SPIRE STM optical alignment campaign
Spectrometer Hartmann test

KD, 15/9/2003

1. Reference documents

RD1 G. Rousset, "HERSCHEL-SPIRE, SPIRE STM MIRRORS, Optical measurement report", LAS.QUA.SPI.PRV.030024 Iss1 Rev0, 31/03/2003.
RD2 K. Dohlen, "Herschel-SPIRE: Optical error budgets", LOOM.KD.SPIRE.2000.002-4, 17/1/2002.
RD3 K. Dohlen, "SPIRE STM optical alignment campaign, Photometer Hartmann test", 11/9/2003.
RD4 K. Dohlen, "Herschel-SPIRE: Analysis of 3-D measurements of CM3", 15/4/2003.
RD5 K. Dohlen, "SPIRE STM optical alignment campaign Estimation of spectrometer beamsplitter tool reflectivity", 1/9/2003

2. Introduction

Measurement of SPIRE image quality is done using a Hartmann test as described in RD3. The test of the spectrometer optics is similar to that of the photometer optics, except only one point in the FOV is measured. However, a D-tool is provided for both detector positions (SSW and SLW, see Fig. 1 a), and, if both beam splitters are in place, each D-tool is seen through the two arms of the interferometer. The Hartmann mask (H-tool) containing a grid of holes is placed in the instrument's internal cold stop pupil, located between SM6 and SM7, where the beam passes through the SPIRE optical bench, see Figure 1 b.

Transverse alignment of the Hartmann lunette with respect to the spectrometer gut ray was done using the MAT. Longitudinal alignment was done using a ruler to measure the distance (e) between the front slide of the Hartmann bench and the upper edge of the SPIRE optical bench along the spectrometer gut ray, as explained in RD3. This distance is given by the equation:

$$e = FFD + a - d$$

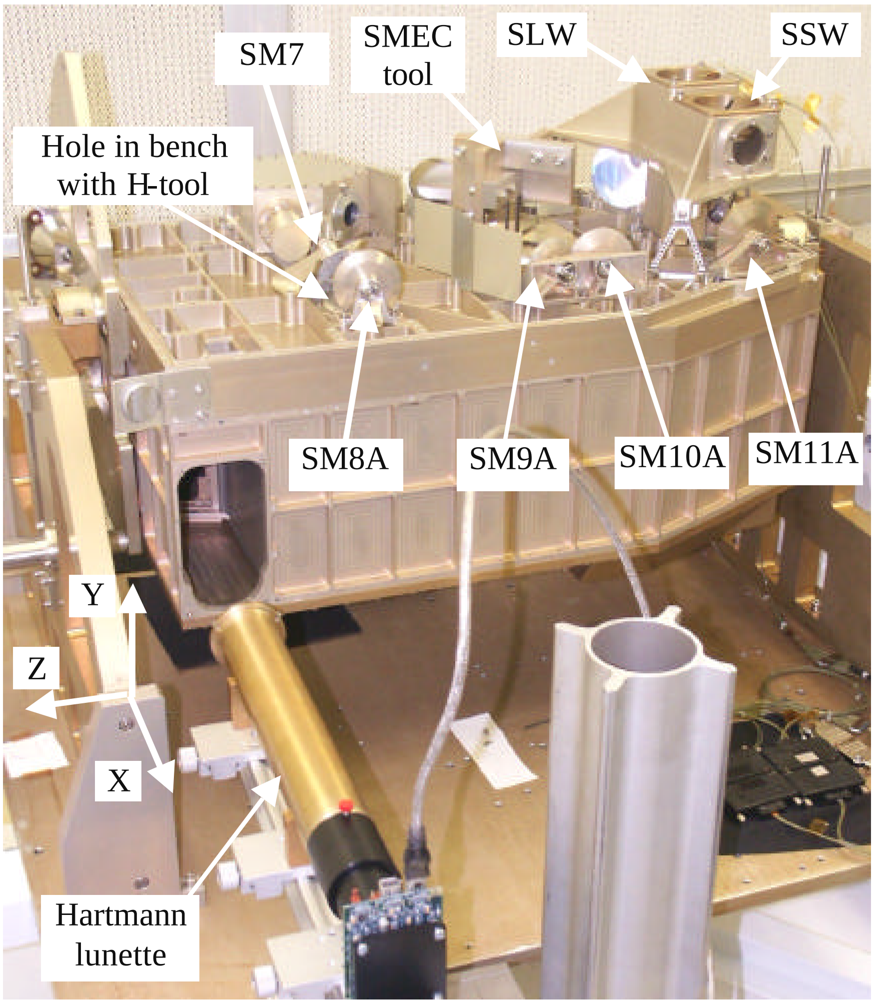
where FFD = 310mm and a = 49.5mm. The distance d, between the upper edge of the Spire bench and the gut ray impact on the Herschel focal surface, is determined by ray tracing (Figure 2). It is 202.303mm cold, ie d = 202.303*1.00415 = 203.14mm at room temperature. Hence e = 156.36mm. Due to some erroneous inputs, the value of e actually used was 157.15mm. The difference of 0.79mm corresponds to 0.4µm WFE RMS.

