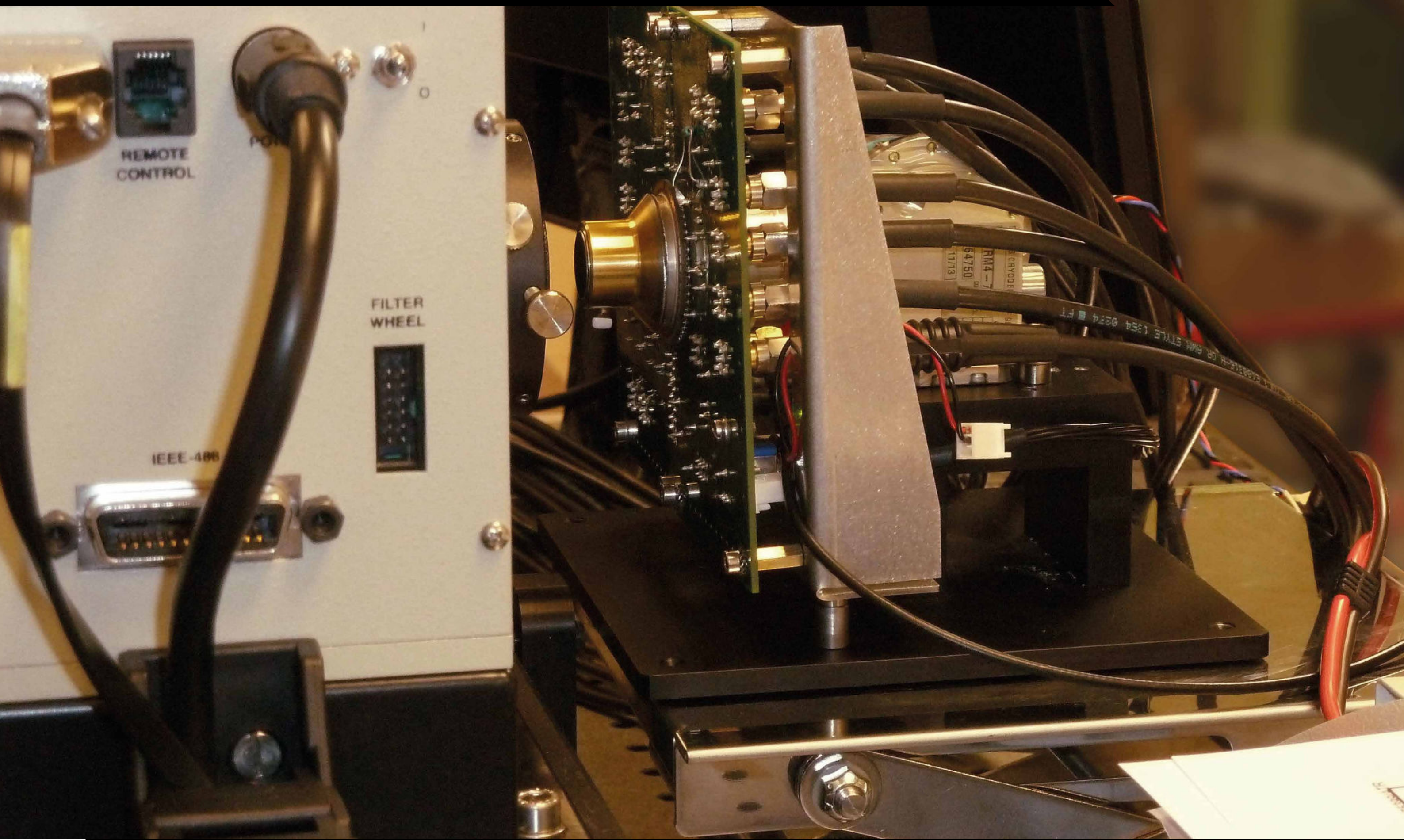

A practical implementation of high resolution relative spectral response measurement of CMOS IRFPAs using Fourier Transform Infrared Spectrometer (FTIR)

The accurate knowledge of IR detectors specifications becomes of higher importance whatever the application. Among these specifications is the relative spectral response. The usual method of relative spectral response measurement uses a source spectrally defined by the wavelength selection through a grating-based monochromator. This simple and proven method has a limited spectral resolution since the signal received by the tested detector is proportional to the width of the wavelength selection slit i.e. the spectral resolution. Another method consists in using a Fourier Transform IR Spectrometer (FTIR) easily allowing a 1 cm^{-1} spectral resolution even in the Long Wave IR range. However, the implementation of this method requires a meticulous analysis of all the elements of the bench and all the parameters to avoid any misinterpretation of the results. Among the potential traps are the frequency dependence of the signals and the parasitic fringes effect on the curves. Practical methods to correct the frequency dependence of the reference detector and to remove parasitic interference fringes are presented in this paper.

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1. MEASURING THE RELATIVE SPECTRAL RESPONSE OF A CMOS IRFPA USING A GRATING BASED MONOCHROMATOR

1.1 Description of the bench

The relative spectral response measurement method is part of the BIRD bench. This bench is a universal testing system of IR CMOS focal plane arrays (IRFPAs). It includes very low noise driving electronics of the IRFPA, opto-mechanical tools presenting accurate optical stimuli to the detector under test and video signal acquisition and processing system with accurate testing algorithms. The list of available measured parameters includes: temporal noise, fixed pattern noise, 3D-noise, responsivity, detectivity, dynamic range and linearity of the signal, quantum efficiency, NETD, bad pixel location, non-uniformity correction, MTF, pixel surface response, crosstalk, relative spectral response and G factor.

The very low noise electronics of the bench includes a bias voltage generation unit with output noise lower than 100 nV/√Hz and a high frequency clock signal generator with slew rate higher than 1000V/μs. The multi-channel analog signal delivered by the IRFPA is digitized through an AD converter with 200 μV maximum input noise and multiplexed as up to a 320 MHz equivalent data flow in order to be transferred in GigE Vision to the acquisition unit. This bench is consequently able to test up to 4k x 4k detectors.

The opto-mechanical table is equipped with a highly stable (3 mK) low temperature extended area blackbody allowing an accurate measurement of noises, the detection of bad pixels and the calculation of the non-uniformity correction parameters. The spatial tests (MTF, crosstalk and pixel surface response) is made by focusing the image of a thin slit or pinhole on the detector surface through aberration free optics with f-number up to 1.

