Relative Spectral Response Function Calibration for the *Herschel*/SPIRE Imaging Fourier Transform Spectrometer

Trevor Fulton[a], Ed Polehampton[b], Rosalind Hopwood[c], Dominique Benielli[d], David A. Naylor[a], Jean-Paul Baluteau[d], and the SPIRE FTS Team

[a]Department of Physics and Astronomy, University of Lethbridge, Lethbridge, Alberta, Canada

[b]Rutherford Appleton Laboratory, Chilton, Oxfordshire, United Kingdom

[c]Imperial College, London, United Kingdom

[d]Laboratoire d'Astrophysique de Marseille, Marseille, France

University of Lethbridge

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Introduction

The spectra recorded by the *Herschel*[1]/SPIRE[2] Imaging Fourier Transform Spectrometer (FTS) when observing any astronomical source, $V_{Meas}(\nu)$, can be expressed as a linear combination of contributions from three distinct entities: the astronomical source itself, $V_{source}(\nu)$; the *Herschel* Telescope, $V_{Tel}(\nu)$; and the SPIRE Instrument $V_{Inst}(\nu)$[3].

$$V_{Meas}(\nu) = V_{source}(\nu) + V_{Tel}(\nu) + V_{Inst}(\nu)$$

The Telescope and Instrument contributions can be expressed as products of an emitting source – the primary (M1) and secondary Telescope (M2) mirrors, and the SCAL calibrator, respectively – and relative spectral response functions (RSRFs) – $R_{Tel}(\nu)$ and $R_{Inst}(\nu)$, respectively.

$$V_{Meas}(\nu) = V_{source}(\nu) + M_{Tel}(T_{Tel},\nu)R_{Tel}(\nu) + M_{Inst}(T_{Inst},\nu)R_{Inst}(\nu)$$

where[4]:

$$M_{Tel}(T_{Tel},\nu) = (1-\varepsilon_{Tel}(\nu))\varepsilon_{Tel}(\nu)B(\overline{T_{M1}},\nu)f(OD) + \varepsilon_{Tel}(\nu)B(\overline{T_{M2}},\nu)$$

and:

$$M_{Inst}(T_{Inst},\nu) = B(\overline{T_{SCAL}},\nu)$$

While the emitting contributions can be computed from the *Herschel* and SPIRE telemetry – $M_{Tel}(T_{Tel},\nu)$ and $M_{Inst}(T_{Inst},\nu)$ (see Fig.1) – it is necessary to derive $R_{Tel}(\nu)$ and $R_{Inst}(\nu)$ in order to remove the Telescope and Instrument contributions from the data.

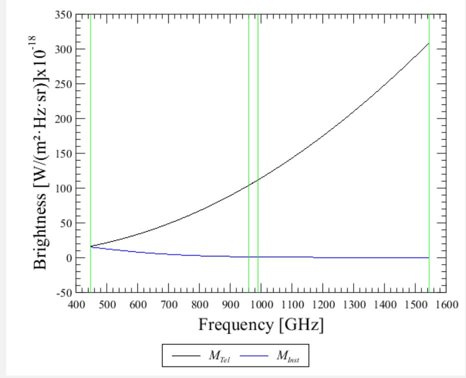

Fig. 1: Models of the Telescope and Instrument emission for a typical SPIRE observation. The long (SLW) and short (SSW) wavelength detector bands are also shown.

HIPE 10 Calibration

Instrument RSRF

The spectrum of an observation of the Dark Astronomical sky, $V_{Dark}(\nu)$, contains no contribution from an astronomical source and therefore may be expressed as:

$$V_{Dark}(\nu) = M_{Tel}(T_{Tel},\nu)R_{Tel}(\nu) + M_{Inst}(T_{Inst},\nu)R_{Inst}(\nu)$$

Consider the plots shown in the Fig. 2. There, the values of spectral scan numbers, n, and the SCAL thermometer, T_{Inst}, are shown for a dark observation as a function of time.

