SUBJECT: **SPIRE FTS Telescope RSRF Derivation**

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Change Record

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Draft 0.1	17 March 2011	First version
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TABLE OF CONTENTS

Glossary

BSM	Beam Steering Mirror
CR	Calibration Resolution
FT	Fourier Transform
HR	High Resolution
LHS	Left Hand Side
LR	Low Resolution
MR	Medium Resolution
NHKT	Nominal Housekeeping Timeline Product
OD	Operational Day
RHS	Right Hand Side
RSRF	Relative Spectral Response Function
SDI	Spectrometer Detector Interferogram Product
SDS	Spectrometer Detector Spectrum Product
SDT	Spectrometer Detector Timeline Product
SLW	Spectrometer Long Wavelength array
SMEC	Spectrometer MEChanism
SNR	Signal to noise ratio
SPIRE	Spectral and Photometric Imaging REceiver
SSW	Spectrometer Short Wavelength array
TBD	To Be Determined
TBW	To Be Written

1. INTRODUCTION

The purpose of this document is to describe the method used to derive the Telescope RSRF calibration curves for each of the SPIRE FTS detectors.

1.1 Documents

1.1.1 Applicable Documents

Number	Document Title	Document Number	Issue
AD01	SPIRE Spectrometer Pipeline Description	SPIRE-BSS-DOC-002966	3.1
AD02	SPIRE Sensitivity Models	SPIRE-QMW-NOT-000642	
AD03	SPIRE FTS Instrument RSRF Derivation	SPIRE-BSS-REP-003261	1.0
AD04	Flux Conversion and RSRF correction for the SPIRE FTS	SPIRE-BSS-REP-003243	1.0

1.1.2 Reference Documents

Number	Document Title	Author(s)	Issue
RD01	Dark Sky spectra evolution with time	Jean-Paul Baluteau	1, 2
RD02	SPIRE FTS Update: Telescope/Instrument Correction, Presentation to the SPIRE SDAG, 18 Feb. 2010	Trevor Fulton	1

2. BACKGROUND

The spectrum recorded by the SPIRE FTS when observing any astronomical source, $V_{Meas}(\sigma)$, can be expressed as a linear combination of contributions from three distinct entities: the astronomical source itself, $V_{Source}(\sigma)$; the Herschel Telescope, $V_{Tel}(\sigma)$; and the SPIRE Instrument (FPU and SCAL), $V_{Inst}(\sigma)$ as expressed in eq. 2.1 (see AD01 eq. 3.41).

$$V_{Meas}(\sigma) = V_{Source}(\sigma) + V_{Tel}(\sigma) + V_{Inst}(\sigma) \tag{2.1}$$

After the application of the Spectrometer Instrument Correction step, the measured spectrum may be expressed as in eq. 2.2,

$$V_{Inst-Corrected}(\sigma) = V_{Source}(\sigma) + V_{Tel}(\sigma) + \cancel{V_{Inst}(\sigma) - M_{Inst}(\sigma)} = V_{Source}(\sigma) + V_{Tel}(\sigma). \tag{2.2}$$

Next, consider an observation that is common to the SPIRE FTS calibration plan; that of the dark astronomical sky. The spectra of these data contains no contribution from an astronomical source and therefore the instrument corrected spectra for these observations may be expressed as in eq. 2.3:

$$V_{Inst-Corrected}(\sigma) = \cancel{V_{Source}(\sigma)} + V_{Tel}(\sigma) = V_{Tel}(\sigma) \tag{2.3}$$

The instrument corrected for a Dark Astronomical Sky observation (OBSID=0x50007F42, N_{Reps}=110 or N_{Scans}=220), $V_{Inst\text{-}Corrected}(\sigma)$= $V_{Tel}(\sigma)$, for the central detectors SLWC3 and SSWD4 are shown in Figure 1.

