



## High acquisition rate infrared spectrometers for plume measurement

Y. Ferrec, S. Rommeluère, A. Boischot, Dominique Henry, S. Langlois, C. Lavigne,  
S. Lefebvre, N. Guérineau, A. Roblin

### ► To cite this version:

Y. Ferrec, S. Rommeluère, A. Boischot, Dominique Henry, S. Langlois, et al.. High acquisition rate infrared spectrometers for plume measurement. OPTRO 2014, Jan 2014, Paris, France. <hal-01082099>

**HAL Id: hal-01082099**

**<https://hal.science/hal-01082099v1>**

Submitted on 12 Nov 2014

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

## HIGH ACQUISITION RATE INFRARED SPECTROMETERS FOR PLUME MEASUREMENT

Y. Ferrec, S. Rommeluère, A. Boischot, D. Henry, S. Langlois, C. Lavigne, S. Lefebvre, N. Guérineau, A. Roblin,

ONERA, centre de Palaiseau, chemin de la Hunière, 91761 Palaiseau cedex, France  
yann.ferrec@onera.fr

### KEYWORDS

IR imaging, multispectral/ hyperspectral algorithms

### ABSTRACT

For a few years, Onera has developed static Fourier transform spectrometers. These spectrometers are snapshot and benefit from a high étendue, thus making them well suited for measuring fast moving scenes, such as rocket plumes. In particular, Onera has developed two cryogenic infrared instruments, Mistere and Microspoc, which can measure spectra at a high repetition rate (few hundred of Hertz), on a wide spectral range ( $[2.9\mu\text{m} ; 9.6\mu\text{m}]$  and  $[1.5\mu\text{m} ; 5\mu\text{m}]$ ), and with a moderate spectral resolution ( $15\text{cm}^{-1}$  and  $30\text{cm}^{-1}$ ). The design of these spectrometers will be presented, as well as examples of experimental results.

### 1. STATIC FOURIER TRANSFORM SPECTROMETERS

Static Fourier transform spectrometers (SFTS) differ from traditional Fourier transform spectrometers by the fact that, while in the latter the variation of the optical path difference is temporal, with a moving mirror and a single detector, in the former the variation of the optical path difference is spatial, with rectilinear fringes measured thanks to a focal plane array (see Fig. 1, where a layout of a SFTS based on a Michelson interferometer has been drawn). Thus, snapshot spectra can be acquired, making SFTS well-suited for fast varying phenomena or transient events. This ability for snapshot measurements is the first advantage of SFTS.

The second advantage is the *étendue* (or Jacquinot's) advantage. Indeed, interference fringes are detected in their localization plane, which means that the size of the source can be increased without blurring fringes, at least at first order (see [1] for a more detailed discussion on the angular acceptance of SFTS). Thus, the field has not to be limited by a slit, as it is the case for dispersive spectrometers.

A third advantage of SFTS is that their spectral range can be very broad (several octaves) with a constant resolution (in wavenumber). Indeed, the spectral range is only limited by the transmission of the optics and the sensitivity of the detector, without any limitations due to multiple orders, as for Perot-Fabry or grating based spectrometers. At last, as an interesting consequence –especially for infrared instruments– of being static, SFTS can be quite easily cryogenic, since they do not need a scanning mechanism. This is a very fruitful property because experience has shown that cooling down the whole instrument facilitates radiometric calibration, particularly for field measurements.

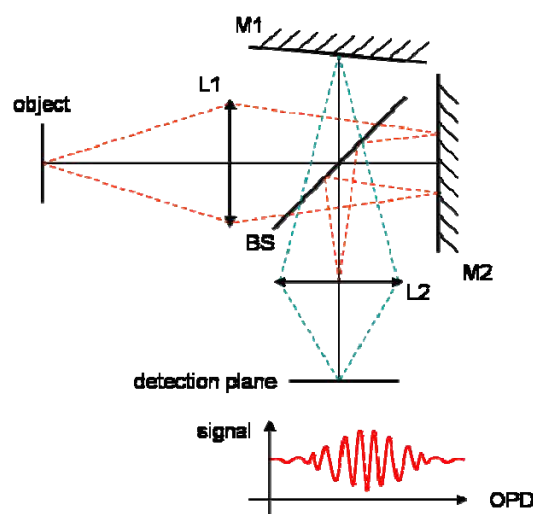


Figure 1. SFTS based on an air wedge Michelson interferometer. The interferometer is made up of the beamsplitter (BS) and the two mirrors (M1 and M2). The tilt of mirror M1 creates rectilinear fringes, which are localized at the level of the mirrors. Lens L2 conjugates this localization plane with the detection plane (green dots). Fore-lens L1 images the object on the pupil of lens L2 (red dots), to have a roughly uniform illumination of the FPA.

