Correction of calibration ringing in the context of the MTG-S IRS instruments

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Abstract.

EUMETSAT is developing the on-ground processing chain of the infrared Fourier transform spectrometers (IRS) on-board of the Meteosat Third Generation sounding satellites (MTG-S). In this context, the authors have investigated the impact of a particular type of radiometric error, called the calibration ringing. It arises in Fourier transform spectrometers when the instrument optical transmission varies within the domain of the spectral response function. The expected radiometric errors are simulated in the context of the MTG-IRS instrument in the long wave infrared (LWIR) band. A software correction methodology is designed and its performance is assessed.

1 Introduction

Fourier transform infrared spectrometry from space allows decomposing the light exiting the atmosphere by its top: the reconstructed spectra exhibit absorption and emission lines representative of the Earth’s atmosphere composition and thermodynamic state. Instruments, such as the Infrared Atmospheric Sounding Interferometer (IASI) on Metop [Blumstein et al. (2004)] and the Cross-track Infrared Sounder (CrIS) on Suomi-NPP [Han et al. (2013)], have proven very effective for both weather forecasting and climate monitoring. Eumetsat is now preparing for the next generation of instruments and in particular, for the first European Fourier transform spectrometer on a geostationary orbit, the infrared Fourier transform spectrometers (IRS) on-board of the Meteosat Third Generation sounding satellites (MTG-S) [Coppens et al. (2017)].

The desire to generate spectra with a radiometric accuracy below the deci-Kelvin limit has recently brought attention to a particular effect in Fourier transform spectrometers that we referred to as calibration ringing. The theoretical background of this effect and supporting simulations have been presented in a previous work by the authors [Dussarrat et al. (2021)]. Such an error arises when the instrument optical transmission varies within the domain of the spectral response (SRF) function. These variations generate distortions of the SRF, which, unaccounted, propagate as radiometric errors into the calibrated Earth view spectra exploited by users.

Transmission variations are actually expected for most instruments. As a first example, transmission cut-offs of the optical elements could lead to strong transmission gradients at the band edges and would produce calibration ringing error as first reported in the case of the CrIS instrument by [Revercomb (2017)]. We have also investigated the impact of another source of
transmission variations, namely the etalon or Fabry-Perot effect. It arises when the light can loop in a cavity inside the instrument and interfere with itself [Perot and Fabry (1899)]. For example, transmissive optical elements such as lenses, windows or protective layers with non-perfect coating can create low finesse etalons; as a result the transmission appears modulated in function of the incident light wavelength.

In the second section of this paper, we recall the theoretical basis of the phenomenon. In section 3, a correction strategy is introduced. Finally, in section 4, the ringing error is evaluated and the correction performance is assessed using a simulation chain representative of the IRS data processing.

2 Calibration Ringing Error

Calibration ringing errors occur when the radiometric calibration fails to perfectly compensate for the optical transmission variations. Usually, the optical transmission is characterised in flight with specific calibration schemes using for example, on-board black-body and deep space measurements (see, e.g., Revercomb et al. (1988) and Tournier et al. (2002)). The optical transmission is then removed from the (raw) Earth view measurements by division by the radiometric calibration factors. However, we still expect the occurrence of high-frequency residual spectral modulations: the calibration ringing error.

We note the spectrum exiting the atmosphere as a function of the wavenumber \( \hat{S}_p(\nu) \) and the optical transmission \( R(\nu) \) (optics, detector and etalon effect included). Then, the spectral response function (SRF) is noted \( SRF(\nu) \), it includes both numerical apodisations and self-apodisation effects at interferogram level, which we assume for simplicity as either negligible or without spectral dependence, such that the SRF is the same for all wavenumbers. Finally, the radiometric calibration factors \( R_c(\nu_0) = [R \otimes SRF](\nu_0) \) is defined at discrete wavenumbers \( \nu_0 \).

Using a simplified model of radiometric calibration and omitting for simplicity the spectral calibration, the calibrated spectrum at \( \nu_0 \) noted \( S_{pr}(\nu_0) \) writes:

\[
S_{pr}(\nu_0) = \frac{[(\hat{S}_p R) \otimes SRF](\nu_0)}{R_c(\nu_0)} \neq [\hat{S}_p \otimes SRF](\nu_0)
\]  

(1)

As evident from Eq. (1) the calibrated spectrum is not perfectly equal to the actual spectrum convoluted with the SRF, which is the goal of the radiometric calibration. The difference between the two terms in Eq. (1) defines the calibration ringing error that will translate in a radiometric error in the final data product. As discussed in Dussarrat et al. (2021), the error depends on the scene and therefore cannot be canceled by a simple bias correction of the product. Correcting this error in the retrieval i.e. accounting for the equivalent SRF distortions in the radiative transfer models is theoretically possible but this proves computationally heavy since the distortions are dependent on the wavenumber and potentially also on the focal plane geometry.

