TITLE: **SPIRE calibration files: Spectrometer beam profiles**

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CHANGE RECORD

ISSUE	DATE	SECTION	REASON FOR CHANGE
0.1	27/10/08	All	First draft, not released
0.2	21/11/08	All	Attempt to generate spectral beam patterns from optical model (for consistency with Phot)
1.0	02/12/08	All	Issue with ASAP internal mode definition so switching to analytical model for spectral beam profiles

CONTENTS

APPLICABLE AND REFERENCE DOCUMENTS

RD1 M.Ferlet, "*SPIRE: calibration files: photometer beam profiles*", SPIRE-RAL-NOT-002949 issue 1.0 (25/07/2007)

RD2 M.Ferlet et al., "*Characterisation of Herschel-SPIRE flight model optical performances*", Proc. SPIE 7010 (2008)

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1. Introduction

This note reports on the generation of static noise-free SPIRE spectrometer beam profiles for the calibration files. Two types of beam profiles are considered: the spectral ones and the continuum ones.

The spectral beam patterns are defined as the optics+detector (one pixel scale) optical response at given in-band wavelengths for SSW and SLW. These are based on a mathematical model based on the coherent-mode representation and detailed in section 3 and as such are left to the end user for implementation and sampling choice.

The continuum beam patterns are similar distribution but representative of a broadband/continuum point source illumination. The continuum source spectrum is assumed Rayleigh-Jeans (RJ) type, matching general case of source including the one (hot black body) used during ILT characterisation. Following results in RD1, the difference between flat spectrum and RJ spectrum was found typically <0.5", not very relevant when nominal data sampling is set at 2". For global consistency with the Photometer files defined in RD1, the following grid size and sampling for the continuum Spectrometer files are used:

	SSW	**SLW**
Grid size (in '' on-sky)	**86"x86"**	**146"x144"**
Grid size (in samples)	**43x43**	**73x73**
Grid sampling (in '')	**2"**	**2"**

The generation of the continuum beam pattern files is discussed in section 2 below.

2. Continuum beam profiles

From ILT tests, we have the following results (see RD2) under broadband continuum illumination: beamsize for SSW was found 17.3+/-1.5" when reported at 250μm and 25.8+/-1.7" for SLW when reported at 350μm. In order to match these, goal of ~16.2" at effective equivalent wavelength 230μm for SSW and 30.0" for SLW at 390μm are used as criteria for the representativity of the final pixel maps in both bands.

Generation of the beam pattern is done with the optical model of the Spectrometer under ASAP2008v2R1. The ASAP project is "**SPIRE_SPEC_BOLSP509E**" and the relevant file are: *BOLSP509E_geom.inr* for the optical surface geometry and prescription from telescope to focal plane arrays along the Spectrometer optical path. The on-axis (Spectrometer FoV centre) source definition as well as trace and focal plane maps generation at the grid size and sampling defined in section 1 above is done with file *BOLSP509E_forward & coherent no split.inr.*
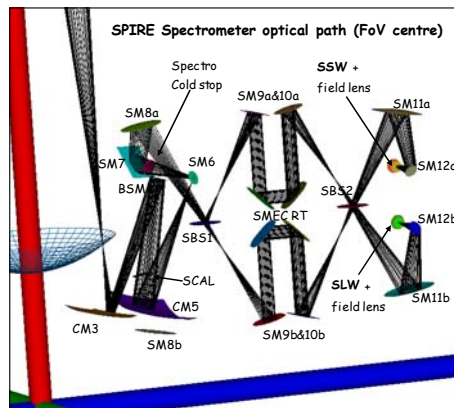
Figure 1: 3D layout with forward ray-trace through the SPIRE Spectrometer optical model under ASAP

The geometry does not contain the full telescope pupil obscuration geometry (i.e. spider, M2 mount structure) but the diffraction effect from such structure have been hardly noticeable in the Photometer case (see RD1), mostly due to the coarse grid sampling so here it is not considered as an issue.

The ILT measured beam pattern have been characterised by a spatial distribution with very Gaussian form factor therefore Gaussian apodisation of the source. A virtual edge taper setting is adapted in each band to obtain the criteria beamsizes above at the respective equivalent wavelengths and typically 4dB and 16dB for SSW and SLW have been chosen.