These properties led Onera to develop SFTS for field measurements of plumes at high repetition rates. However, SFTS do not have only advantages, but also drawbacks. Indeed, they

suffer from what is commonly called the multiplex disadvantage: the signal to noise ratio of the estimated spectra is lower than the one of the measured interferogram. Related to this multiplex disadvantage is the sensitivity of SFTS to the residual fixed pattern noise. Indeed, uncorrected variations of gain between the pixels lead to a multiplicative noise on the interferogram [2]. A non-uniformity correction (NUC) must then be carefully applied. Furthermore, two-point NUC may not be enough, since the basic hypothesis of NUC is that pixels differ only by their offset and their “panchromatic” gain. However, pixels can also differ by the shape of their spectral response. In this case, more complex inversion techniques have to be implemented to correctly deduce the spectrum from the interferogram [3].

A last drawback of SFTS is that the number of spectral bands is limited by the number of pixels in one direction of the FPA. Therefore, SFTS are limited to moderate spectral resolution, or to high spectral resolution but on a narrow spectral band.

## 2. MISTERE SPECTROMETER

The first infrared (LWIR and MWIR) SFTS developed at Onera was named Mistere [4]. It is a Michelson interferometer with a tilted mirror, and with two imaging lenses: a front lens which simultaneously images the object on a field stop and the entrance pupil to the interferometer mirrors, and a rear lens which images the interferometer mirrors (i.e. the fringes localization plane) on the FPA (see Fig. 2).

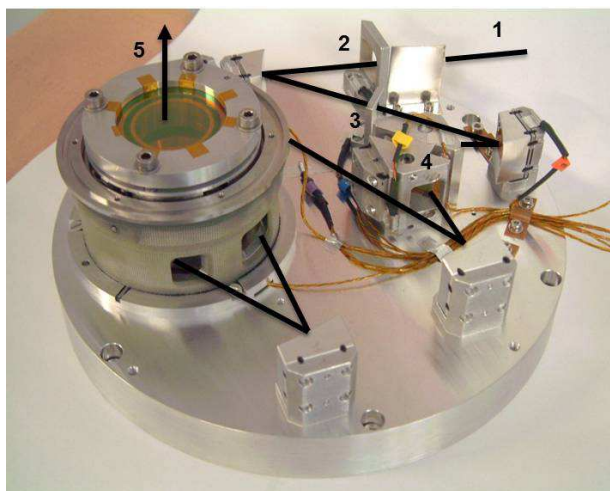


Figure 2. View of Mistere optical system. 1: light incoming from the scene. 2: entrance pupil. 3: field stop. 4: interferometer. 5: light going to the FPA.

Mistere uses a 320x256 HgCdTe FPA from Sofradir, with a spectral range spanning from  $2.9\mu\text{m}$  to  $9.6\mu\text{m}$  (i.e. from  $1050\text{cm}^{-1}$  to  $3450\text{cm}^{-1}$ ). The spectral resolution is about  $15\text{cm}^{-1}$  and the acquisition rate is equal to 200Hz (slightly varying with the integration time).

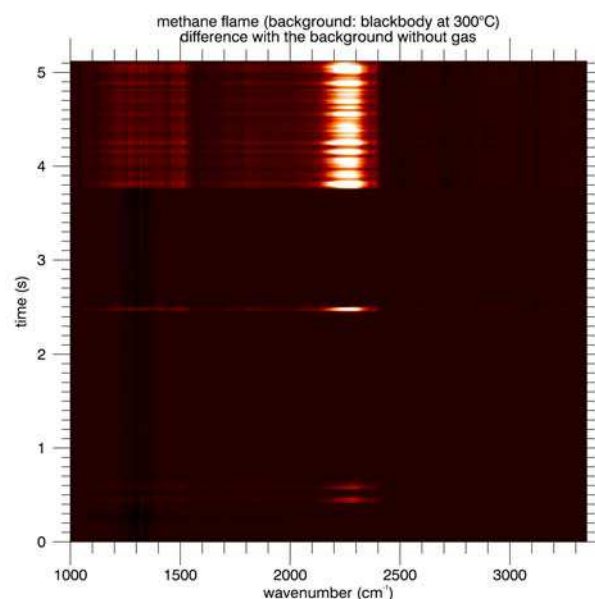


Figure 3. Temporally resolved spectra of a methane flame acquired at 200Hz with Mistere.

To illustrate the ability of Mistere to acquire infrared spectra with a temporal resolution of few ms, we have plotted on Fig. 3 the spectra obtained when observing a methane flame, the background being a blackbody at  $300^\circ\text{C}$ . The signal shown is the difference between the raw spectrum and the background. Before 3.8s, gas is emitted but not ignited, consequently we only observe the absorption bands of methane (Fig. 4). After 3.8s, methane is definitely ignited (infructuous attempts were made around 0.5s and 2.5s), we thus observe emission by hot carbon dioxide and water (Fig. 5). The temporal evolutions of signal at  $1500\text{cm}^{-1}$  ( $6.7\mu\text{m}$ , water emission) and  $2250\text{cm}^{-1}$  ( $4.4\mu\text{m}$ , carbon dioxide emission) are shown on Fig. 6. Note that all Mistere spectra shown here are not radiometrically calibrated.

