

Calibration of dispersive spectrometer using Fourier transform spectrometer

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ABSTRACT

Accurate knowledge of the Instrument Spectral Response Function is essential for spaceborne Earth observation missions focused on atmospheric measurements, as post-launch drifts and environmental factors can degrade calibration quality over time. This paper presents the results obtained using an elegant breadboard Fourier transform spectrometer calibration unit designed to characterize the elegant breadboard of the SWIR1 band of CO₂ imaging spectrometer. The test campaign validates the concept in a representative environment. Key achievements include:

- Characterization of Optical Path Difference without relying on a metrology sub-system.
- Retrieval of the *ISRF* (with a target shape error below 1%).
- Relative positioning of the *ISRF* (with a target below 0.05 spectral sampling interval = 2 ppm).

These results demonstrate the high performance of this approach for long-term *ISRF* monitoring.

Keywords: Dispersive Spectrometer, Fourier Transform Spectrometer (FTS), Instrument Spectral Response Function (*ISRF*), In-Flight Calibration, CO₂M, EBB-CO₂i, Optical Path Difference (OPD), Spectral Characterization

1. INTRODUCTION

Recent space borne Earth observation missions targeting the atmosphere require highly accurate knowledge of the Instrument Spectral Response Function (*ISRF*). Achieving this accuracy demands extensive and costly characterization during the instrument's Assembly, Integration and Test phase. However, post-launch drifts and environmental effects can alter the *ISRF* initially measured on the ground, underscoring the need for on-board equipment capable of accurate in-flight *ISRF* characterization.

The proposed solution is a Fourier Transform Spectrometer (*FTS*), which enables precise *ISRF* measurements across a broad spectral range, typically extending from the ultraviolet (*UV*) to the short-wave infrared (*SWIR*). A preliminary trade-off study, presented at ICSO 2020, identified the *FTS* approach as the most promising among various options [1]. Subsequently, in our ICSO 2024 contribution [2], we presented this novel in-flight calibration concept, which generates modulated calibration scenes for dispersive spectrometers [3]. We also detailed key *FTS* design considerations and performance predictions, demonstrating the feasibility of achieving the targeted measurement accuracy.

A cornerstone of the solution is the elimination of complex Optical Path Difference (*OPD*) metrology systems by leveraging the synergistic use of the *FTS* and the dispersive spectrometer. This approach refines *OPD* knowledge and retrieves the *ISRF* with high precision [4].

In this paper, we present results obtained using the Elegant Breadboard *FTS* (*EBB-FTS*), developed in collaboration with our sub-contractor *Sophia Engineering*, and tested on the *EBB-CO₂i* spectrometer (SWIR1 band with EBB-Slit). This *EBB-CO₂i* is representative of the spectrometer class targeted by this calibration solution, offering a valuable test opportunity. We gratefully acknowledge *CO₂M ESA* team for providing access to the *EBB-CO₂i* for this test campaign.

It should be noted that this paper does not discuss the intrinsic performance of the *EBB-CO₂i* itself. This is due in part to the need for further validation of the calibration solution and because the *EBB-CO₂i* was not fully aligned to its optimal focus during testing, as the tuneable laser required for the alignment procedure was unavailable.

2. TEST SET-UP

Figure 1 presents a schematic of the main components of the overall test setup:

- Calibration unit:
 - Source Block: A Quartz-Tungsten Halogen lamp coupled to an integrating sphere and collimator.
 - Interferometer: Consist of a beam-splitter and two corner cubes. One corner cube is mounted on a translation mechanism that moves to generate *OPD*.
 - Imager: Focuses the beam onto the spectrometer's input slit, replicating the geometric conditions of the front telescope. In the test setup, this is implemented as a periscope with three degrees of translational freedom, enabling precise placement of the focal point on the *EBB*-slit.
- Dispersive spectrometer
 - Slit: Selects a thin slice along the Across-Track (*ACT*) direction of the intermediate image plane.
 - Dispersive element: Disperses the spectral content along the Along-Track (*ALT*) direction.
 - Detector: Records the spectra along the *ALT* direction of any *ACT* position on the detector.