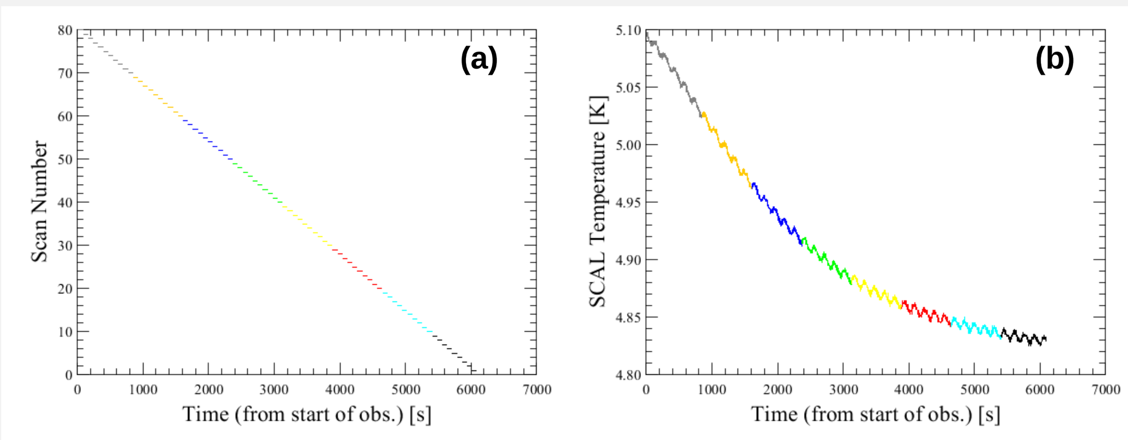

Fig. 2: (a) Scan numbers, n, and **(b)** SCAL Temperatures, T_{Inst}, for dark observation `0x50002C81`.

Under the assumption that the Telescope mirror temperatures do not vary over the course of an observation[3, 4], the Instrument RSRF can be derived from the spectra of a dark observation as:

$$R_{Inst}(\nu) = \frac{V_{Dark-n}(\nu) - V_{Dark-(n-N_{Scans}/2)}(\nu)}{M(T_{Inst-n},\nu) - M(T_{Inst-(n-N_{Scans}/2)},\nu)}$$

Five other dark observations had an SCAL temperature profile like that shown in Fig. 2 and are shown in Fig. 3a.

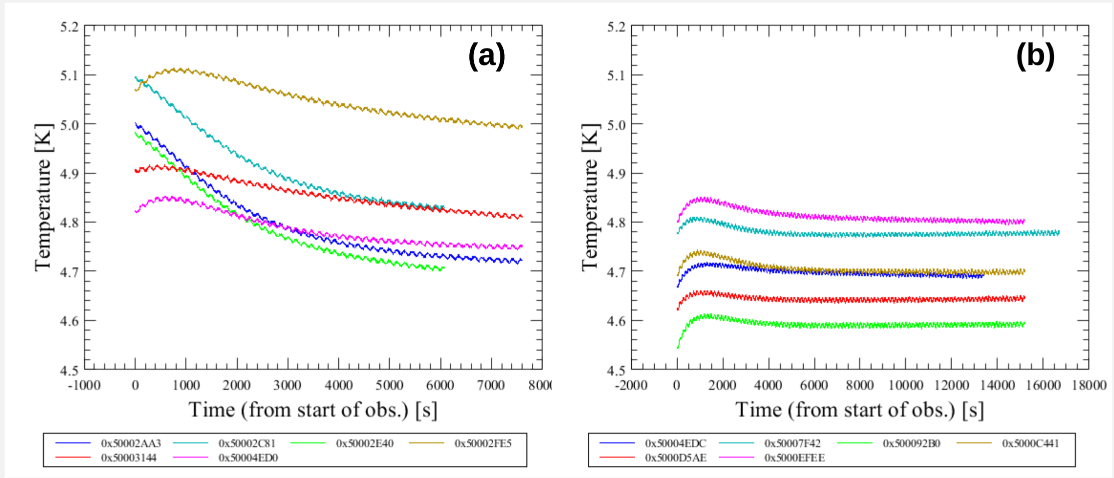

Fig. 3: SCAL Temperatures for a series of dark observations. **(a)** observations used to derive HIPE 10 $R_{Inst}(\nu)$; **(b)** typical SPIRE FTS observations.