Different simulations have been performed to verify that when SMEC is at different position the resulting beam pattern characteristics and not affected. Variations <0.5" on beamsizes in both bands and across the full SMEC travel range have been found. Similarly tests have been done with varying field position across the FoV and similar results have been found so that the nominal case for the centre of FoV at any SMEC position is used in practice.

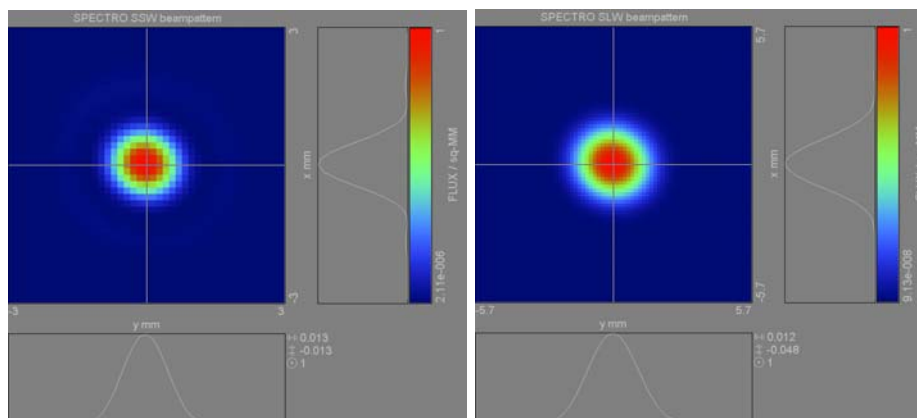Focal plane results of the optical modelling is shown below.

Figure 2: Example of reconstructed broadband SSW (left) and SLW (right) focal plane beam patterns

For illustration, the figure below shows in the case of PMW the results of PFM4 ILT (measured data), along side the one obtained by the above process (simulated, reconstructed) under ASAP, the output of which is a general readable ASCII data file.
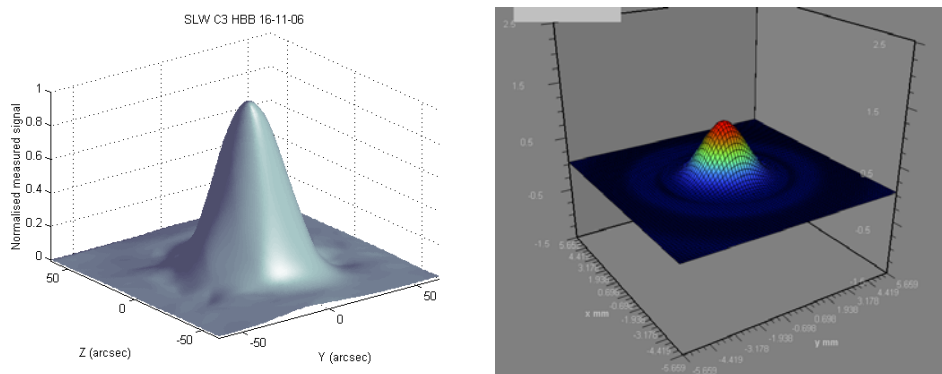

Figure 3: PFM4 ILT example results for SLW C3 with quasi point-source (diameter ~F.λ) and HBB source (left), beam pattern for SLW FoV centre from ASAP simulations (right).

***Remarks*:**
- The baseline telescope geometry and prescription was used in the model. This is now known to be slightly different from the expected flight case (from telescope OICD). Test have been run with the new configuration and ~5% broadening (+some asymmetry/rise of first sidelobe asymmetrically; all due to dominant appearance of coma aberrations) for SLW and ~10% for SSW have been found;
- SLW has shown some anomalous response to aperture size effect (see RD2 for example) possibly related to source mode content/spatial filtering and associated coupling to SLW detector mode so that the actual continuum spatial response characteristics (typically beamsize) may be affected in practice by the scale (when close to λ/D in size) and sub-structure (as mostly unresolved) of the continuum source itself. For that reason, the beamsize value of the attached file for SLW is given with ~+/-15% uncertainty to cover a range of diverse situations, only a few have been can be measured during ground calibration.

