PFM3 CBB/SCAL Transmission Analysis

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1. Introduction

The purpose of this document is to extend the analysis that was presented in an earlier report: "*PFM1/PFM3 Transmission Analysis*", Draft 0.1, 10 August 2006. In the previous report, the relative transmission was derived for each path through the SPIRE spectrometer and it was shown by inspection that this transmission for a given was consistent for a given pixel. In this analysis, a comparison will be drawn between the measured transmission for each path through the SPIRE spectrometer.

2. Background

Here, as in the previous analysis[1], the underlying hypothesis is that the spectrum recorded by the SPIRE spectrometer detectors, $B(\sigma)_{Measured}$, can be described as a linear combination of the spectra from the sources at the two input ports (the telescope port and the SCAL port) with each input signal modified by the *overall* transmission of each path through the spectrometer, $Tr(\sigma)_{Telescope}$ and $Tr(\sigma)_{SCAL}$. Based on this model of the SPIRE spectrometer, the recorded spectrum can be written as:

$$B(\sigma)_{measured} = Telescope\ Input(\sigma)\, Tr(\sigma)_{CBB} + SCAL\ Input(\sigma)\, Tr(\sigma)_{SCAL}$$

The SCAL input consists of three sources of emission; SCAL2 and SCAL4, the 2% and 4% emitters, and SCAL, the remaining SCAL surface and therefore may be expressed as:

$$SCAL\ Input(\sigma) = P(T_{SCAL}, \sigma)\,\epsilon(\sigma)_{SCAL} + P(T_{SCAL2}, \sigma)\,\epsilon(\sigma)_{SCAL2} + P(T_{SCAL4}, \sigma)\,\epsilon(\sigma)_{SCAL4}$$

where each emitting source within SCAL has been expressed as the product of a Planck function, P(T, σ), and an emissivity, ε(σ), particular to that source.

For the PFM test campaign data considered in this analysis, the emitting source at the telescope input port was the cold blackbody (CBB). The telescope input source may therefore be written as:

$$Telescope\ Input(\sigma) = P(T_{CBB}, \sigma)\,\epsilon(\sigma)_{CBB}$$

Taking these sources into account, the equation for the recorded spectrum may be restated as follows:

[1] Trevor Fulton, "*PFM1/PFM3 Transmission Analysis*", Draft 0.1, 10 August 2006.

$$B(\sigma)_{measured} = P(T_{CBB},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} + P(T_{SCAL},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL} + P(T_{SCAL2},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} + P(T_{SCAL4},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL}$$

Consider the case where the temperatures of the emitting elements are set at their own reference levels (T_{CBBref}, $T_{SCAL2ref}$, $T_{SCAL4ref}$, and $T_{SCALref}$). Let the measured spectrum for these reference input temperatures be denoted as $B(\sigma)_{ref}$:

$$B(\sigma)_{ref} = P(T_{CBBref},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} + P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL} + P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} + P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL}$$

Next, consider a scenario in which the CBB temperature is increased to T_{CBBHot} while the SCAL emitters are held at their reference temperatures. The measured spectrum in this case, $B(\sigma)_{CBB}$, can be expressed as:

$$B(\sigma)_{CBB} = P(T_{CBBHot},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} + P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL} + P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} + P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL}$$

The difference between the reference spectrum and the spectrum measured for the higher CBB input is given by:

$$\begin{aligned}
B(\sigma)_{CBB} - B(\sigma)_{ref} &= P(T_{CBBHot},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} + P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL} + \\
&\quad + P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} + P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL} \\
&\quad - P(T_{CBBref},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} - P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL} \\
&\quad - P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} - P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL} \\
&= P(T_{CBBHot},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} \cancel{+ P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL}} \\
&\quad \cancel{+ P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} + P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL}} \\
&\quad - P(T_{CBBref},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} \cancel{- P(T_{SCALref},\sigma)\epsilon(\sigma)_{SCAL} Tr(\sigma)_{SCAL}} \\
&\quad \cancel{- P(T_{SCAL2ref},\sigma)\epsilon(\sigma)_{SCAL2} Tr(\sigma)_{SCAL} - P(T_{SCAL4ref},\sigma)\epsilon(\sigma)_{SCAL4} Tr(\sigma)_{SCAL}} \\
&= P(T_{CBBHot},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} - P(T_{CBBref},\sigma)\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB} \\
&= (P(T_{CBBHot},\sigma) - P(T_{CBBref},\sigma))\epsilon(\sigma)_{CBB} Tr(\sigma)_{CBB}
\end{aligned}$$

In this case, the overall transmission for radiation that travels the path from the telescope (CBB) input port to the detectors can be found as:

$$Tr(\sigma)_{CBB} = \frac{B(\sigma)_{CBB} - B(\sigma)_{ref}}{(P(T_{CBBHot},\sigma) - P(T_{CBBref},\sigma))\epsilon(\sigma)_{CBB}}$$

Similarly, the overall transmission for the SCAL path can be determined from the data of two observations where their only difference is the temperature of one of the SCAL emitting elements (e.g. SCAL2):

$$Tr(\sigma)_{SCAL} = \frac{B(\sigma)_{SCAL2} - B(\sigma)_{ref}}{(P(T_{SCAL2Hot}, \sigma) - P(T_{SCAL2ref}, \sigma))\epsilon(\sigma)_{SCAL2}}$$

3. Analysis

The observations that are the focus of this analysis are given in Table 1 below.