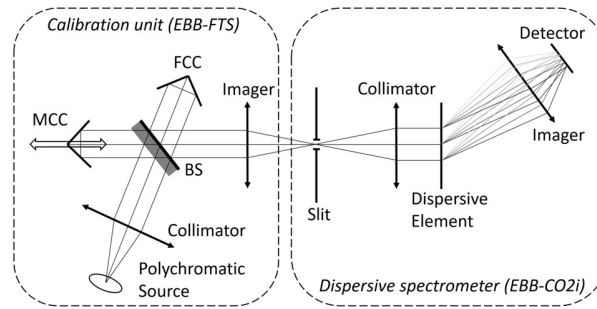


Figure 1. Schematics of the set-up. The calibration unit (*EBB-FTS*) take place where the *CO2i* front telescope is. The slit is enlighten by the same numerical aperture as if it was the front telescope.

This unique configuration, combining a *FTS* with a dispersive spectrometer, provides valuable data where each spectral sample recorded by the dispersive spectrometer corresponds to its own interferograms. These interferograms relate to the *ISRF* of each spectral channel through a Fourier transform, provided that the introduced *OPD* is precisely known. Since the flat spectrum of the *QTH* lamp is modulated by the *OPD*, the modulation period observed across the dispersive spectrometer's spectral channels carries information about the injected *OPD*. This principles enables the *FTS* to operate without requiring a dedicated *OPD* metrology subsystem.

3. PRETREATMENT

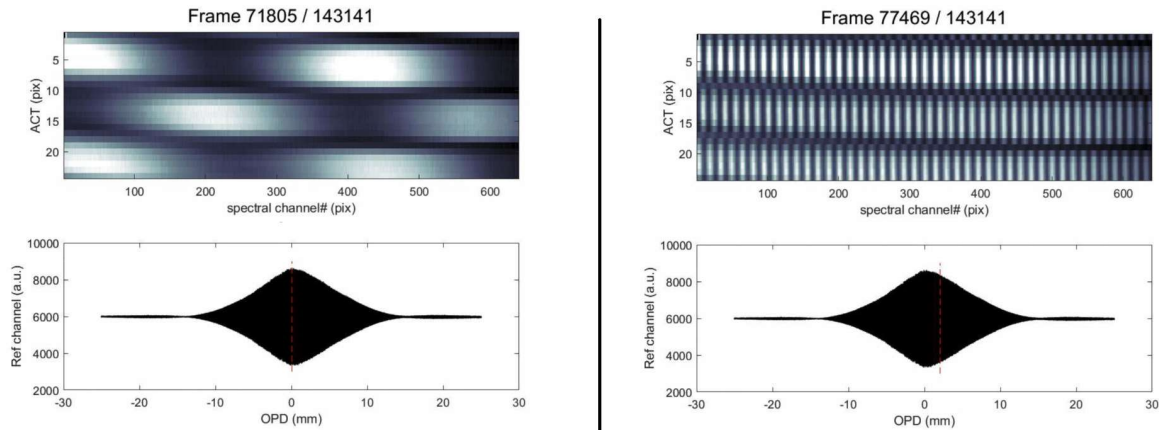


Figure 2. Top figures (left and right) an *ACT* cropping of the *EBB-CO2i* detector, the figure is highly stretch in the y-axis. Bottom figures (left and right) is the interferogram acquired at the spectral channel #295, the dashed red line situated the frame displayed on the top. The left figure are for a frame localized close to the *ZPD* while the right is significantly far from *ZPD*.

Figure 2 illustrates examples of the raw data acquired during the test. The top images show cropped sections of the detector for two distinct positions (left and right) of the moving corner cube. Approximately three fibers of the *EBB-CO2i* slit are visible along the *ACT* y-axis. It is important to note that the *EBB*-slit consists of multiple fibers, which act as a scene homogenizer to maintain a consistent ISRF even under heterogeneous slit illumination. The *FTS* spectra are dispersed across the detector along the spectral channel dimension. Near the close to Zero Path Difference (*ZPD*), the modulation frequency of the spectra is low, while it increases as the measurement moves away from the *ZPD*.