2. Spectral beam profiles

Results from ILT measurement, in terms of beam pattern size for in-band wavelength are reported below (from RD2). The main overall result is that the measured beam patterns no longer follow a pure optical behaviour (such as linear increase of beam size with wavelength in diffraction-limited regime) but appear dominated by detector system behaviour, in particular the modal filtering and spatial coherence reduction effect due to the waveguide between feedhorn and bolometer (a more extended summary is given in RD2). Because of this, a pure optical model of the spectral beam pattern is inadequate/not representative. Instead a mathematical model is proposed below.
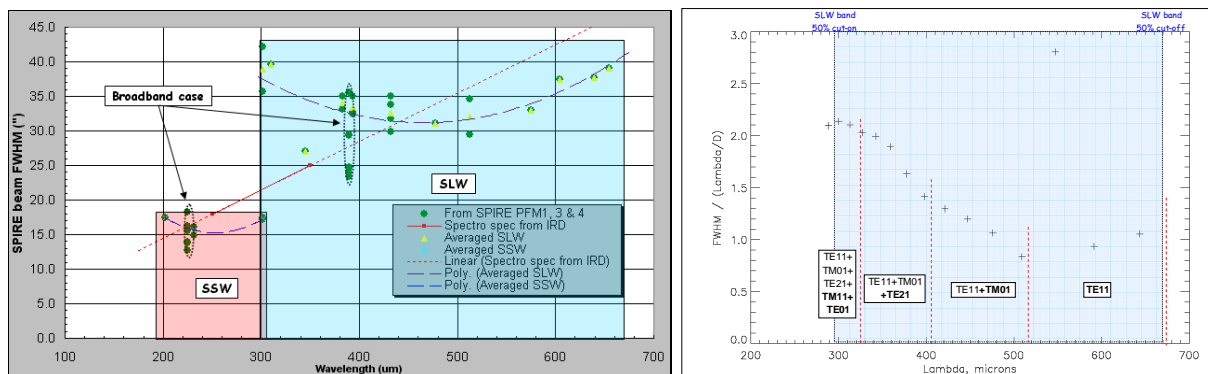

Figure 4: Spectrometer measured spectral beam size variations from ILT campaigns (left) and normalized to diffraction SLW beam size in-band variations with the waveguide modes and associated cut-off spectral locations (right)

Due to the generally Gaussian shape at first order of the beam pattern (departure from it are discussed below), a Gaussian-Shell Model (GSM) beam is assumed for the overall class and characteristics of the spectral beam pattern. The intensity or beam pattern at any given in-band wavelength is actually the diagonal element of the cross-spectral density matrix and from the coherent-mode representation of the cross-spectral density, one gets directly the following expansion:

$$S(r,\lambda) = W(r,r,\lambda) = \sum_{n=0}^{N} c_n(\lambda).|\varphi_n(r,\lambda)|^2 \qquad (1)$$

where the eigenfunctions used in the coherent-mode representation are typically part of family of functions forming an orthonormal basis and here a natural choice (in particular for globally Gaussian-shaped beam such as the case in the GSM approximation) is the well-known Hermite-Gauss functions basis given by:

$$\varphi_n(r,\lambda) = \left(\frac{2}{\pi}\right)^{1/4} \cdot \frac{1}{\sqrt{w_o(\lambda)}} \cdot \frac{1}{\sqrt{2^n.n!}} \cdot H_n\left(\sqrt{2}\,\frac{r}{w_o(\lambda)}\right) \cdot e^{-r^2/w_o^2(\lambda)} \qquad (2)$$

with $H_n(x)$ are the Hermite polynomials recalled below:

$$
\begin{aligned}
H_0(x) &= 1 \\
H_1(x) &= 2x \\
H_2(x) &= 4x^2 - 2 \\
H_3(x) &= 8x^3 - 12x \\
H_4(x) &= 16x^4 - 48x^2 + 12 \\
H_5(x) &= 32x^5 - 160x^3 + 120x
\end{aligned}
\qquad (3)
$$

The beam pattern can then be reconstructed from (1), with (2) and (3), and any in-band wavelength knowing the size parameter $w_o(\lambda)$ and the eigenvalues or expansion coefficients $c_n(\lambda)$.

Modal decomposition of ILT measured beam patterns when Spectrometer arrays were illuminated with unresolved spectral lines in-band led to the derivation of the modal coefficients and the size parameter. These are summarised in the table below. In practice, the expansion does not contain an infinite number of terms but is limited to only the first few non null ones due to fast decrease (exponential in theory in case of GSM) of the coefficient values. Here N=5 was found a good trade-off between good reconstruction without too large number of parameters (6 c_n coefficients & 1 size parameter) for each wavelengths.