An IRS-type instrument could exhibit both radiometric transfer function (RTF) spectral gradients and modulations. Strong gradients could be caused by optics cut-off and RTF cosine modulations could occur due to a low finesse etalon effect produced inside a protective layer. Both effect are illustrated on Fig. 1. The modulation frequency is taken constant and equals \( f = \)}
0.43 cm, thus the simulated modulation is at the scale of IRS SRF whose typical half-width at half-maximum is equal to 0.75 cm$^{-1}$, therefore a ringing error is expected and we have devised an algorithm to correct the calibrated spectra.

3 Calibration ringing Error Correction - RTF Uniformisation

Although the calibration ringing error could be mitigated through the optimization of the optical design of the instrument (e.g. designing the optical coating such that the RTF is flat), this is not always possible, technically out of reach or too costly. In the case of MTG-IRS, assuming a frozen design of the instrument, we have devised a software correction. Since we aim at cancelling the effect of the RTF spectral variations in the products, this method is referred to as RTF uniformisation.

The initial idea originated from the trivial consideration that the target measurement $\hat{Sp} \otimes SRF$ could be recovered after the radiometric calibration by dividing $Sp_r$ by $(\hat{Sp}.R) \otimes SRF$ and multiplying by $R_c \times (\hat{Sp} \otimes SRF)$. Of course, the "true" spectrum $\hat{Sp}$ is unknown; however, we have postulated that we could use instead a high-resolution guess $Sp_{ref}(\nu)$.

In practice, the $R_c$ factors are discrete and require an oversampling to match the sampling of $Sp_{ref}$, noted $\hat{R}_c$. This is achieved through zero-padding the calibration interferograms. Moreover, we assume that the instrument transmission is stable enough so that we can accumulate series of calibration views to accurately model the instrument calibration factors.

Under these hypotheses, the corrected spectrum $Sp_c(\nu_0)$ at discrete wavenumbers $\nu_0$ is computed as follow using the high-resolution guess:

$$Sp_c(\nu_0) = Sp_r(\nu_0) \times f_{corr}(\nu_0)$$

where

$$f_{corr}(\nu_0) = \frac{\hat{R}_c(\nu_0) \times [Sp_{ref} \otimes SRF](\nu_0)}{[(Sp_{ref} \cdot R_c) \otimes SRF](\nu_0)} \approx \frac{\hat{R}_c(\nu_0) \times [Sp_{ref} \otimes SRF](\nu_0)}{[(Sp_{ref} \cdot \hat{R}_c) \otimes SRF](\nu_0)} \tag{2}$$

In Eq. 2, we make the approximation of replacing the true transmission $R$ by the over-sampled calibration factors $\hat{R}_c$ at the denominator. It is valid at a few centi-kelvin level if the transmission modulation amplitude is not damped by the measurement, that is to say if the frequency of the transmission modulation is below the instrument cut-off frequency and no strong numerical apodisation is applied. This approximation is relevant for a IRS-type instrument since the simulated modulation frequency due to etalon effect is 0.43 cm for a maximum OPD of 0.825 cm and we apply a "light apodisation" that damps the interferogram only close to maximum OPD.

In order to build the reference spectrum $Sp_{ref}(\nu)$, we have chosen to use a principal component (PC) decomposition [Pearson (1901)]. The training set is considered composed of high-resolution spectra (greater than the IRS expected resolution) which are associated to various atmospheric states and sounding angles through the atmosphere. One can refer to the section 4 for the details of the simulations. A basis of high-resolution PC vectors are computed as the eigenvectors associated to the largest eigenvalues of the training set correlation matrix (see Fig. 2), the $n$th vector being noted $L_{ref,n}(\nu)$. Then, we construct the IRS-resolution associated PC vectors: $\hat{L}_{ref,n}(\nu_0) = [L_{ref,n} \otimes SRF](\nu_0)$. Note that lowering the resolution breaks slightly the basis orthonormality which will limit the correction efficiency.
Thus, the PC scores of any calibrated spectrum are computed as the scalar product with the IRS-resolution PC vectors, and the high-resolution reference vector is reconstructed combining the PC scores and the high-resolution PC vectors:

\[ \text{PC}(n) = \sum_{\nu_0} \text{Sp}_{\text{r}}(\nu_0) \times L_{\text{ref},n}(\nu_0), \quad \text{Sp}_{\text{r}}(\nu) = \sum_n \text{PC}(n) \times L_{\text{ref},n}(\nu) \]  

