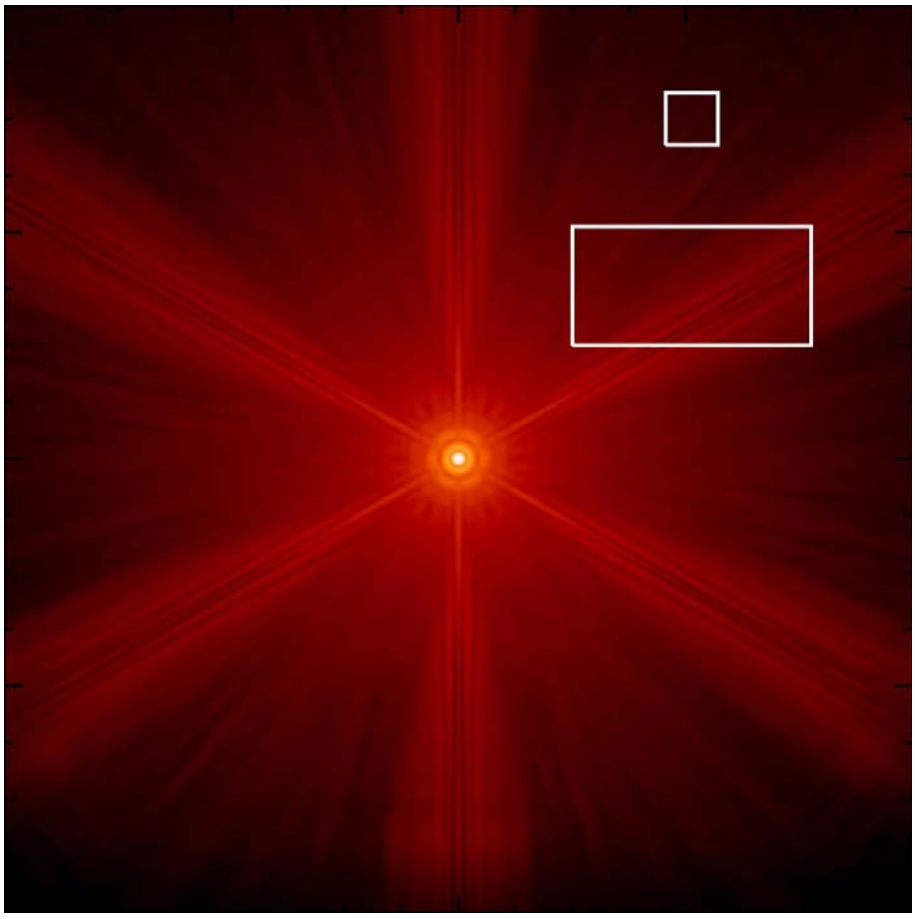
Herschel/PACS modelled point-spread functions

Authors:
N. Geis, D. Lutz



This note describes the methods used to model a set of Herschel/PACS point-spread functions and their conversion into user-friendly monochromatic (spectrometer) and filter-convolved (photometer) images containing the point-spread function.

The models are based on Zemax and a Herschel optical model and will provide better fidelity than more simple approaches that are based on Bessel functions or on Fourier transformation of an aperture map. Nevertheless, Version 1.0 made simplifying assumptions about the telescope properties (ideal lens without wavefront errors) that strongly limited its realism.

Version 2.0 of this note implements a telescope model with wavefront error, as derived on ground. It is able to reproduce the key triangular asymmetry of the in-orbit PSF. It is however not an accurate representation of the in orbit PSF at the level recommended for accurate PSF fitting photometry, or for assessing the reality of faint objects in the PSF wings of a bright source.

Section 5 of this note describes the data products and their access via a web site.

Document Change Log

Document Title		Herschel/PACS modelled point-spread functions	
Reference No:		PICC-ME-TN-029	
Issue	Revision	Date	Reason for change
Issue	1.0	19-Feb 2009	Didn't exist before
	2.0	03-Aug-2010	'As built' model with wavefront error

Applicable and Reference Documents

RD-1: "*Optical Mathematical Model Description note*", HER.NT.0027.T.ASTR, issue 2.0

AD-1: PCD Pacs Calibration Document PACS-MA-GS-001

1 Introduction *4*

2 PSF Modelling *4*

2.1 Optical Model Setup **4**

2.2 The Ideal Telescope **6**

2.3 The "As-Built" Telescope **6**

3 Interpolation of PSF Data *10*

4 Conversion to homogeneous PSF library *11*

4.1 Monochromatic finely sampled PSFs on the sky **11**

4.1.1 Example monochromatic PSFs for 'ideal' telescope 12

4.1.2 Example monochromatic PSFs for 'as built' telescope 13

4.2 Filter-convolved broad-band PSFs for the photometer **15**

4.2.1 Example broadband PSFs for 'ideal' telescope 15

4.2.2 Example broadband PSFs for 'as built' telescope 17

5 Data products *19*

1 Introduction

This note describes the derivation of a set of model PSFs for PACS, presented in the form of 0.4arcsec sampled fits images projected onto the sky. The PSF images are for an assumed Herschel position angle of 0 degree.

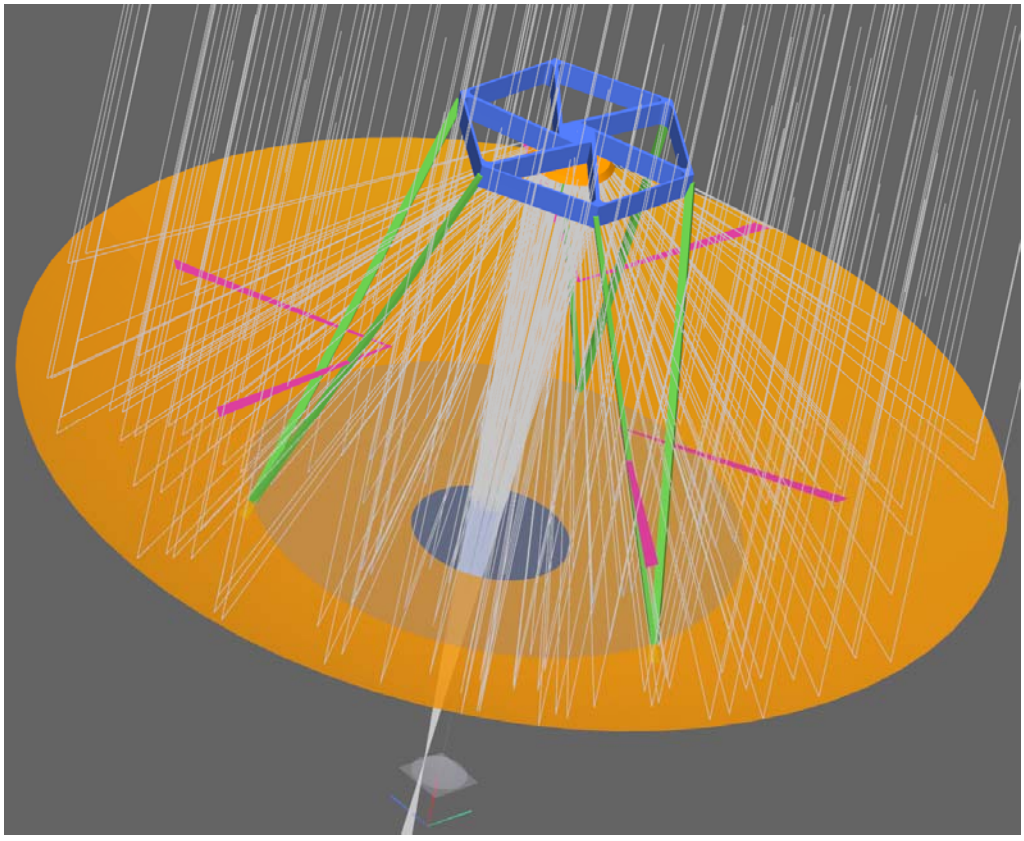
The images only present the projection of the telescope's PSF, without considering optical effect within PACS. They do no include the sampling by the detector pixels. They also do not consider effects like pointing jitter that noticeably affect the effective PSF. Making appropriate assumptions for these and for the telescope position angle may vary from case to case and is left to the user of these products.

2 PSF Modelling

2.1 Optical Model Setup

As an initial model for the *Herschel* telescope, a geometrical obscuration model was developed from a simplified 3D model of the telescope that correctly models the pupil obscuration effects. In addition, off-axis projection effects (including pupil tilt) are realistic in this model.

A simplified 3D-model of the Telescope, based on the interface drawings in IID-A, Annex 11 was built within Zemax. This is shown in the next figure.



