SPIRE STM optical alignment campaign
Photometer cold stop pupil imaging verification

KD, 18/11/2003
LAM.LOOM.SPI.NOT.031024 Ind 1 Rev 0

Reference documents

RD1 "Photometer C.S.-tool" drawing SPI-OAL-30-DD-01-A, 07-08--2002.
RD2 K. Dohlen, "Herschel-SPIRE: Optical error budgets", LOOM.KD.SPIRE.2000.002-4, 17/1/2002.
RD3 Y. Alanou, "Alignment Tools Specifications", LOOM. YA. SPIRE. 2002.001.05, 26/08/2002.

Introduction

The SPIRE alignment plan provides pupil quality verification by observation of the projected cold stop tool onto the M2 tool. Four holes along the M2 tool edge are equipped with slits indicating the edge of the telescope pupil, see Fig. 1. The slits correspond nominally to slits in the CS tool. The coincidence of the slits is observed - using a specially designed Loupe - for five different points in the FOV (centre and corners).

The full nominal pupil imaging verifiacation procedure was not applied to the STM instrument because of severe misalignment of some mirrors (CM3 in particular) and because of erroneous definition of the cold stop tools. Sufficient measurements were made however, partly by different means, to be able to estimate the pupil imaging quality.

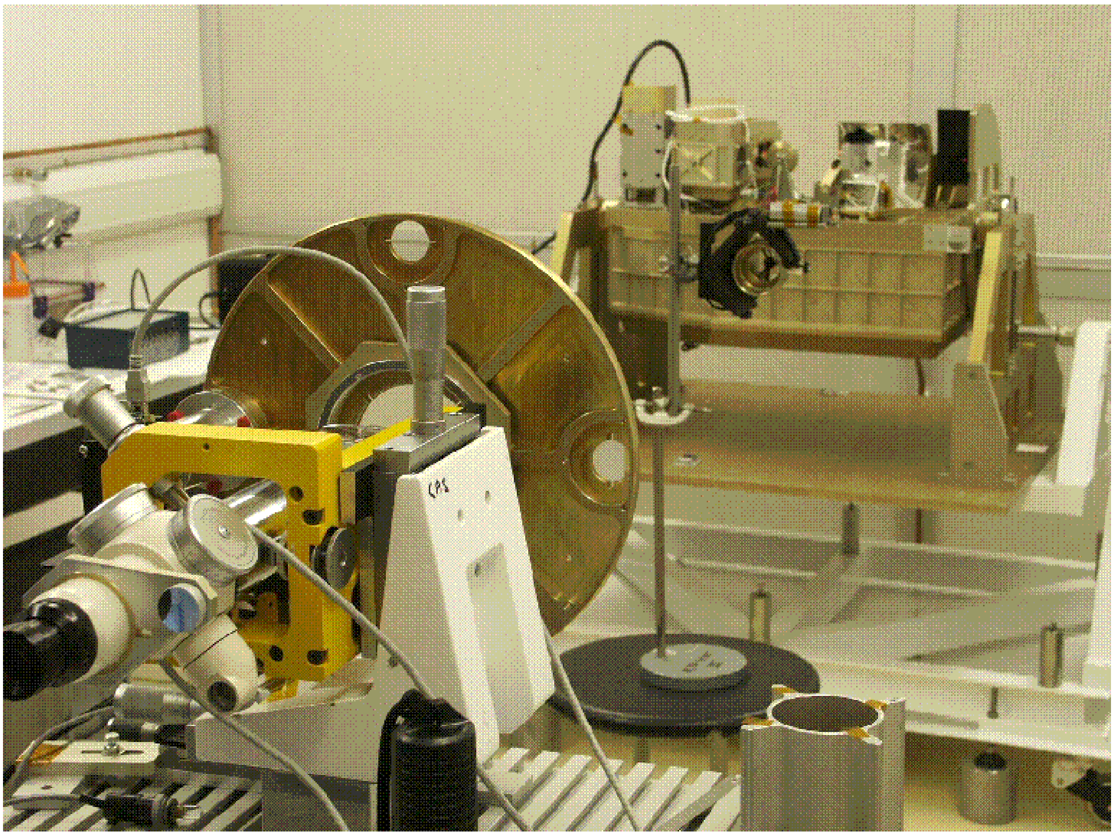

Figure 1. Setup of the M2-tool in front of the SPIRE instrument system.

