

Development and testing of a hyper-spectral imaging instrument for field spectroscopy

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ABSTRACT

Advancements in Mercury Cadmium Telluride (MCT) focal plane arrays (FPA) in recent years have allowed high performance longwave infrared imagers to prosper. In particular molecular and gas/chemical spectroscopy applications can be vastly advanced with these new products. However, for the transition from single pixel spectrometers to FPA base imaging spectrometers to succeed, a couple of parallel advancements must be made as well. Most Fourier transform spectrometers currently available are designed specifically for a 1 mm single pixel detector. Scientists who try to convert these systems into imaging spectrometers quickly run into throughput issues when FPAs reach sizes of up to 12.5mm, thus limiting the performance and greatly impacting the detection capabilities. Furthermore, for large FPAs the readout time can be significantly longer than the integration time. In turn, this requires slower sweep speeds with a higher degree of control of the scanning mechanism. The benefit of these new technologies in spectroscopy can only be demonstrated with a system optimally designed for imaging spectroscopy. This paper will address the issues of imaging spectroscopy and will show how an instrument designed for specifically imaging applications can dramatically improve the performance of the system and quality of the data acquired.

Keywords: Imaging FTS, chemical agent detection, NESR, NEdT, standoff detection, remote sensing

1. Introduction

Advancements in infrared detector focal plane arrays have spawned a proliferation of infrared sensors. The crucial information for these types of sensors is not the raw data coming from of the detector, but the processed data product that gives information about the field of regard. Information like, “Is there a gas present?”, “Is there a hidden tank nearby?”, and most fundamentally “Is there a threat? And if so, what and where?”. That is the basic question that each sensor needs to answer, and the faster, the better.

Telops has developed a field-portable hyperspectral imager. The imager, called Field-portable Imaging Radiometric Spectrometer Technology (FIRST), is the first hyperspectral imager specifically designed for chemical imaging using Fourier transform technology. This paper presents the FIRST and its first performance test results. A more general overview of the FIRST was presented in an earlier paper¹.



2. System Specifications

The instrument is a lightweight and compact imaging radiometric spectrometer. It uses a 320x256 LWIR focal plane array detector that can be windowed and formatted to fit the desired size and to decrease the acquisition time. Spectral resolution depends on the operating parameters and ranges from 0.25 to 150 cm⁻¹, with optimal system designed for 4 cm⁻¹.

The instrument is controlled using an Ethernet communication. The configuration, monitoring and real-time housekeeping data collection is performed using the Ethernet link. The instrument control and configuration is done

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using a TCP/IP 100Base/T communication port. A bore-sight video camera takes simultaneous visible images aligned with the imaging FTS. It provides a larger field of view and enhanced spatial resolution. The bore-sight image is transferred over a standard IEEE1394 interface, also known as Firewire.

The instrument can output either interferograms, or it can perform DFT and output raw spectra. DFT is performed using a radix-4 FFT processing engine. Camera Link is used to transfer data to a computer equipped with a frame grabber. The instrument supports two operating modes: FTS mode and Camera mode. In Camera mode, the instrument generates standard digital video and supports up to 300 fps with the full 320x256 pixels of the focal plane array area. In FTS mode, the interferograms or the raw spectra are transferred along with a header containing all configuration parameters and monitored values to be stored on disk.

Table 1: Key specifications

Parameter	Value
Spectral Range	7.7 – 11.6 μm
Spectral Resolution	0.25 – 150 cm^{-1}
Scan Rate	0.028 – 16 Hz
Instantaneous Field of View	0.35 mrad
Array Size	320 x 256
Input voltage	28 VDC, 250 W
Size	0.45 x 0.44 x 0.25 [m]
Weight	21 kg

3. Performance test results

3.1. Interferometer

The interferometer is used to modulate the infrared spectral radiation from the scene. The interferometer subsystem includes several optical elements for modulating the optical signal, a mechanical drive mechanism, and a series of control loops for the drive mechanism and a temperature control system that allows to maintain the interferometer temperature stable. Fig. 1 shows photographs of the interferometer.