Several factors complicated the STM measurements:

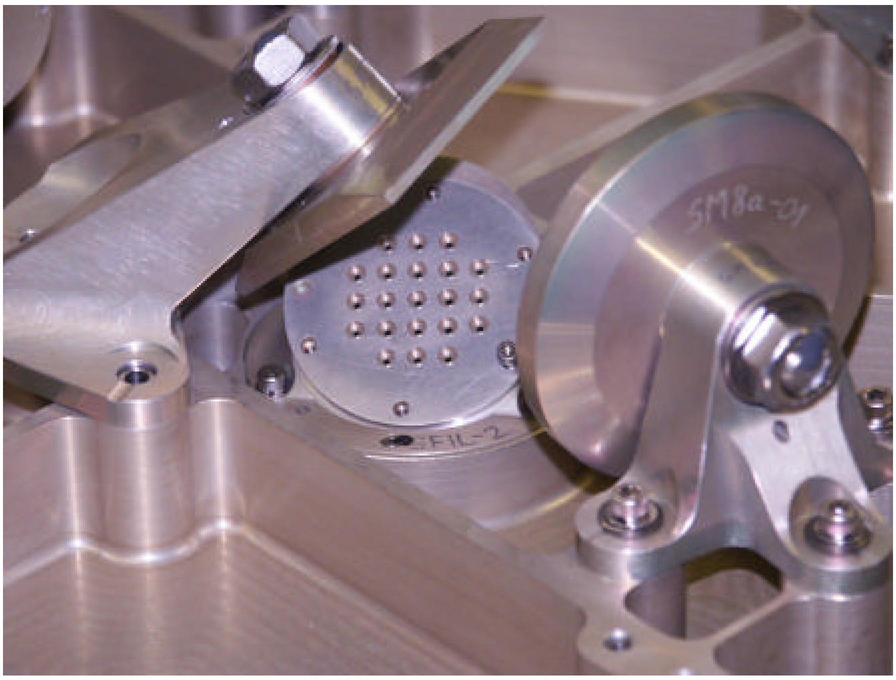
- Only one beam splitter tool was available
- The beam splitter was poorly balanced, with R~90%, T~10% [RD5]
- SM8A had ~12º error in azimuthal rotation due to an error in dowl pin location

The number of observable paths thorough the instrument was limited by the two first problems. The poblem of the SM8A rotation was detected and roughly compensated thanks to the Hartmann test. The results of this correction is quantified below. The origin of the problem has since been determined to be due to a faulty bracket and it will be corrected for the PFM.

Three paths through the instrument were used during the tests as shown in Figure 3. These have been denoted SLW_SBS1, SLW_SBS2, and SSW_noSBS. During tests of the PFM, and if both beam splitters are present and have acceptable transmission/reflection characteristics, four paths should be measured by consequtively turning on and off the two D-tools and opening and closing (by insertion of a screen) the upper and lower arms of the interferometer. Table 1 defines the procedure for this and gives appropriate names for each test.



(a)



(b)

Figure 1. a: Setup of the Photometer Hartmann test.
b: Detail of the Spectrometer Hartmann tool with SM7 (left) and SM8A (right).