PFM3 Observations (OBSID_BBID)	***Temperature [K]***			
	CBB	***SCAL***	***SCAL2***	***SCAL4***
3000E516_82030001	**6.33**	**4.66**	**4.64**	**4.65**
3000E512_82030001	8.07	4.66	4.63	4.64
3000E50F_82030001	8.87	4.66	4.63	4.64
3000E50A_82030001	10.92	4.66	4.63	4.64
3000E5C7_82030001	6.31	4.66	Variable	4.66

Table 1: PFM3 observations considered in this study.

These observations can be separated into two categories:

1. PFM3, CBB variable, SCAL2 constant (10 scans each):
   - 3000E516_82030001 (**reference**)
   - 3000E512_82030001
   - 3000E50F_82030001
   - 3000E50A_82030001
2. PFM3, CBB constant, SCAL2 variable (20 scans):
   - 3000E5C7_82030001 (**reference**: SCAN 01 and SCAN 02)

The spectra from the observations that are highlighted in **bold** were used as the reference spectra; the remaining observations in a given set were denoted as the "hot" spectra. In each case, only the low or medium resolution ($\Delta\sigma$~0.4cm^{-1} and $\Delta\sigma$~0.2cm^{-1}, respectively) portion of the measured interferogram was considered.

In a previous report[2], the relative transmission for each path was computed for each pixel and then normalized in the single-mode region. This normalization allowed for a more direct pixel-by-pixel comparison of the relative transmission but did not allow for a reliable comparison of the relative transmission for the two paths through the spectrometer. In this analysis, the measured relative transmission was left unnormalized to allow for a comparison of the two transmission paths. Examples of the unnormalized measured transmission for each path for active PFM3 pixels are shown in Figure 1.

[2] Trevor Fulton, "*PFM1/PFM3 Transmission Analysis*", Draft 0.1, 10 August 2006.

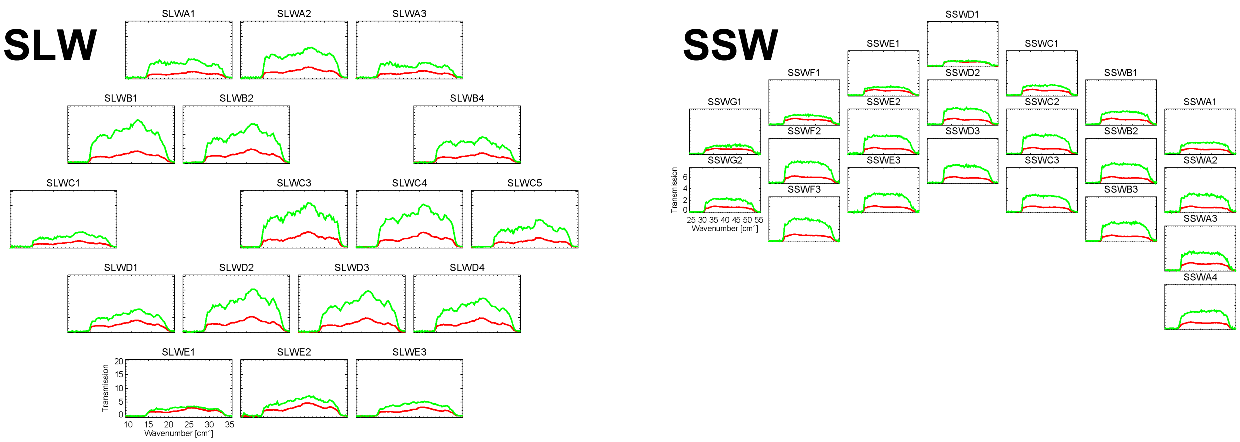

Figure 1: Measured Transmission, PFM3 data. In each case the green curve represents the measured transmission for the SCAL path while the red curve represents the measured transmission for the telescope (CBB) path. A larger version of this figure can be found in the Appendix as Figure 8.

As can be seen from the curves in Figure 1, the transmission for the SCAL path is, in general, greater than that for the telescope (CBB) path. In order to get a quantitative measure of the difference between the measured transmissions, the ratio of the measured transmission of the telescope (CBB) path to that of the SCAL path was calculated. The transmission ratios for the pixels of the SLW and SSW arrays shown in Figure 2.