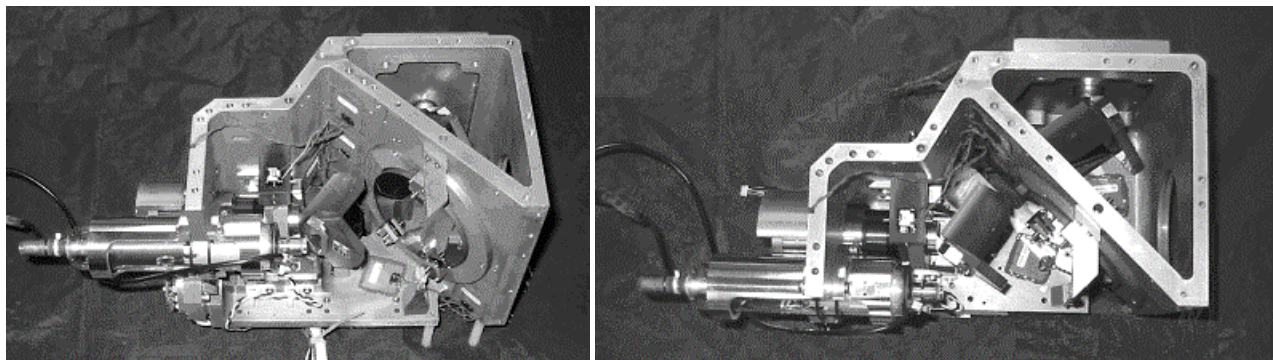


Fig. 1. Photographs of the interferometer subsystem

The Telops interferometer can generate OPDs from -0.6 cm to $+2.5 \text{ cm}$. This allows measuring IR spectra with a resolution of 1 cm^{-1} in a double-sided mode, and down to 0.24 cm^{-1} in single-sided mode. The digital servo maintains a speed stability better than 1%. The speed of the slide is software selected and can be set from $50 \mu\text{m/s}$ up to 20 cm/s . This accommodates almost any FPA (present and future) available on the market.

Fig. 2 shows the measured modulation efficiency of the interferometer in the 64×64 center pixels region of the FPA. The modulation efficiency is the ratio of modulated light to total light. The average modulation efficiency in this region is 74%.

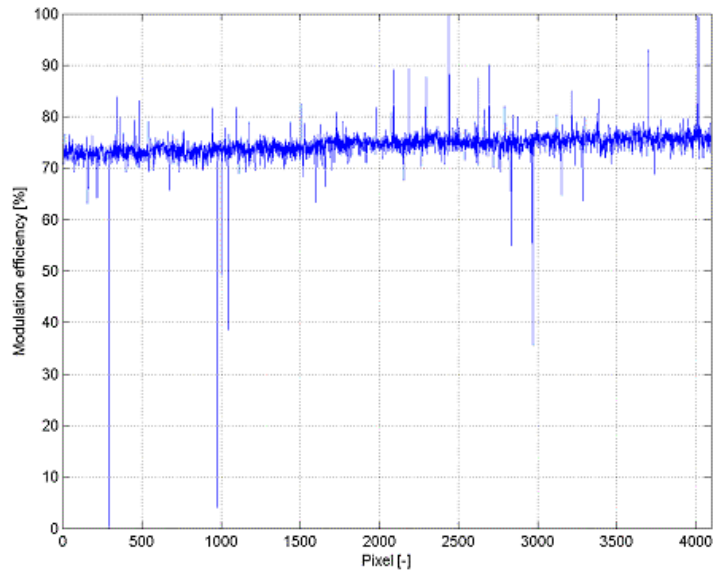


Fig. 2: Interferometer modulation efficiency measurement for a 64x64 pixels FOV

3.2. Optical detection (IR Lens)

To produce a high-quality image of the IR scene, Telops designed the lens such that the blur is smaller than the diffraction from this $f/2$ system. The FPA has $30\ \mu\text{m}$ pixels and the focal length is 86 mm, to get 0.35 mrad IFOV per pixel. The lens produces a pupil image in the interferometer (close to the cube corner) in order to minimize vignetting and maintain high sensitivity without increasing the size of the interferometer. In order to maintain the high quality of the image for variations of temperature, Telops implemented an automatic focus adjustment. The “autofocus” is made by an electronic servo, which keeps the lens focused independent of the temperature, maintaining the diffraction limited performance over a wide range of temperatures. Fig. 3 presents a picture of the lens assembly.

