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To cite this version:

Alain Kattnig. Theoretical and practical analysis of spatial and spectral calibration of static Fourier transform infrared spectrometers. Optics Express, Optical Society of America, 2019, 27 (10), pp.14819-1 - 14819-16. 10.1364/OE.27.014819. hal-02174526

HAL Id: hal-02174526
https://hal.archives-ouvertes.fr/hal-02174526
Submitted on 5 Jul 2019

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Theoretical and practical analysis of spatial and spectral calibration of static Fourier transform infrared spectrometers

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Abstract: Static Fourier transform spectrometers require, especially in the infrared, a spatial calibration step. Unfortunately, the superposition of fringes on the measured images has a major impact on spatial calibration and therefore on the returned spectra. We first study how to pre-process images so that spectral errors are minimized. Then, we develop a spectrum formation model that is used to correct those spectral errors. The performance, evaluated on synthetic data, is remarkable and theoretically justifies the use of this calibration concept.

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1. Introduction

Fourier Transform Infrared Spectrometers (FTIR) are unparalleled tools for extracting as much spectral information as possible above the visible spectrum [1]. But the FTIR temporal exploration of interferometry range limits the accessible temporal resolution to a few seconds without giving up too much spectral and radiometric resolution. Furthermore, FTIR moving parts are difficult to use in vibrationally challenging environments such as vehicles or aircrafts.

Thus instead of temporally exploring the optical path difference (OPD) it makes sense to spatially spread the OPD over a detector array.

This instrument concept has been the subject of numerous studies since the first article of 1965 by Stroke&Funkhouser [2] but has seen few real working instruments [3–9] and even less evidence of high signal to noise spectrum measures [10,11]. Our goal here is to shed light on the potential reasons for these difficulties and to propose remedies.

The origin of all the difficulties lies in the derived nature of spectrum measurements, which means that stringent conditions are necessary to comply with the requirements of the Fourier transform used to generate the spectra.

Since spatial or angular displacement is necessary to explore all available OPDs, the nonuniformity of the array must be corrected as well as the resulting spatial sampling on the scene. It is therefore necessary to design an interpolation scheme. And the extreme sensibility of the Fourier Transform also means that the non-linearity of the real OPD must be evaluated, possibly corrected or taken into account.

Finally, usually an asymmetric interferogram is acquired to increase the spectral resolution, but this step can also generate spectral errors.

Thus, the measurement sought is the result of many processes, all of which are subject to errors with unacceptable consequences on the resulting spectrum.

We will start here by showing how to calibrate the detector array without using the cumbersome and perilous solution of modifying the instrument to block light in one of the arms of the interferometer.

We will then develop a theoretical model of the spectral errors induced by this spatial calibration and the best way to correct it.

From a practical point of view, we will show how to process real interferogram images before using them to retrieve the observed spectra.
The analysis will also be based on synthetic data in order to compare our results with the underlying truth, which is difficult to find on real acquisitions.

2. Detector spatial calibration behind fringes

Spatial calibration of visible detector arrays is not, by far, as important as for Infrared detector arrays. Mainly because the most efficient infrared detectors are still today a ternary mixture, HgCdTe, which requires extreme mixing accuracy. We will therefore explicitly study the case of infrared, but a few decibels SNR improvement in visible matrices is certainly possible and worthy of the effort required.

We started working on this subject twenty years ago [12,13], then applied the oversampled design to build a Cryogenic Infrared Stationary Fourier Transform radiospectrometer called Mistere [14]. Later, we developed an airborne Imaging Infrared Static Fourier Transform Spectrometer, called Sieleters [9] which comes in two flavors; MWIR and LWIR.