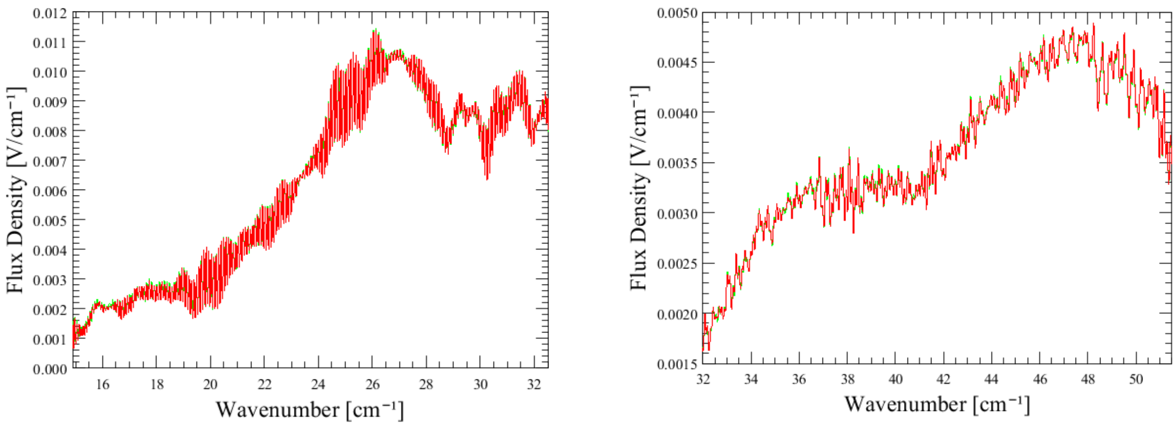

Figure 1: **Telescope spectra, $V_{Tel}(\sigma)=V_{Inst\text{-}Corrected}(\sigma)$, for the Dark Sky observation, OBSID=0x50007F42**. Left: SLWC3; right: SSWD4. The average of the forward spectra is shown in green, the average of the reverse spectra is shown in red.

3. TELESCOPE EMISSION MODEL

In a similar manner as that that was done for the emission of the SPIRE Instrument [AD03], an attempt will be made to represent the contribution from the Herschel Telescope with a model. A first-order model for the emission of the Herschel Telescope, $M_{Tel}(\sigma)$, represented as a product of an emission from a blackbody source, $B_{Tel}(\sigma)$, and a relative spectral response function (RSRF), $R_{Tel}(\sigma)$, is given in eq. 3.1,

$$V_{Tel}(\sigma) \stackrel{\text{def}}{=} M_{Tel}(\sigma) = B_{Tel}(\sigma)R_{Tel}(\sigma), \tag{3.1}$$

which, when applied to an observation of the Dark Sky, becomes

$$V_{Inst-Corrected}(\sigma) = V_{Tel}(\sigma) \stackrel{\text{def}}{=} M_{Tel}(\sigma) = B_{Tel}(\sigma)R_{Tel}(\sigma). \tag{3.2}$$

3.1 Primary and Secondary Mirrors

The first term in the model of the Herschel Telescope is a combination of the emission from the Herschel Telescope's primary and secondary mirrors, M1 and M2, with an additional reflection from the secondary mirror M2 may be expressed as in eq. 3.3,

$$B_{Tel}(\sigma) = \left(1 - \epsilon_{Tel}(\sigma)\right)\epsilon_{Tel}(\sigma)B\left(\overline{T_{M1}}, \sigma\right) + \epsilon_{Tel}(\sigma)B\left(\overline{T_{M2}}, \sigma\right) \tag{3.3}$$

where: $B(T, \sigma)$ is the Planck function,

$$B(T, \sigma) = \frac{2h(100c\sigma)^2}{c^3} \frac{1}{e^{\frac{h(100c\sigma)}{KT}} - 1}; \tag{3.4}$$

$$\begin{aligned} h &= 6.62606896 \times 10^{-34}\ \mathrm{Js} \\ k &= 1.3806505 \times 10^{-23}\ \frac{\mathrm{J}}{\mathrm{K}}; \\ c &= 2.99792458 \times 10^{8}\ \frac{\mathrm{m}}{\mathrm{s}} \end{aligned} \tag{3.5}$$