	SSW			SLW											
lambda (um)	202.5	232.8	302.3	302.3	310	345	382.64	393.6	432.6	477.4	513	575	604.25	642	655
wo (")	10.97	11.13	13.35	20.03	20.45	17.80	21.08	21.17	21.92	22.52	23.67	25.43	27.77	28.70	29.52
c0	60.76%	75.74%	86.76%	40.42%	40.72%	66.12%	58.65%	61.52%	68.69%	77.92%	80.88%	86.47%	81.38%	84.82%	84.00%
c1	28.95%	17.58%	9.50%	46.31%	46.02%	24.81%	30.62%	28.36%	22.85%	15.97%	13.79%	9.71%	13.42%	10.91%	11.50%
c2	8.38%	3.09%	0.90%	21.44%	21.18%	6.16%	9.37%	8.04%	5.22%	2.55%	1.90%	0.94%	1.80%	1.19%	1.32%
c3	2.43%	0.54%	0.09%	9.93%	9.75%	1.53%	2.87%	2.28%	1.19%	0.41%	0.26%	0.09%	0.24%	0.13%	0.15%
c4	0.70%	0.10%	0.01%	4.60%	4.48%	0.38%	0.88%	0.65%	0.27%	0.06%	0.04%	0.01%	0.03%	0.01%	0.02%
c5	0.20%	0.02%	0.00%	2.13%	2.06%	0.09%	0.27%	0.18%	0.06%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 1: Size parameters and expansion coefficients as function of wavelengths used during ILT characterisation for the spectrometer spectral beam patterns reconstruction (extracted from file: "***SPIRE Spectro beam scans deconvolution result (version 1).xls***", spreadsheet "Summary")

For values in-between parameters, e.g. if wavelength of interest is between 2 listed in table above, local interpolation of the coefficients is acceptable.

The sum of the c_n coefficients should be, by definition of the expansion, equal to the integral of the beam pattern intensity distribution i.e. the total power which should be 1 or close to 1 (thanks to the normalisation of c_0 from 1 to the power in the fundamental mode). The difference gives an overall estimate of the model reconstruction error: this difference is, as expected, very low in the single-mode regime (longwave part of each band) while this can reach ~20% in the worst-case (SLW shortwave band edge). Note this encompass the error from ILT spectral beam pattern measurements, the decomposition error and truncation of the expansion in the reconstruction.

Validation is performed here in the worst-case situation, the multi-moded shortwave end of SLW band, via comparative illustration below of the ILT measurement result with the reconstructed beam pattern from the above model. The model can handle the no longer Gaussian shape and the not centrally peaked beam pattern distribution, which is expected from multi-moded waveguide theory and early numerical analysis.
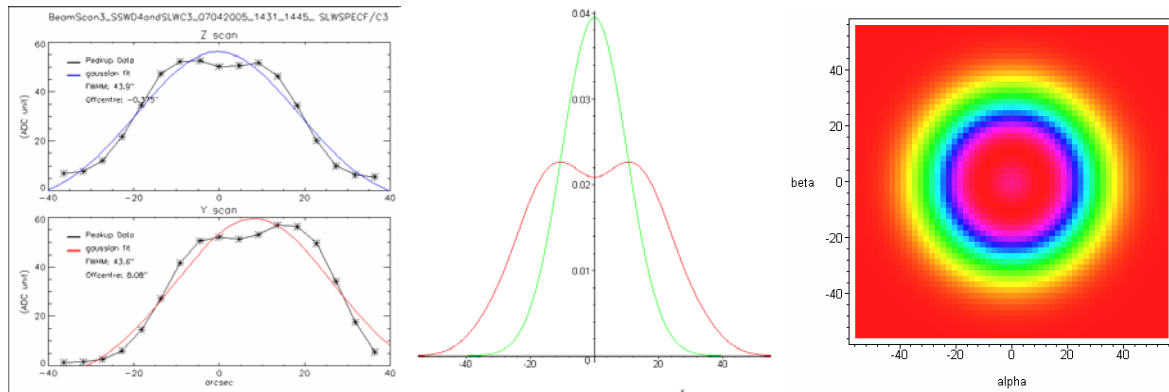
Figure 5: Left: Results from ILT PFM1 characterisation (peak-up on SLW C3) with laser line at 302.3μm i.e. shortwave edge of SLW band, experimental data indicating a not-centrally-peaked pattern; **Centre:** at same wavelength, reconstructed pattern (red) using the coherent mode representation and comparison with the case of a pure single mode Gaussian with similar w_o parameter (green); **Right:** associated false colour 2D density map of the reconstructed pattern on a square grid extending 110" with 2" sampling.