We provide a quick overview of the performance of these instruments for reference purposes in Table 1.

| Parameter               | Sieleters MWIR | Sieleters LWIR | Mistere |
|-------------------------|----------------|----------------|---------|
| Spectral range          | [3-5.3] µm     | [8-11.5] µm    | [3–10] µm |
| Spectral resolution     | 20 cm⁻¹        | 10 cm⁻¹        | < 8 cm⁻¹ |
| Spectral sampling       | 10 cm⁻¹        | 5 cm⁻¹         | n.a. (oversampled) |
| IFOV                    | 0.25 mrad      | 0.25 mrad      | n.a.    |
| Across track FOV        | 15° (1000 pixels) | 15° (1000 pixels) | 4.5° × 0.6° |
| Spatial sampling (2000 m)| 0.5 m          | 0.5 m          | n.a.    |
| NETD (scene at 300K)    | <150 mK at 5 µm| <200 mK at 10 µm| n.a.    |

In both cases, the interferometric stage superimposes fringes on an image (in Sieleters case) or a uniform field (in Mistere case). But both will have the same type of image when illuminated by blackbodies used to calibrate them. Thus the same calibration procedure can be used for both instruments.

The standard spatial calibration procedure [15] is based on the assumption that all focal plane detectors must behave in the same way when illuminated by a collimated light field. Then, to enforce this behavior, an affine transformation is calculated for each elementary detector from two or more different intensities to resemble as much as possible a reference detector output. Unfortunately this strategy cannot be used directly because there will always be fringes in the focal plane now. Thus there are two main possible solutions:

- We can block one of the interferometric optical paths to remove the fringes. This is the best solution as long as you can make sure that it does not introduce any perceptible stray light and that you compensate for the loss of half the light intensity. Since good calibration strategy involves bracketing the expected intensity by your calibration sources. It must also be compatible with the integration time of your experiments and the physical integrity of the instrument.

- If the first solution is not practical you will have to use signal processing solutions to reconstitute the signal as if there were no fringes. Then the calibration can be performed as usual.

Since Sieleters and Mistere are two cryogenic instruments, we did not take the risk to include the means to block one optical path by inserting a screen, either motorized or controlled from the outside. These options were not chosen because of the difficulties and hazards associated with the operation of cryogenic temperature moving parts (~80K), the increased complexity and thermal “pollution” created by an engine in operation or by the thermal bridge induced by a would-be handle.

A digital solution therefore seems to be the best solution, the impact of which will be explored further on.
2.1 Frequentilly “erasing” fringes

The goal here is to recover detectors outputs as if no fringes were present. This is conceivable because in the two-dimensional Fourier space of images taken by well-designed 2D static spectrometers, the fringes occupy a very small area (see Fig. 1 and Fig. 2). It is therefore possible that such erasure may not cause too much damage to the underlying signal.

![Fig. 1](image1.png) Left, raw image corrected of dead pixels of a blackbody taken by our Imaging LWIR FT Spectrometer, Sielerters. Right, a crop of the logarithm of the Fourier Transform of the spatial noise corrected image. Fringes are slightly slanted.

![Fig. 2](image2.png) Left, raw image corrected of dead pixels of a blackbody taken by our static FT spectrometer, Mistere. Right, logarithm of the Fourier Transform of the spatial noise corrected image. Fringes are slanted by design.

As these instruments have been designed to minimize distortion [9,14] as much as possible, the interferometric fringes, which are everywhere in the original images, become 1D segments in 2D Fourier space. Thus erasing these segments in this space will only affect a small part of the energy required to describe the spatial nonuniformities of the instrument’s response to a uniform luminance field.

Thus if care is taken to avoid introducing artefacts while erasing these few frequencies, we will obtain a good estimation of the image without fringes and a good affine correction. But we must then prove that the resulting spectrum errors are below other more fundamental errors.

2.1.1 Induced errors

We have to overcome the loss of information due to the removal of fringes frequencies. It is highlighted by writing the image formation equation (a division by two being dropped) [13]. In order not to burden the notation we have chosen to omit the sampling operator and write equations in the continuous space (see Eq. (1)). The gain and offset can be considered as multiplied by the Dirac comb function to obtain a continuous expression.
\[ \text{Image}_{bb}^{\text{fringe}}(x, y, T) = \text{gain}(x, y) \times \left[ S_{bb}(T, \nu) \cos(2\pi\nu \delta y) \right] + \text{offset}(x, y). \quad (1) \]

\[ S_{bb}(T, \nu) \] being the blackbody spectrum at temperature \( T \) convoluted by the spectrometer response function in the hypothesis that fringes are perfectly horizontal, \( L_{bb}(T) \) being the integrated luminance of the blackbody over the spectral window, \( \delta y \) being the optical path difference (OPD) on the \( y \) axis of the detector. This OPD is in practice measured on the detector by means of a laser. By design the OPD is almost perfectly linear in the detector plane.