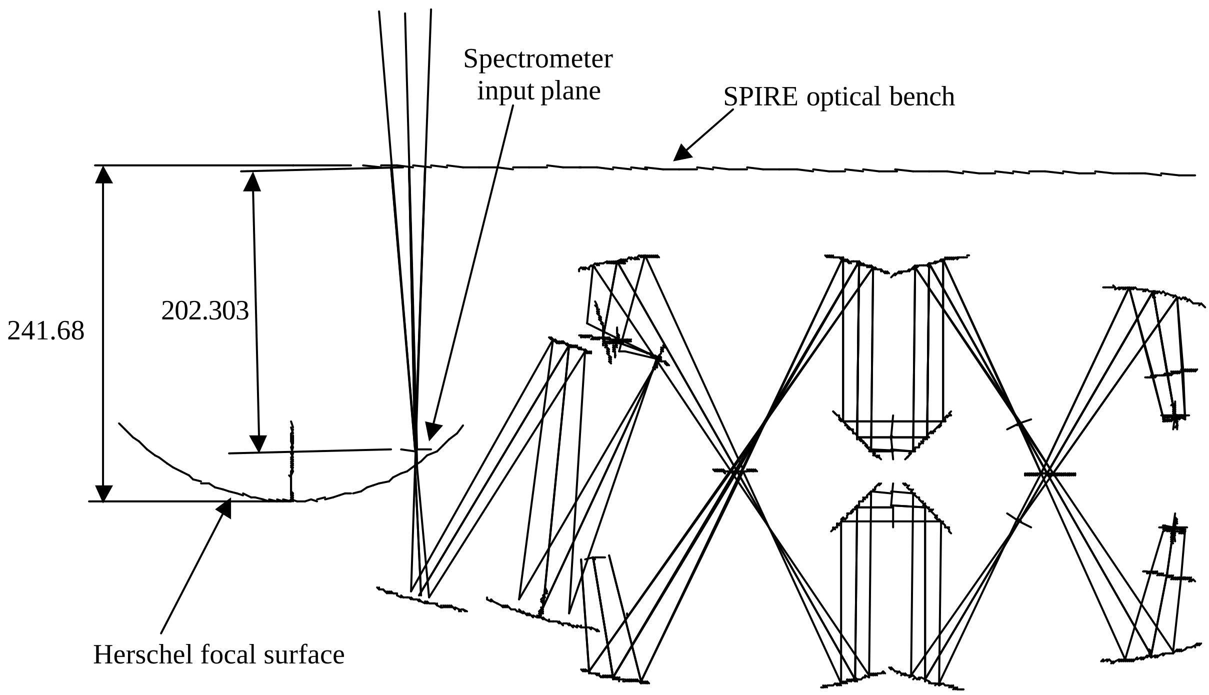


Figure 2. Raytrace diagram showing the position of the spectrometer input plane with respect to the top edge of the SPIRE optocal bench. Dimensions are cold (4K).