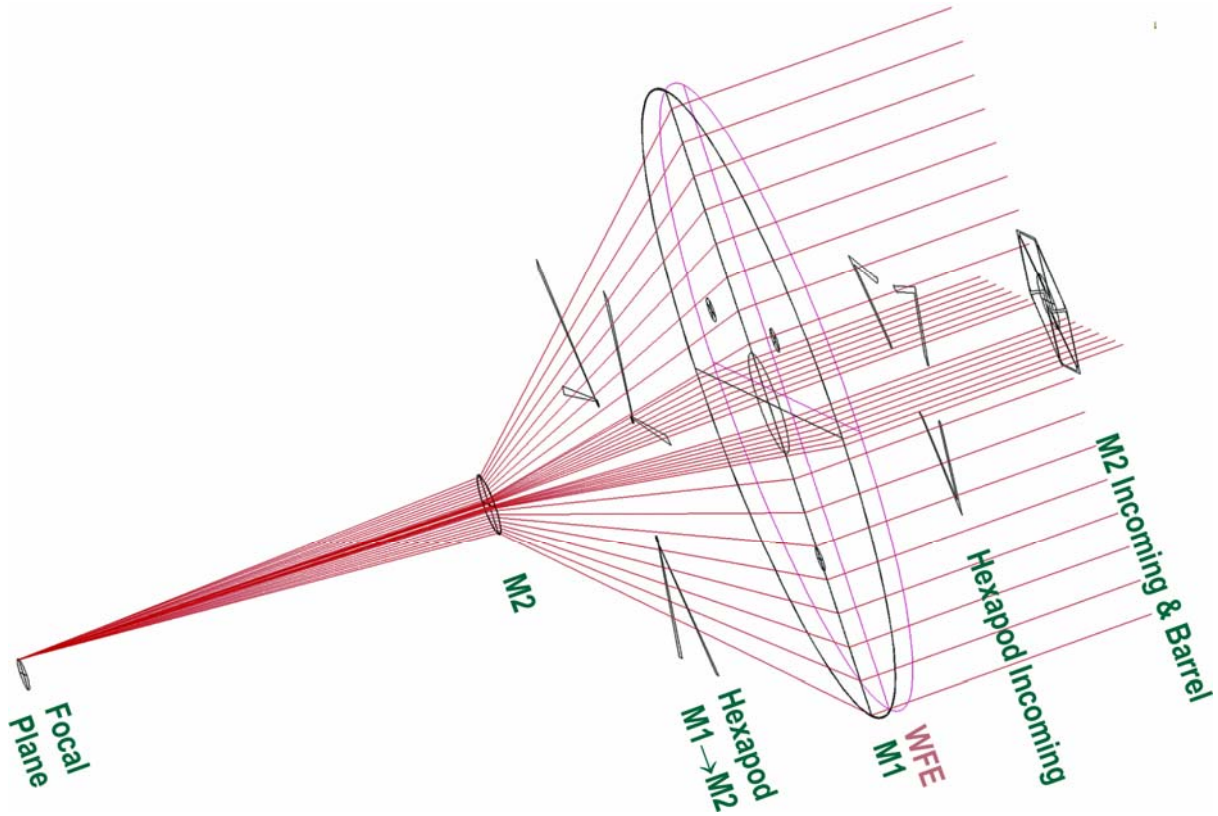
Face-on obscuring elements were introduced as direct outlines in the plane where they occur. E.g., the hexagonal M2 support structure ("barrel", blue) and M2 itself were placed approximately 1.6 m in front of M1.

Tilted obscuring elements like the M2 support hexapod (green) were modelled as shadow maps at their middle position along the optical path (in purple: shadow mask for the converging beam between M1 to M2). For this, non-sequential ray tracing was performed for the 3D-model. The beam shadow cast by the mechanical parts, in forward and reverse projection onto the middle plane, was traced as a polygonal outline and implemented as an obscuration map in the corresponding diffraction optical model shown below.

The mirror outlines themselves were implemented as spatial apodisation maps. This allowed for soft edges, which reduces somewhat the occurrence of very high-frequency components (aliasing) in the diffracted beams.

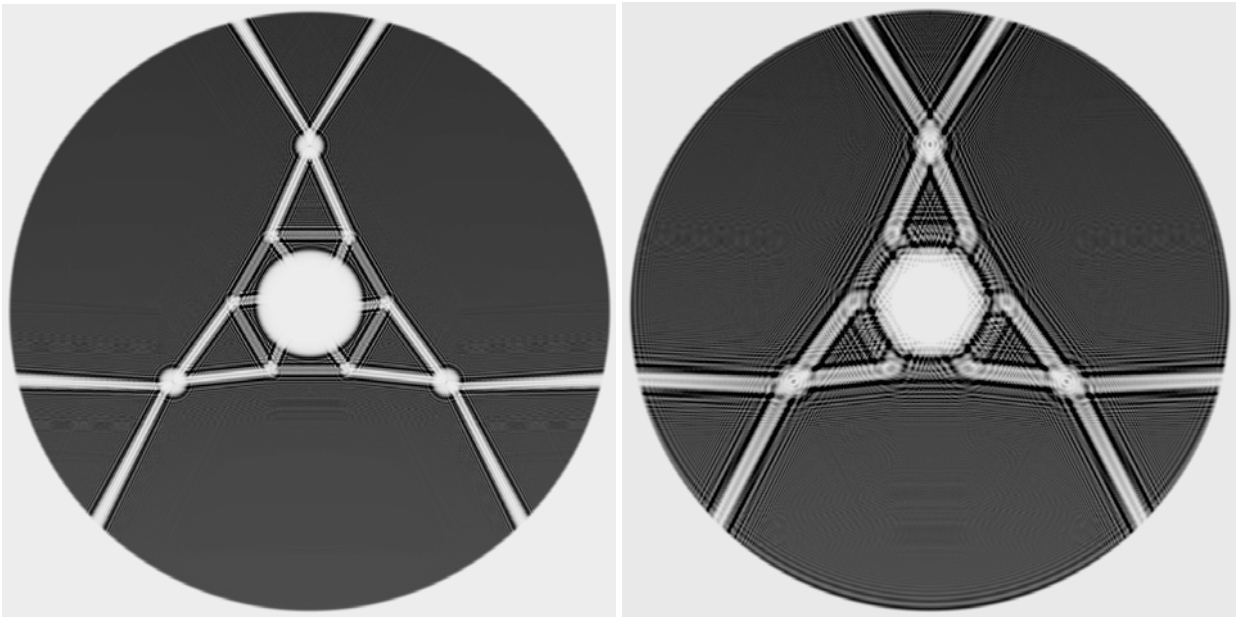
Nevertheless, even at the highest spatial sampling allowed by Zemax at the time of the computing runs (4096×4096 "ideal", 8192×8192 "as-built"), strong aliasing would occur due to the fast beams (high Fresnel-number). To control the artefacts, additional re-sampling and spatial filtering stations had to be introduced every 500 – 1000 mm along the optical path.

The next figure shows the optical layout for which the PSFs were calculated (intermediate re-sampling planes not shown). For the "as-built" telescope, the wavefront error terms (WFE) supplied by industry were inserted immediately in front of M1.



The resulting exit pupil maps of the telescope on M2, including the diffraction effects from preceding elements, are shown as negatives, for the extreme wavelengths of λ = 54 μm (left) and

200 μm (right), in the following panel. Clearly, diffraction effects are already important, including large residual phase variations near the edges, which are not shown here. Consequently, a Fourier transform of the pupil intensity map from straightforward geometrical obscuration will not give valid PSFs, especially at long wavelength.



Zemax offers the option of selecting diffraction propagation modes manually when its built-in automatic propagation code fails. This may happen in very fast beams, or when the Fresnel number does not change very much between subsequent surfaces, i.e. the propagation does not transition between far and near fields.

In the current model, manual propagation parameter selection showed marginally better results (fewer artefacts in the outermost regions of the PSF) only for the shortest wavelengths, $\lambda \sim$ 50 μm – 75 μm.

To keep the data set (coverage and sampling) consistent, only PSFs created in automatic propagation mode have been used for this document.

2.2 The Ideal Telescope

Since the telescope mirrors have been replaced by ideal lenses in the simplified optical model, the "ideal" PSF results described below do not contain any of the optical aberrations of a real telescope. Asymmetries and deviations from hexagonal/circular symmetry occur only due to the off-axis position of the PACS field (Z = 80 mm).

2.3 The "As-Built" Telescope

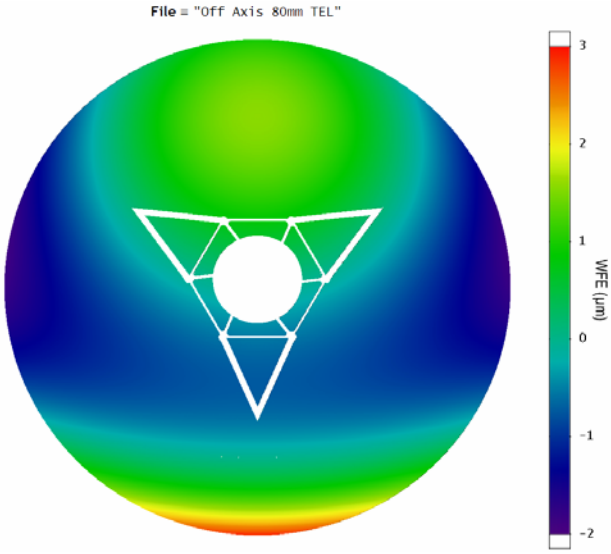
For the "as built" telescope, the model of the ideal telescope was supplemented by the WFE maps and information supplied by Astrium-Toulouse in [RD1]. The Code-V telescope prescription for T = 70 K was converted to Zemax, including the extra in-orbit terms mentioned in the text at the end of chapter 4 of that document, but excluding the estimated error of the ground-to-

orbit 0g extrapolation of 1.4 µm, of which we have no detailed knowledge except for its estimated magnitude.