Figure 1 Electronic cabinet and opto-mechanical table of BIRD

The principle of the relative spectral response function is made by making the ratio of the response to a narrow spectrum optical signal of the detector under test with the response of a reference detector which is supposed to be constant whatever the wavelength. The spectrally defined source is obtained by selecting a portion of a large spectrum source.

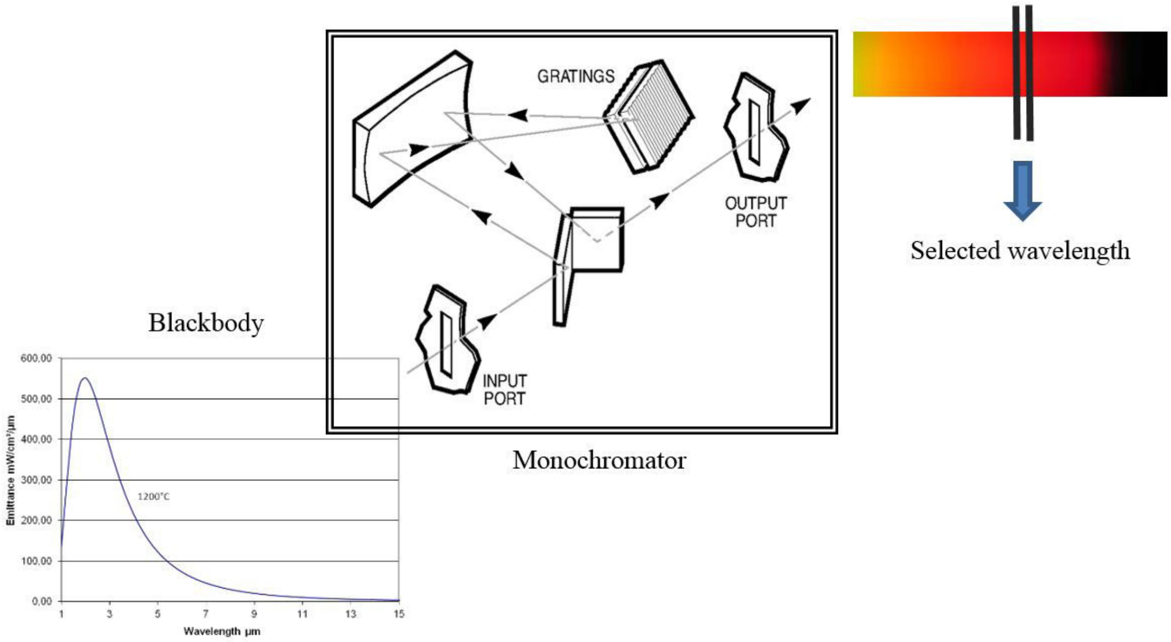


Figure 2 Narrow spectrum optical source generation

The large spectrum source is a 25 mm diameter cavity blackbody with 1300°C maximum temperature and an emissivity greater than 0.98. The radiance of this source is consequently in accordance with the Planck's law. The main specification required for this source is a high temporal stability since the variation of the emittance of the source during the measurement procedure must be negligible. A minimum 0.1°C peak to peak stability at 1200°C is required for this cavity blackbody. The aperture of the cavity lights the input slit of a monochromator. The monochromator is equipped with a set of 2 gratings mounted on a motorized stage. A small portion of the blackbody spectrum is continuously selected through the rotation of the gratings. Thanks to a set of long pass filters, only diffracted first order is taken into consideration and transmitted to the detector through the output slit. The spectral bandwidth, i.e. the spectral resolution, of the output signal is proportional to the width of the output slit and of the input slit since the magnification of the monochromator optics is approximately 1. Consequently, the irradiance received by the detector is proportional to the spectral resolution:

$$I \propto \frac{dR}{d\lambda}(T_{blackbody}) \times \Delta\lambda \quad (1)$$

where $\frac{dR}{d\lambda}$ is the spectral radiance of the blackbody source.

The reference detector is a single element pyroelectric detector. The electric bandpass of this detector excludes continuous signal and a chopper wheel must be inserted at the output of the cavity blackbody to modulate the optical signal for the reference detector only. The chopping wheel is combined to a lock-in amplifier in order to reduce the noise level of the reference signal.

1.2 Limitations of the spectral response measurement method through a monochromator

Equation (1) shows that the smaller the spectral bandwidth of the signal, the lower the irradiance on the detector. For very high resolution analysis, the irradiance received by the detector is below its Noise Equivalent Irradiance (NEI) and the measurement cannot be achieved. This situation is particularly true for Long Wave IR (LWIR) detectors where a high resolution is combined with a low spectral radiance of the blackbody source ($dR/d\lambda$). The solution consisting in increasing the temperature is hardly acceptable above 1300°C for practical reasons. A 2 mm slit width is about 100 nm resolution at 10 µm. Combined with 1200°C blackbody, the irradiance received by a LWIR usual cooled detector through a 2 mm slit monochromator is close to its NEI.

Moreover, the analysis duration is proportional to the ratio between the analyzed spectral range and the spectral resolution. It takes about one hour to get a spectral curve for a 2 mm slit width. Consequently, a 0.1 µm spectral resolution at 10 µm is the best possible spectral resolution for a LWIR detector.

2. MEASURING HIGH RESOLUTION RELATIVE SPECTRAL RESPONSE OF IR CMOS DETECTORS THROUGH FTIR

The principle of the relative spectral response measurement through an FTIR is also made by the ratio of the response of the detector under test with the response of a reference detector which is supposed to be constant whatever the wavelength. The source is based on a broad band IR source such as a blackbody passing through an FTIR. With this configuration, the input source is considered as the sum of monochromatic sources and the interferogram received by the detector through the FTIR is the sum of monochromatic interference fringes and includes the information of the whole spectrum at the same time. Consequently, the signal level on the detector remains above its NEI even for LWIR detectors.