Pupil magnification

Pupil magnification of the theoretical system and the as-built STM system are compared, see Table 1. For the theoretical system, magnification is calculated from ray tracing data (bolpht155d_M2tool). For the as-built STM system, magnification was calculated from PCS tool dimensions (detail of drawing [RD1] shown in Figure 2) and dimensions of its shadow projected onto the M2 tool (Fig. 3). The PCS tool was projected onto the M2 tool by placing a strong light source (fibre) in the SLW detector position. The shadow was drawn on a sheet of paper from which measurements are made using a ruler.

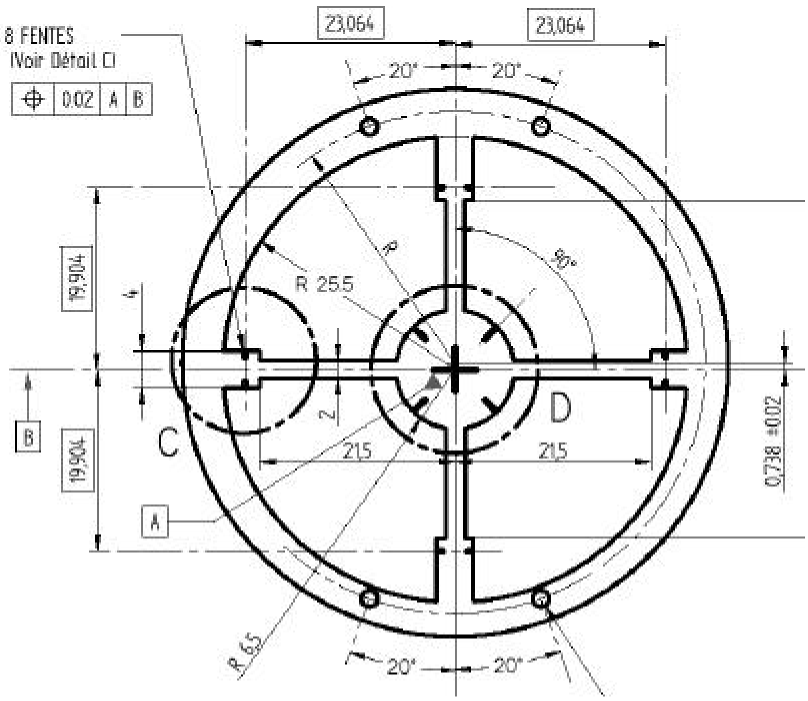

Figure 2. Facsimile of the photometer cold stop tool drawing.