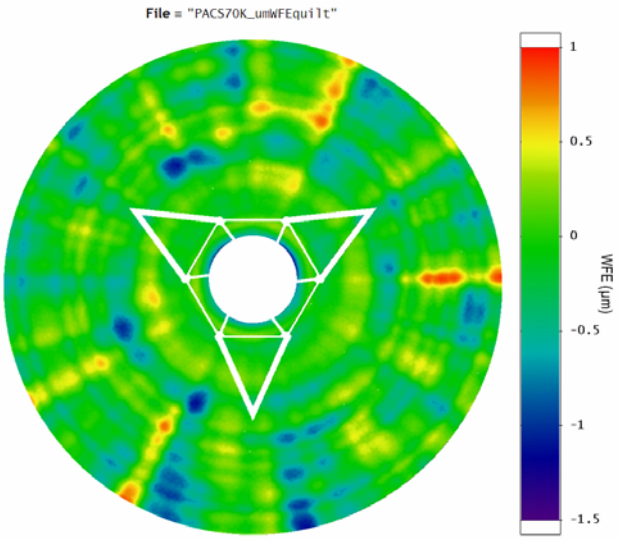
The ideal lens telescope recipe was then adjusted (de-spacing and focal lengths) to give the correct geometry and the same on-axis system effective focal length as the Code V telescope without the explicit WFE terms.

The telescope aberrations at the PACS field-of view were fitted by Zernike fringes within the as-built (without WFE terms) Cassegrain prescription. The resulting WFE map was then added to the ideal lens design in the same way as the manufacturing WFE maps.

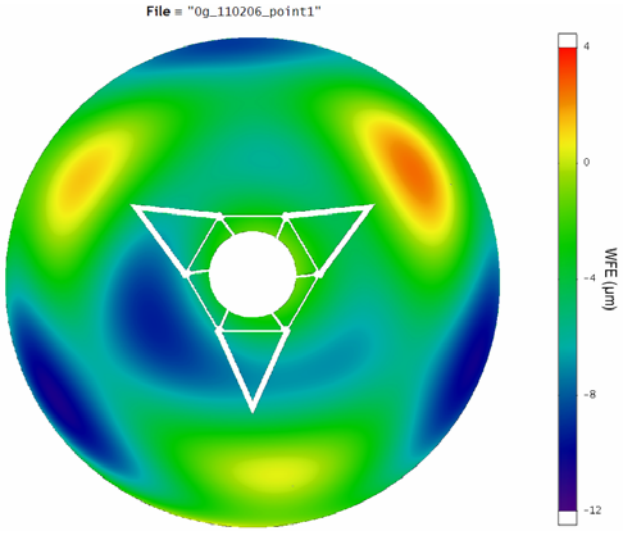
Most of the WFE maps in [RD1] are given as "Arizona fringes". Some of them contain tilt terms which lead to a position shift in the focal plane, independent of wavelength. In the following visualisations the tilt has been removed to better see the higher order terms which affect image PSF shape.



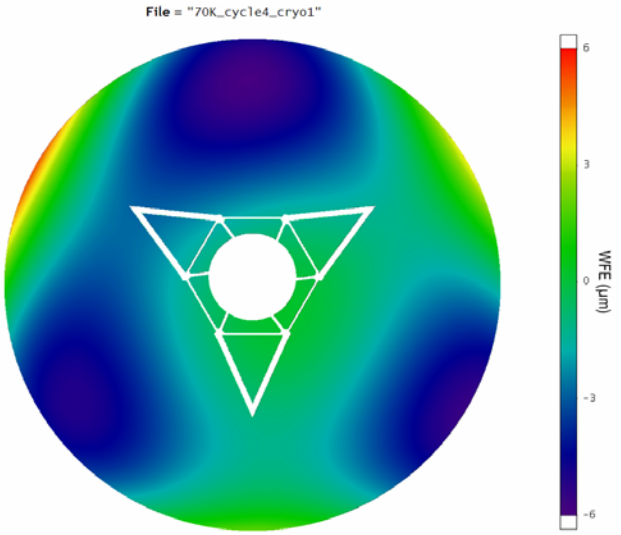
Off-axis WFE of the nominal Cassegrain Telescope for the centre position of the PACS FOV (remains good in an area $\Delta_{Z,Y} \sim 40$mm from [80,0]). Dominated by coma and astigmatism. (RMS = 1 µm)



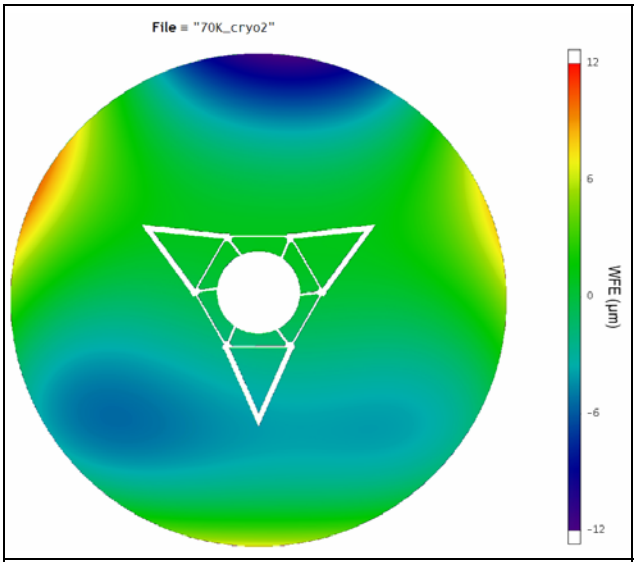
High Frequency polishing errors and quilting (from M. v. d. Vorst, ESA, priv. comm.). (RMS = 0.3 µm)



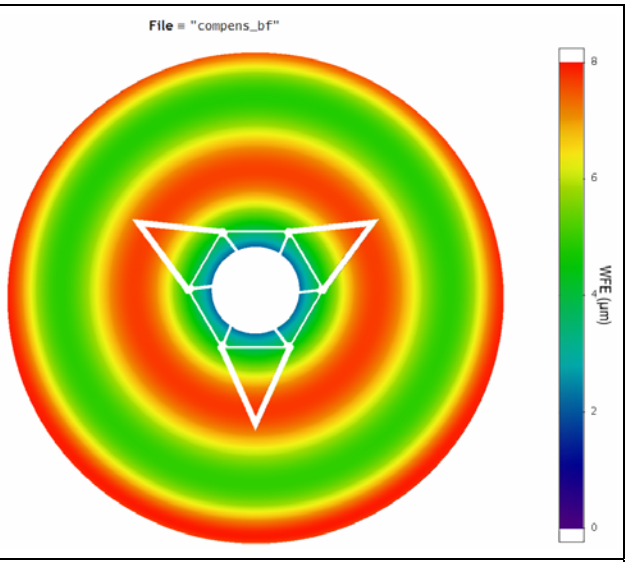
"0g"-measurement 110206_point1 (RMS = 2.8 µm)



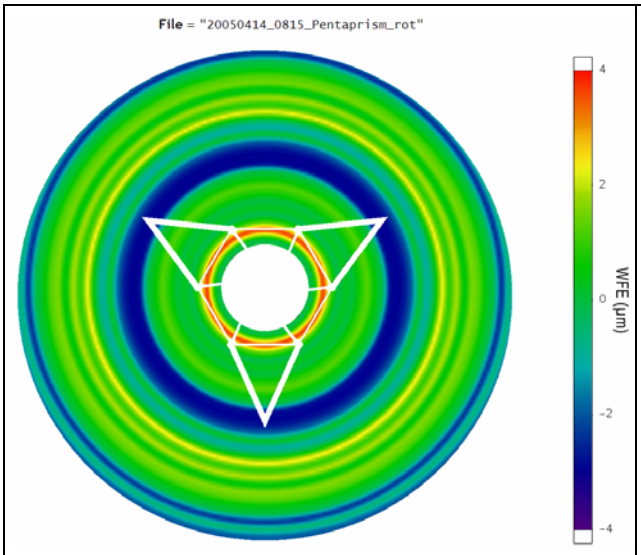
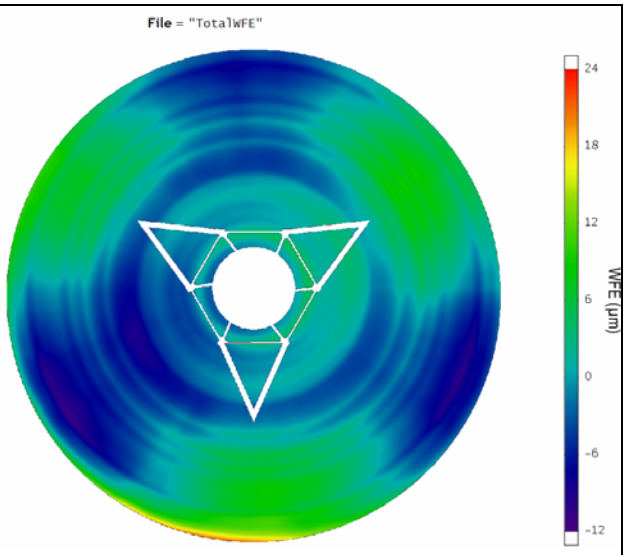
Telescope cool down WFE during cryo-campaign 1, cycle 4, *used for the calculations* (RMS = 1.9 µm)