The principle of the FTIR based spectral response system is shown below:

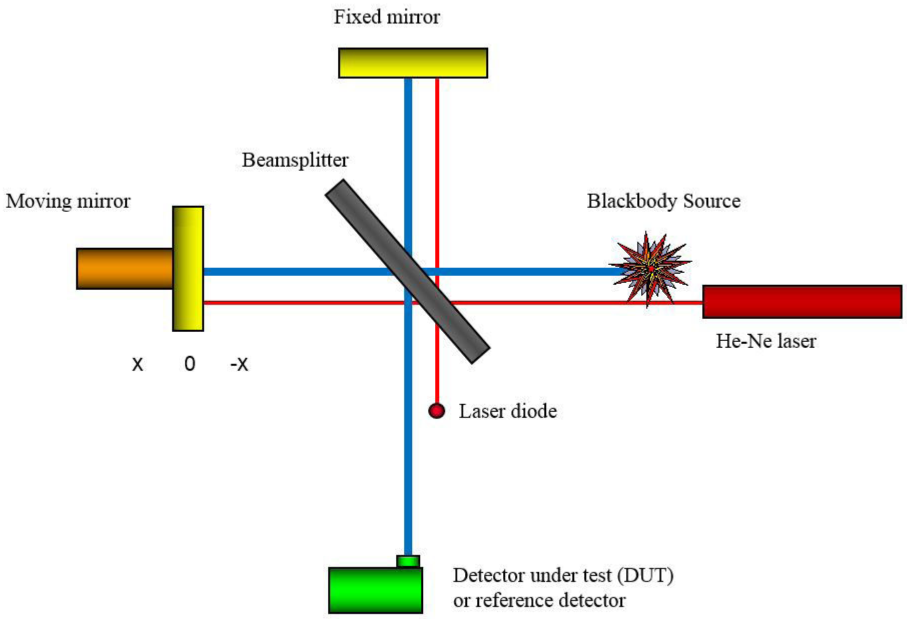


Figure 3 FTIR based spectral response principle

The Fourier Transform spectrometer is based on a Michelson interferometer. The high intensity, broad band source energy is projected into the interferometer. The interferometer consists in a beamsplitter which reflects half of the energy to a fixed mirror and half to a moving mirror. The moving mirror scans back and forth producing a path length difference with respect to the fixed mirror. This path length difference is sampled in time with respect to the internal HeNe laser - making also for internal/ absolute calibration of the wavelength. The reflected beams then combine back at the beamsplitter to create a modulated signal. The detector measures the intensity of the modulated energy to produce an interferogram.

The shape of the interferogram depends on the source spectrum.

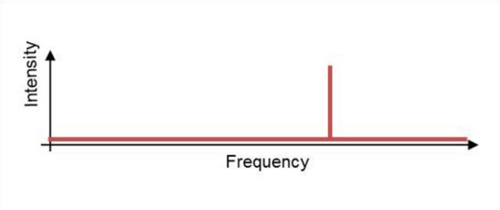
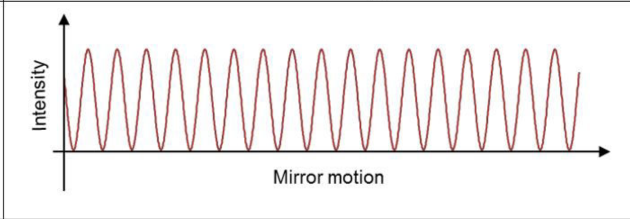
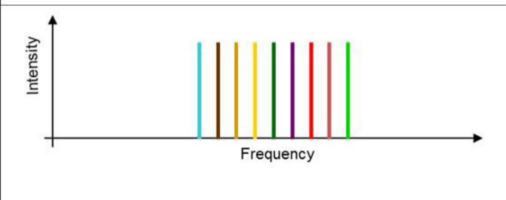
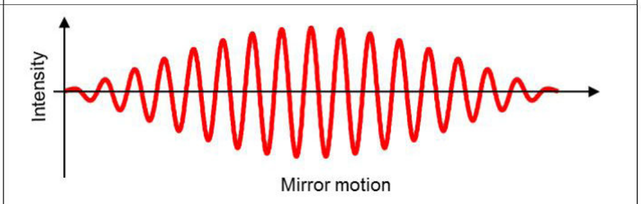
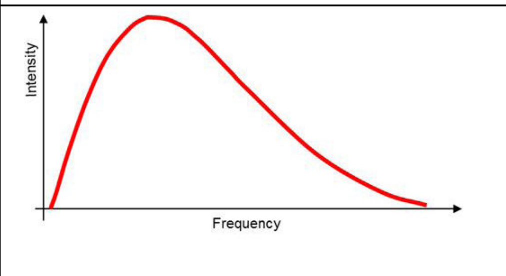
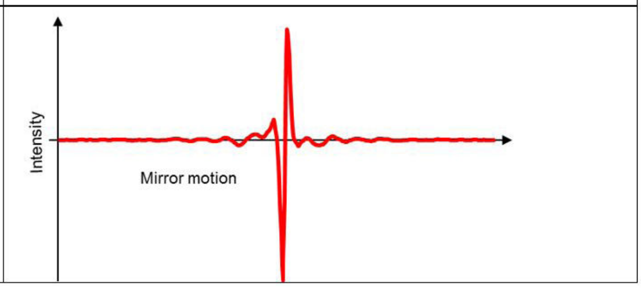
Source type		Modulated signal
Laser (monochromatic light source)		
Several single frequencies		
Broad band IR source		

Figure 4 Interferogram shape vs. source spectrum

The detector simultaneously receives all the frequencies and the interferogram is the sum of the contribution of all the frequencies at the same time. So using a Fast Fourier Transform calculation, the response of the detector to the IR source can be computed.