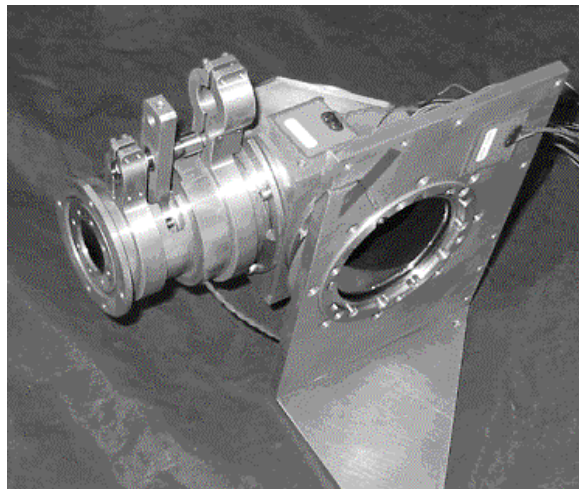


Fig. 3: IR lens photograph

The overall optical transmittance of the instrument, from the input window to the FPA, was measured and is shown in Fig. 4. The average transmittance from 8 to 11 μm is 81%, and it is higher than 50% for the 7.7 to 11.6 μm spectral range.

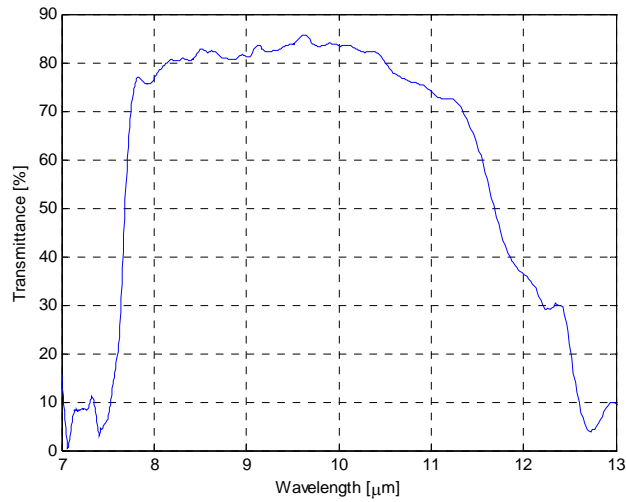


Fig. 4: Measured spectral transmittance of the instrument

The optical blur of the system was measured by looking at a collimated hot source. The divergence of the hot source was 78 μrad , i.e. less than $\frac{1}{4}$ of a detector pixel. Fig. 5 shows the blur spot at the center of the FOV.