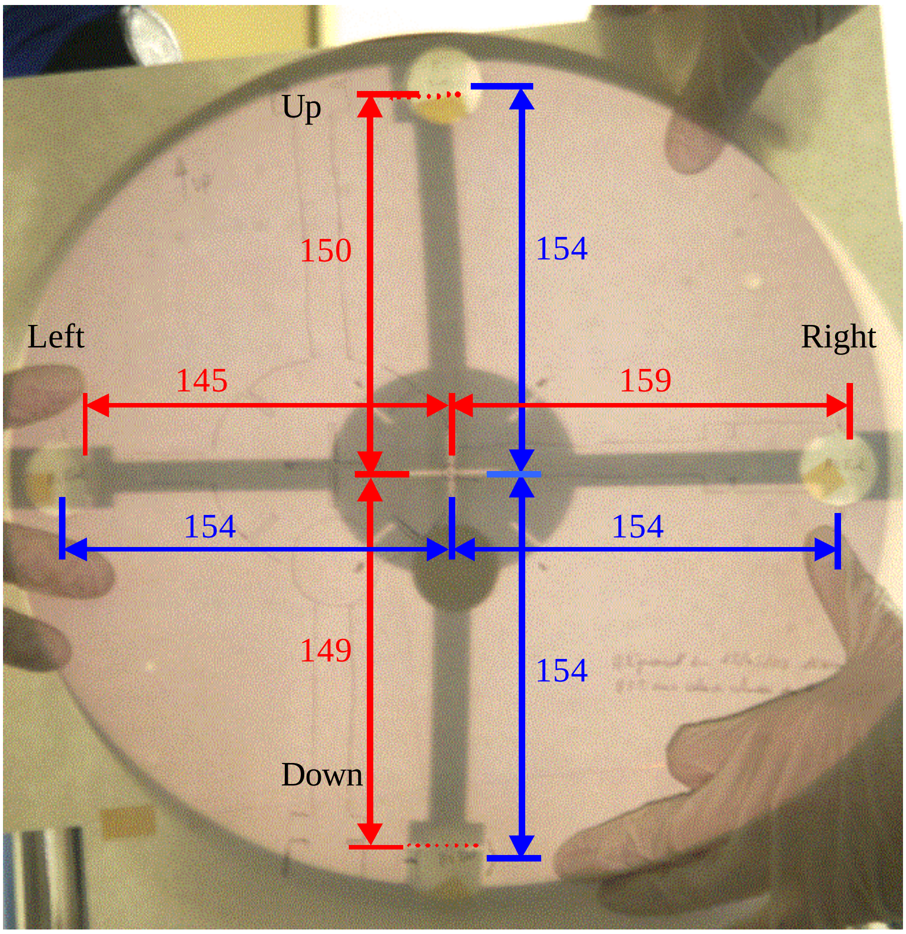

Figure 3. Shadow of the PCS tool projected onto the M2 tool. For clarity, a sheet of paper is held in front of the M2 tool, but the four holes around the edge of the tool indicating the edge of the telescope pupil are seen by transparence. The shadow seen here is obtained after readjustment of the M2 tool so that its centre coincides with the central cross of the PCS tool. The pencil trace on the paper shows the original PCS tool shadow obtained with the M2 tool aligned according to the theoretical instrument gut ray. The darker spot below the central cross is due to the central hole in the BSM mirror, offset be the insertion of a 4mm shim under its feet.

The results of Table 1 show that the magnification is different at different positions around the pupil: Larger horizontally than vertically, and larger Left than Right. Up and Down have the same theoretical magnification; this is to be expected since the system is symmetrical about the horizontal plane.

The measured and theoretical results correspond well for the Left and Right values. They are within 0.5% of each other, corresponding to an error at the M2 plane of 0.7mm. The results do not correspond so well for the Up and Down values, however. Here the difference between theory and measurements is around 2%, corresponding to 3mm at M2 (0.5mm at the CS).

The precision of the measured parameters is between ±0.5 and ±1.0mm in the M2 plane, mainly due to lack of sharpness in the projected shadow, imprecision in the shadow drawing, and imprecision of the ruler-based measurement. While the Left/Right results are within this error estimate, the Up/Down results are significantly larger.

Known error sources not taken into account in this analysis include:

- Erroneous M2 distance: The M2 tool was set at a distance of 2999mm from the LAM-HOB reference plate. This distance was calculated for the cold instrument design. Its correct warm value is 3011.44mm. The error in projected pupil dimension due to this error is 12.44/(2*8.68) = 0.7mm, equal in all directions.
- Mirror orientation errors: The orientation error of CM3 of 27' is estimated to give an anamorphic error due to the increased angle between the M2 tool and the gut ray of about 0.5mm. Errors of a few arcminutes are assumed to be negligible.
- Mirror surface errors: It can be seen that mirrors coinciding with the pupil (CM4) or with the image (PM6) cannot influence the pupil magnification. Mirrors concerned are therefore CM3, CM5, PM7, PM8. Errors in Radius of curvature and toricityof these mirrors will give rise to both overall and anamorphic pupil magnification errors and this is likely to be the prominent cause of the discrepancies noted.

An error of 3mm is compatible with the pupil alignment error budget [RD2] (residual pupil aberrations of the optical design: 7.7mm, instrument internal alignment: 6.2mm). Moreover, since the actual magnification is smaller than the theoretical magnification, the projected cold stop will under-fill M2, hence producing a loss of astronomical signal, but not increasing stray light from the M2 surround.

Table 1. Parameters and results of pupil magnification calculations.