By stating that the OPD is linear we recognize the real part of a Fourier Transform in the above equation and knowing that the spectrum is real we can write the fringe-polluted image:

\[ \text{Image}_{bb}^{\text{fringe}}(x, y, T) = \text{gain}(x, y) \times \hat{\delta}_{bb}(T, \nu) + \text{gain}(x, y) \times L_{bb}(T) + \text{offset}(x, y). \quad (2) \]

We will remove fringes from blackbody images by frequency filtering, since they are inherently sinusoidal. Thus the Fourier Transform is the natural tool to do it. We note by \( \Pi \) (gate function) the frequency filter designed to remove fringes frequencies. Then we have in Fourier space:

\[ \text{Image}_{bb}^{\text{fringe filtered}}(\nu, \nu, T) = \left[ 1 - \Pi(\nu, \nu) \right] \times \text{Image}_{bb}^{\text{fringe}}(\nu, \nu, T) \]

\[ = \left[ 1 - \Pi(\nu, \nu) \right] \times \left[ \text{gain}(\nu, \nu) \times \hat{S}_{bb}(T, \nu) + \text{gain}(\nu, \nu) \times L_{bb}(T) + \text{offset}(\nu, \nu) \right] \quad (3) \]

We have seen in Fig. 1 and Fig. 2 that the observed spectrum is strongly concentrated in the 2D Fourier space, since it is a 1D segment (hence the \( \nu_y \)-only dependence of the blackbody spectrum). On contrary, the Fourier transform of both gain and offset are much more spread out, obeying a 1/f law [16]. Thus by virtue of the convolution of \( S_{bb}(T, \nu) \) by the Fourier Transform of the gain, the blackbody spectrum energy will be spread over the gain frequencies, widening the frequency area in need of removal.

Let’s assume that the chosen filter is wide enough to remove completely any fringes influence in the resulting blackbody image. Thus we can give an expression of the affine spatial transformation computed by using these filtered blackbody images on two temperatures:

\[ \text{gain}_{\text{affine filtered}}(x, y) = \frac{\text{Image}_{bb}^{\text{fringe filtered}}(x, y, T_1) - \text{Image}_{bb}^{\text{fringe filtered}}(x, y, T_2)}{L_{bb}(T_1) - L_{bb}(T_2)} \]

\[ = \left[ 1 - \hat{\Pi}(x, y) \right] \times \left[ \hat{S}_{bb}(T, \nu) - \hat{S}_{bb}(T_1, \nu) \right] \times \text{gain}(x, y) \quad (4) \]

Since fringes exist on a narrow frequency domain and that the Fourier Transform of the gain is strongly concentrated at the origin (1/f), we will neglect the blurring effect of this transformation. And because by definition the difference of spectrum exists only on the frequency we filter, we will have:

\[ \hat{\Pi}(x, y) \times \left[ \frac{\hat{S}_{bb}(T_1, \nu) - \hat{S}_{bb}(T_0, \nu)}{L_{bb}(T_1) - L_{bb}(T_0)} \right] \times \text{gain}(x, y) \]

\[ = \frac{\hat{S}_{bb}(T_1, \nu) - \hat{S}_{bb}(T_0, \nu)}{L_{bb}(T_1) - L_{bb}(T_0)}. \quad (5) \]

Thus
\[
\text{gain}^{\text{fringe filtered}}(x, y) = \left[1 - \hat{\Pi}(x, y)\right] \ast \text{gain}(x, y) + \frac{\hat{S}_{bb}(T_x, y) - \hat{S}_{bb}(T_0, y)}{L_{bb}(T_x) - L_{bb}(T_0)} \ast \left[\text{gain}(x, y) - 1\right].
\] (6)

and

\[
\text{offset}^{\text{fringe filtered}}(x, y) = \text{Image}_{bb}^{\text{fringe filtered}}(x, y, T_y) - \text{gain}^{\text{fringe filtered}}(x, y) \times L_{bb}(T_y)
\]