and $\overline{T_{M1}}$ and $\overline{T_{M2}}$ are the time-averaged temperatures recorded by the Herschel telescope's nine M1 and three M2 thermometers (see Figure 2), respectively; and $\epsilon_{Tel}(\sigma)$ is defined as in eq. 3.6 [AD02],

$$\epsilon_{Tel}(\sigma) = 0.0366\left(\frac{10^4}{\sigma}\right)^{-0.5} + 0.273\left(\frac{10^4}{\sigma}\right)^{-1}. \quad (3.6)$$

The locations of the 9 thermometers on the primary mirror, M1 and 3 thermometers on the secondary mirror, M2 are shown in Figure 2.

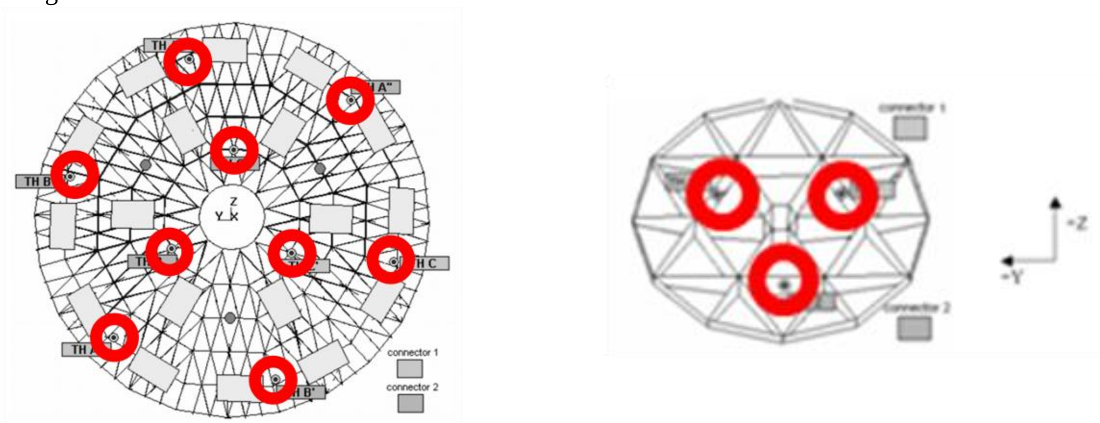

Figure 2: **Location of the Herschel Telescope thermometers**. Left, Primary mirror, M1 ; right, Secondary mirror, M2.

Examples of the Herschel Telescope thermometer timelines for a selected Dark Sky observation (OBSID=0x50007F42) along with a plot of the emissivity of the mirrors M1 and M2 are shown in Figure 3.

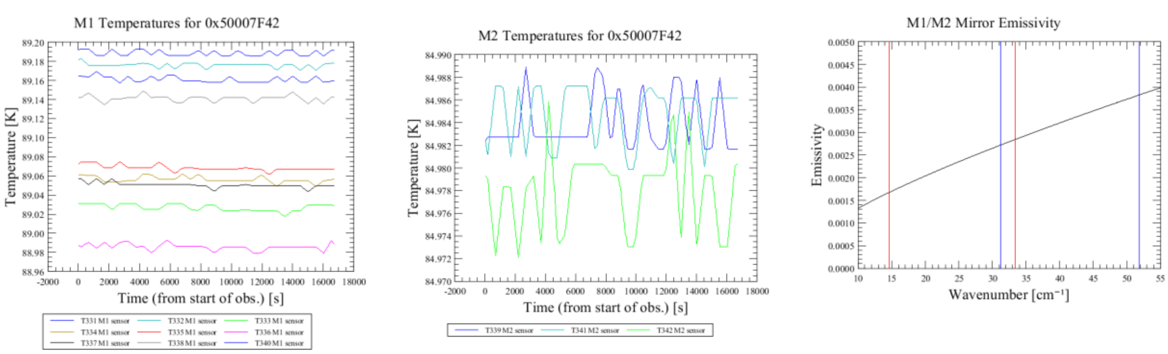

Figure 3: **Herschel Telescope thermometer timelines for the Dark Sky observation OBSID=0x50007F42**. Left, Primary mirror, M1, thermometers; middle, Secondary mirror, M2, thermometers; right, Emissivity of mirrors M1 and M2 [AD02] – also shown are the passbands for SLW (red) and SSW (blue).