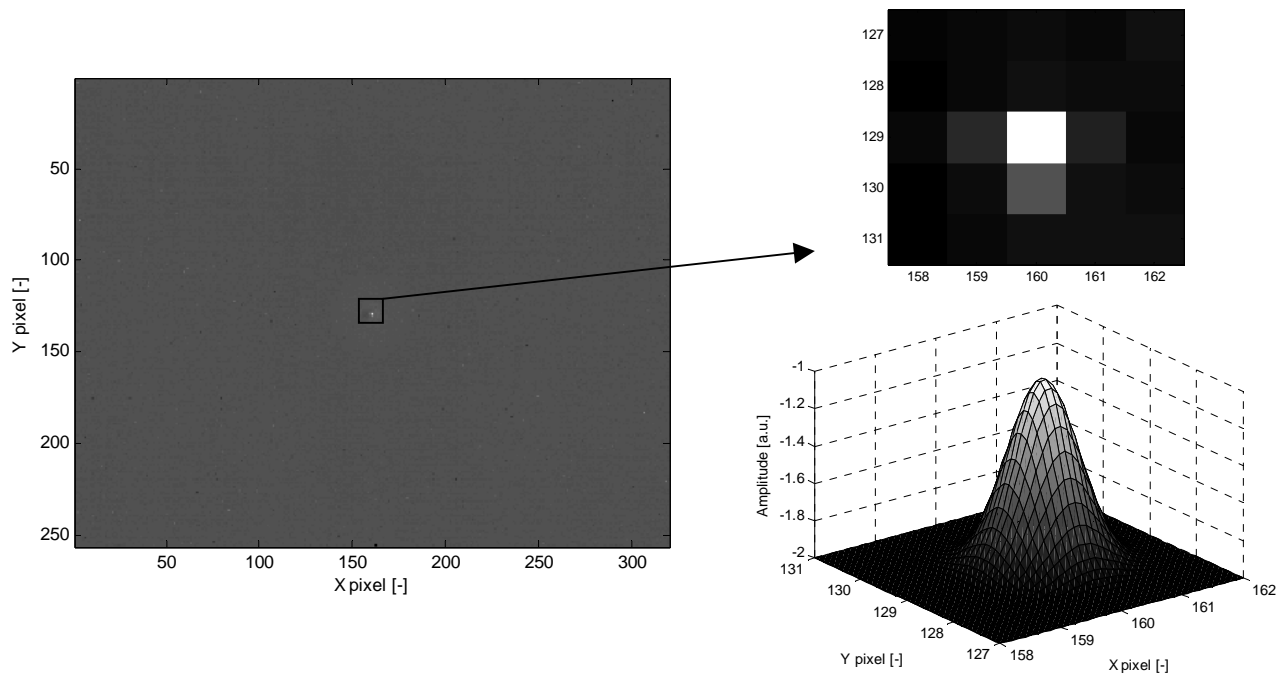


Fig. 5: Measured optical blur for a collimated source in the center of the FOV

Table 2 gives the measured optical blur for different locations in the field-of-view. The optical blur FWHM is of the same order of magnitude as the pixel IFOV (350 μrad), and the autofocus allows to achieve this performance for a wide range of temperature exceeding 0 to 50°C.

Table 2: Optical blur measurements

Position in FOV	Blur FWHM [μrad]
Center	386
Top-left corner	386
Top-right corner	486
Bottom-left corner	426
Bottom-right corner	419

3.3. Data acquisition and processing

In order to meet the specific interferometer operation requirements, a high performance electronic system has been developed to control the focal plane array and handle the acquired data. This system is designed as a focal plane array controller and a data processing unit with interferometer specific functionalities. It allows high frame rates of up to 300fps for full array utilization, and as much as 1400fps in 128x128 operation with no lost frame. Direct sampling synchronization is done by means of trigger input from the interferometer controller.

With this data acquisition electronics, the FIRST sensor can produce in output one image of 128x128 interferograms or spectra with a 4 cm^{-1} spectral resolution every 2 seconds. This gives an output data rate of 96 Mbytes/s. The spatial resolution or the interferometer sweep speed can be decreased to reduce the output data rate. Binning pixels is another way to ease the output data rate.

The spatial resolution is user configurable, and can reach up to 320x256 pixels. The spectral resolution is also user selectable and can reach 1 cm^{-1} with double-sided interferograms, or 0.24 cm^{-1} in single-sided mode. In any configuration, the interferometer sweep speed is automatically adjusted to set the output data rate to the desired value.

3.4. Calibration module

The two-point radiometric calibration consists in characterizing the radiometric gain and offset of the instrument by measuring two targets of known radiance. In order to perform this two-point radiometric calibration, two blackbodies are included in the sensor. They are mounted on a motorized slide which allows remote and unattended operation of the system in a stand-alone mode. The blackbodies are brought in front of the input window for the calibration of the entire optical path of the system. Fig. 6 shows a photograph of the calibration subsystem. It also shows a cut view of a blackbody target.