\[
= \left[1 - \hat{\Pi}(x, y)\right] \ast \left[\text{gain}(x, y) \times \hat{S}_{bb}(T_x, y)\right] + \left[1 - \hat{\Pi}(x, y)\right] \ast \text{offset}(x, y)
\]

\[
= \left[1 - \hat{\Pi}(x, y)\right] \ast \left[\text{gain}(x, y) \times L_{bb}(T_x) - \frac{\hat{S}_{bb}(T_x, y) - \hat{S}_{bb}(T_0, y)}{L_{bb}(T_x) - L_{bb}(T_0)} \times \left[\text{gain}(x, y) - 1\right] \times L_{bb}(T_y)\right]
\] (7)

\[
= \frac{\hat{S}_{bb}(T_x, y) \times L_{bb}(T_y) - \hat{S}_{bb}(T_0, y) \times L_{bb}(T_y)}{L_{bb}(T_x) - L_{bb}(T_0)} \times \text{gain}(x, y) + \text{offset}(x, y)
\]

\[
= \left[\hat{S}_{bb}(T_y, y) \times L_{bb}(T_0) - \hat{S}_{bb}(T_0, y) \times L_{bb}(T_0)\right] / L_{bb}(T_0) - L_{bb}(T_y)
\]

In practice, since the calibration temperatures are very close, a few tens of degrees, the shape of spectral luminances are very similar. Thus, when weighted by the integrated luminance of the blackbody at the other temperature, the multiplicative of the gain in Eq. (7) will be very small. So:

\[
\text{offset}^{\text{fringe filtered}}(x, y) = \left[1 - \hat{\Pi}(x, y)\right] \ast \text{offset}(x, y).
\] (8)

Thus any raw image of homogenous spectrum \(S(\nu)\) will be spatially corrected by the resulting affine transformation:

\[
\text{Image}_{\text{Corrected}}^{\text{fringe filtered}}(x, y)
\]

\[
= \frac{\text{Image}_{bb}^{\text{fringe filtered}}(x, y, T_y)}{\text{gain}_{bb}^{\text{fringe filtered}}(x, y)} - \text{offset}_{bb}^{\text{fringe filtered}}(x, y)
\]

\[
= \frac{\text{gain}(x, y) \times \hat{S}(y) + \text{gain}(x, y) \times L}{\text{gain}_{bb}^{\text{fringe filtered}}(x, y)} + \frac{\text{offset}(x, y)}{\text{gain}_{bb}^{\text{fringe filtered}}(x, y)} - \text{offset}_{bb}^{\text{fringe filtered}}(x, y)
\]

\[
= \hat{S}(y) + \frac{\text{gain}_{bb}^{\text{fringe filtered}}(x, y) \times \hat{S}(y)}{\text{gain}_{bb}^{\text{fringe filtered}}(x, y)} + \text{gain}(x, y) \times \hat{\Pi}(x, y) \ast \text{offset}(x, y)
\] (9)

While

\[
\text{gain}_{bb}^{\text{fringe filtered}}(x, y) - \text{gain}(x, y)
\]

\[
= \left[1 - \hat{\Pi}(x, y)\right] \ast \left[\hat{S}_{bb}(T_x, y) - \hat{S}_{bb}(T_0, y)\right] \times \text{gain}(x, y)
\] (10)

\[
= \frac{\hat{S}_{bb}(T_y, y) \times L_{bb}(T_0) - \hat{S}_{bb}(T_0, y) \times L_{bb}(T_0)}{L_{bb}(T_0) - L_{bb}(T_y)} \times \text{gain}(x, y) + \hat{\Pi}(x, y) \ast \left[\hat{S}_{bb}(T_x, y) - \hat{S}_{bb}(T_0, y)\right] \times \text{gain}(x, y)
\]

We can also overlook the difference of fringes in the previous equation which are filtered by \(\Pi\). Thus:
\[ Image_{\text{Corrected}}(x, y) = \hat{S}(y) + \left[ \frac{\hat{S}_{fh}(T_r, y) - \hat{S}_{fh}(T_0, y)}{L_{fh}(T_r) - L_{fh}(T_0)} \right] \times \frac{\text{gain}(x, y)}{\text{gain}_{\text{fringe filtered}}(x, y)} \times \hat{\Pi}(x, y) \times \text{offset}(x, y) \times L \times \hat{S}(y) + \text{(11)} \]