The first correction applied to the detector frames is the offset correction. This involves subtracting an averaged frame obtained from multiple images captured before the acquisition, with *QTH* lamp turned off. After offset correction, a binning step is performed, which consists of averaging the pixels of each spectral channel corresponding to a single fiber. This process is done by automatically detecting the fiber boundaries, identified as dark valleys between successive fibers. The signal between these boundaries is then interpolated and averaged. A typical result after this step is shown at the bottom of the figure 2, representing the interferogram acquired from the fiber N°55 at spectral channel 320. After these steps, a system relative spectral gain correction is performed. This involves normalizing each interferogram by its baseline value, which is determined by taking the median of the interferogram (for example, approximately 6000 *lsb* for channel #295). Following this correction, effects such as the lamp spectra variations, test setup vignetting (visible on the right part of the detector), or potential imperfections of the binning process are effectively canceled out. This results in a perfectly flattened effective illumination spectrum, which is essential for the proposed theoretical expansion of the signal.

4. METHODOLOGY

Table 1. Notation.

Symbol	Unit	Description
$I_k(opd)$	-	Synthetic interferogram of spectral channel k
$Data_k(opd)$	-	Corrected acquired interferograms of spectral channel k
$S_k(\omega_{ISRF})$	-	Total Instrument Spectral Response Function of channel k , complex, defined on ω_{ISRF} . This account for the ISRF of the specimen and phase term due to chromatism in FTS.
ω_{ISRF}	m^{-1}	Spectral axis of S_k , centred on 0 support ± 3 FWHM.
B_k	m^{-1}	Spectral centroid (barycenter) of channel k
ZPD	m	Zero path difference
opd	m	OPD vector, common to all channel k
δopd	m	OPD correction vector estimated
α	-	Global wavelength scale factor derived from laser reference

The interferogram recorded by spectral channel k is modeled as the real part of the Fourier transform of the Total Instrument Response Function evaluated over positive frequencies for a given opd :

$$I_k(opd) = 2 \cdot \text{Re} \left\{ \int_{-3 \text{ FWHM}}^{+3 \text{ FWHM}} S_k(\omega_{ISRF}) \cdot \exp[i \cdot 2\pi \cdot (B_k + \omega_{ISRF}) \cdot (opd - \delta opd - ZPD)] d\omega_{ISRF} \right\} \quad (1)$$

The ISRF retrieval algorithm aims at refining this forward model to match the model I_k and the acquisition $Data_k$.

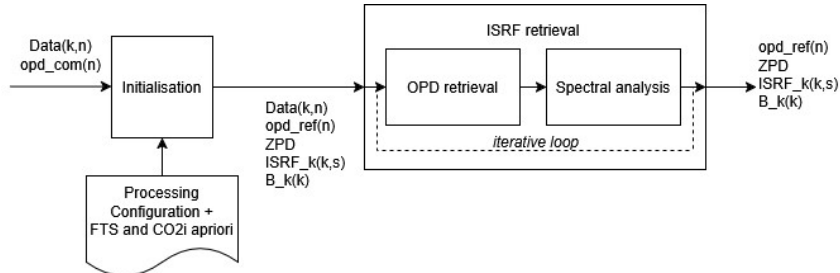


Figure 3. Schematic of the retrieval processing

The algorithm iteratively calls two independent blocks:

- OPD retrieval, this step refines the *OPD* correction term δopd by minimize the error between the modeled and the measured data, assuming given values of S_k , B_k , and ZPD . The goal is to find the *OPD* correction that explains the spectral modulation observed in each frame n . A sum of squared errors cost function is used for minimization, and the *ODP* is updated accordingly.
- Spectral analysis, the Discrete Fourier Transform (*DFT*) of the interferograms is computed. A modified version of the *DFT* is used to account for non-evenly sampled (and aliased) interferograms, which provides an updated estimates of S_k .
 - The linear phase dependence on B_k is removed from S_k , and the *ZPD* position is updated.
 - $\varphi_k @ \omega_{ISRF} = (B_k) = -2\pi \cdot B_k \cdot ZPD + NL_k$
 - The nonlinear phase residue with respect to B_k is removed to update the barycentric position.
 - $B_k = \frac{\sum \omega (B_k + \omega_{ISRF}) \cdot Re\{s_k(\omega_{ISRF}) \cdot \exp(-iNL_k)\}}{\sum \omega Re\{ISRF_k(\omega_{ISRF}) \cdot \exp(-iNL_k)\}}$, S_k is then resampled accordingly.
 - A spectral anchor α is evaluated using the precise knowledge of one reference channel position and apply to both spectral and spatial dimension. $\alpha = B_k^{ref} / B_k(k^{ref})$.
 - $B_k \times \alpha$; $\omega_{ISRF} \times \alpha$; opd / α ; ZPD / α
 - The specimen's *ISRF* shape function is finally defined as: $Re\{s_k(\omega_{ISRF}) \cdot \exp(-iNL_k)\}$

In the results section, the iteration loop ruins five times. During the initialization block, a spectral analysis evaluation is performed to obtain an initial estimate of the *ISRF*, which is best fitted by Gaussian function. Starting from this rough estimate helps prevent capturing *OPD* perturbation within the *ISRF* shape itself.

5. RESULTS

Algorithm convergence

The Following figure presents intermediate results (after *OPD* retrieval step) illustrating the algorithm's convergence.

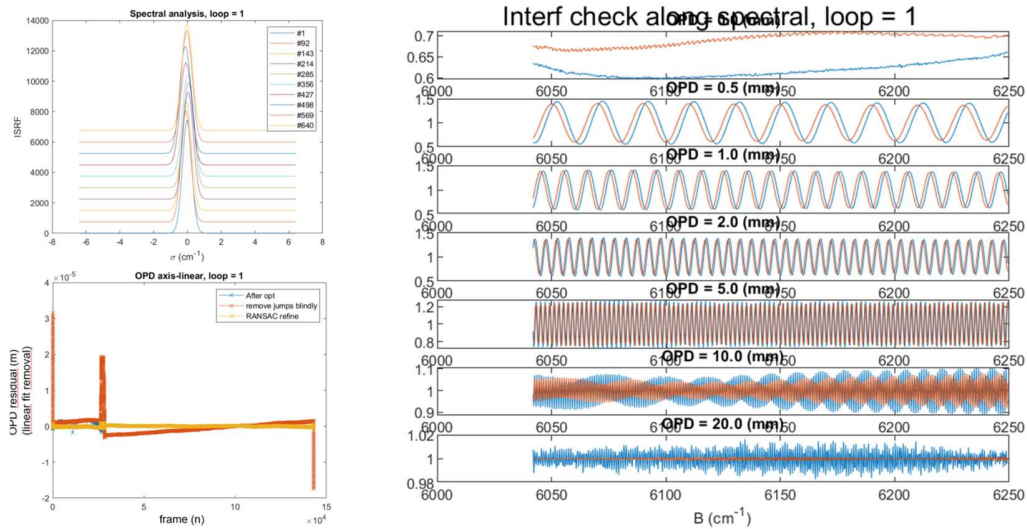


Figure 3. After the first loop. With *ISRF* Gaussian fit assumption and first *OPD* retrieval.

