIELETTERS MTF measurement

The modulation transfer function (MTF) is affected by several factors:

- diffraction, aberration and light scattering of the optics (nearly diffraction-limited at all fields and all wavelengths);
- pixel size (theoretically square pixels with a 100% fill factor);
- movement of the line of sight during the integration time;
- reconstruction process (individual interferometric images are registered and interpolated to reconstruct complete interferograms of ground points).

The two former points can be quite easily estimated in the laboratory; however it is more difficult to experimentally measure the two latter ones in the lab, which is why it was decided to fly over the Cobra target.

The image used to evaluate the MTF of SIELETTERS is the panchromatic image obtained by the addition of the 440 individual images (see Figure 4, right). This allows having an excellent radiometric signal to noise ratio while including the filtering due to the reconstruction process.

Results are presented in *Figure 13*. The flight MTF measured at  $0.83 \text{ m}^{-1}$  is higher than 0.71 (well above the 0.45 specification value), and the flight MTF measured at  $0.33 \text{ m}^{-1}$  is higher than 0.22 (0.1 specified).

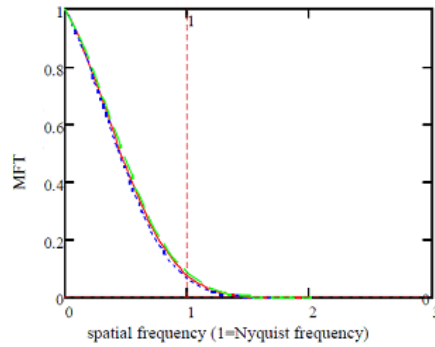


Figure 13. MTF of SIELETTERS (red curve). The dash blue and green curves are the error bar.

### 3.3 ODIN and SIELETTERS image registration

The spectral images acquired over the Fauga-Mauzac center by the ODIN and SIELETTERS systems are used to test the inter-instrument registration and to build the full wavelength hyperspectral product. **Figure 14** shows the quicklook images of the ODIN and the SIELETTERS flight lines. The image orientations are different: the Geographic North orientation for ODIN image and the flight line orientation for SIELETTERS image.

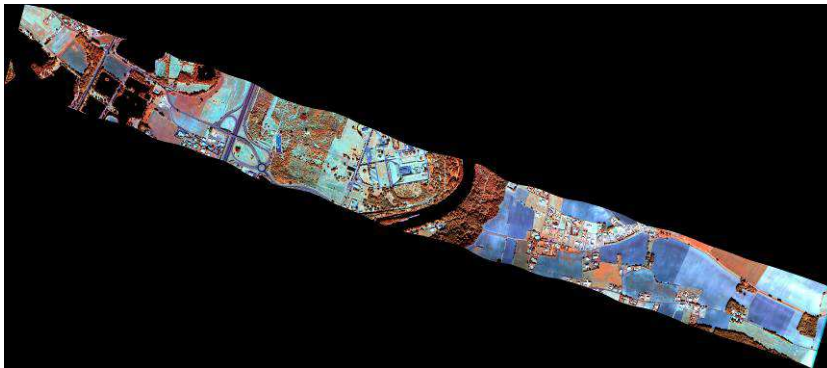
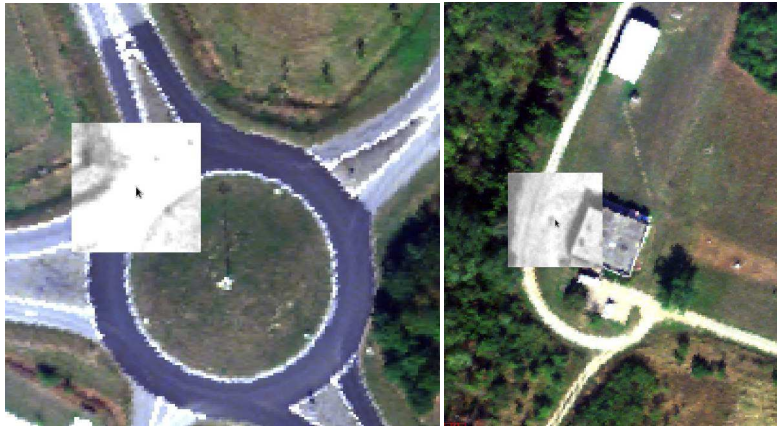


Figure 14. Quicklooks of ODIN image (left) and SIELETTERS image (right).

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

In order to globally assess the georeferencing precision, the images are compared to a reference georeferenced mosaic image built based on BD ORTHO imagery provided by IGN, the French mapping agency. The BD ORTHO® includes colour orthophoto with spatial resolution of 0.5m covering France in the Lambert 93 projection system. The georeferencing precision of ODIN is about 1 to 2 pixels. The georeferencing precision of SIELETTERS is about 10 pixels, essentially because SIELETTERS images are not yet orthorectified. The misregistration between ODIN and SIELETTERS is illustrated in *Figure 15*.



*Figure 15. Misregistration illustration between the ODIN product and the SIELETTERS product. The RGB (Red-Green-Blue) image is constructed with the corresponding spectral bands of the ODIN hypercube and the grayscale SIELETTERS image representing a given spectral band is superposed on the RGB image.*

The first stage of the STAD consists in the reorientation of the SIELETTERS product according to the Geographical North and resampling at the spatial resolution 0.5m x 0.5m.