To form an image we have to use and process single columns, thus we will Fourier Transform the following quantity at a given column \( x_0 \):

\[ Image_{\text{Corrected}}(x_0, y) = \hat{S}(y) + \left[ \frac{\hat{S}_{fh}(T_r, y) - \hat{S}_{fh}(T_0, y)}{L_{fh}(T_r) - L_{fh}(T_0)} \right] \times \frac{\text{gain}(x_0, y)}{\text{gain}_{\text{fringe filtered}}(x_0, y)} \times \left( \hat{\Pi}(x_0, y) \times \text{offset}(x_0, y) \right) \times L \times \hat{S}(y) + \text{(12)} \]

We don’t take into account here the errors made by symmetrizing the partial interferogram often recorded in such instruments, like in our Sieleters design among others [17]. Thus:

\[ S_{\text{Corrected}}(x_0, \nu_r) = S(\nu_r) + \left[ \frac{S_{fh}(T_r, \nu_r) - S_{fh}(T_0, \nu_r)}{L_{fh}(T_r) - L_{fh}(T_0)} \right] \times \left( \frac{\text{gain}(x_0, \nu_r)}{\text{gain}_{\text{fringe filtered}}(x_0, \nu_r)} \right) \times \left( \hat{\Pi}(x_0, \nu_r) \times \text{offset}(x_0, \nu_r) \right) \times L \times S(\nu_r) + \text{(13)} \]

We expect the multiplicative factors A and B to have similar behaviour and magnitude, but since L is the integrand of S we can also expect to be able to neglect the A part of this last equation. In any case it would have been difficult to build a model of the convolution. Thus our tentative corrective model will be:

\[ S_{\text{Corrected}}(x_0, \nu_r) = S(\nu_r) + \left( \frac{\text{gain}(x_0, \nu_r)}{\text{gain}_{\text{fringe filtered}}(x_0, \nu_r)} \right) \times \left( \hat{\Pi}(x_0, \nu_r) \times \text{offset}(x_0, \nu_r) \right) \times L \times S(\nu_r) + \text{(14)} \]

Now, the most reliable calibrated spectral source available in infrared being the blackbody, we need to know if a blackbody spectral calibration of this approximate model would give good enough results on non-blackbody sources of radiation.

To this end we have simulated the whole process with synthetic but realistic spatial gain and offset.

2.2 Testing quality of spectral calibration on fringe filtered blackbody images

We chose to closely model the Infrared band III of Sieleters with synthetic gain and offset given Fig. 3. Although this simple model cannot explain the classical [18] error divergence for luminance values outside the calibrating luminances, it is widely used to perform correction of spatial noise. It is thus used here.
Then we simulated blackbody spectra at 11 temperatures ranging from 15°C to 65 °C, as well as different spectra shapes in order to evaluate the quality of the model outside generic blackbody shapes, which are very similar over this temperature range (see Fig. 4). We applied on these spectra a phase measured on Sieleeters band III (see Fig. 5). Then they were reverse Fourier Transformed as in Eq. (2) and the resulting images affine transformed by the [gain, offset] of Fig. 3.

![Fig. 3. Left, gain with a range of [0.8, 1.3]. Right, offset with a range of [-0.22e18,0.17e18] ph/s/m²/cm⁻¹/sr.](image)

And we give Fig. 6 its transcription in real space measurements.
All blackbody images must then be ridden of their fringes. We will consider below practical means to disturb as less as possible the image. Please notice that we will use as example real calibration images from the Sieleters Band III instrument since its slanted fringes are more challenging than the horizontal simulation.

2.2.1 Practical means to remove slanted fringes from image

The greatest enemy of frequency manipulation is the implicit periodicity of the Discrete Fourier Transform that brings together the opposite boundaries of images. This creates Heaviside-like signals that generate Gibbs oscillations on these borders after any frequency manipulations.