Fig. 6: Photograph of the calibration subsystem and cut view of a blackbody

The blackbodies are sliding on the frame to protect the high-emissivity cavity from external contaminants, such as dust or sand. The blackbody electronics control the positioning and the temperature of both blackbodies with respect to commands sent by the Main Controller. The temperature range is between 20°C under ambient and 50°C above

ambient. The temperature knowledge is $\pm 0.175\text{ }^{\circ}\text{C}$, and the temperature stability has a standard deviation better than 5 mK, as shown in Fig. 7. Also shown in Fig. 7 is the emissivity of the blackbody cavities as a function of wavenumber. It is higher than 0.9996 for the whole spectral range of the instrument.

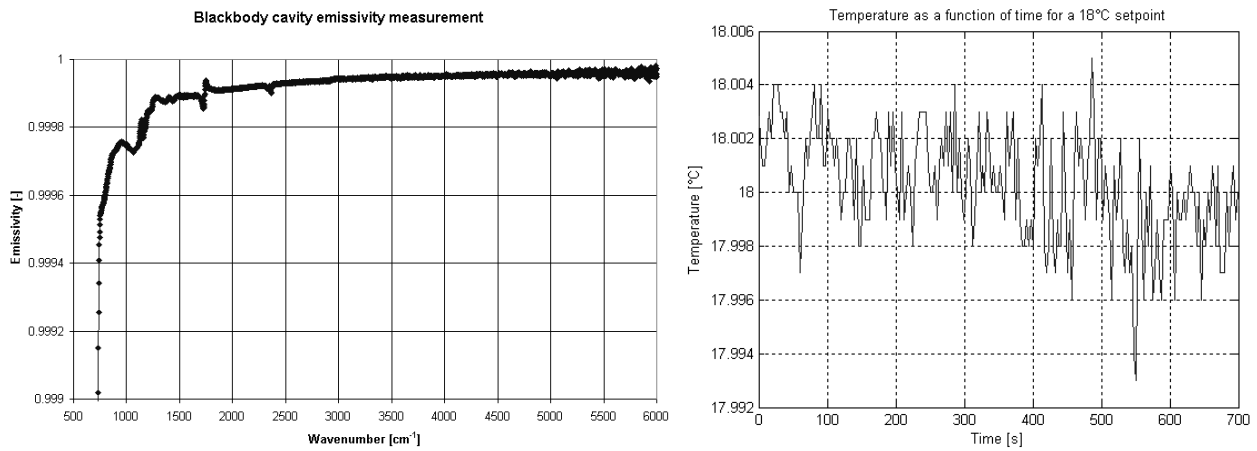


Fig. 7: Blackbody cavity emissivity and temperature stability measurements

Fig. 8 shows the temperature uniformity of the blackbody cavities, measured with a LWIR thermal camera. The temperature standard deviation in the region of interest (black circle of the top left image) is 0.059°C.