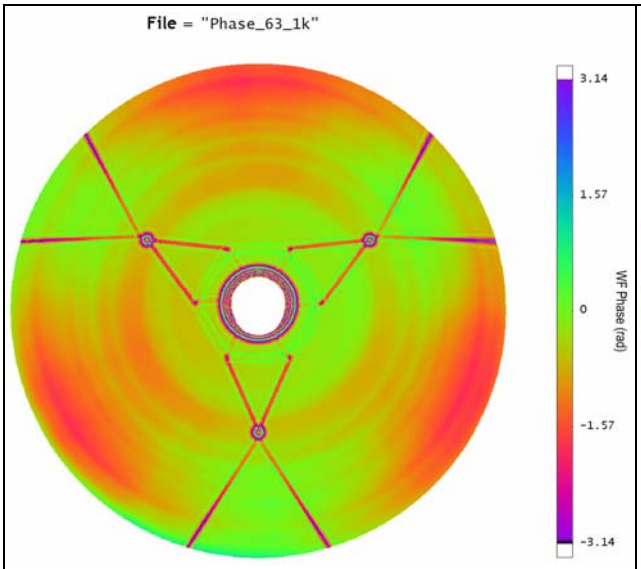
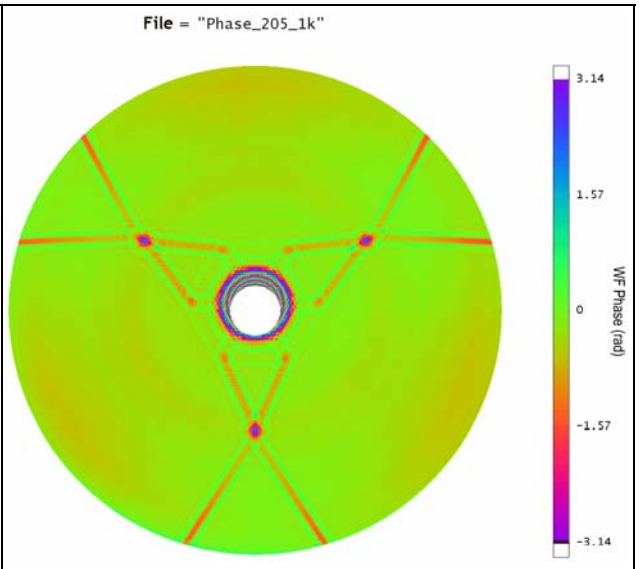
Telescope cool down WFE during cryo-campaign 2, *not used for the calculations* (RMS = 3.3 µm)

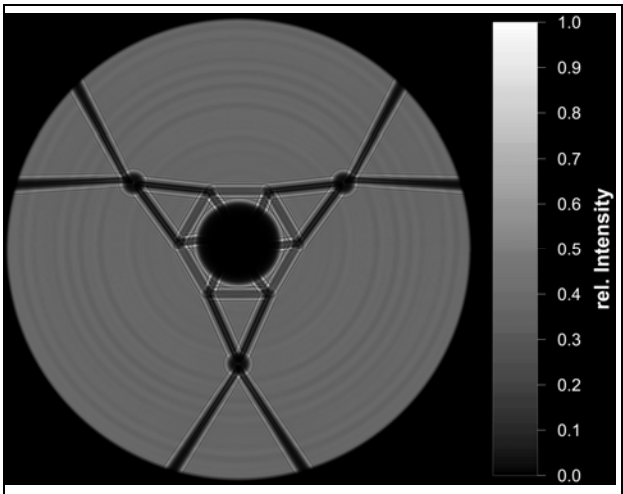


Ring-like polishing residuals, radially averaged, low spatial frequency (RMS = 1.1 µm)

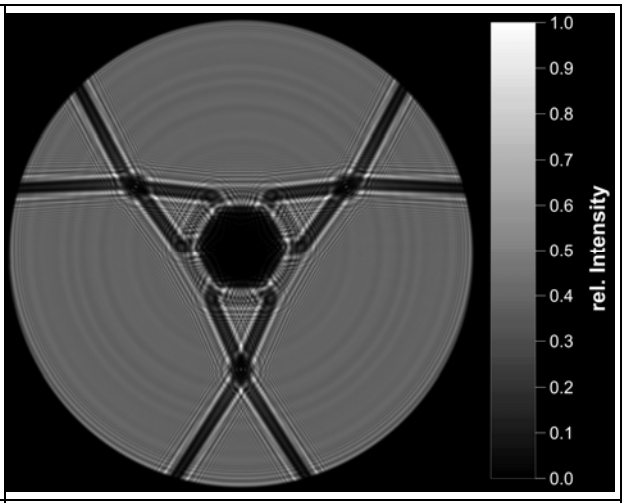
	
Ring-like polishing residuals, radially averaged, high spatial frequency (RMS = 1.4 µm)	Sum of all wavefront error components (with signs according to [RD1] (RMS = 4.6 µm)

All these WFE terms were added in front of M1. At the M2 pupil, with additional shadowing and diffraction propagation after the obscuring structures, the wavefront map at the system pupil evolves to the following appearance in phase and amplitude, shown for two different wavelengths:

	
Wavefront Phase Map for λ = 63 µm at centre of the PACS FOV.	Wavefront Phase Map for λ = 205 µm at centre of the PACS FOV.



Wavefront Intensity Map for λ = 63 μm at the centre of the PACS FOV.



Wavefront Intensity Map for λ = 205 μm at the centre of the PACS FOV.

3 Interpolation of PSF Data

We wish to interpolate a PSF for a certain wavelength **λo**, the PSF of which has not been provided as a data product. Making use of the fact that PSF shape scales approximately linearly with wavelength, one can interpolate given PSF data from nearby wavelengths.

Let **λ1** and **λ2** be the wavelengths of the nearest shorter and longer wavelengths in the PSF data catalogue such that $\lambda 1 < \lambda o < \lambda 2$.

The following recipe can be used for interpolation:

1. In the FITS header of PSF(**λ1**), replace these three values:
   `WAVELEN = λ1` ➔ `WAVELEN = λo`
   `CDELT1 = val1` ➔ `CDELT1 = val1 * λ1/λo`
   `CDELT2 = val2` ➔ `CDELT2 = val2 * λ1/λo`
2. In the FITS header of PSF(λ2), replace these three values:
   `WAVELEN = λ2` ➔ `WAVELEN = λo`
   `CDELT1 = val1` ➔ `CDELT1 = val1 * λ2/λo`
   `CDELT2 = val2` ➔ `CDELT2 = val2 * λ2/λo`
3. Save as new FITS files or buffers, PSF1(**λo**) and PSF2(**λo**). The extent and pixel pitch for these two maps will naturally be different.
4. Re-grid/interpolate each FITS array, PSF1 and PSF2, separately to a common pixel pitch, using a package that respects WCS headers for individual pixel positions:
   $PSF1_{m,n}(\lambda o)$ ➔ $PSF1'_{i,j}(\lambda o)$
   $PSF2_{p,q}(\lambda o)$ ➔ $PSF2'_{i,j}(\lambda o)$
5. The – linearly-weighted by wavelength-distance – interpolated average for each pixel [i,j] of the new grid, at the :
   $$PSF_{i,j}(\lambda o) = (1/|\lambda 2 - \lambda 1|) \times \left[|\lambda 2 - \lambda o| \cdot PSF1'_{i,j}(\lambda o) + |\lambda 1 - \lambda o| \cdot PSF2'_{i,j}(\lambda o)\right]$$

4 Conversion to homogeneous PSF library

4.1 Monochromatic finely sampled PSFs on the sky

The Zemax output describes the PSF in the focal plane of Herschel in mm. For technical reasons, these images have scales that differ slightly between the two dimensions and from wavelength to wavelength. Assuming a Herschel focal length 28498.4mm, we have used the IDL astrolib hastrom utility with cubic interpolation to interpolate all Zemax PSFs to a consistent 0.4arcsec pixel image on sky, and saved as fits images. The original Zemax pixel scale is similar, so that interpolation effects will be small. Orientation has been adjusted so that these fits images follow the usual astronomical convention of north being on top and east to the left. The library PSFs refer to Satellite position angle 0, and have been normalized to integrated flux 1. The PSF is centred on pixel 1000,1000 (FITS convention) i.e. 999,999 (IDL convention). This is the case by default for the 'ideal telescope' PSFs. For the 'as built' PSFs the wavefront error includes a tilt component that moves the PSF centre. We re-centred the library PSFs so that a 2D Gaussian fit retrieves again pixel 1000,1000 but note that due to asymmetries of the `as built' PSF the exact centre will depend on the measurement method used.