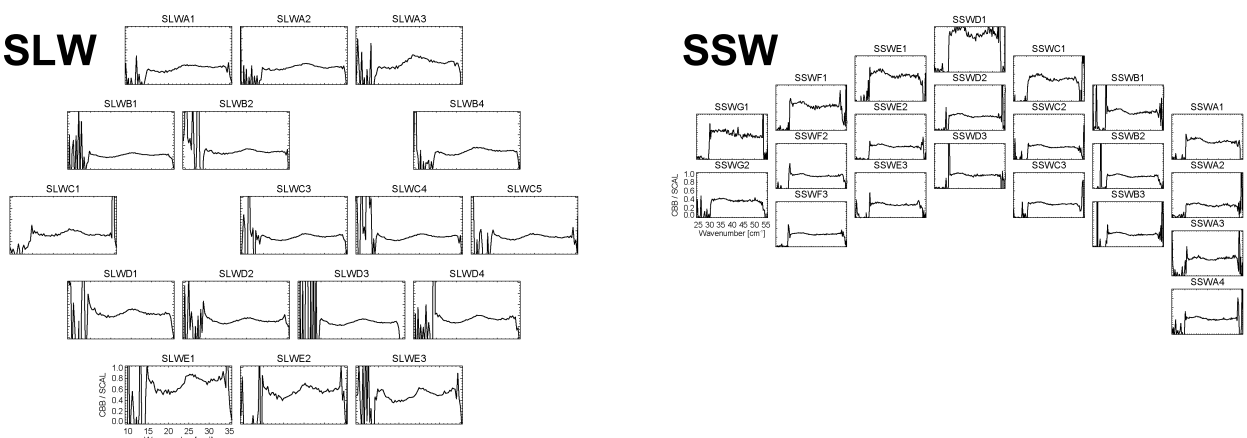

Figure 2: Measured Transmission Ratio, PFM3 data. In each case the curve represents the ratio of the measured CBB transmission to the measured SCAL transmission. A larger version of this figure can be found in the Appendix as Figure 9.

As can be seen from the plots in Figure 2, not only is the difference between the two transmission paths a difference in scale, but there also appears to be a wavelength-dependent difference the two transmission curves.

To see what sort of difference (if any) is to be expected between the two transmission paths, consider the optical layout for the SPIRE spectrometer (Figure 3). If one considers just the two transmission paths <u>within the SPIRE spectrometer</u> (paths that start at **1** and **2** and end at SLW and SSW in Figure 3), the only differences between the two paths are the faces of the spectrometer beamsplitters that are seen in reflection and transmission. Based on an analysis of the behaviour of the two beamsplitters[3], these differences are expected to be negligible and it is expected that the transmission for each path within the SPIRE spectrometer should be roughly the same, i.e. $Tr_1(\sigma) \approx Tr_2(\sigma)$.

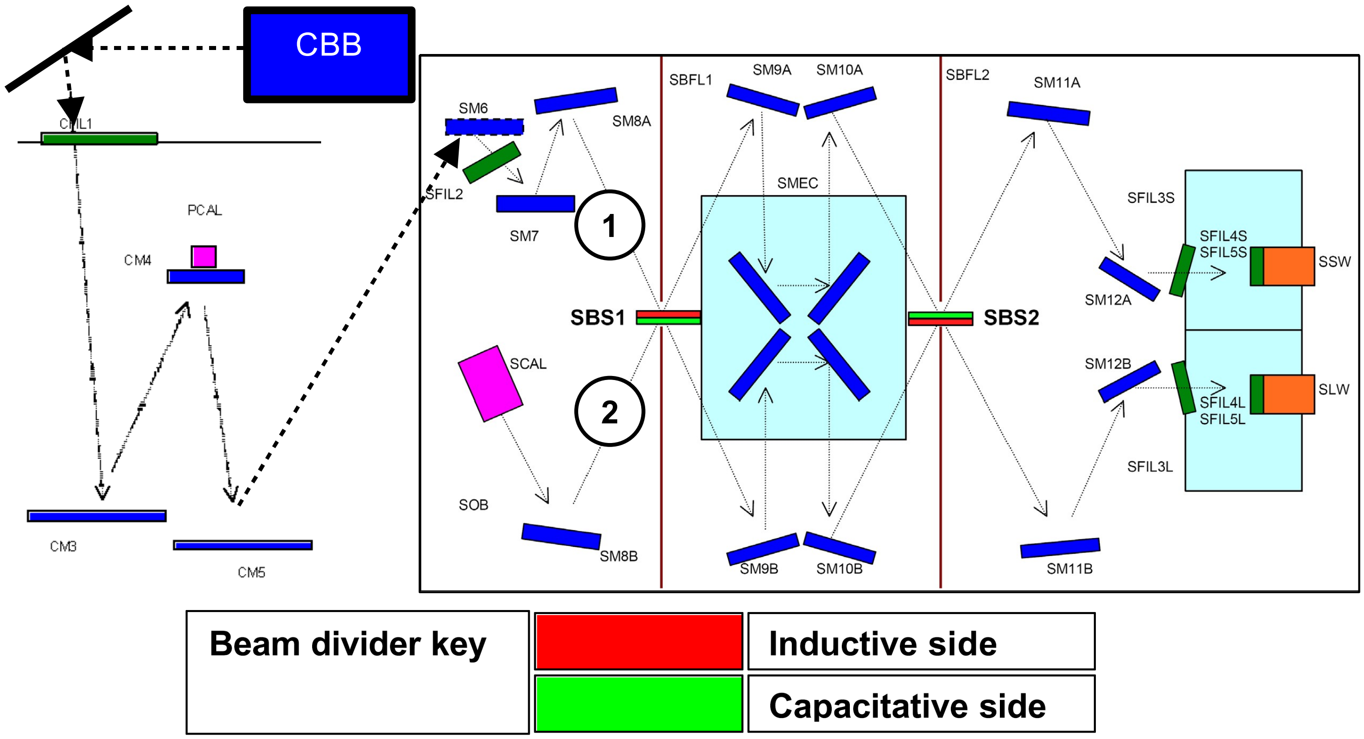

Figure 3: SPIRE Spectrometer Optical Layout. The labels **1** and **2** represent the start of the transmission path from the telescope (CBB) and SCAL, respectively, *within the SPIRE spectrometer*. The telescope (CBB) path contains an seven additional mirrors (SM8A, SM7, SM6, CM5, CM4, CM3, and the CBB flip mirror) and two additional filters (SFIL2 and CFIL1); the SCAL path contains one additional mirror (SM8B).