(3)

The authors mention a particular case which could be of interest for some readers looking for a simple correction methodology, choosing to use only one PC for the decomposition, the correction vector becomes unique that is to say independent of the measurement and writes:

\[ f_{\text{corr},1}(\nu_0) = \tilde{R}_c(\nu_0) \times \left[ (L_{\text{ref},1} \otimes \text{SRF})(\nu_0) \right] / \left[ (L_{\text{ref},1} \otimes \tilde{R}_c \otimes \text{SRF})(\nu_0) \right] \]  

Moreover, considering an RTF rather constant in time, one can pre-compute the following reference matrices

\[ V_{\text{ref},n}(\nu_0) = \tilde{R}_c(\nu_0) \times \left[ (L_{\text{ref},n} \otimes \text{SRF})(\nu_0) \right] \]  

and

\[ W_{\text{ref},n}(\nu_0) = \left[ (L_{\text{ref},n} \otimes \tilde{R}_c \otimes \text{SRF})(\nu_0) \right] \]

and compute the correction vector as follow:

\[ f_{\text{corr}}(\nu_0) = \frac{\sum_n \text{PC}(n) \times L_{\text{ref},n} \otimes \text{SRF}(\nu_0)}{\sum_n \text{PC}(n) \times (L_{\text{ref},n} \otimes \tilde{R}_c \otimes \text{SRF})(\nu_0)} = \frac{\sum_n \text{PC}(n) \times V_{\text{ref},n}(\nu_0)}{\sum_n \text{PC}(n) \times W_{\text{ref},n}(\nu_0)} \]  

(4)

This strategy avoids many calculations and greatly speeds up the on-line processing. Since the correction vector is insensitive to RTF scaling, long term optics deterioration without strong wavenumber dependencies (such as icing) would not harm the processing efficiency. Thus, for an IRS-type instrument one could update \( V_{\text{ref},n} \) and \( W_{\text{ref},n} \) only between once a month and once a year.

4 Simulation

In the following, we present simulations of the ringing error induced by a RTF spectral variations in the context of the IRS long-wave band (LWIR) and evaluate the efficiency of the RTF uniformisation processing.

4.1 Simulation parameters

Simulations are run on the spectral range 660 to 1230 cm\(^{-1}\) and all performance assessments are represented between 680 to 1210 cm\(^{-1}\), which is the spectral range accessible to all users. Moreover, a light apodisation \( \text{Apod}(x) \) is applied to all interferograms as expected in the IRS data processing, the SRF is therefore given by \( \text{SRF}(\nu) = FT^{-1}[\text{Apod}(x)](\nu) \).

We first define the transmission without etalon effect, its shape is inspired by the author’s current knowledge of the IRS instrument but excluding the possible multiple light reflections (Fig. 1). It exhibits a strong gradient and bounces related to the expected material properties and coating behaviour in the band. Then, the simulated etalon adds a modulation on top of the transmission with frequency \( f = 0.43 \) cm and a relative amplitude between 1 and 6 %, with a maximum around 700 cm\(^{-1}\) as represented on Fig. 1.

We use a dataset of simulated IASI-NG data\(^1\)(Infrared Atmospheric Sounding Interferometer Next Generation) as high resolution inputs to simulate the earth views. The dataset gathers two full orbits with various sounding angles and a high diversity of atmospheric states including all main trace gases and clouds. Their sampling step is equal to 0.125 cm\(^{-1}\) which is almost five times denser than IRS (\( \approx 0.6 \) cm\(^{-1}\)).

\(^1\)The dataset has been computed using a forward model by Noveltis as part of a previous collaboration.
Figure 1. The RTF with etalon (blue), without (red) and the user spectral range accessible to users (black) are represented (top). The ringing minimum, maximum and average errors induced by the RTF with (bottom) and without etalon (middle) are represented in equivalent temperature at 280 K as function of the wavenumber.

4.2 Calibration ringing error simulation

The interferogram that would be recorded by the instrument has been computed as a discrete sum of all input spectral components and the measured spectrum, \((\hat{S}_p.R) \otimes SRF\), is recovered by inverse Fourier transform as done in the processing of actual measurements from Fourier transform spectrometers. The same method has been applied to generate the undistorted spectrum \(\hat{S}_p \otimes SRF\) and the radiometric calibration factor \(\tilde{R}_c\):

\[
(\hat{S}_p.R) \otimes SRF = FT^{-1}\left[\left(\sum_{\nu} S_p(\nu) \times R(\nu) \times \cos[2\pi \nu x]\right) (x) \times Apod(x)\right]
\]

\[
\hat{S}_p \otimes SRF = FT^{-1}\left[\left(\sum_{\nu} S_p(\nu) \times \cos[2\pi \nu x]\right) (x) \times Apod(x)\right]
\]

\[
\tilde{R}_c = FT^{-1}\left[\left(\sum_{\nu} R(\nu) \times \cos[2\pi \nu x]\right) (x) \times Apod(x)\right]
\] (5)
Figure 2. The correlation matrix of the training set is represented (up-left). Three PC vectors at high (middle) and IRS-resolution (right) are plotted on the up-right (1:blue, 2:red, 3:gold), they are computed on a slightly larger window than the user range (black dotted lines). In the bottom panel, the average correction vector $< f_{corr} >$ is represented.