			Left	**Right**	**Up**	**Down**
Theoretical						
	PCS dimension	(mm)	21.0608	-19.1819	-23.2996	23.2996
	M2 projection	(mm)	154.06	-154.06	-154.06	154.06
	Magnification (Mt)		7.32	8.03	6.61	6.61
Measured						
	PCS dimension (drawn)	(mm)	19.904	-19.904	-23.064	23.064
	M2 projection	(mm)	145	-159	-150	149
	Magnification (Mm)		7.28	7.99	6.50	6.46
Comparison						
	dM/M = (Mm-Mt)/Mt		-0.41%	-0.54%	-1.64%	-2.30%
	dR = R dM/M	(mm)	-0.63	0.83	2.53	-3.54

Pupil aberrations

Pupil aberrations are measured by observing the shadow of the slits machined into the CS tool at the pupil edge as seen through the holes with corresponding slits in the M2 tool. This observation is made possible by the use of a specially designed Loupe interfaced with a CCD camera, see Figure 4. Figure 5 shows images taken for four positions in the FOV, three corners (A, B, C) and the centre (E), see Figure 6. The fourth corner (D) was unavailable because of a faulty LED. The image corresponding to field point E indicates the orientation of the images and illustrates the method used for analysis of the images:

- Image scale (mm/pixel) is determined by considering the M2-tool hole diameter.
- Position of the M2-tool is given by point P
- Position of the CS-tool shadow is given by point Q
- Pupil aberrations are the variations in the difference between the coordinates of P and Q.

For a correctly manufactured CS-tool, the difference between P and Q would be expected to be close to zero for image point E (taking account of the gap between the CS-tool shadow and the M2 tool edge). This is clearly not the case due to CS-tool definition errors. To help comparison with theoretical values, an arbitrary offset has therefore been added to the measured results.

According to the alignment plan, a series of five images (A, B, C, D, E) should be acquired for each of the four M2-tool holes (Up, Down, Left, Right). During STM testing it was only done for one hole (Right) due to time constraints.

Table 2 lists theoretically expected values obtained by ray tracing, as well as the measured values, to which an arbitrary offset has been added. Figure 7 illustrates graphically the expected pupil aberrations in the M2 plane, and Figure 8 shows close-up views at each M2-tool hole. The measured results are added in the panel corresponding to the Right hole. The average error of the measured values is 1mm, indicating that the as-built STM is well representative of the designed instrument.

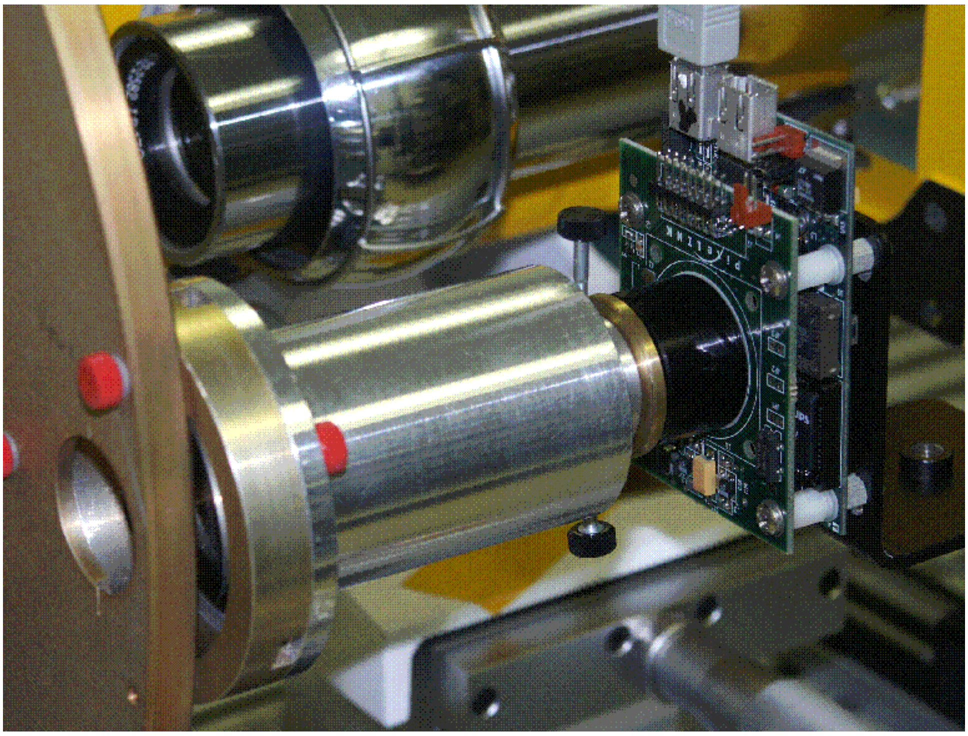

Figure 4. The M2 loupe with CCD camera attached.