Extension of the transmission paths back from points **1** and **2** to the actual input sources (see Figure 3), results in seven additional mirrors (SM8A, SM7, SM6, CM5, CM4, CM3, and the CBB flip mirror) and two additional filters (SFIL2 and CFIL1) for the telescope (CBB) path and one additional mirror (SM8B) to the SCAL path. A high reflectivity (r>99%) has been assumed for the additional mirrors then these so their effects have been ignored. The effects due to the additional filters in the telescope (CBB) path may not be negligible, however.

To see how the measured transmission ratio compares with the additional filters in the telescope (CBB) path, consider the plots in Figure 4. For the majority of the pixels in the SLW and SSW arrays, the measured transmission ratio (black curves) does not agree with the product of the transmission of the two additional filters (red curves). A pixel-dependent scaling factor was then introduced. This factor was calculated by dividing the average in-band value of the raw filter transmission by the average in-band value of the measured transmission ratio. The quotient of the combined filter transmission for CFIL1 and SFIL2 and these scaling factors are shown as the green curves in Figure 4.

[3] Jean-Paul Baluteau, "*SPIRE FTS Simulations*", Powerpoint presentation, 22 September 2006.

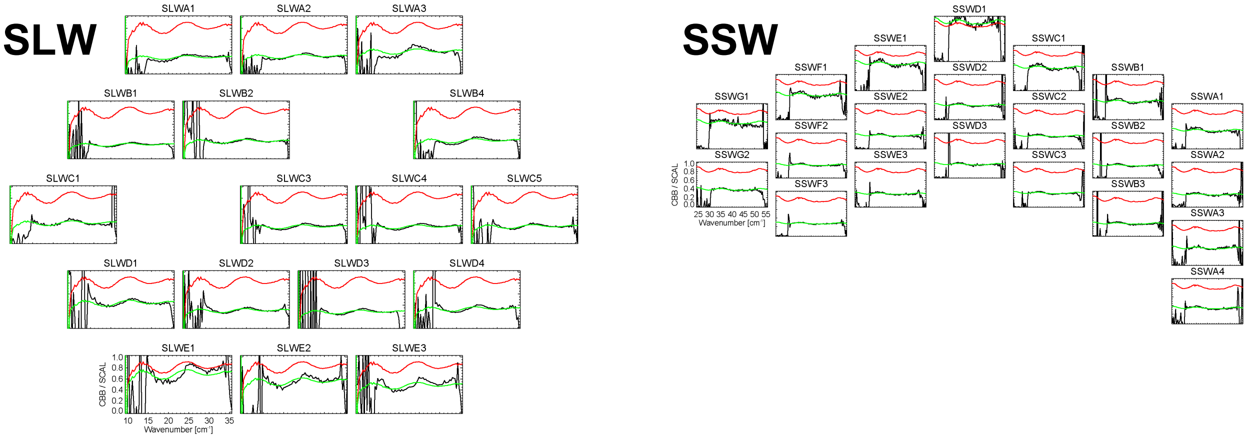

Figure 4: Measured Transmission Ratio, PFM3 data. In each case the black curve represents the ratio of the measured CBB transmission to the measured SCAL transmission. The extra curves shown are the products of the transmission of filters CFIL1 and SFIL2; the red curve is the unmodified product and the green curve is a scaled version of the product. A larger version of this figure can be found in the Appendix as Figure 10.

As can be seen from the plots in Figure 4, the inclusion of the pixel-dependent scaling factors brings the filter transmission into good agreement with the measured transmission ratio. It is also apparent from the plots in Figure 4, that the optimal scaling factor differs from pixel-to-pixel. Plots of the distribution of these scaling factors are shown in Figure 5 (**NB**: the pixels shown in black were not active during the PFM3 test campaign).