The equation to derive the Instrument RSRF was applied to all six of the dark observations in Fig. 3a, with the result that the overall $R_{Inst}(\nu)$ could be expressed as:

$$\overline{R_{Inst}(\nu)} = \sum_{\text{Dark Obs.}} \sum_{n=N_{Scans}/2}^{N_{Scans}} \left[\frac{V_{Dark-n}(\nu) - V_{Dark-(n-N_{Scans}/2)}(\nu)}{B(T_{Inst-n},\nu) - B(T_{Inst-(n-N_{Scans}/2)},\nu)}\right]$$

Telescope RSRF

The Instrument RSRF having been derived, spectra from dark observations can then be corrected for the Instrument contribution as[3]:

$$V_{Dark-Inst.Corrected}(\nu) = V_{Tel}(\nu) + V_{Inst}(\nu) - M_{Inst}(T_{Inst},\nu)R_{Inst}(\nu)$$
$$= V_{Tel}(\nu) \equiv M_{Tel}(T_{Tel},\nu)R_{Tel}(\nu)$$

The Telescope RSRF for any given dark observation can then be solved by dividing the Instrument-corrected dark spectrum by the telescope model[4]:

$$R_{Tel}(\nu) = \frac{V_{Dark-Inst.Corrected}(\nu)}{M(T_{Tel},\nu)}$$

The overall Telescope RSRF is given by the average of $R_{Tel}(\nu)$ over *all* dark observations.

$$\overline{R_{Tel}(\nu)} = \sum_{\text{All Dark Obs.}} R_{Tel-Obs}(\nu) = \sum_{\text{All Dark Obs.}} \frac{V_{Dark-Inst.Corrected-Obs}(\nu)}{M(T_{Tel-Obs},\nu)}$$

HIPE 10 Limitation

The major limitation of the HIPE 10 derivation methods for the Instrument and Telescope RSRFs was that the Instrument RSRFs could only be derived using dark observations that had SCAL Temperature profiles as shown in Fig. 3a. If the method was applied to dark observations whose SCAL temperatures did not vary significantly – as was the case for most SPIRE FTS observations (see Fig. 3b) – added noise would be imparted to the final Instrument RSRF. Even though there is in principle no such limitation on the Telescope RSRF, it too was affected by the aforementioned limitation on the Instrument RSRF because the derivation of the Telescope RSRF *uses* the Instrument RSRF and is thus affected by its noise, in particular at the low frequency end of the SLW spectra where the Instrument contribution is at its maximum (Fig. 1).

HIPE 11 Calibration

In an effort to circumvent the limitation of the HIPE 10 RSRFs, a new derivation method has been adopted for HIPE 11. Consider the spectra of two different dark observations, A and B:

$$V_{Dark-A}(\nu) = M_{Tel}(T_{Tel-A},\nu)R_{Tel}(\nu) + M_{Inst}(T_{Inst-A},\nu)R_{Inst}(\nu)$$
$$V_{Dark-B}(\nu) = M_{Tel}(T_{Tel-B},\nu)R_{Tel}(\nu) + M_{Inst}(T_{Inst-B},\nu)R_{Inst}(\nu)$$

If each spectrum is divided by its telescope model, the following is the result:

$$V_{Dark-A}(\nu)/M_{Tel}(T_{Tel-A},\nu) = R_{Tel}(\nu) + M_{Inst}(T_{Inst-A},\nu)R_{Inst}(\nu)$$
$$V_{Dark-B}(\nu)/M_{Tel}(T_{Tel-B},\nu) = R_{Tel}(\nu) + M_{Inst}(T_{Inst-B},\nu)R_{Inst}(\nu)$$

