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The *Herschel*/SPIRE Spectrometer Phase Correction Data Processing Tasks

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Abstract. Asymmetries in the recorded interferograms of Fourier Transform Spectrometers (FTS) can be caused by optical, electronic, and sampling effects. Left uncorrected, these asymmetries will result in a spectrum with both real and imaginary components and thus a non-zero phase. One or more phase correction steps are applied in FTS data processing pipelines to correct for these effects. In this paper we describe the causes of non-zero phase particular to the *Herschel*/SPIRE FTS and present the two phase correction processing steps employed. The evolution of the phase correction algorithms is also described.

1. Background

The Spectral and Photometric Imaging Receiver (SPIRE) Fourier-Transform Spectrometer (FTS) is a sub-millimetre imaging spectrometer that operated on board the Herschel Space Observatory between May 2009 and April 2013 (Pilbratt et al. 2010; Griffin et al. 2010). The SPIRE FTS contains two bolometer detector arrays that cover the range from 194 to 671 μm (1546 to 447 GHz). Interferograms are produced by scanning the spectrometer mechanism (SMEC), the moving mirror that modulates the optical path difference (OPD).

The power measured in the image plane of the FTS should depend strictly on the difference between the optical path lengths of the two beams of the interferometer. The measured interferograms should possess even symmetry with respect to zero path difference (ZPD) the unique point where the path lengths of the two beams are identical and constructive interference occurs for radiation at all frequencies. On the other hand, any random noise component in the interferogram will transform to a complex random variable. Restoring the symmetry of the interfrogram associated with the astronomical observation, a process known as phase correction, allows a cosine Fourier transform to be applied which carries with it only one half of the noise component, thereby increasing the signal-to-noise ratio in the resulting spectrum. The recorded interferograms are not perfectly symmetric for several reasons, which include random noise, discrete sampling, dispersive elements within the interferometer, non-linear detector response, read-out electronics, and thermal inertia of the detectors and random noise (Swinyard et al. 2014; Naylor et al. 2014). The degree of this asymmetry is referred to as a phase, $\phi_i(\nu)$, which can be characterized as

$$\phi_i(\nu) = \phi_{\text{Electrical}-i}(\nu) + \phi_{\text{NonLin}-i}(\nu) + \phi_{\text{Random}-i}(\nu) \tag{1}$$

where $\phi_{\text{Electrical}-i}(\nu)$ is a phase delay imparted by the detector (i) readout electronics and thermal behaviour, $\phi_{\text{NonLin}-i}(\nu)$ is a non-linear phase that represents the effects of the remaining dispersive elements, and $\phi_{\text{Random}-i}(\nu)$ represents any phase due to noise. Left uncorrected, these phase errors produce spectral artefacts, which limit the accuracy of parameters derived from the spectrum (e.g. line intensity, width and shape). The following sections describe the phase correction process for SPIRE FTS data.

2. Correction Methods

2.1. Time Domain

The detector and read-out electronics that convert the analog detector signal into digital, computer-readable format introduce a frequency-dependent phase that will in general be non-linear. The thermal response of each of the SPIRE bolometers is well modelled as a single pole low pass filter (LPF) having a time constant, τ. When combined with the electrical phase introduced by the read-out electronics which contain a 6-pole Bessel low pass filter (LPF) as well as an additional RC LPF, the resulting transfer function, $H_{Total-i}(\nu)$ becomes,

$$H_{\text{Total}-\text{i}}(\nu) = H_{\text{LPF}-\text{i}}(\nu) + H_{\text{Thermal}-\text{i}}(\nu) \tag{2}$$

The combined response of the electronic LPFs and the thermal behaviour of the SPIRE bolometer detectors, $H_{Total-i}(\nu)$, affects the phase of the signals recorded by the SPIRE detectors.

$$Phase(H_{Total-i}(\nu)) = \phi_{\text{Electrical}-\text{i}}(\nu) = \tan^{-1}\left[\frac{Im(H_{\text{Total}-\text{i}}(\nu))}{Re(H_{\text{Total}-\text{i}}(\nu))}\right] \tag{3}$$

The inverse Fourier Transform of the electrical phase shift is applied to the input timelines and corrected by way of time convolution, resulting in a set of corrected timelines,

$$V_i^*(t) = V_i(t) \otimes \text{FT}^{-1}\left[e^{-i\phi_{\text{Electrical}-\text{i}}(\nu)}\right] \tag{4}$$

2.2. Interferogram Domain

The remaining phase components are best corrected in the spatial domain where the recorded signals are a function of mirror position, $V_i(x)$. Regardless of resolution mode, the phase at this stage can be characterized by the double-sided portion of the measured interferograms and subsequently removed from the data (Forman et al. 1966). In this section we describe the algorithms that have been used for this step, which is applied just prior to the final Fourier transformation.