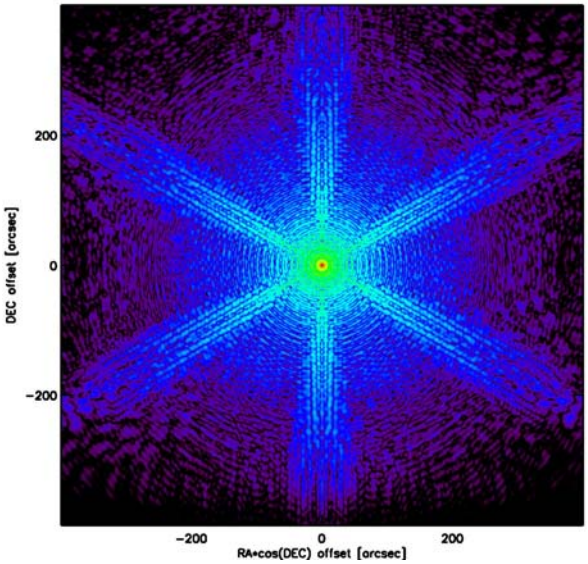
We show below two sets of Figures with examples of monochromatic PSFs for 70, 110, and 170μm, for the two types of models. For these and other PSF examples in this note, two panels show the entire 800*800arcsec image of the PSF, plus a zoom into the inner 80*80arcsec of the PSF. Both panels are shown with suitable (logarithmic) colour scaling and range.

Note that on large scales (in particular North-South), the PSFs are not strictly symmetric. This is caused mainly by the non-central location of PACS in the focal plane. The effect occurs at flux levels that are hard to observe in reality, however.

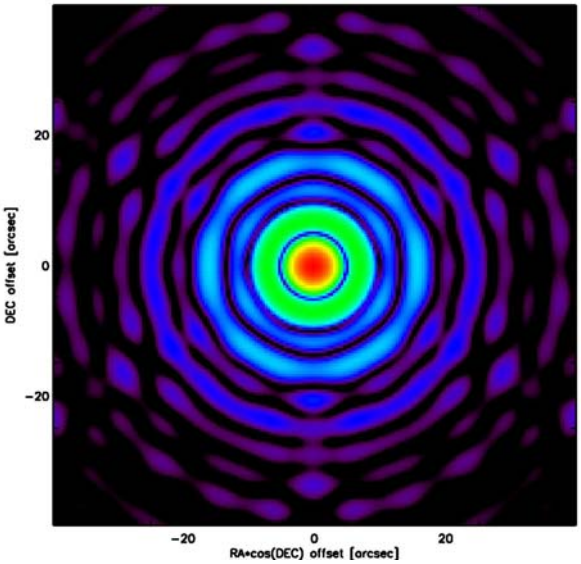
Example of a fits header:

```
SIMPLE =          T / Written by IDL: Tue Feb 17 14:32:30 2009
BITPIX = -64
NAXIS  = 2
NAXIS1 =         1999 /
NAXIS2 =         1999 /
CRPIX1 =       1000.00 /
CRPIX2 =       1000.00 /
CRVAL1 =       0.00000 / R.A. (degrees) of reference pixel
CRVAL2 =       0.00000 / Declination of reference pixel
CDELT1 =     -0.000111111 /
CDELT2 =     0.000111111 /
CTYPE1 = 'RA---TAN'      /
CTYPE2 = 'DEC--TAN'      /
CUNIT1 = 'deg    '      /
CUNIT2 = 'deg    '      /
WAVELEN = 54
COMMENT Telescope is made of 2 ideal lenses. Physical obscurations introduced
COMMENT at correct places along the path. Eff.focal length is 28498.4 mm.
COMMENT PSF projected onto paraxial focal plane using cosec(incoming angle)
COMMENT Peak Flux ["W"/pix]: 0.003660057149
COMMENT Peak Flux ["W"/mm2]: 2.579161107
COMMENT Map Flux ["W"]  : 0.748276
COMMENT WAVELEN unit: microns
END
```

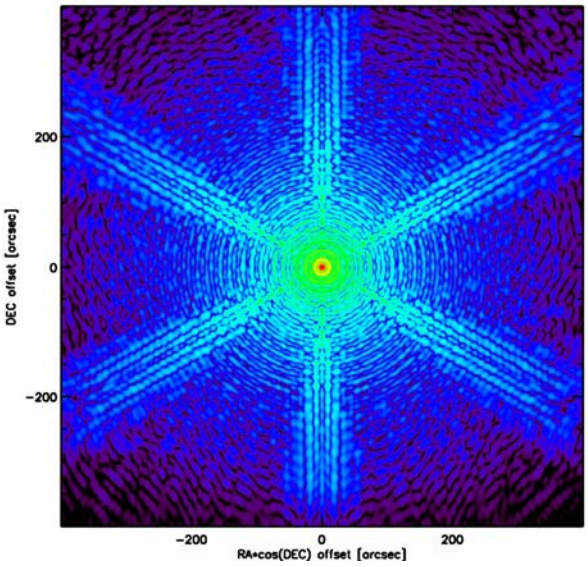
4.1.1 Example monochromatic PSFs for 'ideal' telescope