The difference between the two ratios is:

$$V_{Dark-A}(\nu)/M_{Tel}(T_{Tel-A},\nu) - V_{Dark-B}(\nu)/M_{Tel}(T_{Tel-B},\nu) = M_{Inst}(T_{Inst-A},\nu)R_{Inst}(\nu) - M_{Inst}(T_{Inst-B},\nu)R_{Inst}(\nu)$$

The Instrument RSRF is then given as:

$$R_{Inst-A/B}(\nu) = \frac{V_{Dark-A}(\nu)/M_{Tel}(T_{Tel-A},\nu) - V_{Dark-B}(\nu)/M_{Tel}(T_{Tel-B},\nu)}{M_{Inst}(T_{Inst-A},\nu) - M_{Inst}(T_{Inst-B},\nu)}$$

In a similar fashion, the Telescope RSRF is given by:

$$R_{Tel-A/B}(\nu) = \frac{V_{Dark-A}(\nu)/M_{Inst}(T_{Inst-A},\nu) - V_{Dark-B}(\nu)/M_{Inst}(T_{Inst-B},\nu)}{M_{Tel}(T_{Tel-A},\nu) - M_{Tel}(T_{Tel-B},\nu)}$$

The overall Instrument and Telescope RSRFs are then derived as the average of *all* of the possible pair-wise (A/B) combinations of dark observations.

Comparisons and Results

Number of Observations

There are significantly fewer restrictions on the HIPE 11 method used to derive the RSRFs, particularly for the Instrument RSRF, as the HIPE 11 method only requires that the Instrument Temperatures of $V_{Dark-A}(\nu)$ and $V_{Dark-B}(\nu)$ be different. Many more spectra can therefore be included in the derivation as shown in Tab. 1:

Number of Spectra	HIPE 10		HIPE 11	
	BSM1	BSM2	BSM1	BSM2
R_{Inst}	140	140	1,473,743	1,397,987
R_{Tel}	2,242	1,200	1,473,743	1,397,987

Tab. 1: Number of spectra used to derive the RSRFs. BSM 1 and BSM 2 refer to the rest position of the SPIRE Beam Steering Mirror that was changed on OD1011[5].

Calibration Noise

The reduction in noise due to the increased number of spectra used to derive the RSRFs is evident from a visual comparison between the HIPE 10 and HIPE 11 calibration curves, as shown in Fig. 4.