2.2.1. Fitted Polynomial

The first iteration of the phase correction algorithm involved fitting a low-order polynomial to the measured in-band phase of each interferogram. The double-sided portion of the recorded interferograms, $V_{DS}(x)$, were transformed to the spectral domain ($V_{DS}(\nu)$) and the phase of these spectra was computed as:

$$\phi_{\mathrm{i}}(\nu) = \tan^{-1}\left[\frac{Im(V_{\mathrm{DS-i}}(\nu))}{Re(V_{\mathrm{DS-i}}(\nu))}\right] \tag{5}$$

A fourth-order polynomial was then fit to this phase,

$$\phi_{\mathrm{NonLin}-i}(\nu) = Fit\left[\phi_{\mathrm{i}}(\nu)\right] = a_i + b_i\nu + c_i\nu^2 + d_i\nu^3 + e_i\nu^4 \tag{6}$$

and the measured interferograms were corrected by way of convolution with the inverse transform of the fitted phase (Forman et al. 1966).

$$V_i^*(x) = V_i(x) \otimes \mathrm{FT}^{-1}\left[e^{-i\phi_{\mathrm{NonLin}-i}(\nu)}\right] \tag{7}$$

Subsequent analysis or in-flight data revealed that, while the fitted phase was a good first approximation to the measured phase, the actual measured phase contained structure that a well-behaved polynomial could not approximate. As more in-flight data accumulated, a new algorithm was adopted.

2.2.2. Calibrated Phase

The next iteration of the phase correction algorithm involved the use of a fixed or calibrated non-linear phase. Analysis of the first in-flight SPIRE FTS data showed that for most observations, the phase-correction function required at the spatial phase correction step was of a similar shape. For each detector of the SPIRE FTS, a non-linear phase correction function was derived. The non-linear phase correction functions were derived by combining the scans from all of the dark sky observations for each detector and for each scan direction.

$$\phi_{\mathrm{NonLin}-i}(\nu) = \phi_{\mathrm{CAL}-i}(\nu) = \tan^{-1}\left[\frac{Im\left(\overline{V_{Dark-i}(x)}\right)}{Re\left(\overline{V_{Dark-i}(x)}\right)}\right] \tag{8}$$

The non-linear calibrated phase correction function was then applied directed to the spectral of the recorded interferograms.

$$V_i^*(\nu) = V_i(\nu) \times e^{-i\phi_{\mathrm{NonLin}-i}(\nu)} \tag{9}$$

While this algorithm was quite successful in removing the measured phase from SPIRE FTS observations of faint sources (flux $<$ 10Jy), it did not work as well for brighter sources. As there was insufficient data to derive a calibrated phase for sources of different brightness, a new algorithm was developed.

2.2.3. Hybrid Method

The current phase correction algorithm (Fulton et al. 2014) is a hybrid of the first two algorithms. The non-linear phase is split into two components: $\phi_{\mathrm{NonLin-i}}(\nu)$, which is derived per detector from all of its interferograms in a given observation; and $\phi_{\mathrm{Lin-i}}(\nu)$, which is a linear fit to the phase performed on each spectrum.

The current correction algorithms is summarized below:

1. **Transform to the spectral domain.** The Fourier transform is applied to both the measured interferograms, $V_i(x)$, and the average double-sided interferograms, $\overline{V_{DS-i}(x)}$,
$$V_i(\nu) = \mathrm{FT}\left[V_i(x)\right], \overline{V_i(\nu)} = \mathrm{FT}\left[\overline{V_{DS-i}(x)}\right] \tag{10}$$

2. **Derive the non-linear phase and apply to the transformed interferograms.** The spectra are multiplied by the non-linear phase, $\phi_{\mathrm{NonLin-i}}(\nu)$, which is derived from the inverse tangent of the average spectra,
$$\phi_{\mathrm{NonLin}-i}(\nu) = \tan^{-1}\left[\frac{Im\left(\overline{V_{DS-i}(x)}\right)}{Re\left(\overline{V_{DS-i}(x)}\right)}\right], V_i^*(\nu) = V_i(\nu) \times e^{-i\phi_{\mathrm{NonLin}-i}(\nu)} \tag{11}$$

3. **Apply the linear phase to the once-corrected spectra.** The spectra are then multiplied, $\phi_{\mathrm{Lin-i}}(\nu)$ – a linear fit to the remaining phase of $V_i^*(\nu)$,
$$\phi_{\mathrm{Lin-i}}(\nu) = a_i + b_i\nu, V_i^{**}(\nu) = V_i^*(\nu) \times e^{-i\phi_{\mathrm{Lin}-i}(\nu)} \tag{12}$$

3. Conclusion

The phase correction algorithms for *Herschel*/SPIRE FTS data and their evolution have been presented. While developed specifically for the SPIRE FTS these techniques can be readily applied to data obtained with other infrared imaging Fourier transform spectrometers.

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