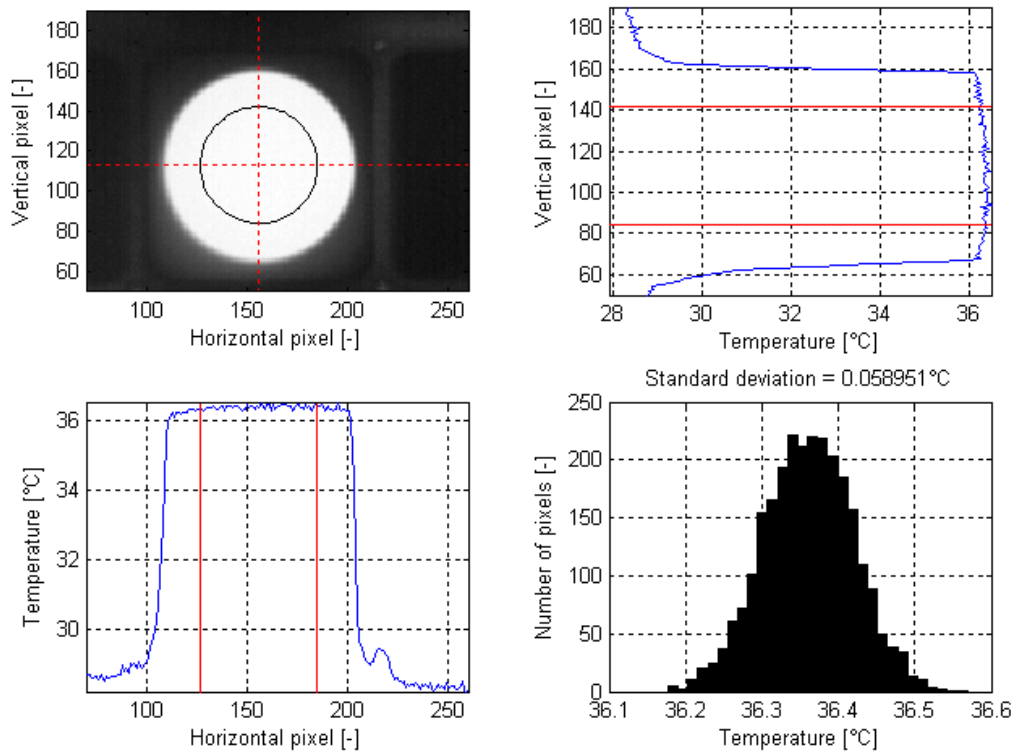


Fig. 8: Blackbody temperature uniformity measurements

3.5. Radiometric performance

The NESR (Noise Equivalent Spectral Radiance) is the sensor noise in the same units as the spectral radiance. Fig. 9 shows the NESR measurement of a single pixel made for 10 seconds of observation time of a 300 K scene. The bin spacing for this measurement was set to 1.3 cm^{-1} .

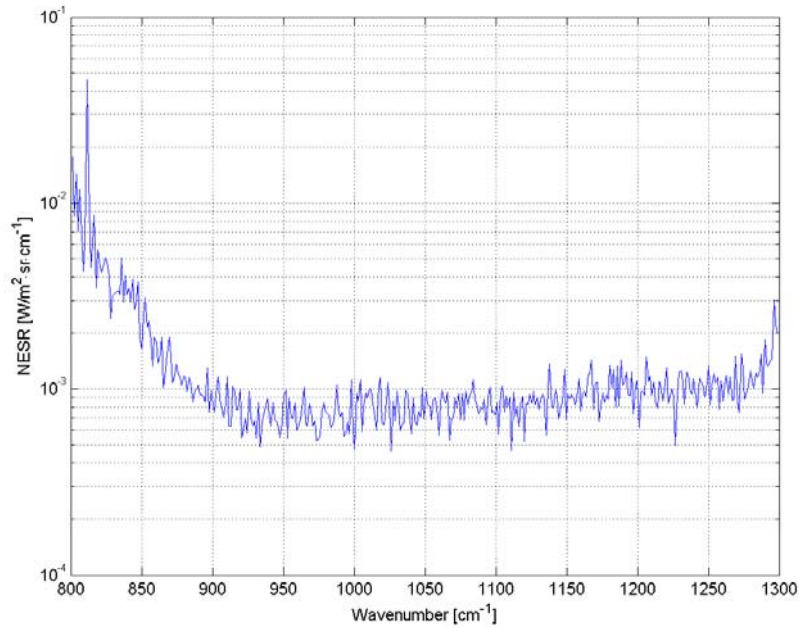


Fig. 9: Measured NESR for a single pixel

Fig. 10 shows the distribution of the NESR measurement for 64x64 pixels. The dominant noise sources have been identified and will be reduced in a near future. It is expected that the NESR will be decreased by a factor of 3.