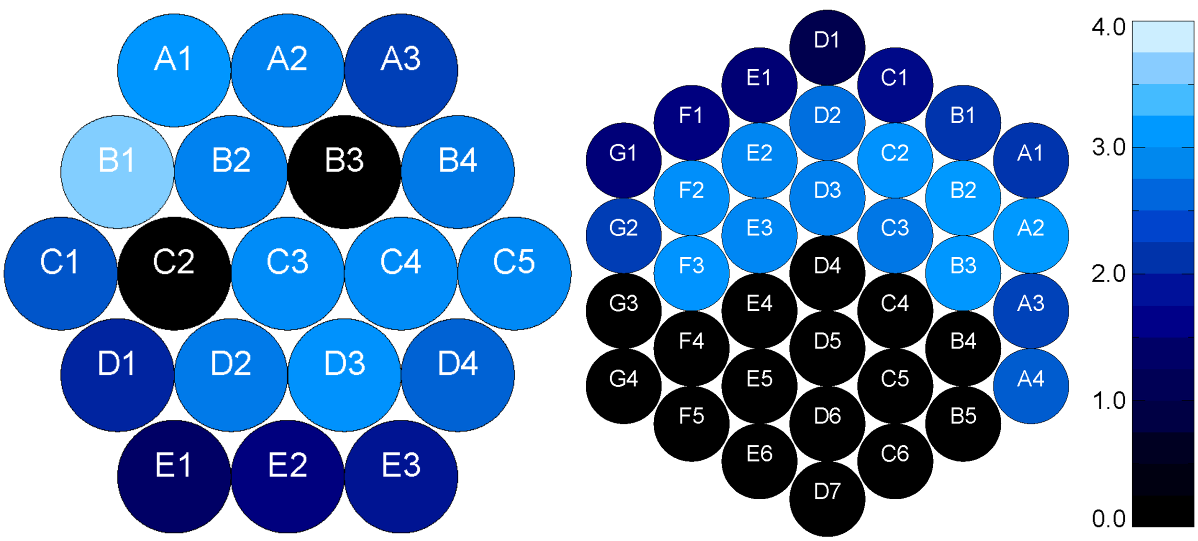

Figure 5: Scaling factors, PFM3 data. The colour code on the right represents the factor by which the combined transmission of CFIL1 and SFIL2 must be divided in order to achieve agreement with the measured ratio of the transmission of the CBB path to that for the SCAL path.

4. Discussion

The results presented in Figure 4 and Figure 5 show that the differences between the measured transmission of the two paths through the SPIRE spectrometer are primarily differences in scale. It has been shown that these differences in scale are not constant from pixel-to-pixel; the transmission through the SCAL path is greater than that for the telescope (CBB) path by a factor that ranges from ~2.5 to 3 for the unvignetted pixels to ~1 for some of the edge pixels. In light of these differences it is worthwhile revisiting some of the assumptions that were made in the transmission model that was described in §2.

1. **Emissivities of the CBB and of the SCAL elements.** In this analysis, it was assumed that the emissivity of the cold blackbody (ε_{CBB}) was independent of wavelength and was equal to one. Similar assumptions were made for the emissivity of the elements within SCAL; ε_{SCAL2} was assumed to be 2% (0.02), ε_{SCAL4} was assumed to be 4% (0.04), and ε_{SCAL} was assumed to be 94% (0.94), and each emissivity was assumed to be ndependent of wavelength. Additionally, for a given emitter, the emissivity was assumed to be consistent across the detector array. Deviations from these assumptions, particularly if the effective emissivity for the CBB was significantly less than 100% could explain some of the observed differences in scale between the measured SCAL and telescope transmissions.
2. **Mirror reflectivity.** It was assumed that the extra mirrors in the CBB path had an insignificant effect. In the case that the reflectivity of each mirror is 99%, the overall reflectivity would be of the order of 90%. If, however, the reflectivity of each mirror is closer to 95% then the overall reflectivity would be ~70% and would result in a reduction of the transmission from the CBB path by ~30%. Even though this potential effect does not entirely account for the difference in scale between the two transmission paths, such an effect would no longer be insignificant and should be taken into account.
3. **Filter re-emission**. An assumption was made that heating up the CBB would not cause the the filters in the telescope (CBB) path to change temperature. If the extra filters in the telescope (CBB) path (SFIL2 and CFIL1, see Figure 3) did heat up upon illumination by the CBB then these filters would effectively act as additional sources, an effect that was considered in the transmission model.
4. **Misalignment of the CBB during PFM3**. It was discovered that the CBB was misaligned during the PFM3 test campaign. A misalignment of this component could result in a reduced illumination of some portions of the SLW and SSW detector arrays, which in the end would result in a reduction in the effective emissivity of the CBB. In addition, this reduced emissivity may be directional in nature and would vary from pixel-to-pixel.
   For some context on this matter, the scaling factors that are presented in Figure 5 were also calculated using PFM1 data (see Figure 6). At first glance there does not appear to be a significant difference in the distribution of these scaling factors, but this topic may nonetheless merit further investigation.

As an aside, recall the distributions of the positions of ZPD for the SPIRE spectrometer that were measured in a previous note[4]. These distributions were revisited to see if it is similar to the distribution of the scaling factors. As can be seen from the plots in Figure 6 and Figure 7, there does not appear to be a correlation between the two distributions.

[4] David Naylor, et.al., "*Phase Study of SPIRE PFM1 Spectrometer Data*", **SPIRE-UOL-REP-002421**, Version2.0, 25 May 2005.