3.2 Telescope RSRF

The second term in the model of the Herschel Telescope emission represents the relative spectral response function (RSRF) of the Telescope or Sky Port, $R_{Tel}(\sigma)$. Consider again the first order model of the Telescope emission when applied to an observation of the Dark Sky, eq. 3.2. One may solve for the RSRF of the Telescope or Sky port by rearranging eq. 3.2 as in eq. 3.7.

$$R_{Tel}(\sigma) = \frac{V_{Inst-Corrected}(\sigma)}{B_{Tel}(\sigma)}. \quad (3.7)$$

Put another way, the Telescope RSRF may be derived from the Instrument-corrected spectra of any observation of the Dark Sky, so long as the temperatures of the Herschel Telescope mirrors M1 and M2 are known for that observation.

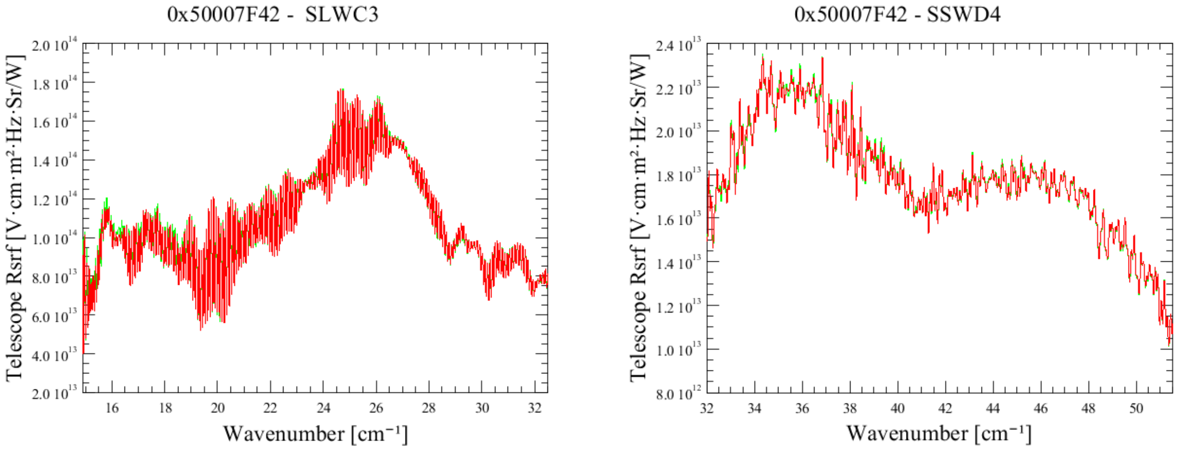

Figure 4: **Telescope RSRF, $R_{Tel}(\sigma)$, derived from the Dark Sky observation, OBSID=0x50007F42**. Left: SLWC3; right: SSWD4. The average of the forward RSRF curves is shown in green, the average of the reverse spectra is shown in red.

3.3 Model Assumptions

At this point, it may be useful to consider the assumptions made when positing the first-order model of the Telescope emission model.

3.3.1 Detector and SMEC Scan Direction

As the plots in Figure 4 show, the Telescope RSRF curves are noticeably different from detector-to-detector and there is a slight difference between the RSRF curves for each detector depending on the scan direction of the SMEC mechanism.

$$R_{Tel-bb-d}(\sigma) = \frac{\overline{V_{Inst-Corrected-d}(\sigma)}^{\text{SMEC Dir.}}}{B_{Tel}(\sigma)} \tag{3.8}$$

where the subscripts and superscripts:

- *bb* refers to a science building block of a SPIRE FTS observation;
- *d* refers to a SPIRE FTS detector;
- *SMEC Dir.* refers to an average that takes SMEC scan direction into account.