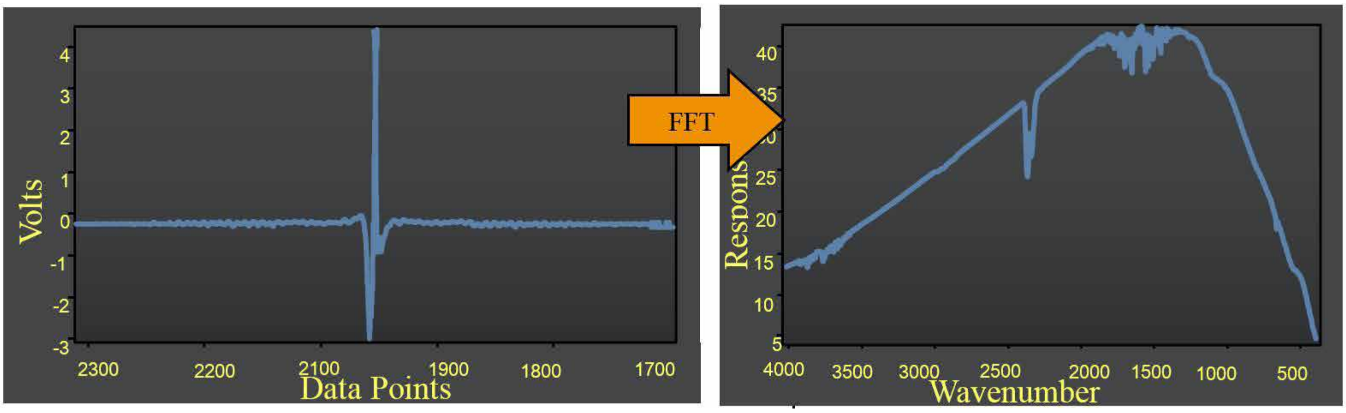


Figure 5 Response calculation through FFT algorithm

The domain of the measured data is the temporal or spatial domain. The Fourier Transformed domain is the frequency or spectral domain.

Spatial/temporal domain	Frequency /Spectral domain
Interferogram	Response
Mirror position (cm)	Wave number (cm^{-1})
Sampling period (cm)	Spectral range (cm^{-1})
Optical path difference (cm)	Spectral resolution (cm^{-1})

Table 1: Corresponding parameters

The optical path difference between the 2 beams of the interferometer is given by:

$$\delta = 2d$$

where d is the travel distance of the moving mirror. A 0.5 cm travelling distance leads to a 1 cm optical path difference. In the Fourier domain, a 1 cm optical path difference is equivalent to a 1 cm^{-1} spectral resolution. So a 0.5 cm mirror travel leads to a 1 cm^{-1} i.e. 10 nm at 10 μm so 10 times better than with the monochromator method.

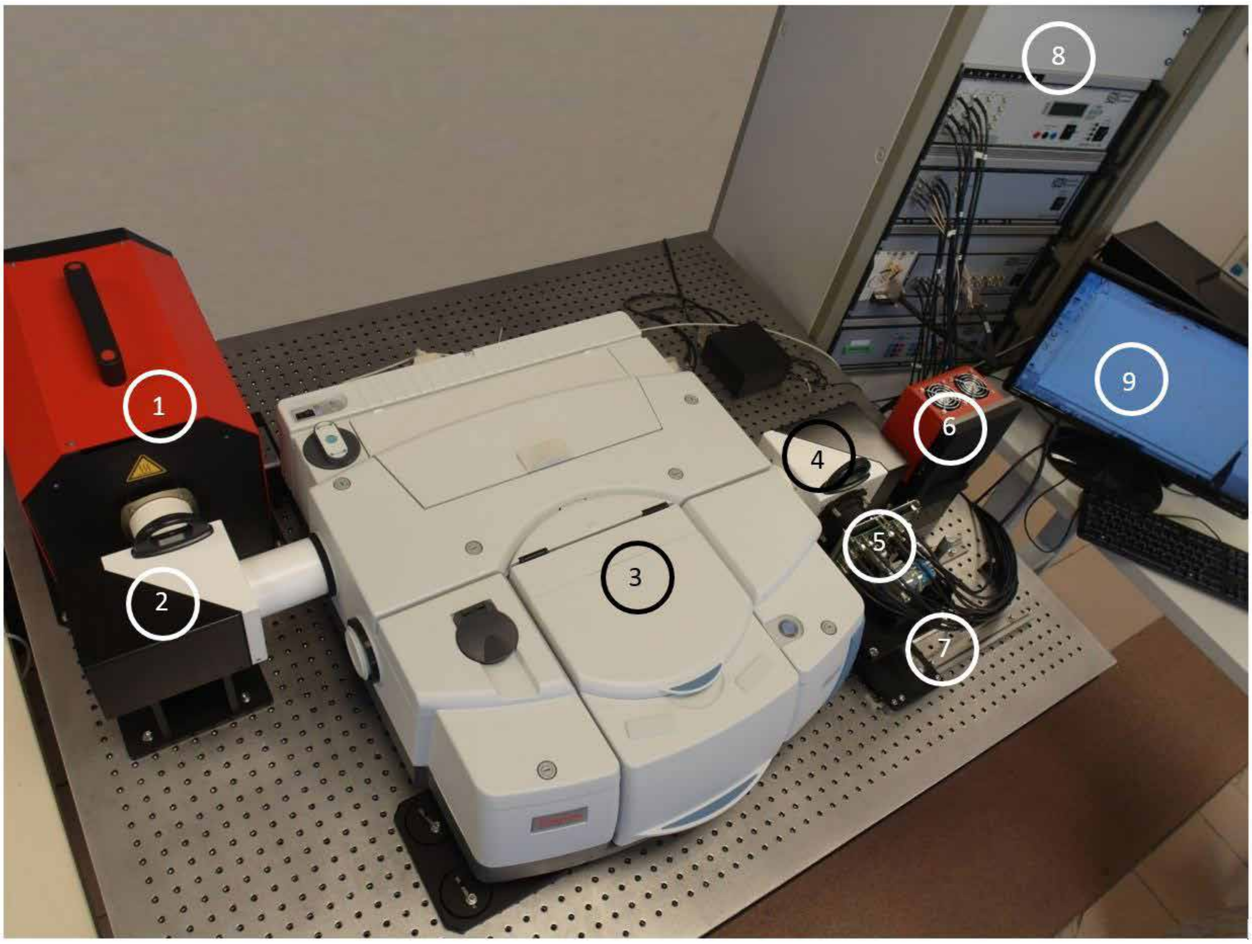


Figure 6 BIRD bench with FTIR based spectral response assembly

Figure 6 shows a view of the manufactured BIRD bench with FTIR spectrometer with:

1. Cavity blackbody
2. Input optics
3. FTIR spectrometer
4. Output optics
5. Detector under test
6. Extended area blackbody for noise test configuration
7. Trolley to switch from spectral response to noise test configuration
8. Electronic cabinet with clock signal and bias voltage generator and ADC converter
9. Acquisition and data processing computer

3. CORRECTION OF THE TEMPORAL DEPENDANCE OF THE MEASUREMENTS

An IR CMOS Focal Plane Array delivers data over one or several channels with 100 Hz maximum frequency whereas a pyroelectric detector behaves like a high-pass circuit being insensitive to continuous signal. Consequently, making the ratio of the response of these two different detectors requires special care.