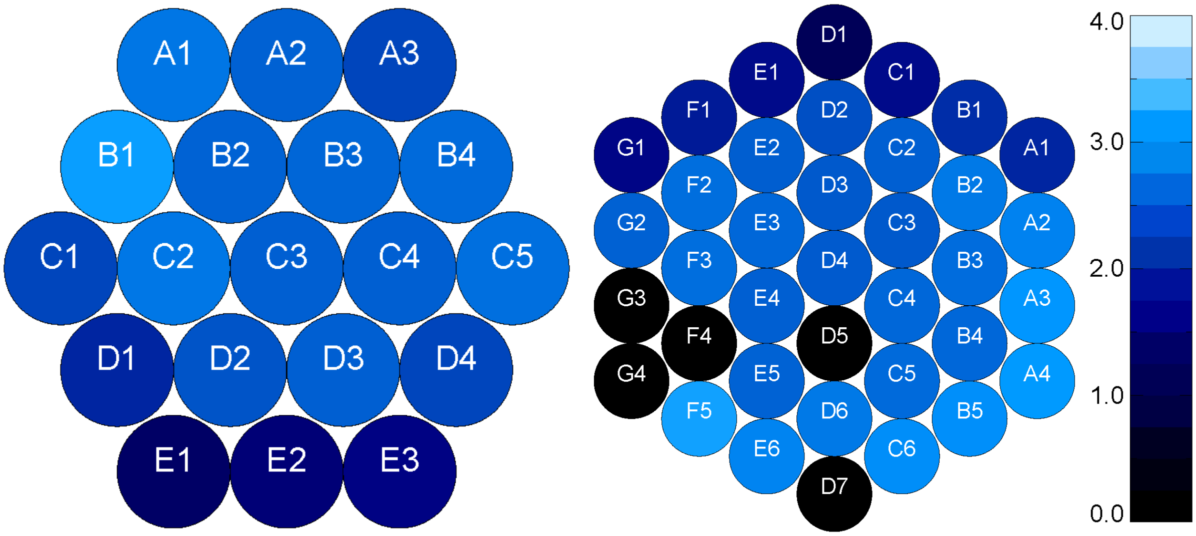

Figure 6: Scaling factors, PFM1 data. The colour code on the right represents the factor by which the product of transmission of CFIL1 and SFIL2 must be divided in order to have agreement with the measured ratio of the transmission of the CBB path to that for the SCAL path.

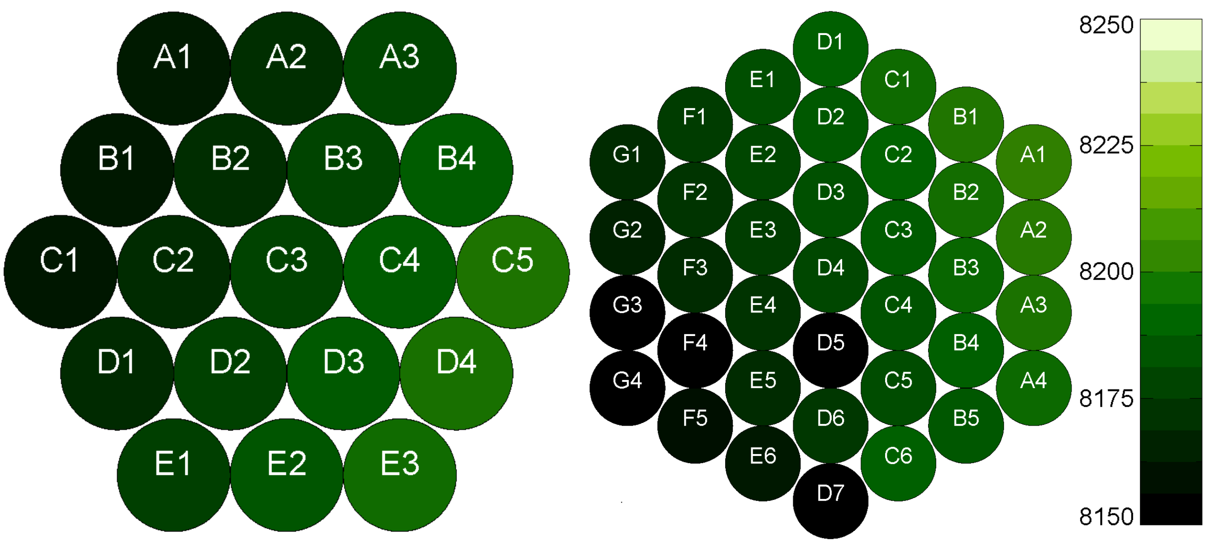

Figure 7: ZPD Locations, PFM1 data. The colour code on the right represents the measured ZPD position from the SMEC cold stop in units of µm MPD.