The interferograms are generated between $\pm 4$cm with a 17.5 $\mu$m sampling step. The light apodisation function takes into account an IRS-type maximum sampling OPD canceling the interferogram values above 0.825 cm. After the inverse Fourier transform, the spectra are interpolated on the spectral range 660 to 1230 cm$^{-1}$ with a 0.6 cm$^{-1}$ sampling step.

Then, the calibration ringing errors are computed for one orbit of the dataset (5300 spectra) from the difference between the calibrated products $Sp_r$ and the undistorted measurement without ringing $\tilde{Sp} \otimes SRF$. The results are converted in equivalent temperature error dividing by the derivative of the Planck black body relation $\Gamma(\nu, T_{ref})$ at a reference temperature $T_{ref}$ of 280 K.

The simulated calibration ringing minimum, maximum and average errors are represented on Fig. [1]. For both cases, we witness a mean error called the bias and a dispersion induced by the scene diversity. We notice that the RTF gradients and bounces slightly contribute to the overall ringing, but the dominating source of ringing is the etalon.

In presence of the etalon, the calibration ringing error reaches up to 500 mK peaking around 740 cm$^{-1}$ wavenumber, which is approximately five times the typical target for radiometric accuracy being 100 mK. Moreover, the error arises near the CO$_2$ lines which could limit the usability of the data in this spectral region (Fig. [1]).
Figure 3. The maximum calibration ringing bias and standard deviation on the band is plotted as function of the number of PCs used in the RTF uniformisation (up). The minimum and maximum ringing errors are represented before and after RTF uniformisation using 10 PCs, as well as the average residual (bottom).

4.3 RTF Uniformisation simulation

To define the PC decomposition, we use the second full orbit of the data set. In Fig. 2 the correlation matrix and three PC vectors at high and IRS-resolution are represented.

Figure 3 illustrates the maximum bias and standard deviation in the band computed for the first orbit data set and as function of the number of PCs used in the RTF uniformisation. We witness that the maximum bias decreases as soon as we use one PC, then to reduce the error dispersion (standard deviation) it requires approximately 7 PCs, above 7 PCs the correction efficiency saturates. The dispersion bounce at 4 PCs has not been investigated at the moment. In conclusion, both metrics are approximately decreased by a factor three using 7 PCs and above which validates the method.

In the bottom panel of Fig. 3 the ringing error is represented before and after RTF uniformisation using "conservatively" 10 PCs. The ringing error decreases and stays approximately below 100 mK over the whole LWIR band. Nevertheless, the error is not perfectly cancelled, due to the intrinsic limitation of the method, which cannot perfectly guess the high resolution spectrum from a low-resolution measurement.
5 Conclusions

Transmission spectral variations and in particular the etalon effect can significantly hamper the radiometric performances of future infrared hyperspectral missions. We have shown that, in the case of IRS-type instruments, scene-dependent calibration ringing errors can reach up to 500 mK around 740 cm\(^{-1}\) in presence of a 5% RTF modulation. A correction scheme, referred to as RTF uniformisation, has been developed and successfully tested. Based on a scene recognition algorithm, it allows computing a correction vector to be directly applied to the radiance spectra after radiometric and spectral calibration. We have shown that, when applied on simulated IRS spectra, the maximum residual error after correction is of the order of 100 mK.

Since timeliness of the operational processing is a crucial constraint, one could choose to apply the RTF uniformisation only partially in spectral domains where the ringing errors are most important. This would allow reducing the number of PCs of the scene recognition, thus lighten the processing burden. Such partial application could be foreseen for the IRS processing if necessary, targeting the error only below 830 cm\(^{-1}\).

We hope that these investigations on the ringing error will foster further performance assessments for the current and future hyperspectral spectrometry missions: considering this subtle error in their budget. The authors stress that the correction is applied as a post-processing on the radiometric calibration product and stays computationally very light if the RTF perturbation is stable in time as discussed in section 3. It is then potentially easy to be implemented in any on-line processing chain of current or future missions.
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