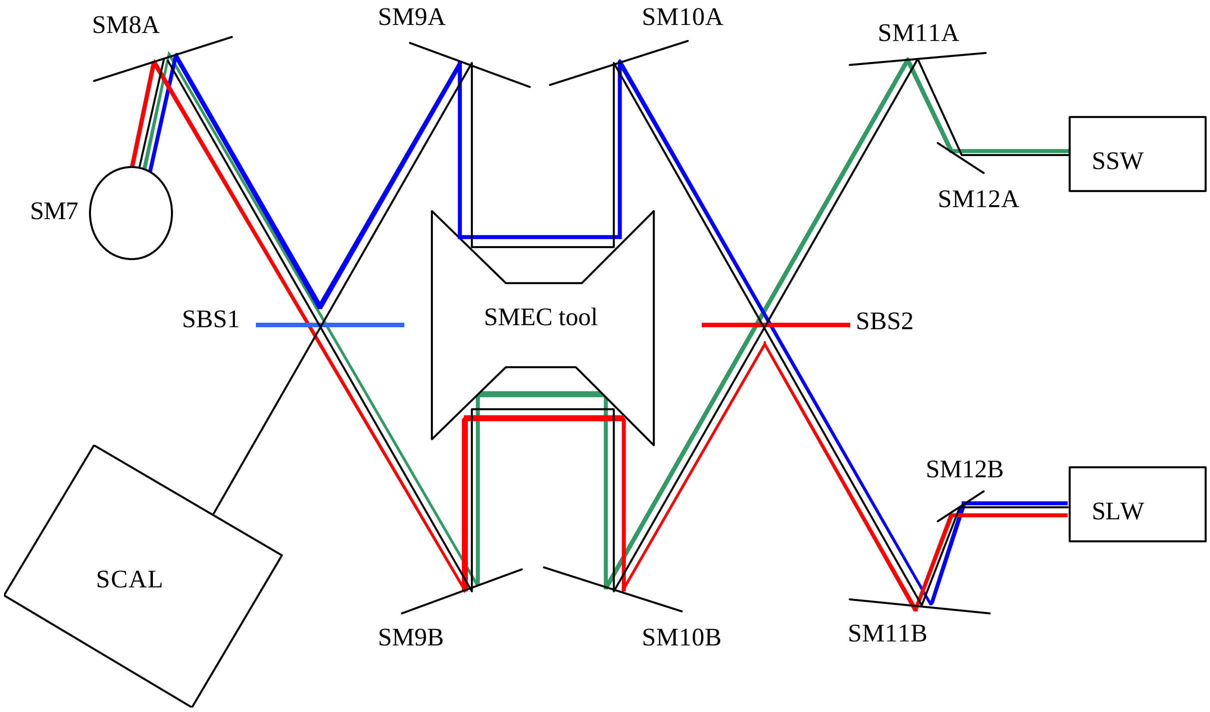


Figure 3. The three beam paths for which Hartmann test was performed: The blue path (SLW_SBS1) realized by placing the beamsplitter tool in the SBS1 position, the red path (SLW_SBS2) realized by placing it in SBS2 position, and the green path (SSW_noSBS) realized by removing the beam splitter.

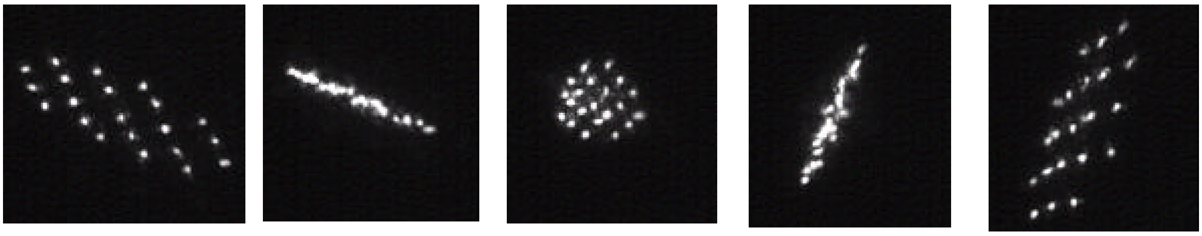
Table 1. Procedure for measuring the four paths of the spectrometer.

PFM naming	**STM naming**	**SLW**	**SSW**	**Upper arm (A)**	**Lower arm (B)**
SLW_A	SLW_SBS1	On	Off	Open	Closed
SLW_B	SLW_SBS2	On	Off	Closed	Open
SSW_A		Off	On	Open	Closed
SSW_B	SSW_noSBS	Off	On	Closed	Open

3. Results

3.1. SM8A rotation

Figure 4 shows a series of images obtained with the Hartmann lunette at 5 different focus positions separated by 9mm in the F/5 Hartmann focus before correction of the SM8A rotation. Clearly, the system suffers from a large amount of astigmatism. At the best focus position (central image), the spot has a diameter of about 230 pixels, corresponding to 1.7mm, almost the size of the Airy disk at 250µm whose diameter is 3.0mm. With a separation between astigmatic focal lines of about 20mm, this corresponds to a Zernike astigmatism of 50µm or an RMS WFE of 21µm. This is twice the total SPIRE error budget and clearly not acceptable for SPIRE science.



c = 83mm	c = 92mm	c = 101mm	c = 110mm	c = 119mm
defoc = -18mm	defoc = -9mm	defoc = 0mm	defoc = 9mm	defoc = 18mm

Figure 4. Hartmann through-focus images for the spectrometer in its original as-built configuration.