5. Appendix

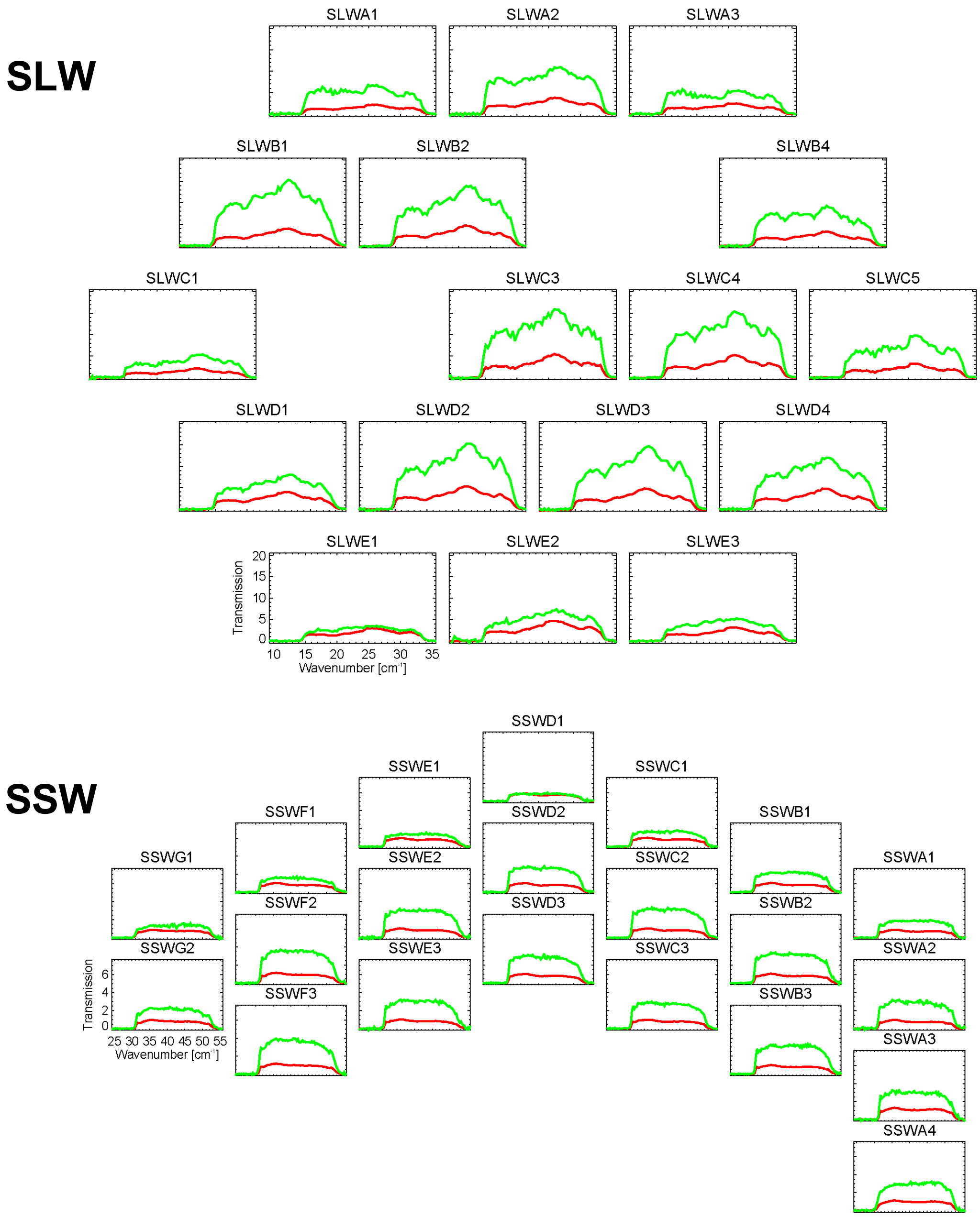

Figure 8: Measured Transmission, PFM3 data. In each case the green curve represents the measured transmission for the SCAL path while the red curve represents the measured transmission for the telescope (CBB) path. This is a larger version of Figure 1.