The first step to be taken is to reduce as much as possible the amplitude of these border-to-border contrasts. To do this, an elegant solution is to remove a 2D polynomial on each overlapped sub-windows. The assembly between the sub-windows is ensured by a gaussian mixing function. And since the Fourier Transform of $x^p$ is proportional to $\delta(w)/wp$, the frequency content of interest will not be affected by polynomials subtraction (see Fig. 7 and Fig. 8). The only potential frequency pollution will come from the sub-window size. This size must be larger than the size of the relevant details otherwise these details could be erased.

![Image simulation obtained with a blackbody at 15 °C.](image-url)

**Fig. 6.** Image simulation obtained with a blackbody at 15 °C.

![Illustration of the “flattening” of a Sieleters band III image of a 10 °C blackbody.](image-url)

**Fig. 7.** Illustration of the “flattening” of a Sieleters band III image of a 10 °C blackbody. Image size is 1016 × 440 and the sub-window size is 30 × 30 with a polynomial of order 3 used to fit them. These parameters enable us to keep shapes found in the image. The image down on the right will be used on subsequent processes.
This first step has already direct effects on the image spectrum since it almost completely wipes out the vertical part of the classical “cross” shape plaguing careless image Fourier Transform (see Fig. 8).

But this step can’t completely reduce border discrepancies; the usual solution is to build a larger image using four axial symmetries on each border. Gibbs-like oscillations will then be spatially located on new borders and can be expected to spare the “useful” content. This solution enforces a C⁰ property on the original image but is not C¹.

This mirroring does work on the current simulation but is not suitable for real instruments in which the fringes can be tilted, accidentally or voluntarily as for Mistere (see Fig. 1 and Fig. 2). We need a solution that can extend the inclined fringes to a larger image. Several solutions were tried, including an autoregressive model but we finally opted for a Fourier-based solution.

In this new proposal, a conventional mirroring solution is used as a seeding solution, then the fringes will be extended by a Fourier space manipulation involving zeroing fringes frequencies (see Fig. 10).

2.2.1.1 Selecting fringe frequencies

To do this we must of course remove as few frequencies as possible but also avoid destroying too much information by doing so. It is therefore necessary to find a rule for detecting anomalies. To do this we must find a model of the Fourier Transform of blackbody images when they are free of fringes. Under the affine hypothesis we can write the blackbody image as the sum of two different images (see Eq. (15)).

\[
\text{Image}_{bb}(x, y, T) = \text{gain}(x, y) \times L_{bb}(T) + \text{offset}(x, y).
\] (15)

It is our experience that gain and offset behave like classical images [16], apart from being noisier. Thus we can expect that their Fourier Transform will be mostly made of a quickly decreasing 1/fp signal and on most frequencies by the Fourier transform of a white noise.

And since any orthogonal transform will output a gaussian white noise from an inbound gaussian white noise, the real and imaginary part of the Fourier Transform of a white noise should have an homogeneous statistics.
We have verified that this property does hold on the real processed image of Fig. 7 (see Fig. 9).

![Image](image_url)

**Fig. 9.** Real and imaginary part of the Fourier Transform of the processed image of Fig. 7. The black parts of these images correspond to ignored areas which could contain other signals than the noise and which aren’t used in calculation. The root mean square of the amplitude outside the ignored frequency area lies within a range as low as a tenth of its average amplitude value.

Diagonals seen in Fig. 8 cannot be seen in these views but are still there.

The step of automatic detection stage of fringe frequencies is then built on the Rayleigh statistic of the norm of the image Fourier Transform with, for example, a limit set to six times its root mean square. But, as shown on Fig. 8 we must limit as precisely as possible the area in which the fringe frequencies can be found. Otherwise we would detect and erase non-fringe frequencies. Fortunately the spectral band of the spectrometer (usually precisely set by a filter) considerably limits the affected area as all frequencies from zero to the upper band frequency must appear on the measure.

Thus frequency zeroing will only be allowed on an area corresponding to the red circles in Fig. 8, and indeed, in the same Fig. we can see three spots nearby that must not be affected by the zeroing process.

Now we can proceed with the extension of the fringes.