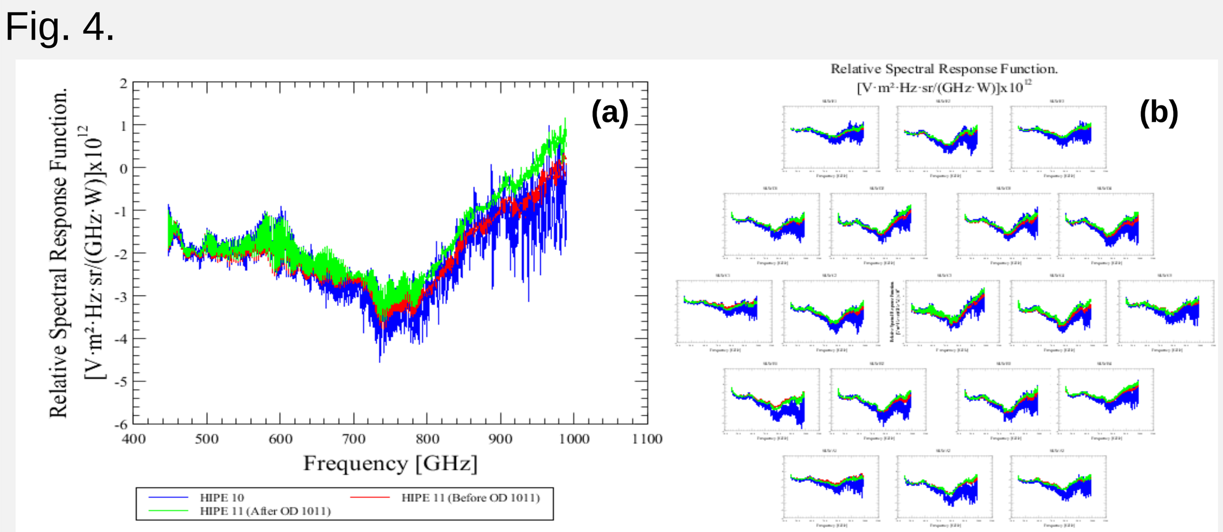

Fig. 4: (a) Instrument RSRFs for detector SLWC3 (sparse sampling detector). **(b)** Instrument RSRFs for all SLW detectors.

Spectral Noise and Sensitivity

Fig. 5 shows a comparison of the Level-2 spectra for two dark and two science observations using the HIPE 10 and HIPE 11 RSRF calibration and qualitatively illustrates the improvement in signal to noise ratio achieved.