3.3.2 Telescope Temperature Stability

The timelines of the Herschel Telescope thermometers, shown in Figure 3, reveal that while there are thermometer-to-thermometer differences – in particular for the set of M1 thermometers – over the course of an observation, any given thermometer is fairly stable. This stability, and the fact that the Herschel Telescope thermometers are sampled every 512s (a single HR spectrometer scan takes ~66s), confirms that the first-order model of the Herschel Telescope need only use the time-averaged values of the thermometers over the course of a SPIRE FTS observation building block.

3.3.3 BSM Position

The Instrument RSRF calibration curves [AD03] were derived based on a model of the SPIRE Instrument that is independent of BSM or Jiggle position. This same assumption is not valid for the Telescope RSRF since the radiation from the emitting elements in the model of the Telescope – mirrors M1 and M2 – must pass through the BSM before reaching the SPIRE FTS detectors. As a result, the first order model of the Telescope emission, eq. 3.2, is thought be dependent on BSM position.

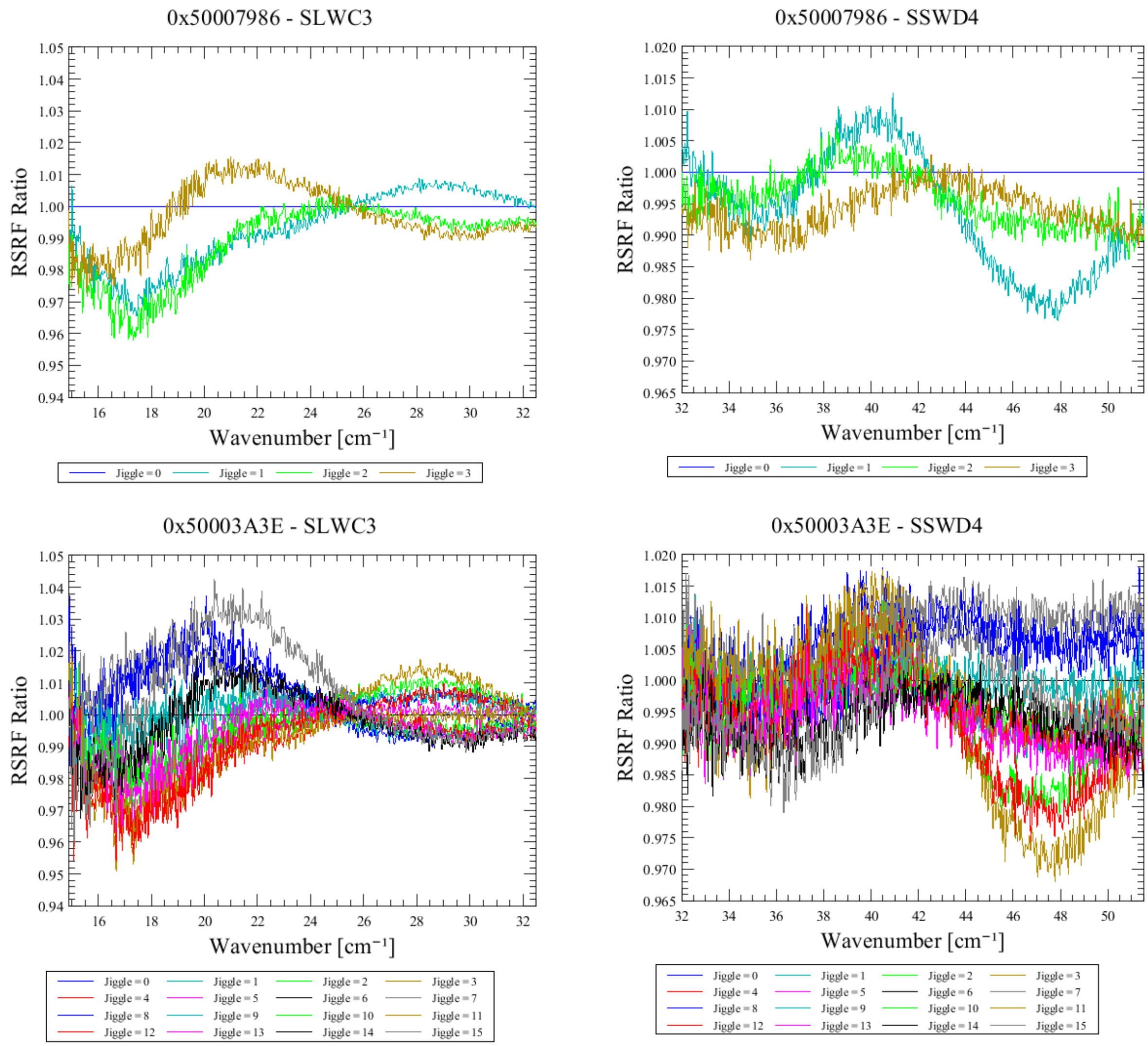

Figure 5: **Telescope RSRF ratios, $R_{Tel\text{-}j}(\sigma)/R_{Tel\text{-}Sparse}(\sigma)$, derived from the Dark Sky observations, OBSIDs=0x50007986 and 0x50003A3E**. Left: SLWC3; right: SSWD4. Each curve represents the ratio of the RSRF for a given BSM position to the RSRF for the Sparse sampling equivalent BSM position.

As a check on this assumption, a set Telescope RSRF curves were derived for two mapping observations of the Dark Sky: OBSID=0x50007986, intermediate spatial sampling; 0x50003A3E, full spatial sampling. A separate Telescope RSRF was derived for each detector for each BSM position for these observations. The curves in Figure 5 show the ratios of $R_{Tel}(\sigma)$ for a given BSM (Jiggle) position to the BSM position that corresponds to sparse spatial sampling