Then the inter-instrument registration is done taking ODIN product as reference and the SIELETTERS product is registered to the ODIN product. The registration process is applied on the the 1.55 $\mu$ m spectral image for ODIN and the 4.7 $\mu$ m spectral image for SIELETTERS. The resampling is done with an optimized bi-cubic filter, and a morphologic gradient pre-process is applied to improve the precision of the correlator, highlighting the structures of the scene. The result is illustrated in the *Figure 16*. Detail results are given *Figure 17*.

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



Figure 16 : STAD registration result illustration by superimposition of the  $4.7 \mu\text{m}$  spectral band over a RGB image of ODIN spectral image



Figure 17. Zoom on the STAD registration results.

### 3.4 Reflectance data first results

The ODIN spectral image acquired on the 25<sup>th</sup> of September, 2013, over the Fauga-Mauzac Onera center has been processed with the COCHISE tool [4] integrated in the STAD for atmospheric compensation in the reflective domain.

The first results are shown on *Figure 18* for some parts of the ground truth measurement area shown in *Figure 12*. 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 FieldSpec. 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). Though imperfect, the results show good accordance between spectral features of airborne and ground truth spectra, indicating that the COCHISE software and the ODIN instruments work together. 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.

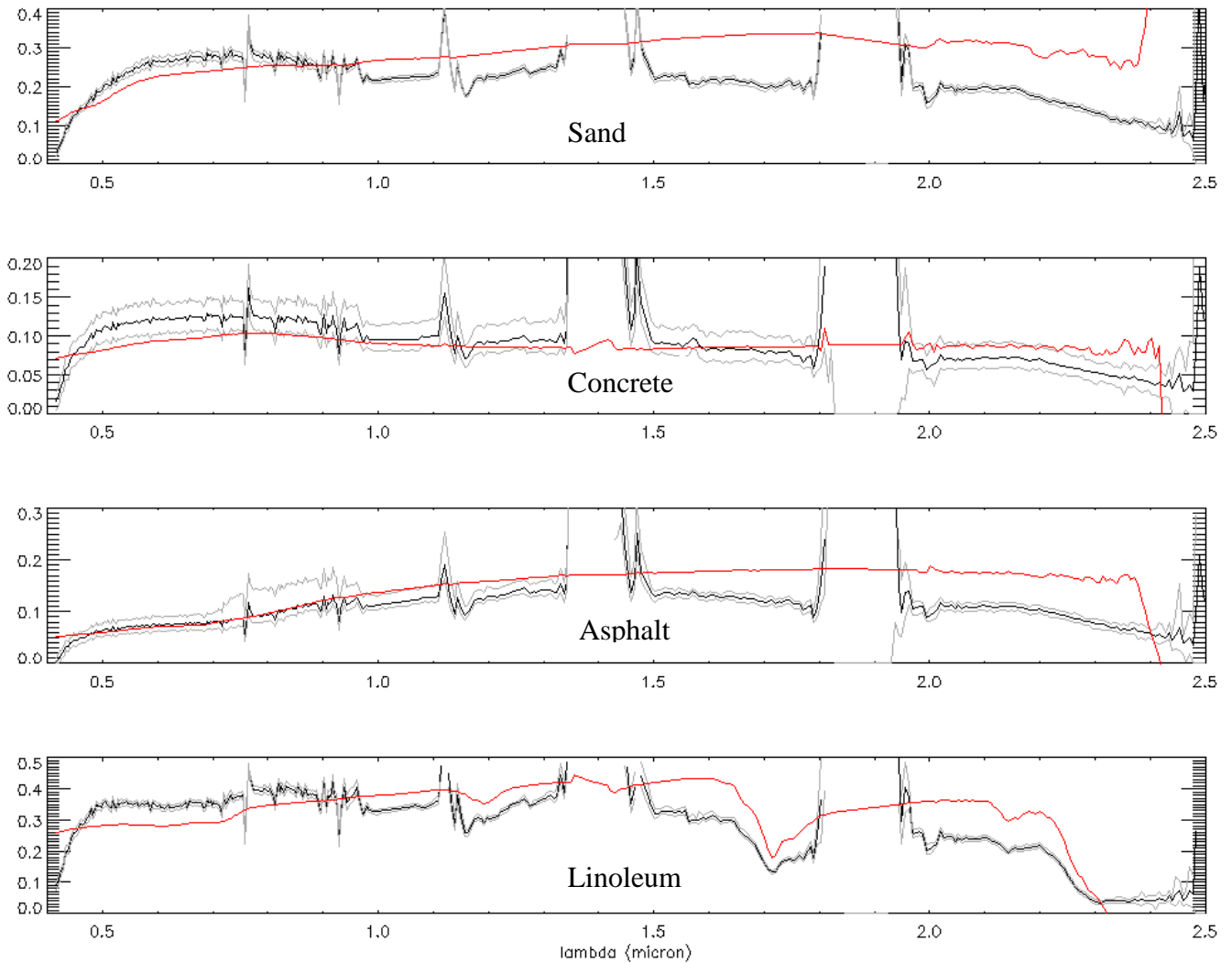


Figure 18: First reflectance results on ODIN image with the COCHISE software. Red: ASD FieldSpec measures, Dark : COCHISE output reflectance (mean and standard deviation)

#### 4. CONCLUSION

The SYSIPHE development program is nearing completion. 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 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 SIELETTERS data processing.

The SYSIPHE program is continuing with new airborne campaigns scheduled for French and Norwegian defence needs. It will be also open soon to the wider scientific community as a unique tool for airborne data collection campaigns.



## ACKNOWLEDGMENTS

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