3.1 Measuring conditions

The spectral response of the IR CMOS focal Plane Array under test (DUT) is measured using the step-scan mode of the FTIR. Instead of a continuous move of the moving mirror of the interferometer, the mirror moves step by step and an image is acquired by the DUT at each step in order to build the interferogram. The step position is given by the selected sampling frequency based on the He-Ne laser frequency.

In order to avoid any transmission and optical differences, the reference pyroelectric detector is located outside the FTIR spectrometer at the same location as the DUT. The spectral response of the reference pyroelectric detector is measured during the continuous scan of the mirror since this detector does not work in DC. However, whereas the spectral response of a pyroelectric detector is flat, the response of this detector strongly depends on the temporal frequency of the detector.

Our correcting method consists in measuring the temporal transfer function of the continuous scan mode of the FTIR combined with the reference pyro detector response and to apply this correction to the pyro detector spectral response.

3.2 Temporal transfer function

For a given wavelength λ of the spectrum received by the reference detector, the apparent frequency is calculated by the Doppler effect:

$$f_{app} = \frac{2V_s}{\lambda} \tag{2}$$

where Vs is the scanning speed of the moving mirror. This apparent frequency is the modulation frequency of the interferogram corresponding to the wavelength λ. The temporal transfer function is the response of the reference detector in continuous mode vs. the modulation or apparent frequency. The calculation procedure is described hereafter.

For 11 scanning speeds of the interferometer, we acquire the spectral response of reference detector as shown on Figure 7. The speed dependence of the response is particularly obvious on this figure: for example, the location of the maximum depends on the speed value.

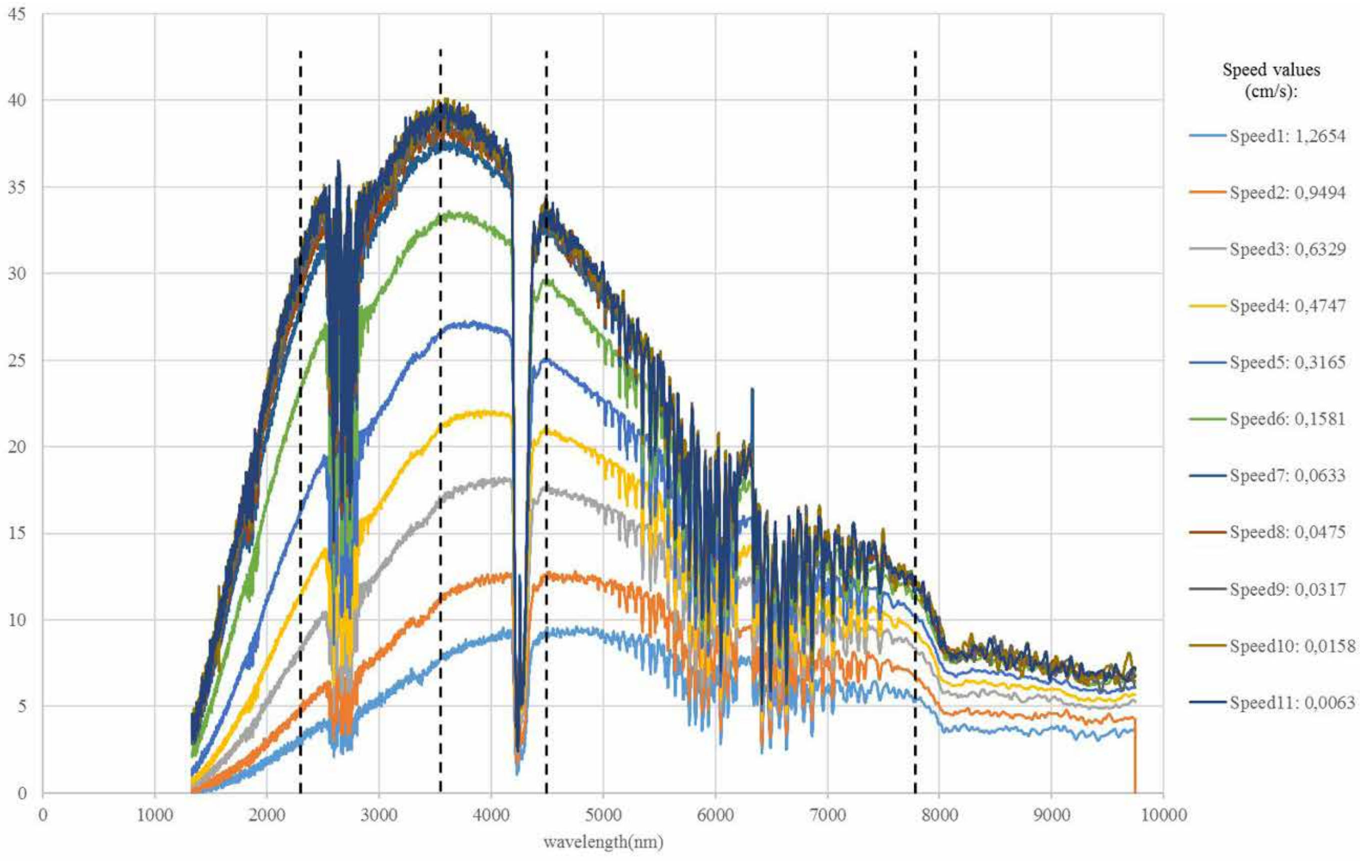


Figure 7 Spectral response of reference detector for various scanning speeds

Four wavelengths (doted lines above) with highest signal to noise ratio are selected. For each wavelength and each speed, the modulation frequency is calculated and the signal normalized to the maximum value is also calculated vs. the modulation frequency. We consequently get a table of 4x11 =44 normalized response values vs. modulation frequencies. The Bode diagram of this transfer function is shown below with a logarithmic scale for the frequencies.