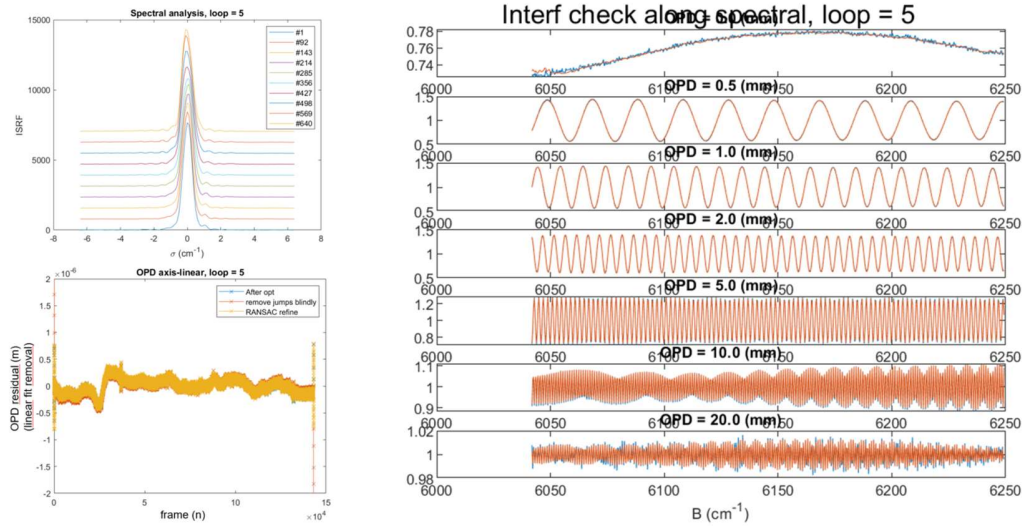


Figure 4. After the fifth loop. $Data_k$ (blue) and I_k (orange) are undistinguishable in right figure.

Figure 3 and 4 show, on the left side, the current assumption for the $ISRF$ (top) and OPD (bottom). Together with ZPD and B parameter, the equation (1) generates the signals displayed on the right side. This right images the signal along the spectral channels for different OPD values: 0; 0.5; 1; 2; 5; 10; and 20 millimeters. After five iterations of the algorithm, the modeled signal and the measured data become indistinguishable, and further corrections or iterations have negligible impact.

OPD physical refinement

Once the OPD has been retrieved, it is possible to compare the overall spectra before and after the OPD refinement.

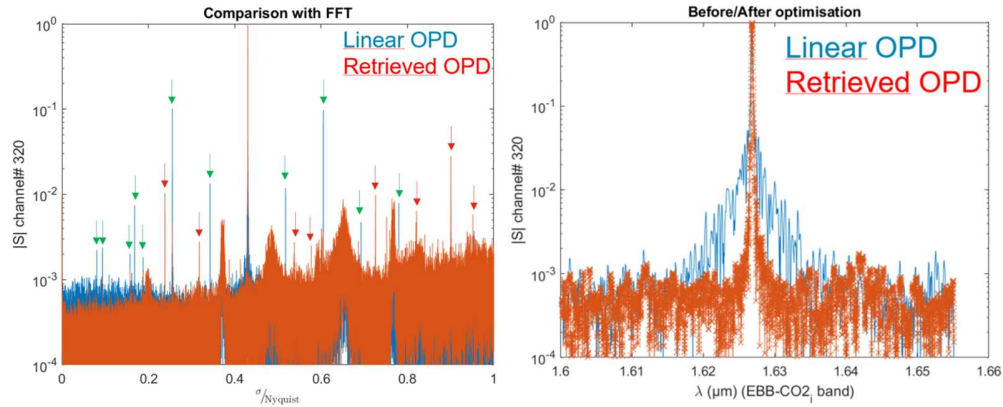


Figure 5. Left, Comparison between classic FFT and after the processing for the spectral channel #320. Right, zoom around nominal spectral response of channel #320. Log-scale for y-axis.

In the left panel of Figure 5, the blue curve corresponds to the linear OPD hypothesis, while for the orange curves uses the refined OPD vector. The nominal spectral response peak is located around 0.45 in Nyquist normalized frequency. The arrows indicate the positions of several spectral ghosts, which are typically associated with harmonic perturbation of the OPD . The fact that most of these spectral ghost (marked by green arrows) vanish when using the refined OPD provides a clear qualitative demonstration that the OPD correction converges toward the true physical OPD perturbation. It is worth noting that for the orange arrows, the ghost are superposed rather than amplified.