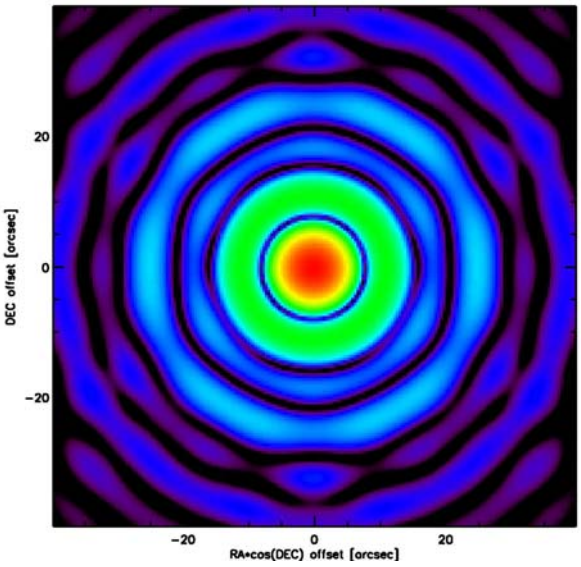
70µm monochr. PSF Display range 8dex



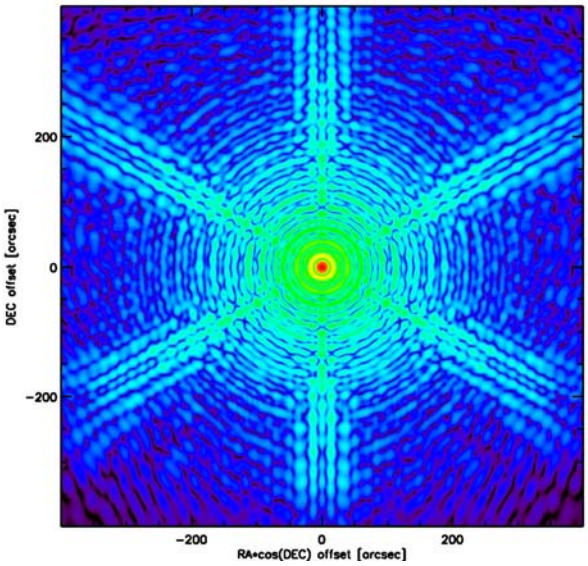
70µm monochr. PSF. Display range 4dex



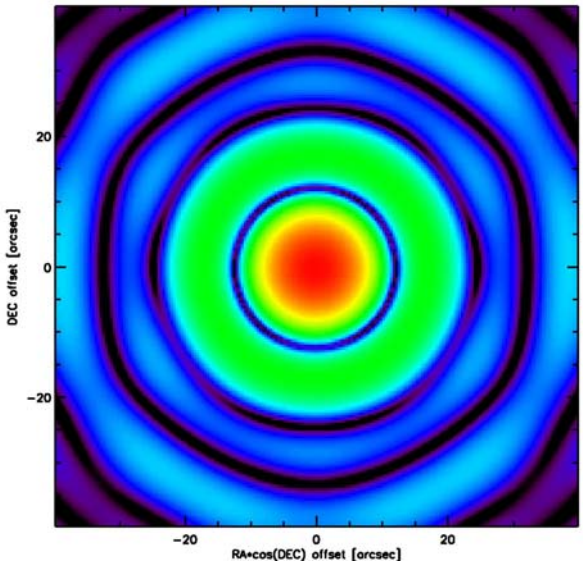
110µm monochr. PSF. Display range 8dex



110µm monochr. PSF. Display range 4dex

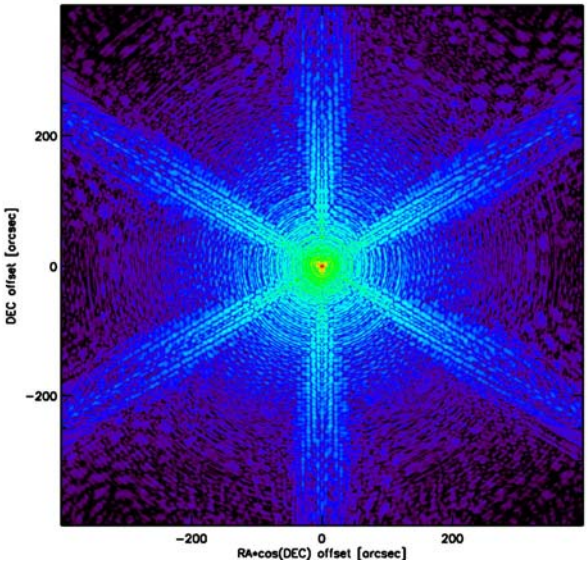


170µm monochr. PSF. Display range 8dex

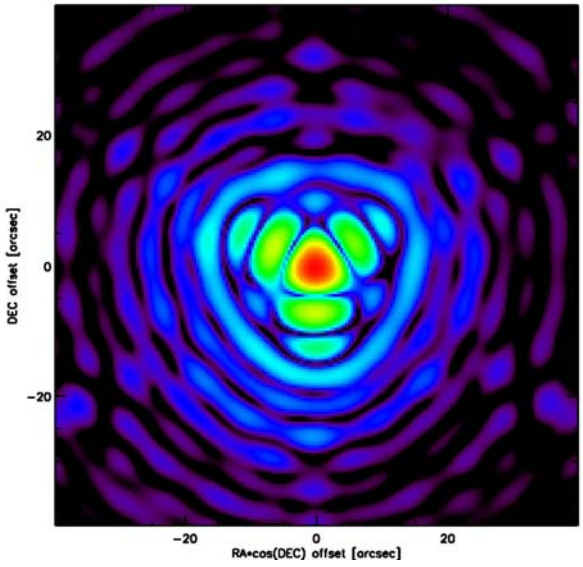


170µm monochr. PSF. Display range 4dex

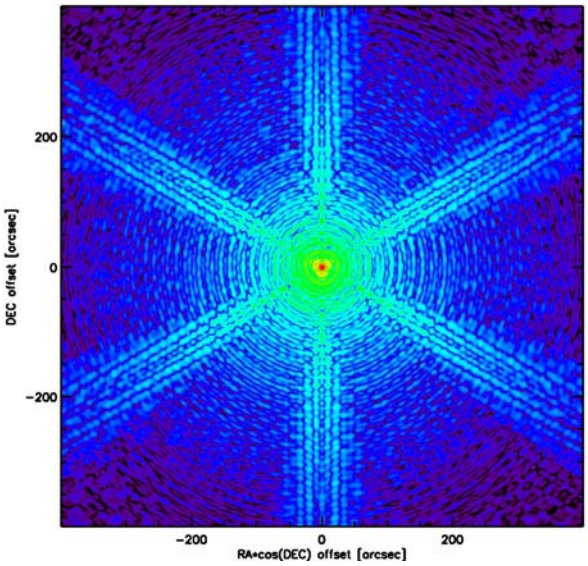
4.1.2 Example monochromatic PSFs for ‘as built’ telescope



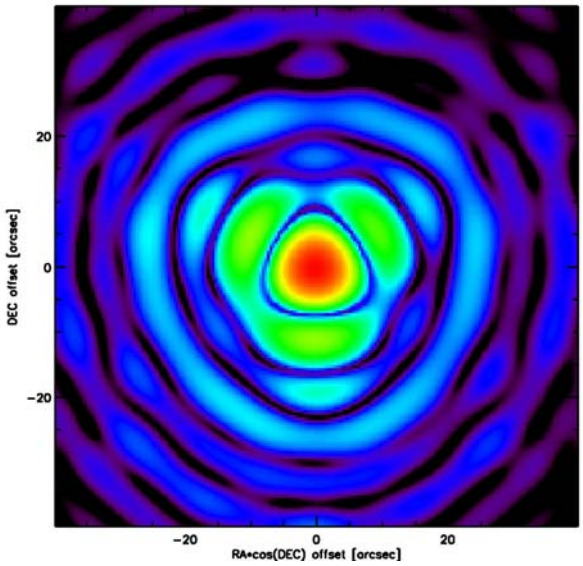
70µm monochr. PSF Display range 8dex



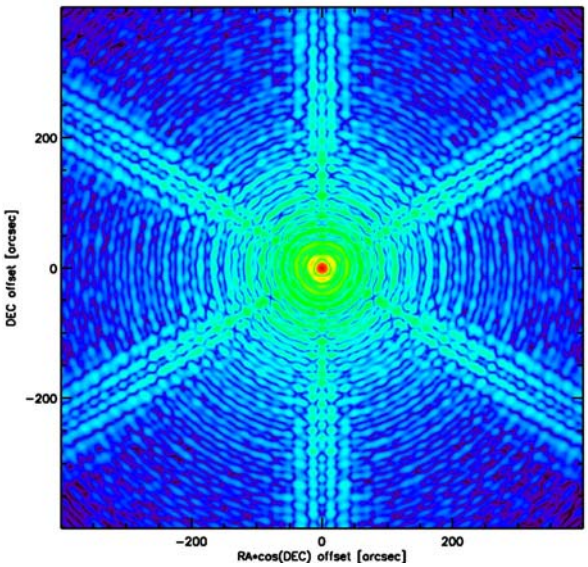
70µm monochr. PSF. Display range 4dex



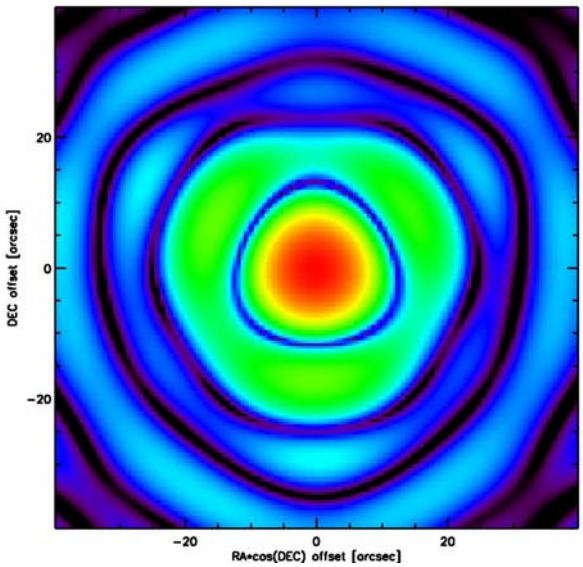
110µm monochr. PSF. Display range 8dex



110µm monochr. PSF. Display range 4dex



170µm monochr. PSF. Display range 8dex



170µm monochr. PSF. Display range 4dex

4.2 Filter-convolved broad-band PSFs for the photometer

The PACS photometric filters have rather wide transmission profiles. This smoothes the structure of the PSF heavily and makes it noticeably dependent on the spectral energy distribution of the source that is observed. We have computed simple broadband PSFs as

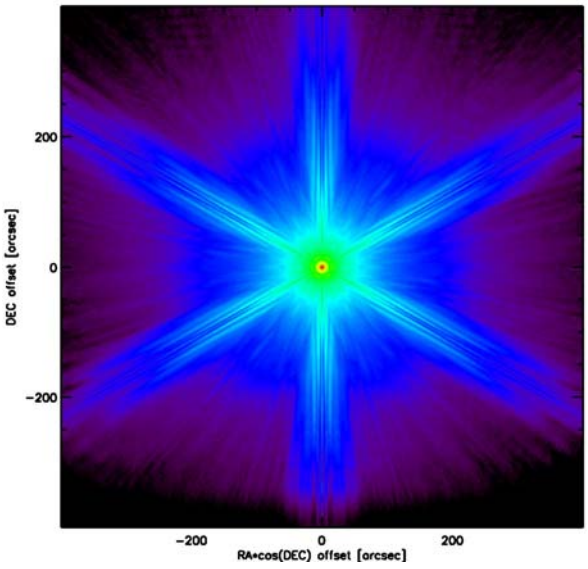
$$PSF(band,slope) = \Sigma\ PSF(\lambda)*T(\lambda)*W(\lambda)*\lambda^{slope}$$

where PSF(λ) are the monochromatic PSFs computed on a discrete wavelength grid, T(λ) is the 'transmission' of filters + detector for the photometric band at the respective wavelength, taken from Mariano Kornberg's cold PFM filter measurements + detector and averaged over 1μm or 2μm intervals, W(λ) is the width of this interval, and the spectral energy distribution is assumed as $f_\lambda \sim \lambda^{slope}$. To have reasonable wavelength sampling over the full range, 1μm intervals were used below 114μm, and 2μm intervals above, over a total range 53 to 250μm. The broadband PSFs were then again normalized to integrated flux 1. We computed PSFs for the three PACS bands blue = '70μm', green = '100μm', and red = '160μm', and for three spectral slopes –4, 2, and –1, thus including extremely blue/hot and red/cold spectra as well as one that is flat in energy per octave.