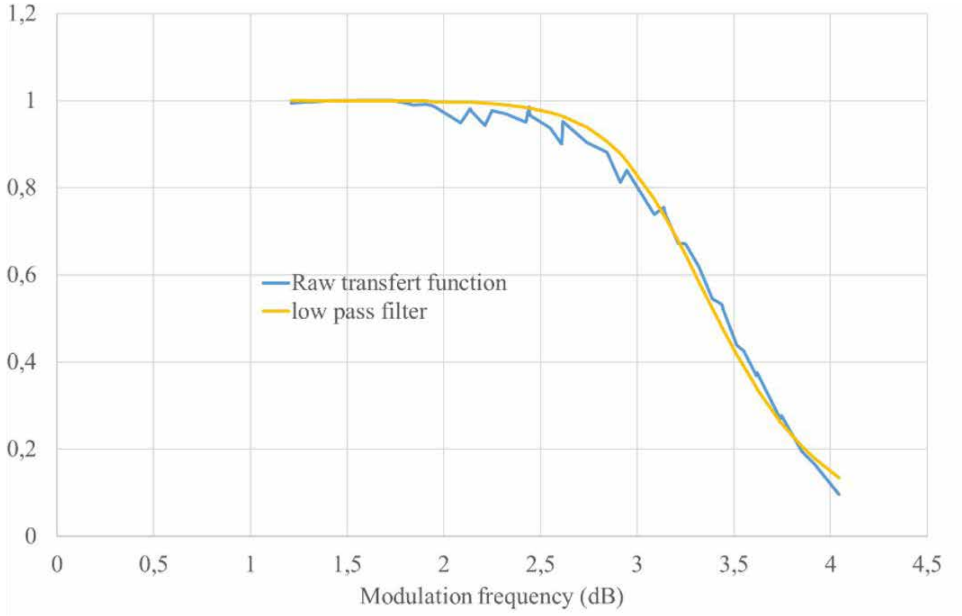


Figure 8 Bode diagram of the transfer function

The transfer function of the reference detector response in continuous mode can be approximated to a low pass filter over this range of interest of modulation frequencies. The corresponding correction is applied to the measured spectra for different values of scanning speed and the corrected normalized spectral responses of the reference detector are shown below.

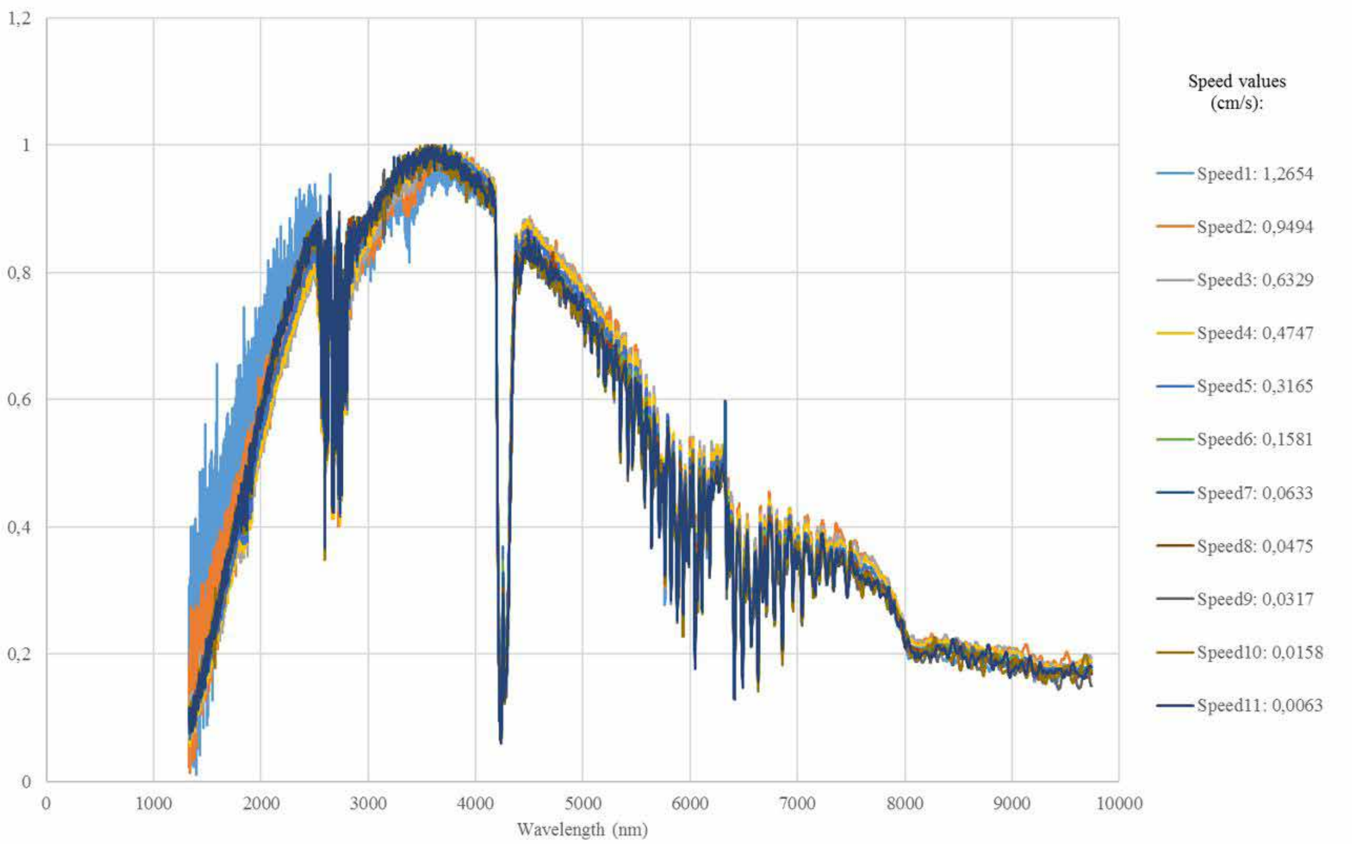


Figure 9 Corrected normalized spectral response of the reference pyroelectric detector for various scanning speeds

The reference detector behaves like a low pass filter over the modulation frequency range corresponding to the IR spectrum and we are now able to apply a correction filter to its spectral response in order to get rid of this temporal dependence. The high pass filter behavior of the reference detector does not affect the spectral response over the IR range.

4. REMOVING PARASITIC FRINGES FROM IR CMOS IRFPA SPECTRAL CURVES

A LWIR IRFPA detector with 288x4 resolution is tested with the FTIR BIRD bench. The IR source is a blackbody stabilized at 1200°C and the travel range of the interferometer is 0.5 cm i.e. 1 cm^{-1} spectral resolution. Based on the measured interferogram, the calculated spectral response curve seems to be "noisy" as shown on Figure 10. And accurately measuring the cut-on and cut-off wavelengths becomes impossible.