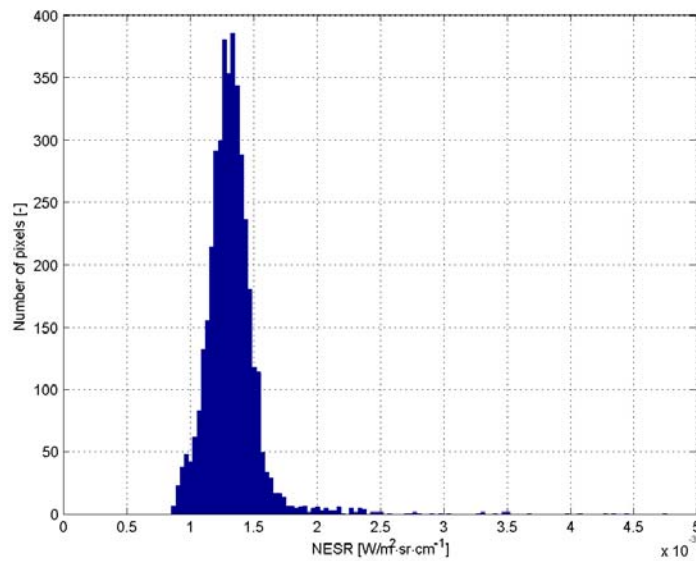


Fig. 10: Average measured NESR in the 900 – 1250cm⁻¹ spectral band for 64x64 pixels

Another important measurement is the radiometric accuracy of the radiance measurement. Fig. 11 shows the average radiometric accuracy measured by 64 different pixels of a 300 K scene. The radiometric accuracy is better than 2% of the radiance for the instrument spectral range. Note that 1% of radiometric error corresponds to a 0.62 K brightness temperature error.

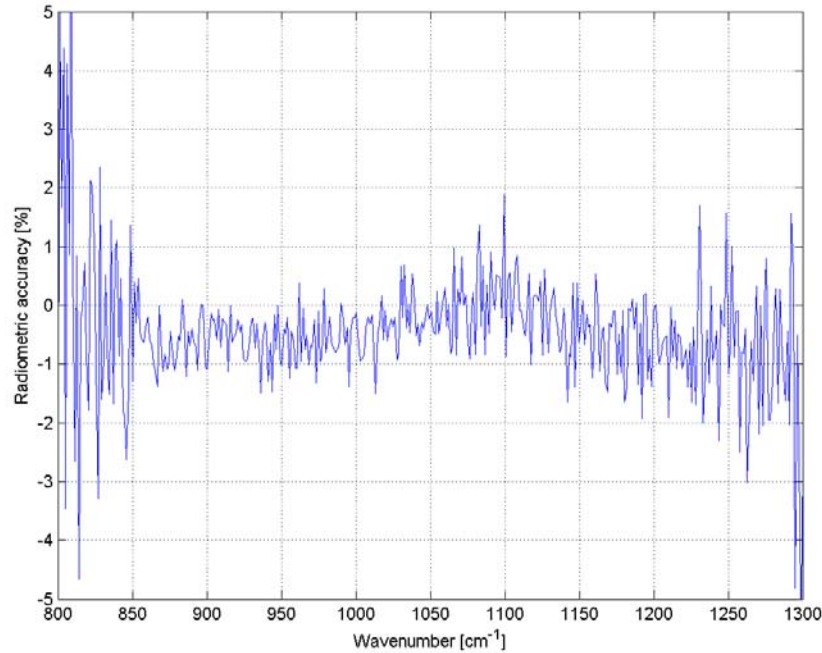


Fig. 11: Average radiometric accuracy measurement

4. Conclusion

FIRST is an excellent sensor with outstanding radiometric and spectral performances. It can provide spectral data with a resolution down to 0.25cm⁻¹, and spatial data down to 0.35 mrad. The interferometer, the IR lens, the data acquisition and the calibration module have been tested and show outstanding performances. The NESR performance is also excellent, and is expected to be improved to reach the shot noise limit.

In addition, the sensor includes onboard processing capabilities such as DFTs, spatial co-addition and spectral cropping. Even with this, the onboard electronics have processing capacity to spare. It is foreseen to implement gas detection algorithms in the onboard electronics in order to reduce the quantity of data output. This way, the FIRST sensor will more efficiently answer to the essential question: “Is there a threat? And if so, what and where?”.

REFERENCES

1. M. Chamberland et al., *Advancements in field-portable imaging radiometric spectrometer technology for chemical detection*, SPIE 5416-40, USA, April 2004.