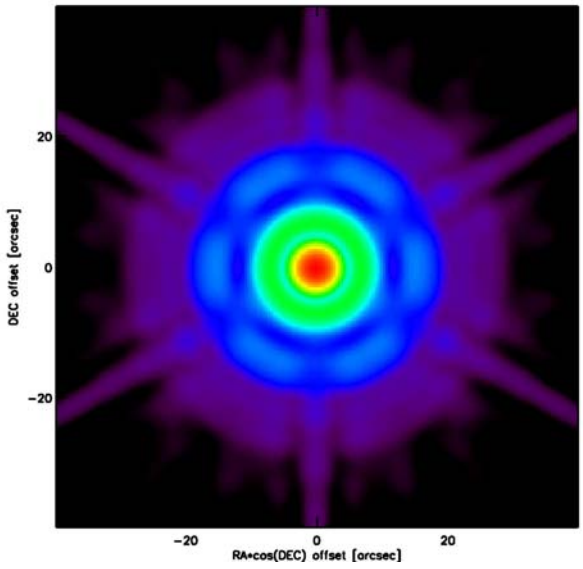
The broad band-pass leads to a considerable smoothing of diffraction rings, fine structures and ripples in the PSF.

The two sets of figures below, for 'ideal' and 'as built' telescope, show the PSFs for the three bands and a spectrum that is flat in λf_λ. The noticeable variation between an extremely blue/hot and an extremely red/cool SED is also shown, for the very broad red filter.

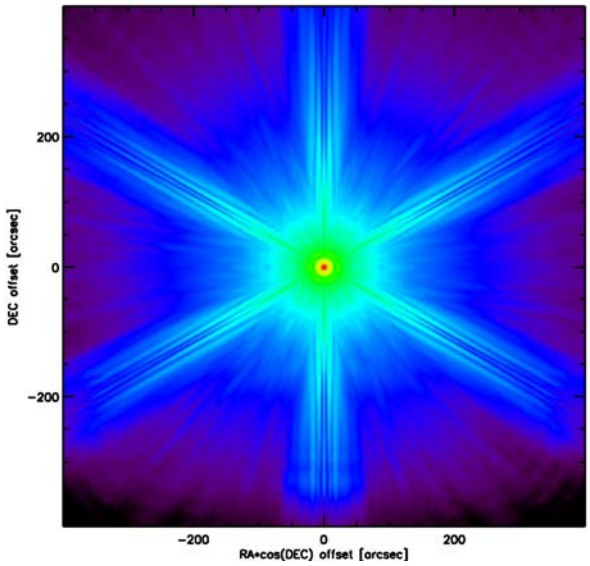
4.2.1 Example broadband PSFs for 'ideal' telescope



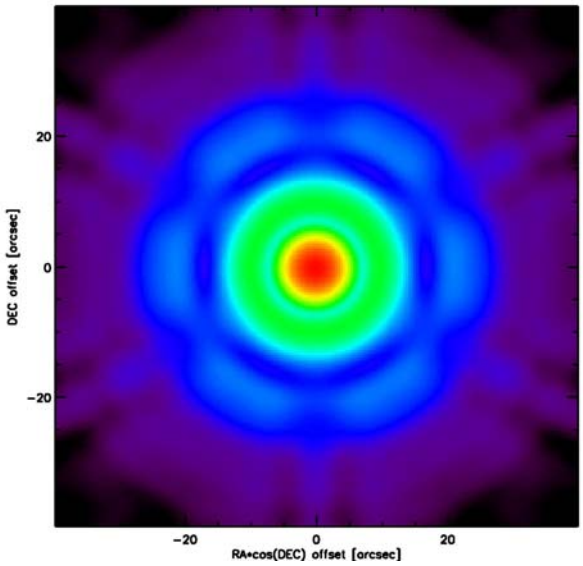
Blue PSF slope -1. Display range 8dex



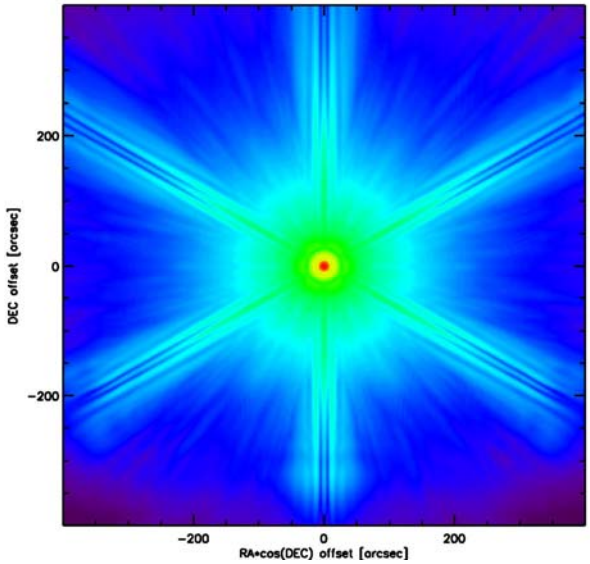
Blue PSF slope -1. Display range 4dex



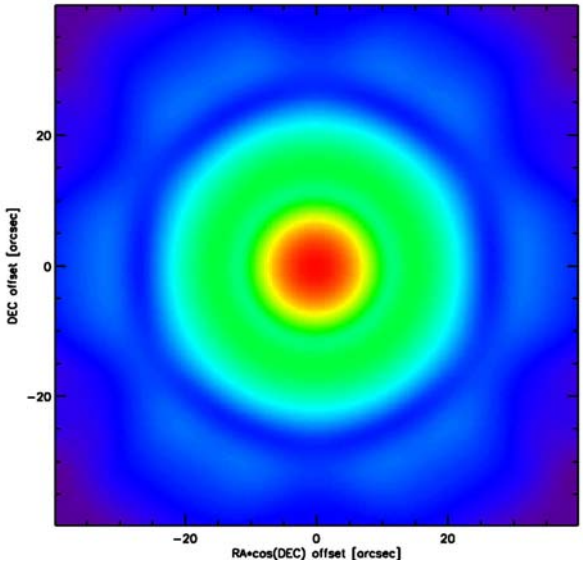
Green PSF slope -1. Display range 8dex



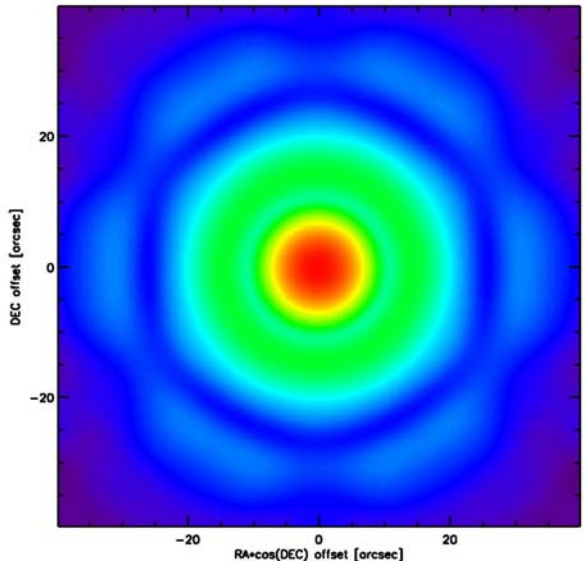
Green PSF slope -1. Display range 4dex



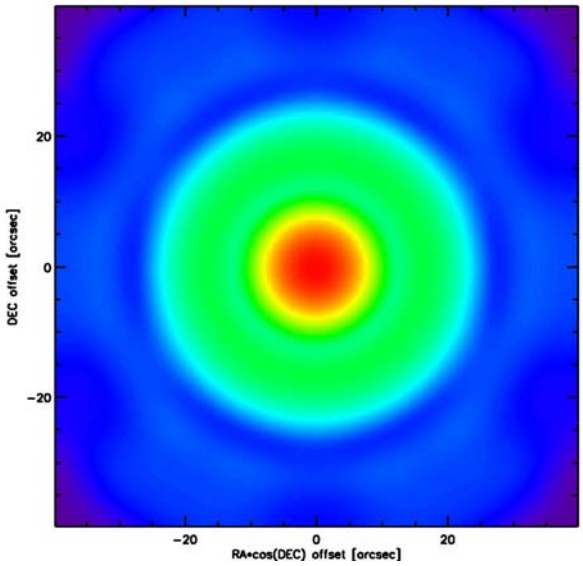
Red PSF slope -1. Display range 8dex



Red PSF slope -1. Display range 4dex

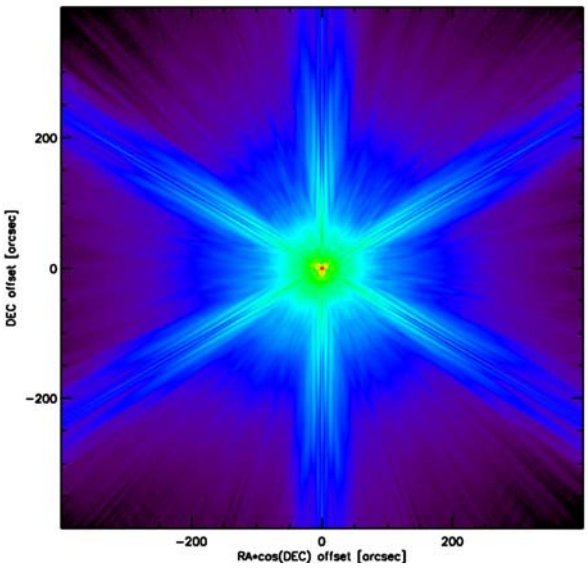


Red PSF slope -4 (Extremely blue/hot source)