Another qualitative indication of good algorithm convergence is seen in the right panel of Figure 5. A zoom around the nominal peak shows large wings in the spectral response without OPD refinement, whereas with the retrieved OPD these wings are significantly reduced. These large wings without refinement can be explained by very low-frequency perturbations of the OPD , which are effectively retrieved, as illustrated in the bottom-left of Figure 4.

Barycenter of the spectral channel

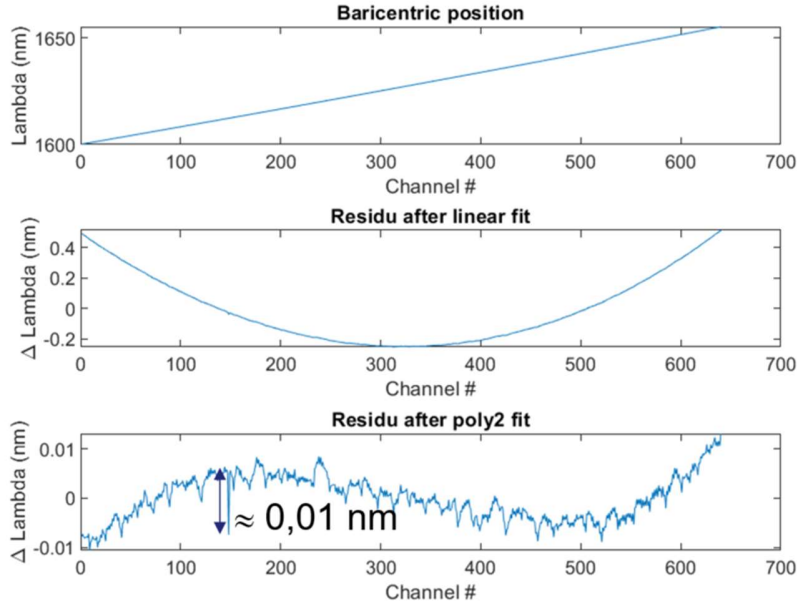


Figure 6. Barycenter positioning of the spectral channels.

Figure 6. shows the barycentric positioning of the spectral channels. A conservative worst-case performance of 7ppm (calculated as $0,01/1590$) is observed. When comparing the barycenter data to a third-order polynomial fit, the $1\text{-}\sigma$ uncertainty reduce to 0,98 ppm. Because barycenter function is expected to be smooth due to physical considerations, it is highly likely that the third-order fit provides a barycenter relative knowledge with an accuracy better than 1 ppm.

In field shape error

Data were gathered for five different fibers, spaced every 10 fibers: specifically fibers #35, 45, 55, 65, and 75. Five independent acquisitions were performed on different days. Figure 7 presents, on a log scale, the five measured *ISRF* for the various spectral channels across the full *EBB-CO2i* spectral range. The bold black curve represents the average value across the spatial samples, while the dashed black lines show the $\pm 1\%$ shape error envelope.

Most of the response lie within the 1% shape error envelope, with only a bump of F55 near $\omega_{ISRF} = 1,1 \text{ cm}^{-1}$ and a dip of F65 near $\omega_{ISRF} = -0,9 \text{ cm}^{-1}$ significantly exceeding that envelope. This results suggest two important conclusions:

- The *EBB-CO2i ISRF* is very stable and homogenous across the field.
- The reproductibility of the measurements using the *EBB-FTS* system is high.

The *ISRF* shape remains exceptionnally consistent both in spatially and temporally. This suggest that, for this specimen, routine monitoring does not require acquisition or checking of all field-of-view fibers. Overall, the FTS *ISRF* shape error performance stays well bellow the 1% shape error threshold.

