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Characterisation of instrumental line shape distortions due to path difference dependent phase errors in a Fourier transform spectrometer

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Abstract

In Fourier transform spectroscopy, path difference dependent misalignments, such as those due to imperfect mechanical movement of the scanning mirror, can be modelled as path difference dependent apodisation and phase errors. The theoretical model that relates the mirror drive characteristics to the path difference dependent error is used to verify the consistency of the optical instrument line shape with the measurements of the mechanical drive quality. This procedure can be used as a diagnostic and qualification tool. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The quality of the instrument line shape (ILS) is one of the main properties of a spectrometer. In a Fourier transform spectrometer (FTS), ILS distortions are caused by path difference dependent fringe amplitude and sampling errors. The optics and the sampling method of an FTS instrument can be carefully designed in order to avoid these errors. A typical solution in order to avoid errors due to variations of fringe contrast is the use of tilt compensated optical configuration to have a path difference independent wavefront alignment of the interfering beams [1]. A typical solution in order to avoid sampling errors is the use of accurate path difference measurements provided by a laser interferometer that travels the same optical path as the analysed beam [2].

If, for any reason, these compensation methods cannot be applied, irregularities in the mirror movement (tilt and shear) can result in amplitude and sampling errors, and cause ILS distortions.

One example is that of imaging FTS in which, a few interferograms are simultaneously acquired with different off-axis angles and the laser interferometer travels the path of only one of these interferograms [3]. A second example is the one considered in this paper, i.e. a polarising

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interferometer [4]. This instrument requires the use of roof-top mirrors that provide tilt compensation only in one direction [1] and uses a beam splitter that cannot be shared with the laser beam.

The long wavelength region in which the polarising instrument operates leads to requirements for tilt and shear of the mirror drive that are, in our experience, usually mechanically feasible. However, in one experimental setup, we also encountered the case of poor instrument alignment which made visible the effect of ILS distortion caused by tilt and shear errors in the mirror drive.

In this paper, we recall the procedure used for the correction of this ILS distortion, already discussed in a previous paper [7], and verify the model that relates this spectral distortions to the characteristics of the mirror drive with experimental measurements.

2. Field observations

The field observation herewith considered are far infrared high resolution spectra of the atmospheric limb emission aimed at the determination of the vertical distribution of trace atmospheric constituents. These spectra were recorded during the balloon flight on 4th May, 1994 from Fort Sumner, New Mexico, with a Martin–Puplett [4] polarising interferometer as part of the infrared balloon experiment (IBEX). The instrument, described in detail in Ref. [5], was mounted on board a stratospheric balloon flying at approximately 36 km. Two widely spaced spectral regions, the first covering 49–51 cm^{-1} and the second covering 115–125 cm^{-1}, were recorded at the orthogonal polarisation outputs of the instrument. With rapid scanning, a full interferogram with maximum optical path difference of 2 m (an unapodised spectral resolution of 0.00246 cm^{-1}) was obtained in 180 s. Calibration spectra recorded at an angle of $+40°$ above the horizon were measured to provide the zero-level for the emission signal, apart from a few sharp lines that are due to the residual emission of the strongest atmospheric features.

The high signal-to-noise ratio and the excellent spectral resolution of the measurements made visible systematic ILS distortion reproducible for all lines and all measurements. This distortion, present also after correction of the frequency dependent phase error [6], was found [7] to be induced by path difference dependent fringe amplitude and phase errors in the interferogram.

3. Correction procedure

The correction procedure is based on the determination of the complex distortion function, that is the function modulating the interferogram due to misalignment errors and responsible for the spectral distortions.

If we call $I(z)$ the ideal interferogram, i.e. the inverse FT of the atmospheric spectrum $S(\sigma)$, the real (measured) interferogram is given by

$$I_m(z) = M(z)I(z) = M(z)\mathrm{FT}^{-1}\{S(\sigma)\}, \qquad (1)$$

where $M(z)$ is the interferogram modulation function characteristic of the instrument.

The main component of $M(z)$ is the box function extending from $z = 0$ to the maximum z value permitted by the instrument, giving the spectral resolution limit. Other "expected" components of $M(z)$ are the instrument finite field of view (FOV) and vignetting. The complex distortion function is a further "unexpected" component of the modulation function $M(z)$.