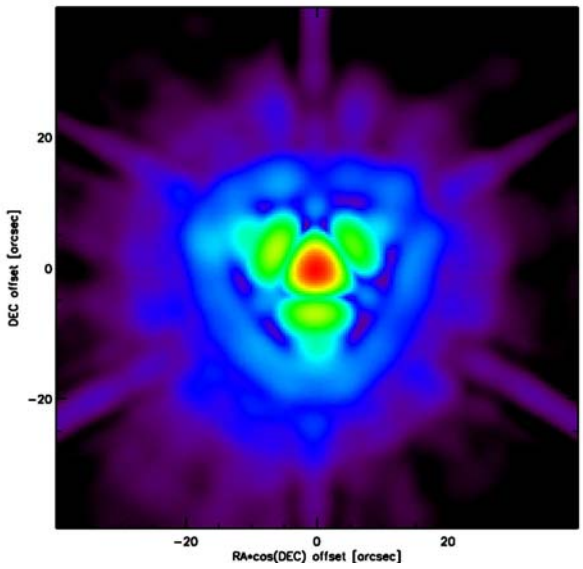


Red PSF slope 2 (Extremely red/cold source)

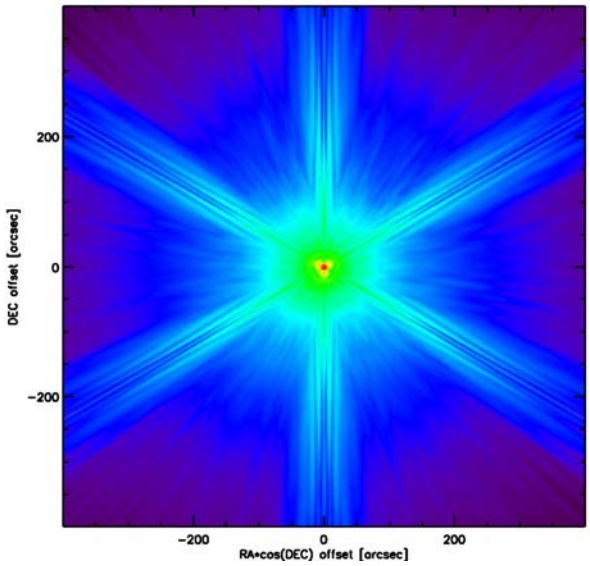
4.2.2 Example broadband PSFs for 'as built' telescope



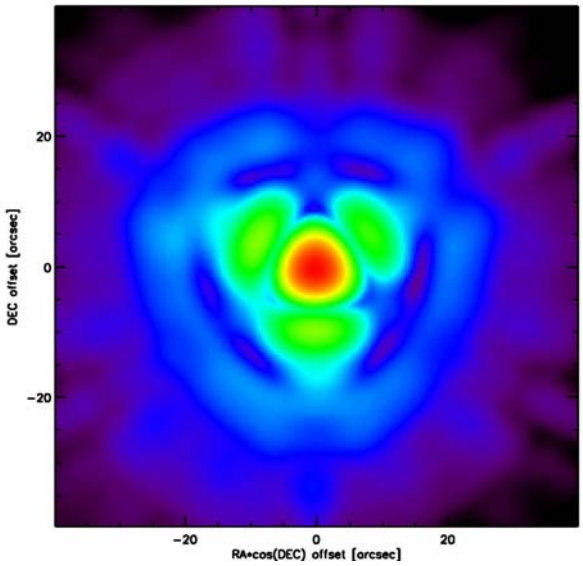
Blue PSF slope -1. Display range 8dex



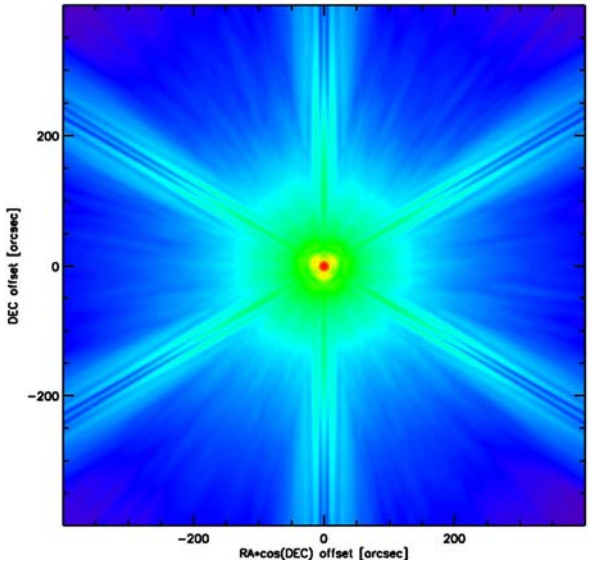
Blue PSF slope -1. Display range 4dex



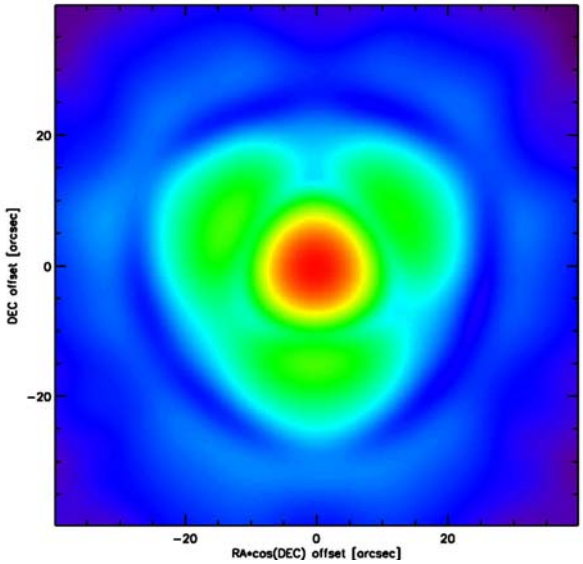
Green PSF slope -1. Display range 8dex



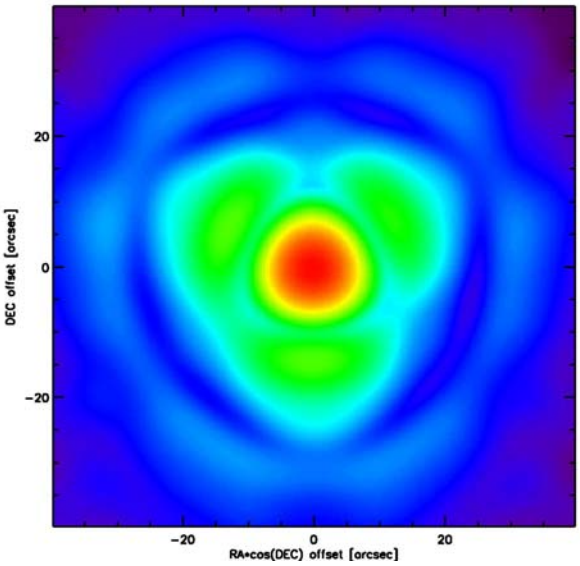
Green PSF slope -1. Display range 4dex



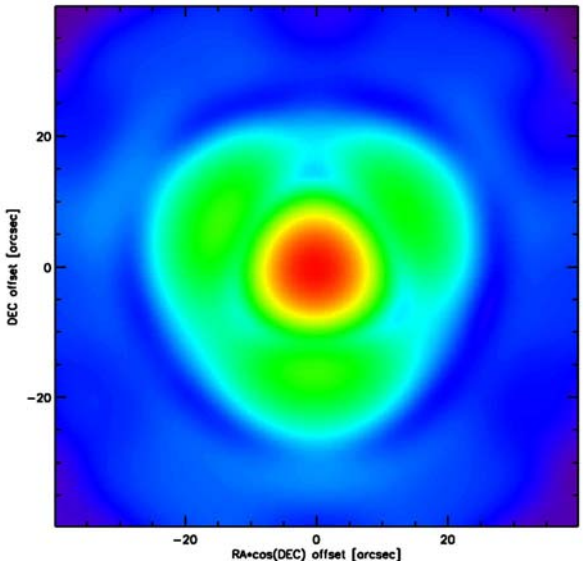
Red PSF slope -1. Display range 8dex



Red PSF slope -1. Display range 4dex



Red PSF slope -4 (Extremely blue/hot source)



Red PSF slope 2 (Extremely red/cold source)

5 Data products

The following data products can be found on the PACS site http://pacs.ster.kuleuven.ac.be following the PSF library link under 'Public Tools':

PACSPSF_PICC-ME-TN-029_v2.0.pdf (~2 M)

- this document

PACSPSF_monochromatic_v1.0.tar.gz (~290 M)

- monochromatic 'ideal telescope' PSFs at 60,70,80,90,100,120,140,160,180,200µm

PACSPSF_broadband_v1.0.tar.gz (~259 M)

- broad-band photometric 'ideal telescope' PSFs for blue, green, red and for spectral slopes -4, -1, 2 in f_λ

PACSPSF_monochromatic_v2.0.tar.gz (~290 M)

- monochromatic 'as-built telescope' PSFs at 60,70,80,90,100,120,140,160,180,200µm

PACSPSF_broadband_v2.0.tar.gz (~259 M)

- broad-band photometric 'as-built telescope' PSFs for blue, green, red and for spectral slopes -4, -1, 2 in f_λ

--ooOOoo--