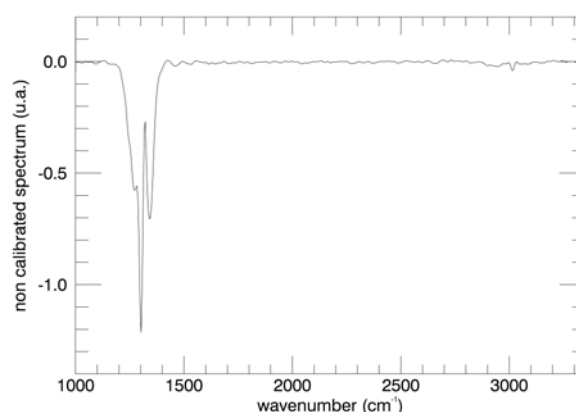


Figure 4. Raw single spectrum of methane gas (uncalibrated spectrum, background subtracted).

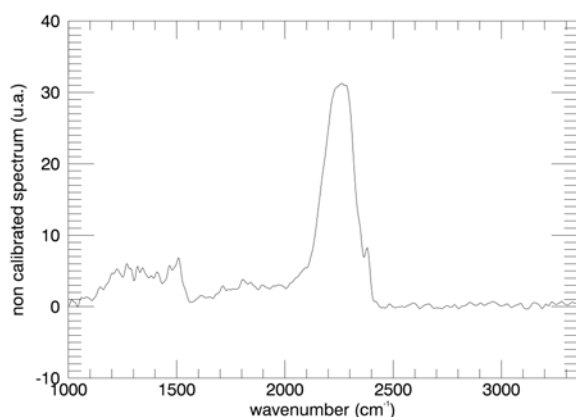


Figure 5. Raw single spectrum of the flame (uncalibrated spectrum, background subtracted).

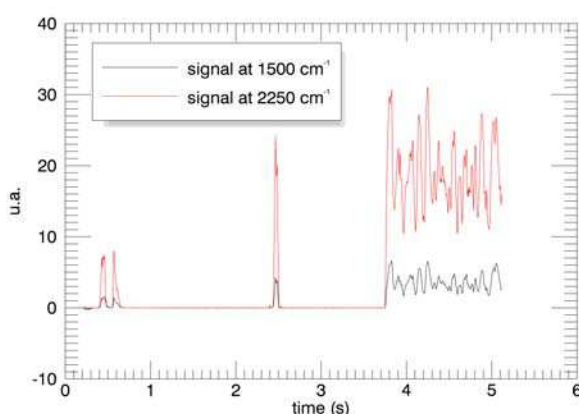


Figure 6. Temporal evolution of the signal at  $1500\text{cm}^{-1}$  and  $2250\text{cm}^{-1}$ .

### 3. MICROSPOC SPECTROMETER

A second infrared (SWIR and MWIR) SFTS developed at Onera is Microspoc. The main characteristic of Microspoc is that the interferometer is directly integrated on the FPA. The spectrometer is thus very compact, all the more since that the front imaging system (for field definition) is reduced to a single refractive lens which is also the window of the cryostat of the FPA and a cold stop inside the cold shield (Fig. 7). We therefore obtained a system which can be very easily integrated and operated on a field experiment. The other side of this dramatic compacity is on the one hand the difficulty to reach very low optical path differences (near to the "zero OPD"), and on the other hand the parasitic interference signals due to multiple reflections inside the cavity. A more thorough description of Microspoc is presented in paper OPTRO-2014-2940749 ([5]).