If we compute the Fourier transform (FT) of Eq. (1), we obtain

$$\mathrm{FT}\{I_m(z)\} = \mathrm{FT}\{M(z)I(z)\} = \mathrm{FT}\{M(z)\}S(\sigma). \qquad (2)$$

The FT of the modulation function, thus, gives the instrumental response to a Dirac-delta shaped spectrum (i.e. the ILS). The component in $M(z)$ due to the complex distortion function can be determined by the FT of the ILS, after filtering out the other instrumental effects.

In order to determine the ILS, an isolated spectral line selected in the calibration spectra can be used. This represents the best approximation we have of a Dirac-delta function. However, since this line only approximates a Dirac-delta function, its FT depends also on the inherent broadening of the feature. In particular, the modulus of the FT of the selected line is equal to the product of the amplitude of distortion function with broadening effects inherent with the observed atmospheric line (Doppler and pressure broadening) and the finite instrumental resolution (maximum path difference, finite FOV and vignetting). The phase is equal to the sum of the phase of the distortion function and a slope due to the random phase with which the line is sampled in the spectral grid.

Since all these multiplicative and additive effects vary slowly and monotonically with the path difference, they can be removed with a fitting procedure (a function of the form $\exp(-ax - bx^2)$ is fitted in the case of the modulus, a slope in the case of the phase). Comparable distortion functions are obtained using lines with different inherent widths from the same calibration spectrum, proving that an adequate model has been used for the filtering of the inherent line shape including all the instrumental effects.

In Fig. 1, the amplitude and the phase of the distortion function, as a function of the path difference, obtained using the same spectral feature in different calibration spectra and filtering out broadening effects inherent in the observed feature and in the instrument are provided. We see that different spectra produce consistent results, indicating that reproducible distortions are present in the instrument.

The effect of the ILS distortion on the broadband spectrum is thus eliminated convolving the spectrum with the FT of the correction function obtained from the distortion function as follows: its modulus is given by the inverse of the modulus of the distortion function, its phase by the opposite of the phase of the distortion function [7].

4. Model of the instrument line shape distortion

A model of the interferogram modulation function due to alignment (tilt and shear) and sampling errors for simple geometrical shapes of the beam section and simple FOV is described in Refs. [7–9]. Considering a square beam shape, the amplitude of the distortion function is given by

$$A(z,\sigma) = \mathrm{sinc}(\pi\sigma\alpha(z)l)\mathrm{sinc}(\pi\sigma\delta(z)\Theta), \tag{3}$$

where $\alpha(z)$ and $\delta(z)$ are tilt and shear of interfering wave fronts as a function of path difference z, l and Θ are the width and the divergence of the beam. The phase of the distortion function is given by

$$\Phi(z,\sigma) = 2\pi\sigma(\alpha(z)\Delta_0 + \delta(z)\theta_0 + \Delta(z)) \tag{4}$$