(Jiggle = 0 for intermediate sampling, Jiggle=6 for full sampling) for each observation. Clearly, there is a systematic difference between the Telescope RSRF curves at different Jiggle positions for a given detector.

$$R_{Tel-j-d}(\sigma) = \frac{\overline{V_{Inst-Corrected-d}(\sigma)}^{SMEC\ Dir.}}{B_{Tel}(\sigma)} \quad (3.9)$$

where the subscripts common to eq. 3.8 are as defined in §3.3.1 and:

- *j* refers to BSM or Jiggle position;

3.3.4 Daily RSRF curves

Implicit in the equation for the derivation of the Telescope RSRF (eq. 3.9) is that it should be possible to combine the curves derived for the same detector and Jiggle position from different observations of the Dark Sky. This assumption was investigated by computing the ratio of the Telescope RSRF curves derived from the Dark Sky observations listed in Table 1 to those derived from OBSID=0x50007F42 (OD557). These ratios, for the detectors SLWC3 and SSWD4 are shown in Figure 6.

OBSID	OD	Resolution	N_{reps}	$\overline{M1}$ [K]	$\overline{M2}$ [K]
0x50007F42	**557**	**CR**	**110**	**89.3984**	**85.1888**
0x50002972	209	CR	50	87.8791	84.1593
0x50002AA3	217	CR	50	88.0534	84.2699
0x50002C81	227	CR	40	88.1564	84.3816
0x50002E40	240	CR	40	88.2620	84.4789
0x50002FE5	250	CR	50	88.5968	84.7139
0x50003144	261	CR	50	88.7190	84.8549
0x50003453	275	CR	16	88.7071	84.7915
0x50003670	288	CR	16	88.7401	84.8127
0x50003A3D	302	CR	6	88.7614	84.8320
0x50003CC6	317	CR	16	88.3726	84.5199
0x50004012	327	CR	16	88.2351	84.3476
0x50004681	342	CR	16	88.1885	84.2822
0x50004ED0	383	CR	50	88.1873	84.2871
0x50004EDC	383	CR	100	88.1979	84.2900
0x50005205	395	CR	16	88.2014	84.3199
0x50005490	404	CR	16	88.1841	84.2786
0x500055D7	410	CR	16	88.0615	84.1616
0x50005972	423	CR	16	87.8814	84.0588
0x50005978	423	CR	16	87.8811	84.0561
0x5000596B	423	CR	16	87.9056	84.0826
0x50005E98	428	CR	4	87.9350	84.0455
0x50005D73	438	CR	4	88.0130	84.1012
0x5000619B	451	CR	4	88.3747	84.4557
0x50006883	466	CR	40	88.5172	84.5104
0x50006C06	495	CR	10	88.7807	84.7833
0x50007987	543	CR	20	88.7221	84.6351
0x50008322	571	CR	100	89.0072	84.9092
0x500088E0	601	CR	110	89.3984	85.1888