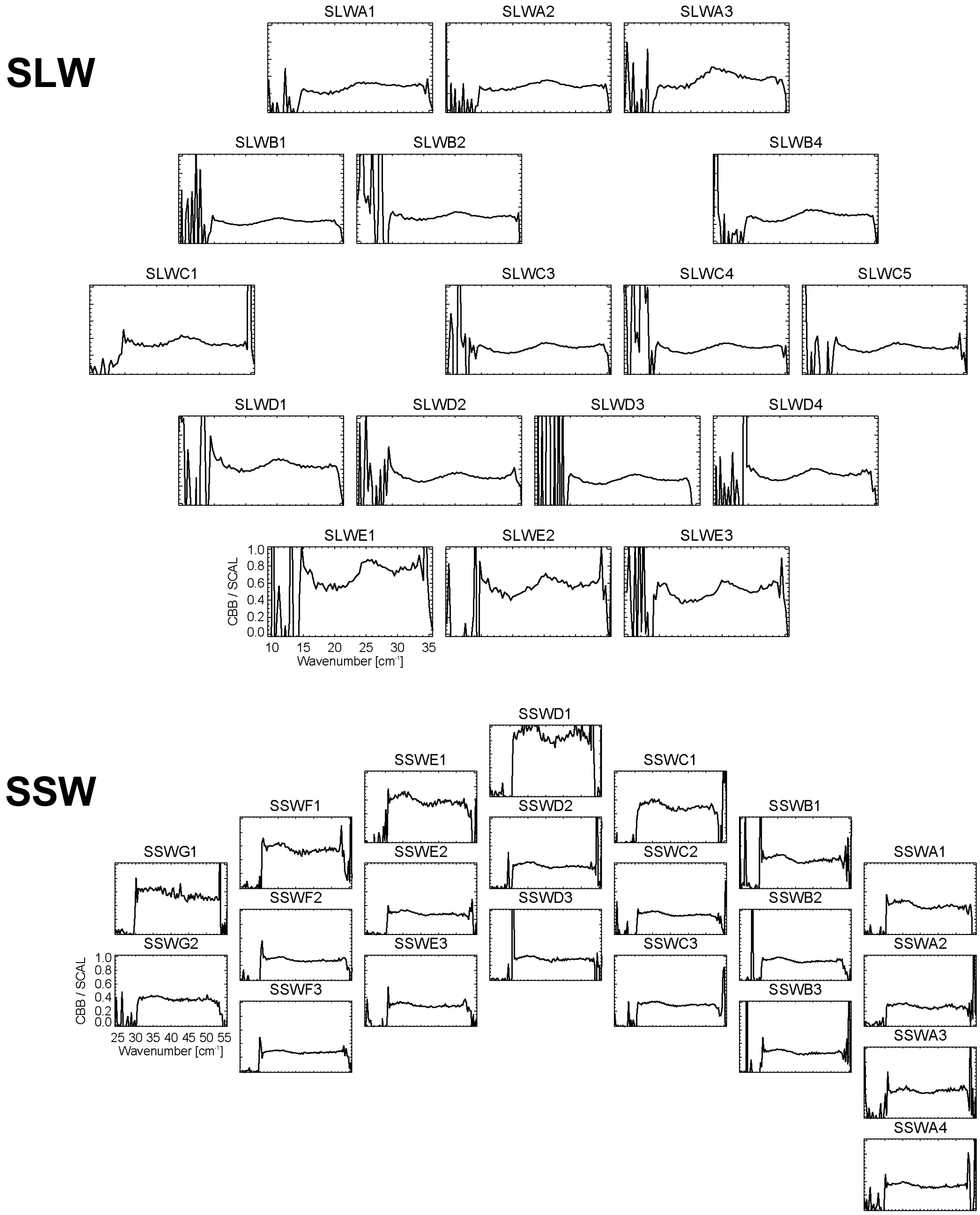

Figure 9: Measured Transmission Ratio, PFM3 data. In each case the curve represents the ratio of the measured CBB transmission to the measured SCAL transmission. This is a larger version of Figure 2.

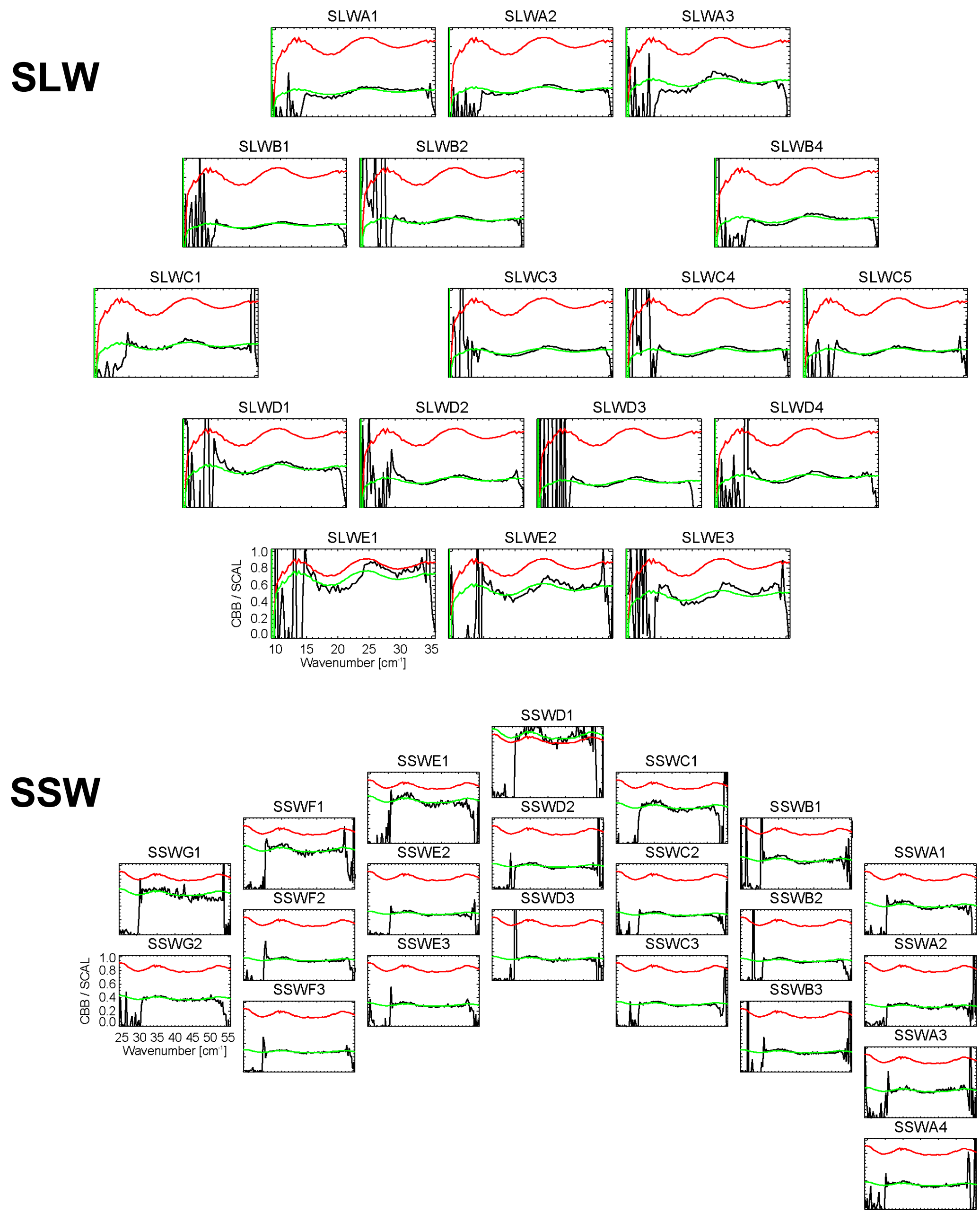

Figure 10: Measured Transmission Ratio, PFM3 data. In each case the black curve represents the ratio of the measured CBB transmission to the measured SCAL transmission. The extra curves shown are the products of the transmission of filters CFIL1 and SFIL2; the red curve is the raw product of the two filters and the green curve is a scaled version of that product. This is a larger version of Figure 4.