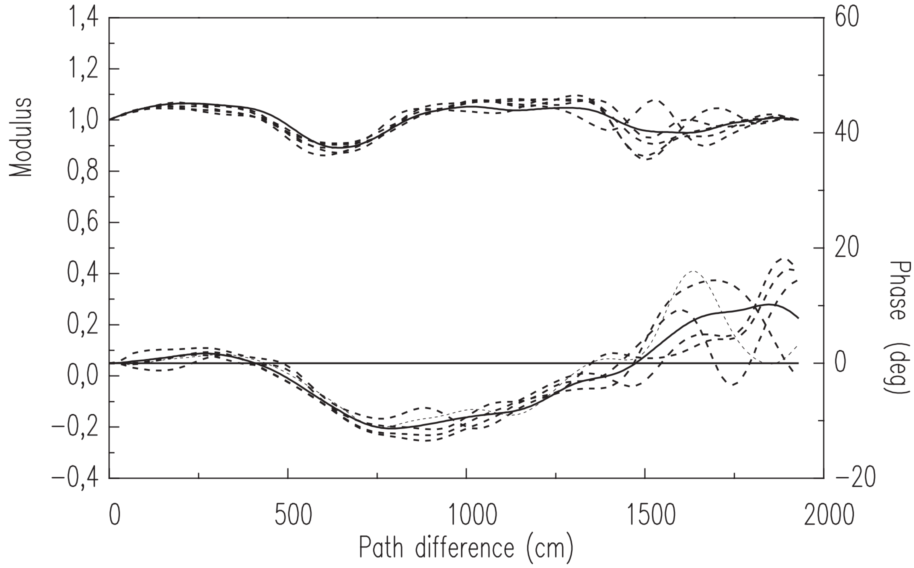

Fig. 1. Modulus (left axis) and phase (right axis) of the ILS distortion function obtained from different calibration spectra. Dashed lines represent estimates obtained from single spectra, the continuous line is obtained from the average spectrum.

with Δ_0 and θ_0, respectively, are the off-axis distance and off-axis angle of the infrared beam with respect to the interferometer optical axis measured in the planes perpendicular to the total tilt and shear and $\Delta(z)$ path-difference-dependent sampling error.

In Ref. [7], this analysis has been used for developing a recovery procedure to correct the distorted spectra. Herein, starting from the consideration that these distorted spectra provide macroscopic evidence of the effect of alignment errors on ILS distortion, we provide a further validation of the model with regard to the dependence on misalignment errors, as well as a method for the a priori estimation of the ILS distortion of a FT interferometer.

5. Mirror drive characterisation

The IBEX FTS [5] is characterised by 2 m max path difference, 120 mm diameter roof-top mirrors and linear mirror drive. The roof-top mirrors have the edge along the horizontal direction, so during the scan lateral shift along horizontal direction and tilt in the vertical plane are compensated. In this case, therefore, path difference dependent phase error arises only from shift in the vertical direction and tilt in the horizontal plane.

The experimental set-up we used for the characterisation of the wavefront tilt and shear versus path difference is shown in Fig. 2. A laser beam is aligned parallel to the optical axis of the interferometer (i.e. the axis of the mirror movement) and

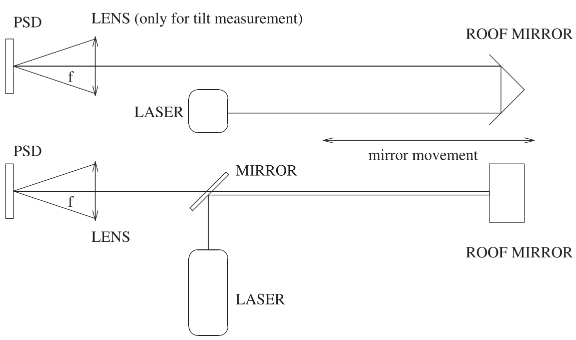

Fig. 2. Experimental set-up for wavefront tilt/shear characterisation of the FTS.

retroreflected by the moving roof-top mirror. The position of the retroreflected beam spot is monitored by means of a position sensitive detector (PSD). The PSD (Hamamatsu, model S1300 with type C4757 signal processing circuit) has an active surface of 13 mm × 13 mm, and permits a measurement of spot center independent of beam waist, with an absolute accuracy of about 100 μm and a resolution of few microns.

A vertical deviation, Δy, of the moving mirror from the laser beam axis gives a $\delta_y = 2\Delta y$ displacement of the retroreflected spot. The continuous line in Fig. 3 shows the measured deviation of the moving mirror from optical axis as a function of path difference. This quantity, excluding an offset and a slope that may be introduced by a difference between the instrument axis and the laser axis, is equal to the vertical shear.

The tilt measurement is made placing a $f = 50$ cm lens before the PSD, at a distance equal to the focal length (see Fig. 2). The spot horizontal displacement, δ_x, now corresponds to a wavefront tilt equal to δ_x/f (where f is the lens focal length) in the horizontal plane. The dashed line in Fig. 3 shows the result of this measurement. This quantity, excluding a constant offset determined by the orientation of the fixed mirror of the interferometer, is equal to the tilt in the horizontal plane.