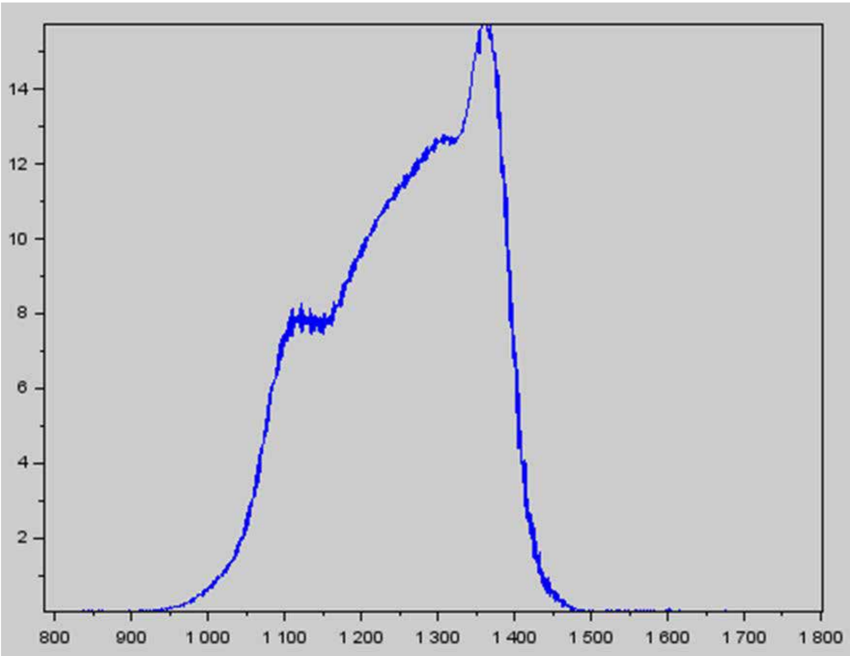


Figure 10 FFT of raw IRFPA detector interferogram

These unexpected oscillations originated from ghost fringes into the interferometer. They are linked to multiple reflections between parallel surfaces such as the beamsplitter of the spectrometer or any other filter. Whereas the maximum signal is given for the zero path difference where all wavelengths have the same phase, these multiple reflections create other maxima for a path difference depending on the index and the thickness of the beamsplitter or filter. They can be easily detected on the interferogram corresponding to the above curve (see Figure 11 – red circle)

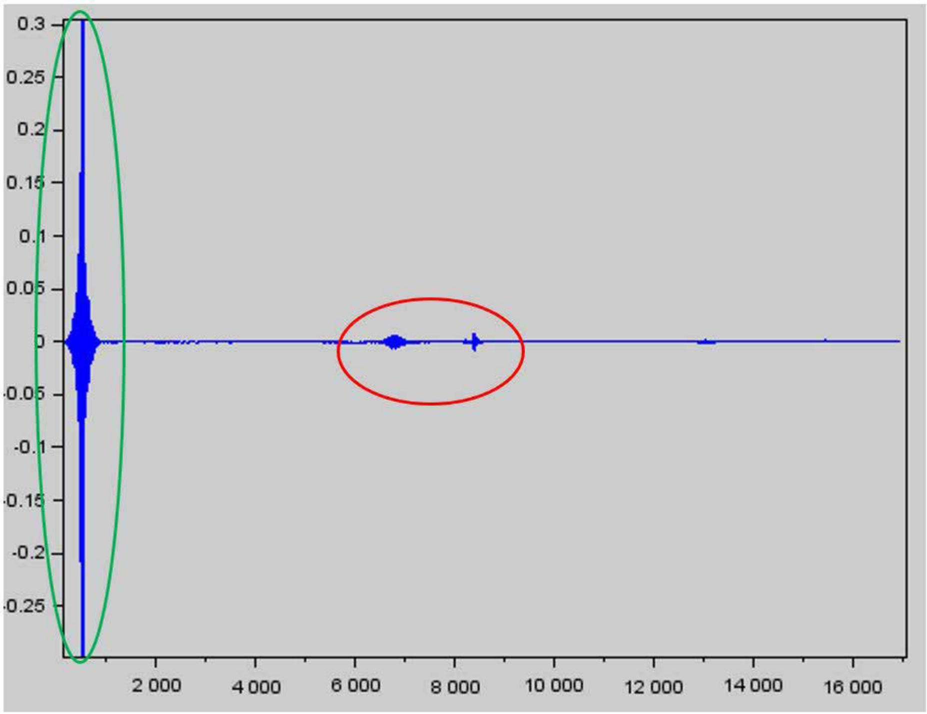


Figure 11 Interferogram of IRFPA detector with parasitic fringes effect

Usual method to remove these fringes consists in using polarized light using a polarizer oriented at Brewster angle. For practical reasons, we prefer applying a numerical filter to the interferogram.

Since the parasitic fringes are echoes of the zero path difference signal, the zero path difference pattern, circled in green in Figure 11, is correlated with the complete interferogram curve.