### 2.2.1.2 Extending fringes on supplementary borders

Abrupt frequency-related changes in an image, such as borders or sinusoids that do not completely fill the image require many perfectly phased frequencies. This is because each Fourier space descriptor codes only one frequency that intrinsically fills the entire image. Thus when some frequencies are deleted (zeroed), the deletion will also affect the whole image.

We illustrate this in the image of Fig. 7 image where the fringes must be removed (see the results in Fig. 10).
Fig. 10. Up, flattened Sieletters band III image of a blackbody at 10 °C. Below on left is the fringe filtered image. Notice that mirrored fringes aren’t suppressed because of their different orientation. Below on right is the difference image which is removed by the Fourier zeroing operation.

It’s the difference image of Fig. 10 that is interesting because it has a perfect continuity with the fringes of the original image on the added borders. Thus, the borders of the original image are simply replaced by these new borders, which gives the image of Fig. 11.

Fig. 11. Continuous fringes on the whole image built from Fig. 7.

Then, we can proceed with the fringe removal in Fourier space as exposed in 2.2.1.1 (see Fig. 12).
Thanks to this fringe extension no visible artefacts can be easily found in the fringe-less image of Fig. 12.

We have now the means to remove fringes from blackbody images in order to measure a fringe-less affine spatial correction. Being a simple operation, results are given below (Fig. 13).

It remains to evaluate the impact of the whole procedure on spectra.

2.2.2 Evaluation of spectral errors on simulation

To understand and evaluate the impact of a pure spectrum reconstruction algorithm, it is advantageous to start with a full simulation. It allows ignoring any instrumental or setup errors that can be numerous when using IR filters (such as reflection of stray IR light). We will therefore resume the procedure after the production of images of Fig. 6.

As before, several temperatures (eleven, ranging from to 15 °C to 65°C) were used to generate blackbody images as seen by the simulated Fourier Transform Imaging Spectrometers in band III. The affine correction (gain, offset) has been estimated and is used to spatially correct each generated image. We give Fig. 14 an example of the image obtained after calibration.
We observe here clearly the difference with a perfect process since fringes should be horizontally homogenous. This discrepancy will certainly have consequences in the resulting spectrum.

2.2.2.1 Spectra reconstruction

As shown in Table 3.1 of [17], we chose the Forman rather than the Mertz [1] method to reconstruct a complete interferogram. This step is no more error-free than what is explored here but its study goes beyond the scope of this article and will be the subject of further work. However, it can be expected that this is not the limiting factor of this simulation since we did not choose rapidly varying spectra as test sample.

2.2.2.2 Complete signal processing chain results

Let’s first examine raw spectra, obtained after spatial calibration but before spectral calibration (see Fig. 15).

Parameters of Eq. (14) can then easily be found through linear regression computed on blackbody raw spectra. The parameter of luminance is computed by integrating the raw spectrum.
Since the spectral calibration of black bodies is almost perfect, it is preferable to check the spectral restitution of different spectra shapes (see Fig. 17).

No errors can be seen without building the difference with the original input spectrum, on the contrary calibration errors are directly visible on the corrected spectrum when using a generic spectral affine model of correction (see Fig. 18).

We can also compute the root mean square of this error by using all columns (see Fig. 19).
These results wholly validate the spatial and spectral calibration model with spectral SNR often in excess of 1000, well above the 200 design value on our Sieleters band III example [9,14].

3. Conclusions

We have shown that the nonuniformity spatial correction of detector arrays involved in sampling an interferogram has a deleterious effect on the recovered spectra. But we have also demonstrated that a subsequent spectral calibration step is able to recover very good spectra, without being able to attribute residual errors either to spatial correction or spectrum estimation.

We also gave often overlooked practical advice on how to pre-process the image in order to minimize the degradation of the frequencies we want to measure.

We will continue to introduce and correct other sources of errors in the future, such as the displacement of fringes after calibration against the detector array, non-linear OPD and the influence of the interpolation required to produce an interferogram of each pixel-sized scene piece.

Acknowledgment

We would like to thank the entire Sieleters and Mistere team responsible for the design, building and operation of these instruments and who made them available for other uses. We also want to thank the Direction Générale de l'Armement (the French Ministry of Defense) for its support and interest in this work.

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