Table 1: Sparse Sampled Dark Sky observations from OD209 to OD601. Note that the temperatures listed for are time averages of nine and three thermometers, respectively, over the course of the observation.

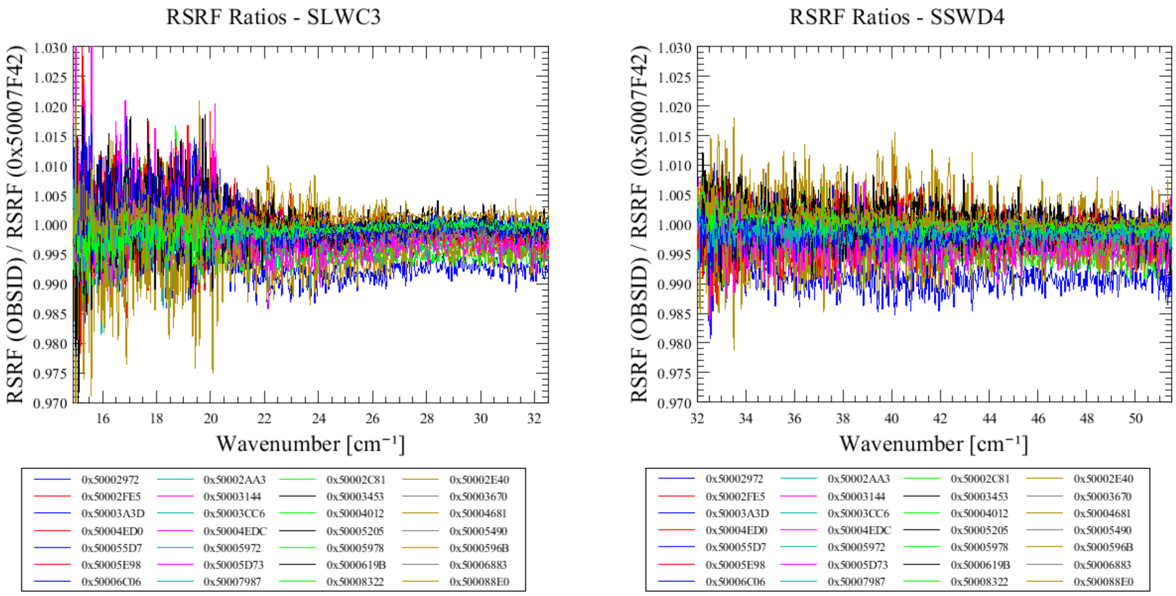

Figure 6: **Telescope RSRF ratios, $R_{Tel\text{-}obs}(\sigma)/R_{Tel\text{-}0x50007F42}(\sigma)$, derived from all Sparse Dark Sky observations, ODs 209 to 601**. Left: SLWC3; right: SSWD4. Each curve represents the ratio of the RSRF derived from a given Dark Sky observation to that derived from 0x50007F42.

The RSRF ratios in Figure 6 show that the RSRF curves, with the exception of a few Dark Sky observations (0x50002972), are consistent to within ±<0.5% over a large portion of the SPIRE FTS passband.