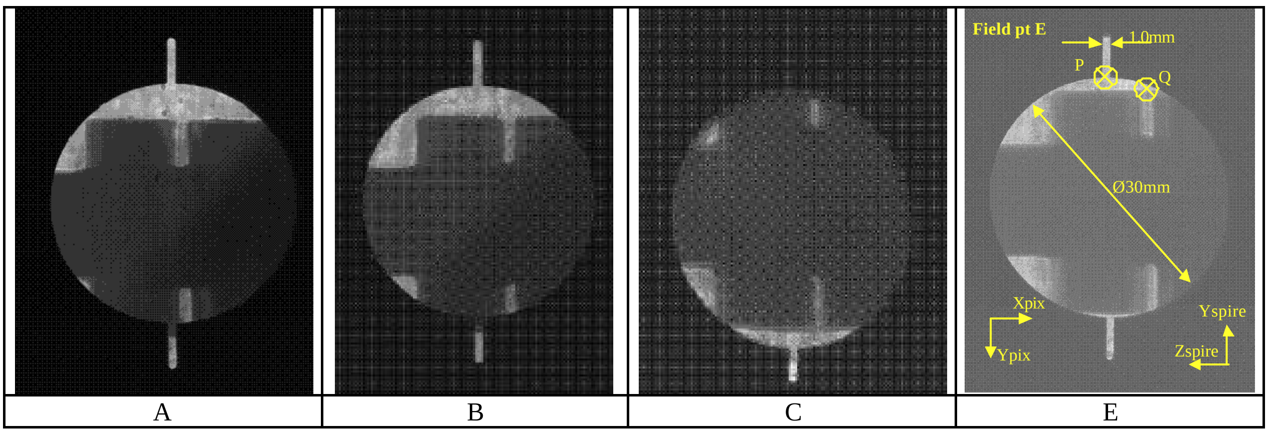

Figure 5. Images observed with the Loupe through the Right-hand M2-tool hole for D-tool sources A, B, C, and E.

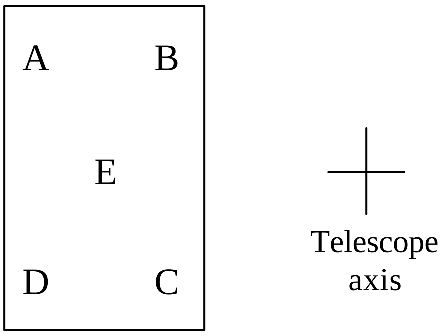

Figure 6. Definition of D-tool sources as seen by observing the instrument input focal plane from the M2 tool.

Table 2. Theoretically expected pupil aberration (design residual) compared with measured results. Left, Right, Up, Down corresponds to the four measurement positions around the M2 edge. Field points A, B, C, D, and E correspond to the five image plane (D-tool) sources. For the STM, measurements were done only for the Right measurement position. For the PFM, this table should be completed.

			Left		**Right**		**Up**		**Down**	
Theoretical			Zspire	Yspire	Zspire	Yspire	Zspire	Yspire	Zspire	Yspire
	Field point A	(mm)	-3.53	-2.09	2.69	2.57	3.43	3.60	-3.88	-5.28
	Field point B	(mm)	-0.51	1.20	1.83	1.05	2.39	1.10	-0.51	-0.77
	Field point C	(mm)	-3.53	2.09	2.69	-2.57	-3.88	5.28	3.43	-3.60
	Field point D	(mm)	-0.51	-1.20	1.83	-1.05	-0.51	0.77	2.39	-1.10
	Field point E	(mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Measured										
	Field point A	(mm)			3.70	2.18				
	Field point B	(mm)			1.02	1.53				
	Field point C	(mm)			1.60	-1.91				
	Field point D	(mm)								
	Field point E	(mm)			-0.50	-0.80				
Difference										
	Field point A	(mm)			1.01	-0.40				
	Field point B	(mm)			-0.82	0.49				
	Field point C	(mm)			-1.09	0.67				
	Field point D	(mm)								
	Field point E	(mm)			-0.50	-0.80				
Error (length of difference vector)										
	Field point A	(mm)		NA	1.09	NA		NA		NA
	Field point B	(mm)		NA	0.95	NA		NA		NA
	Field point C	(mm)		NA	1.28	NA		NA		NA
	Field point D	(mm)		NA		NA		NA		NA
	Field point E	(mm)		NA	0.94	NA		NA		NA
	Mean error	*(mm)*		NA	*1.06*	NA		NA		NA