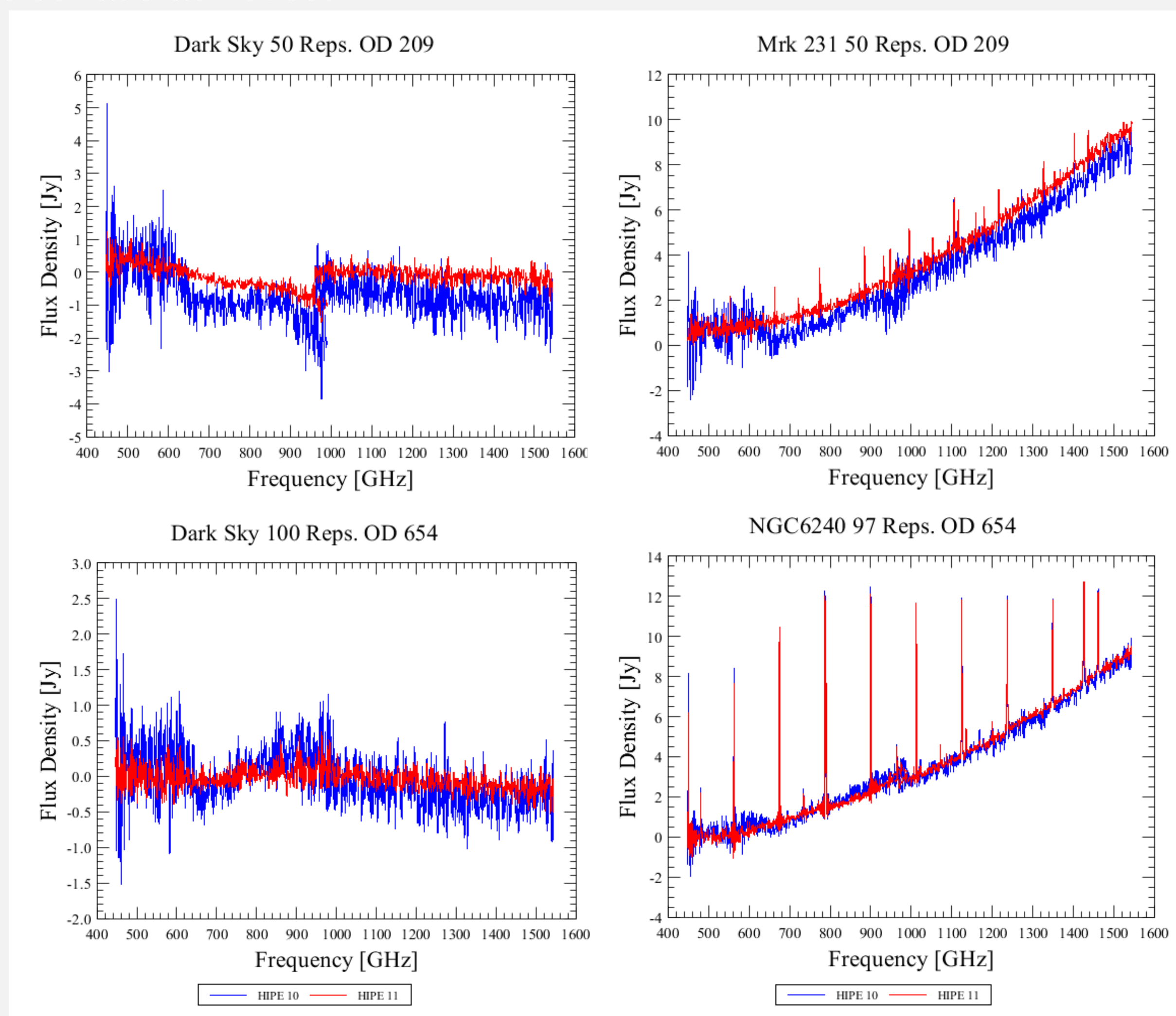

Fig. 5: Level-2 Spectra for selected SPIRE FTS calibration and science observations.

The sensitivity levels for the HIPE 10 and HIPE 11 calibrations are presented in Fig. 6 and compared with the values listed in HSPOT[6].

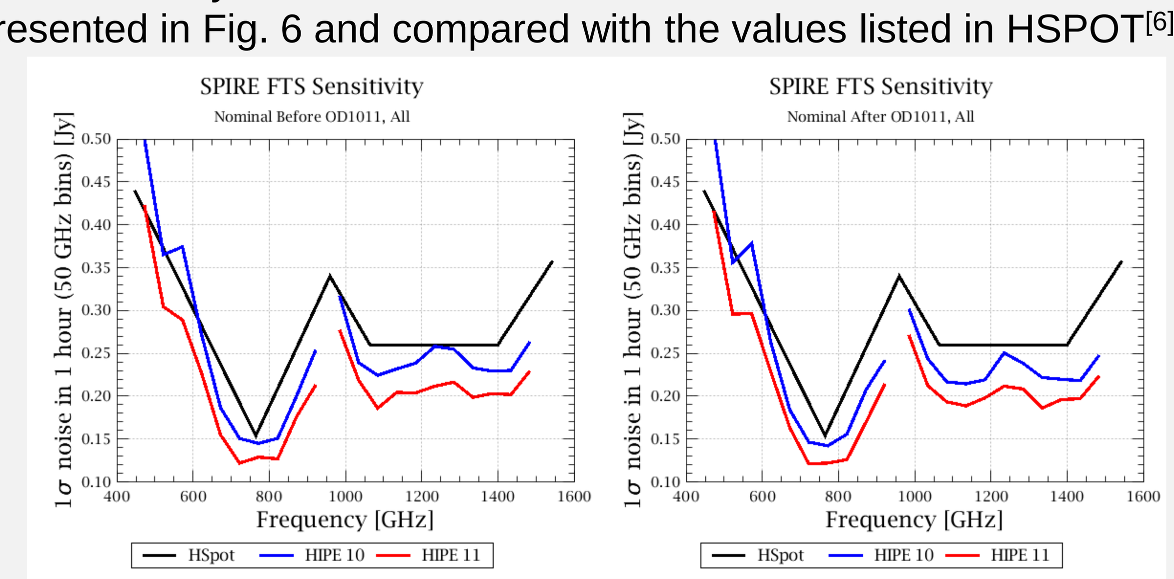

Fig. 6: Sensitivity for nominal mode SPIRE HR FTS observations.

Conclusion

An update to the method used to derive the SPIRE FTS Relative Spectral Response Functions has been presented. A comparison of the calibration noise, Level-2 spectra, and overall sensitivity levels for the HIPE 10 and HIPE 11 calibrations show that, both qualitatively and quantitatively, significant improvements have been achieved.

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