The optical design prescribes a rotation of the symmetry axis of SM8A through -6.22º around its normal with respect to the instrument axes. The as-built STM turns out to have SM8A rotated by +6.22º, ie with an error of 12.44º. Figure 5 shows theoretical spot diagrams produced with this error introduced in the model. The similarity between Figures 4 and 5 is convincing. The Zernike astigmatism of the modified system is 51µm.

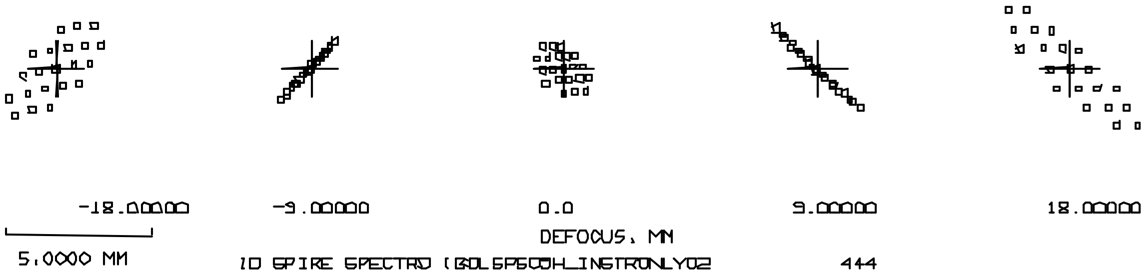
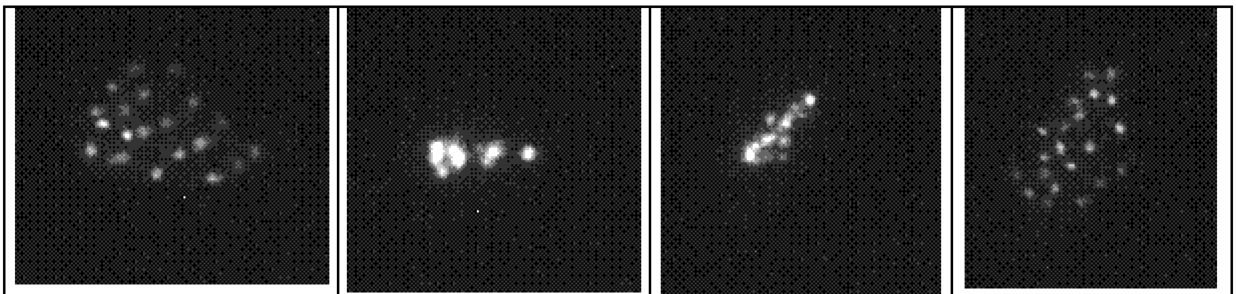


Figure 5. Through-focus spot diagrams produced by ray tracing for a system where SM8Ahas been rotated in the wrong direction.

After removing the dowling pin, approximate correction of the SM8A rotation was done by rotating the mirror around its spigot axis. No precise means of angular measurement was possible, so the adjustment was done by optimizing the best-focus Hartmann image. Figure 6 shows images taken at approximately 3º intervals near the optimal rotation. The optimum was estimated to be close to image c. Marks were made on the back of the mirror showing the position before and after rotation, see Figure 7. From the photograph, the angle between the two marks is estimated to 15±1º hence 2.5º more than the required 12.44º rotation.



a: ~9º	b: ~12º	c: ~15º	d: ~18º

Figure 6. Images taken at approximately 3º intervals near the optimal rotation of SM8A.

Figure 7. View of the back of SM8A showing marks made before and after rotation.

3.2. Through-focus spot diagrams

Hartmann images obtained before rotation of SM8A were too distorted for useful treatment by the Hartmann software. After rotation adjustment, two series of images were taken, corresponding to the paths SLW_SBS1 and SLW_SBS2. Figure 8 shows through-focus spot diagrams produced for both series, compared with spot diagrams produced by raytracing in a system with a SM8A rotation error of 2.5º (γ_{SM8A} = -8.72º).

Notice that the best image plane of the theoretical model appears to lie some 1.5mm upstream of the theoretical plane. This is due to the fact that the input plane of the "Instrument Only" model was taken to lie on a Herschel image surface assumed to be spherical. In fact it is not, and the difference between the actual telescope focus and the spherical surface is 5.4mm at F=8.68, corresponding to 1.8mm at F=5.0.