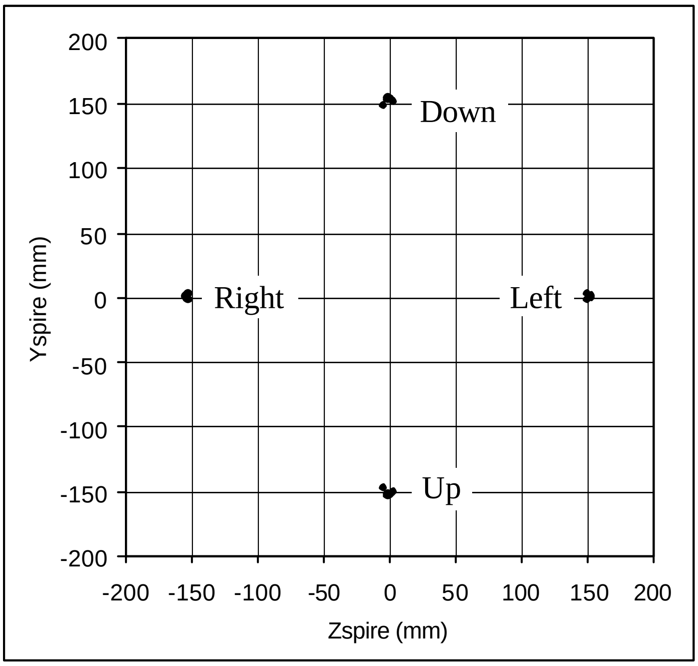

Figure 7. To scale view of the expected pupil aberrations at the four holes of the M2 tool.

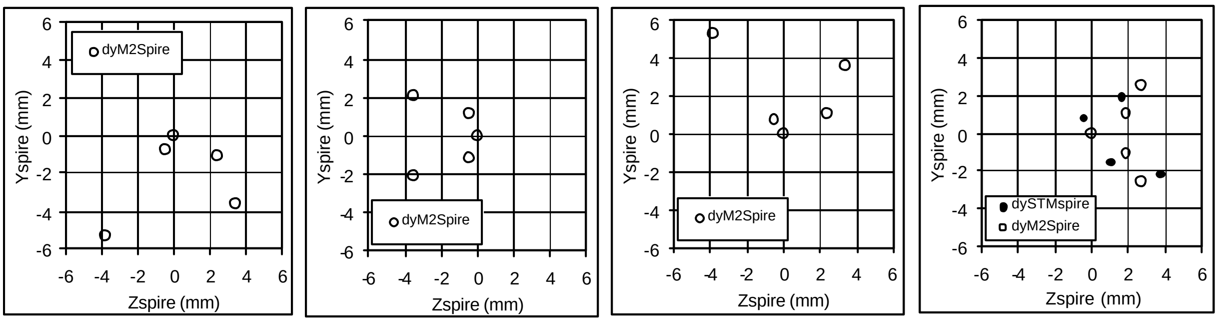

Figure 8. Enlarged views of the pupil aberrations at each of the M2-tool holes. Open circles are theoretical values, filled circles are measurement results (Right only).

Conclusion

Pupil magnification is found to have very good agreement with theory in the horizontal plane, but a discrepancy corresponding to an error of 3mm in the M2 plane, has been found in the vertical plane. Probably due to radius of curvature and toricity errors of certain mirrors, this error is compatible with the instrument error budget.

Pupil aberrations have been measured at one position along the M2 edge. Good agreement with theoretical values have been found.