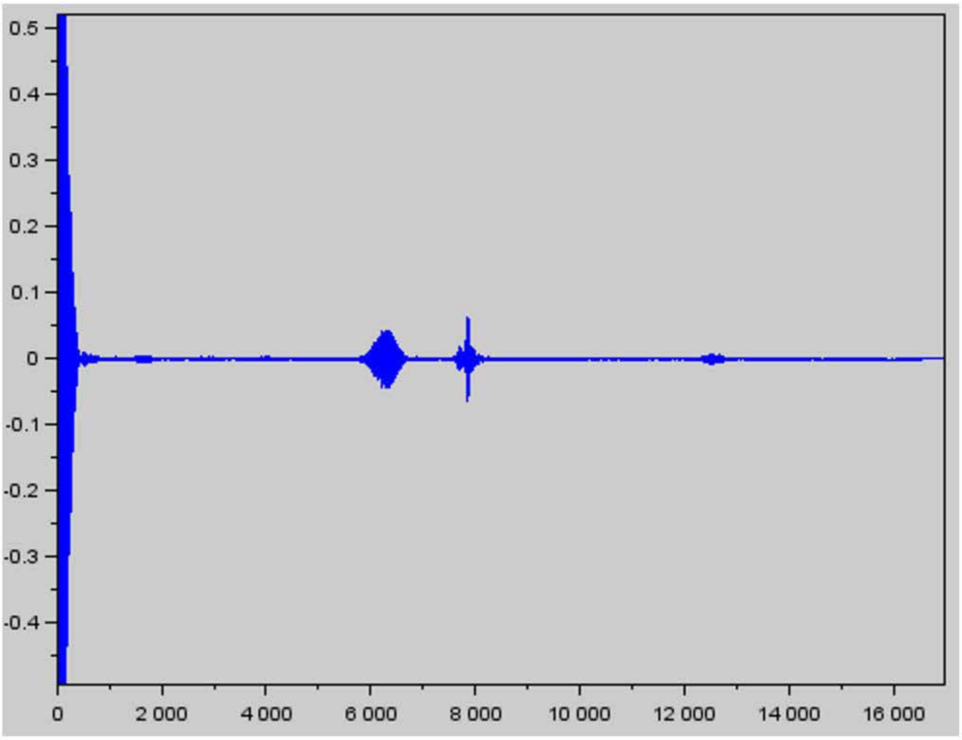


Figure 12 Correlation curve of the zero path difference pattern with the interferogram

The sliding average of the correlated curve is computed and values higher than 0.1% of the zero path difference are automatically set to 0. This threshold is determined experimentally through several tests over the infrared range up to 20 µm. It can be noticed that for low spectral resolution, i.e. for a shorter mirror interferometer travel, the interferogram has less data points and parasitic fringes might not be visible.

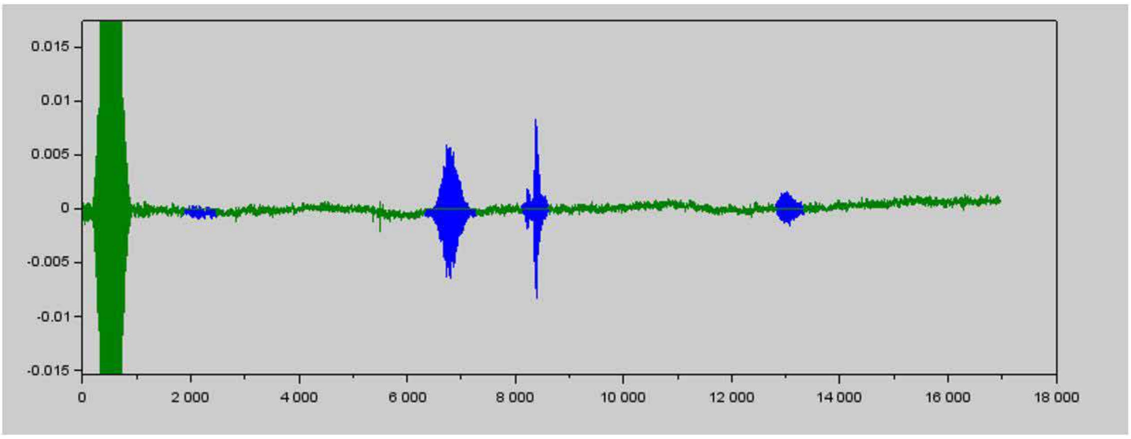


Figure 13 Detected parasitic patterns

Figure 13 shows in blue the detected parasitic patterns. The interest of the preliminary correlation is demonstrated around point 2000 where a set of parasitic fringes is detected. Figure 14 shows the corrected spectrum.

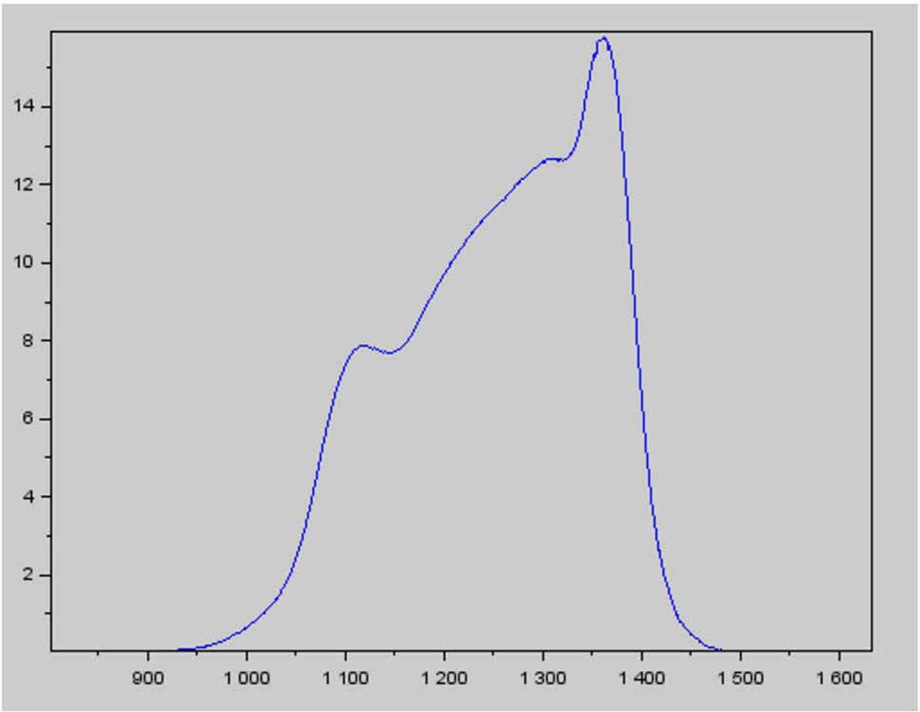


Figure 14 Corrected spectral

5. CONCLUSION

Due to complex constraints of implementation, high resolution relative spectral response benches were up to now limited to experimental means. Thanks to its long experience in IR CMOS Focal Plane Arrays testing through the BIRD bench, HGH developed a practical FTIR-based solution for relative high resolution spectral response measurement. Associated with an easy-to-use software and a universal low noise electronics, the bench allows the implementation of any IR Focal Plane Array and provides accurate measurements of noises, non-uniformity correction, bad pixel detection and high resolution relative spectral response measurement, all these tests being processed in a few minutes. Building on these encouraging results, some tests are in the process to extend the measurement of relative spectral response to near IR and visible spectrum.

6. REFERENCES

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«A practical implementation of high resolution relative spectral response measurement of CMOS IRFPAs using Fourier Transform Infrared Spectrometer (FTIR)», SPIE # 9987-33

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