6. Comparison with theory

The measurements of tilt and shear presented in Fig. 3 can be used in Eqs. (3) and (4) for an estimation of the complex distortion function, which can be compared with the values obtained in the field and shown in Fig. 1. The result of this comparison is shown in Fig. 4. The values of tilt and shear are known with the uncertainty of their offsets. Furthermore, in the case of the amplitude of the distortion function, only well-known parameters such as the solid angle Ω and the beam size l are required in Eq. (3), but in the case of the phase of the distortion function, some assumptions must be made in Eq. (4) on the values of the off-axis angle, θ_0, and the off-axis distance, Δ_0. The fitting procedure that has been used to determine the uncertain parameters in comparison of Fig. 4

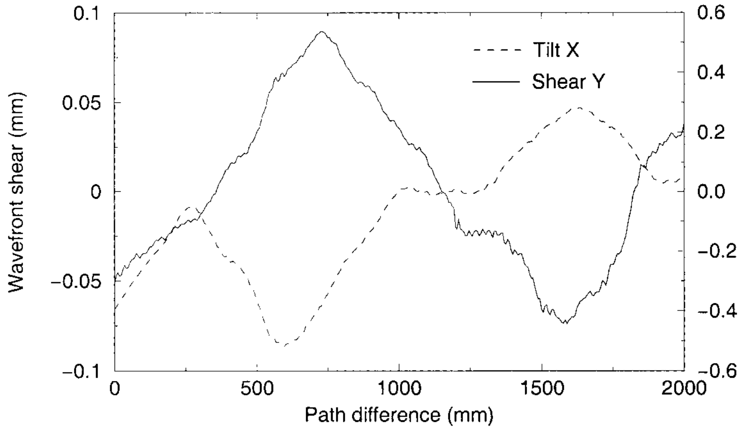

Fig. 3. Results of tilt/shear measurement on the FTS. Only the non-compensated degrees of freedom (vertical shear and horizontal shift) are shown.

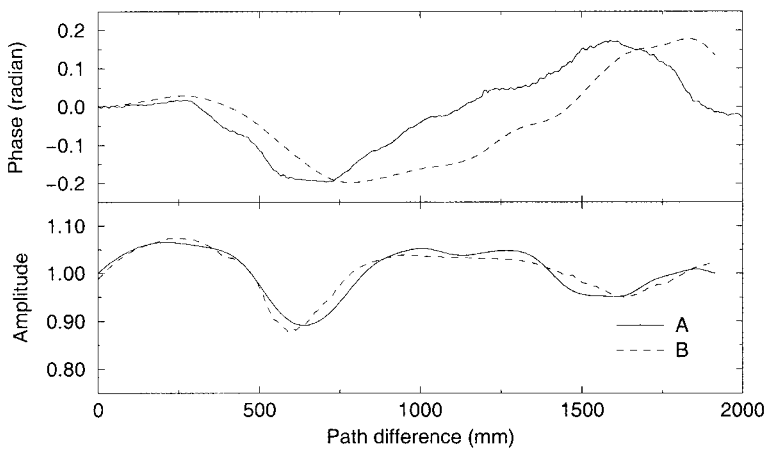

Fig. 4. Comparison of instrumental line shape distortion (amplitude and phase) as obtained from flight data and as estimated from laboratory measurement.

provides the estimate of an off-axis distance of 2.5 mm and of an off-axis angle of 20 mrad. The first value is consistent with the expected accuracy, and the second value is well outside the alignment requirement confirming the suspicion of an in-flight loss of alignment experienced by the instrument.

It should be noted that a good agreement between model and experimental data is obtained for the amplitude of the distortion function, but not equally good for the phase. The latter quantity depends on several parameters and it is reasonable to expect that some of these vary with temperature, and the values experienced at about 5°C during the flight are not fully reproduced in the laboratory.

7. Conclusions

In FT spectroscopy, the line shape distortions that arise from path difference dependent phase error are one of the most difficult to correct error sources. We have investigated the dependency of instrumental line shape distortion on the variation of alignment parameters of the mirror drive mechanism during the scan.

A good agreement has been found between the distortion function obtained from measured spectra and the distortion function obtained from model calculations based on the mechanical characterisation of the mirror drive. The consistency of the two independent estimates has also made it possible to infer conclusions on the alignment of the spectrometer.

The fact that the same result is obtained from the characterisation of the mechanics and optics of the instrument and from the analysis of the instrument measurements provides a strong basis on one hand for the determination of reliable instrument specifications and on the other hand for the use of ILS measurements as a diagnostic tool.

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