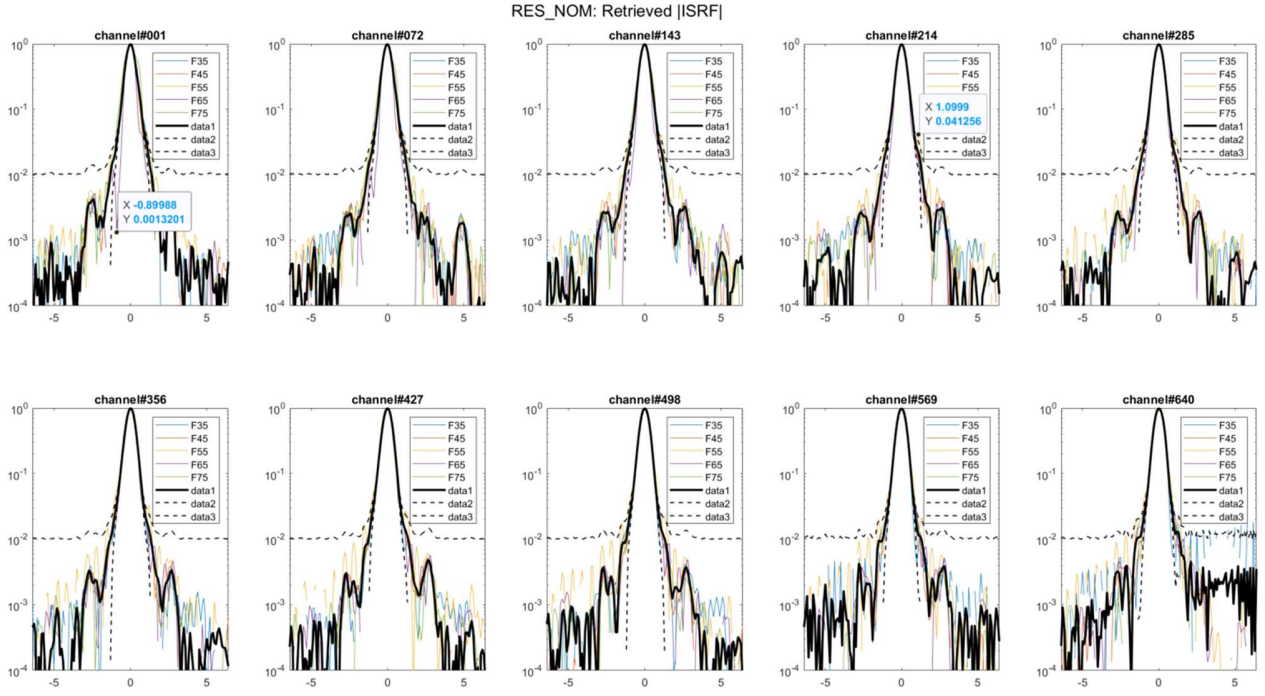


Figure 7. In field of view variability of the *ISRF* shape. The wavenumber axis ω_{ISRF} is centered on the barycenter.

6. DISCUSSION

We have specified and designed an *FTS* serving as an elegant breadboard model of a flight calibration unit for *ISRF* characterization. This *FTS* was implemented on the elegant breadboard of the CO2i SWIR1 instrument. We developed a processing chain leveraging the synergy of multiple simultaneous acquired interferograms for each spectral channel to refine the optical path difference in the *FTS*, thereby eliminating the need for a dedicated metrology system. The achieved performance aligns well with the expectations from the design. In the presented results, we focus on a dense (non-aliased) acquisition of interferograms, but we have also demonstrated the feasibility of working with aliased data (5.25 μm opd step) and single-sided interferograms.

We have demonstrate that the collected data is rich and enables performance assessment at the required accuracy. We believe that such on-board *FTS* calibration unit offers a highly promising solution for on-flight *ISRF* monitoring and calibration. However, although the proposed system does not include a metrology subsystem, we acknowledge that the hardware solution itself remains relatively complex. In our view, focusing on the operational advantages offered by this solution and leveraging more advanced data processing tools will be the crucial final step toward making this solution fully space-qualifiable.

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