**Remarks****:** Because of the dominance of the detector behaviour in the spectral beam patterns, the proposed model can be in principle applied for any SSW or SLW pixels. Actually the mathematical nature of the model and its circular symmetry makes it more relevant to Spectrometer FoV central pixels, expected more free of vignetting and associated diffraction broadening which can induce increase ellipticity of the beam pattern. As the expansion parameters are derived from the actual measurements, they would include some effect (broadening) from residual optical aberrations. The diffraction effects of telescope obscuration is not included here as proposed model not originated from optical model but from previous modelling on the Photometer (see RD1) the low level diffraction sidelobe structure is smoothed out by grid sampling with step larger than ~1".

3. List of attached files

A total of 2 files are attached to this note. They stand for the representative peak-normalised broadband/continuum Spectro beam profiles obtained from the process described in section 2 of this note. The details are as follows:

- for SSW: file "_**spectro_ssw_continuum.din**_"

- for SLW: file "_**spectro_slw_continuum.din**_"

Their format is the standard ASCII output (".din" extension) of data distribution from the ASAP software. Import to general processing tool/language such as IDL can be done via the suggested basic IDL script listed in Appendix.

The spectral beam profiles are not generated as attached file(s) because described by a mathematical model (see section 3) and therefore left to the user to choose the its preferred format and environment (as well as grid sampling for example) for the implementation of the proposed model.

Appendix   IDL script to read the Photometer beam ASAP ".din" files

```
; IDL file:   read_asap.pro
; by Marc Ferlet (STFC, RAL/SSTD), July 07
; & based on similar general scripts used for MSG/GERB and others
;
; this scripts  reads the ASAP ".din" ascii file format and
; uses the header info to generate the absicca values
; and returns a 2-d array of values v for v=f(x,y) plotting
;

name='D:\phot_pmw_flat.din'  ; this is an example

 openr,unit,name,/get_lun

 title='abcdefghijk'
 readf,unit,format='(a12)',title
 print,title

 ztitle='abcdefghijk'
 valtitle='abcdefghijk'
 readf,unit,format='(a11,f8,a30)',ztitle,zpos,valtitle
 print,ztitle,' ',zpos,' ',valtitle

 xtitle='abcdefghijk'
 nxpts=intarr(1)
 ;readf,unit,format='(a20,f10,f15,i10)',xtitle,xmin,xmax,nxpts
 readf,unit,format='(a20,g15,g13,i10)',xtitle,xmin,xmax,nxpts
 print,xtitle,' ',xmin,' ',xmax,' ',nxpts

 ytitle='abcdefghijk'
 nypts=intarr(1)
 ;readf,unit,format='(a20,f10,f15,i10)',ytitle,ymin,ymax,nypts
 readf,unit,format='(a20,g15,g13,i10)',ytitle,ymin,ymax,nypts
 print,ytitle,' ',ymin,' ',ymax,' ',nypts

 dum='abcdefghijk'
 readf,unit,format='(a20)',dum
 print,dum

 arrsiz=intarr(1)
 arrsiz(0)=abs(round(nxpts)*round(nypts))  ; size of data grid

 array=fltarr(nxpts(0),nypts(0))
 readf,unit,array

 close,unit
 free_lun,unit

print,'************ read asap data ************'
print,'data read from ',name,' is :',nxpts,' by ',nypts

 x=fltarr(nxpts(0),nxpts(0))
 y=fltarr(nxpts(0),nxpts(0))

for i=0,nxpts(0)-1 do begin
 x(i,*)=(xmin+i*(xmax-xmin)/(nxpts(0)-1))*12.57887
 y(*,i)=(ymin+i*(ymax-ymin)/(nxpts(0)-1))*12.57887
endfor

v=transpose(array)

shade_surf, v, x, y   ; this is just for visu check
```