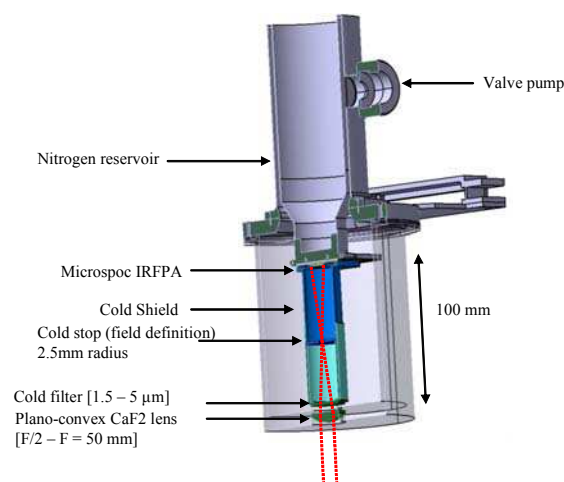


Figure 7. Illustration of Microspoc optical system

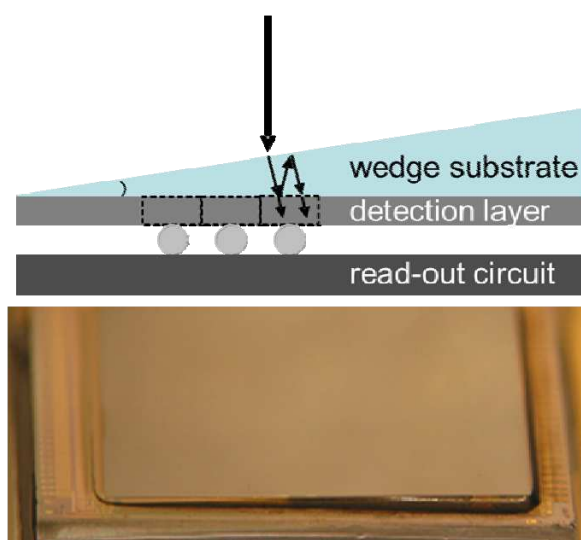


Figure 8. Layout and photograph of the wedge interferometer integrated on the IRFPA

Different architectures are possible for the interferometer ([6]). Results presented here were obtained with a "monolithic" device, i.e. the interferometer is made by the detector substrate which has been polished with a wedge shape (Fig. 8). This instrument is based on a  $640 \times 512$  Scorpio FPA from Sofradir, operating at 125Hz for full-frame measurements. Higher frame rates, up to 500 Hz (slightly varying with the integration time), can be reached if only a fraction of the FPA is used. The spectral range is  $[1.5\mu\text{m}; 5\mu\text{m}]$  ( $[2000\text{cm}^{-1}; 6660\text{cm}^{-1}]$ ), with a spectral resolution close to  $30\text{cm}^{-1}$ . Fig. 9 shows a verification of spectral calibration from a hot blackbody observed through a filter.

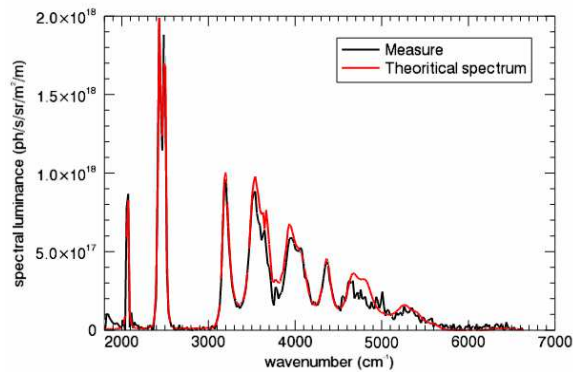


Figure 9. verification of spectral calibration

#### 4. CONCLUSION

Static Fourier transform spectrometers are well-suited instruments for infrared plume measurement at moderate spectral resolution and high temporal rate. Indeed, they are snapshot, with a high étendue and they can be easily cooled down, while their main limitation is the sensitivity to non-uniformity of the FPA. Onera has currently developed two infrared SFTS, one for LWIR and MWIR measurements (Mistere) and a very compact one for SWIR and MWIR measurements (Microspoc). Even though instruments and interferogram processing are still to be improved, experimental results are yet satisfactory and encouraging. Data are used for understanding physical phenomena and increased database of IR signature.

#### 5. REFERENCES

1. Gillard, F., Ferrec, Y., et al., "Angular acceptance analysis of an infrared focal plane array with a built-in stationary Fourier transform spectrometer," *JOSA A*, 29(6), 936-944 (2012)
2. Ferrec, Y., Ayari-Matallah, N., et al., "Noise sources in imaging static Fourier transform spectrometers," *Optical Engineering*, 51(11), 111716-1 (2012)
3. Gillard, F., Lefebvre, S., et al., "Inverse problem approaches for stationary Fourier transform spectrometers," *Optics letters*, 36(13), 2444-2446 (2011)
4. Ferrec, Y., Rommeluère, S., Henry, D., and Guérineau, N., "First results from Mistere, a cryogenic static Fourier transform spectro-radiometer," in *Proc. of Fourier Transform Spectroscopy*, Optical Society of America (2009)
5. Mouzali, S., Lefebvre, S., Rommeluère, S., Ferrec, Y., Primot, J., "Modeling of an infrared stationary micro-spectrometer integrated on a focal plane array", in *Proc. of OPTRO 2014*, paper 2940749 (2014)
6. Ferrec, Y., Guérineau, N., et al., "Infrared focal

plane array with a built-in stationary Fourier-transform spectrometer: recent technological advances," in *Proc. of SPIE Defense, Security, and Sensing*, paper 835323 (2012)