The two series of measured spot diagrams are nearly identical, indicating that the two paths through the interferometer have similar optical performance. They also resemble the theoretical spots (given a rotation of the these through 90º clockwise), but there are clearly differences. The Zernike analysis below quantifies these differences.

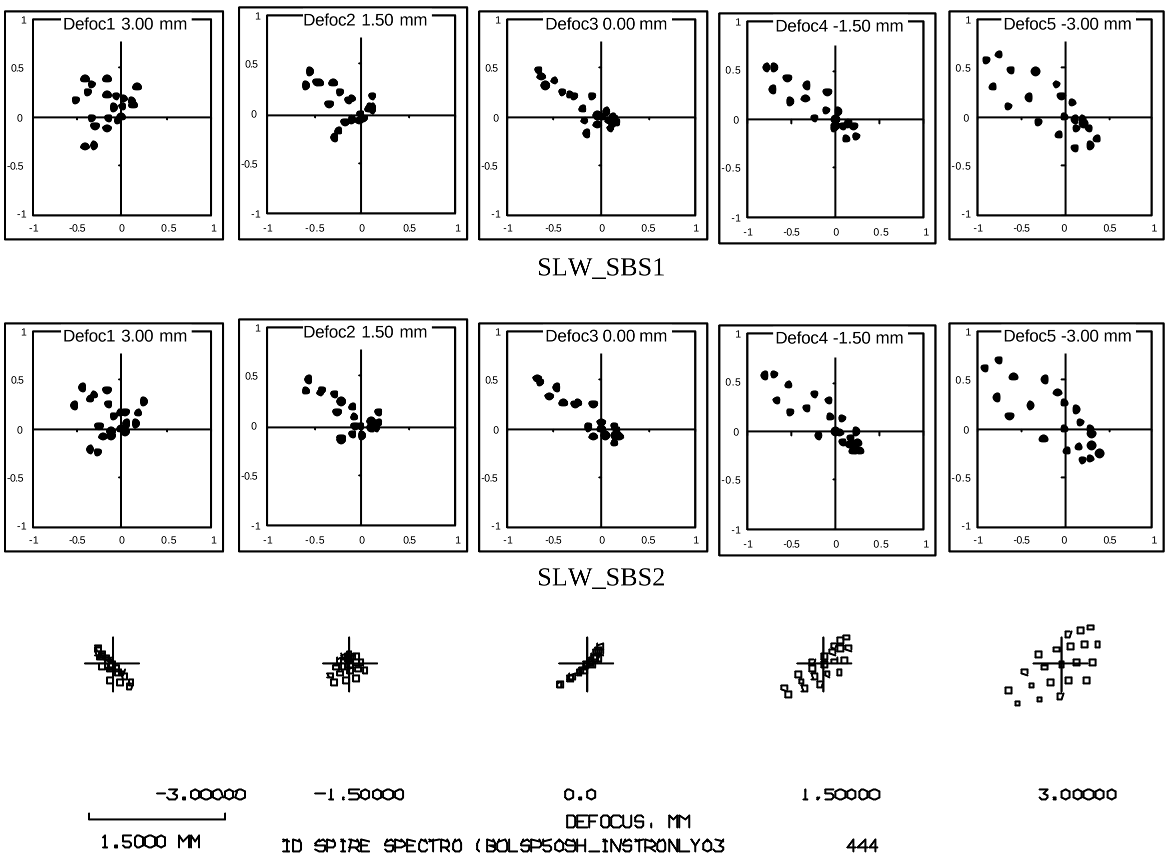


Figure 8. Through focus spot diagrams obtained from the Hartmann rmeasurements (upper and middle row) compared with theoretical spot diagrams for the model including 2.5º rotation of SM8A (lower row).

3.3. Zernike analysis

Table 2 shows Zernike coefficients obtained from the Hartmann measurements, compared with the theoretical coefficients of the ideal instrument (BolSp509h_InstrOnly) and for the case of a 2.5º error in SM8A. The following observations can be made with respect to each aberration type:

Focus:

- The theoretical results have a defocus coefficient of Z3 = -4.5µm. This corresponds to 1.8mm image displacement at F = 5, as noted above.
- The measured results indicate defocus coefficients of Z3 = -7.7µm and -9.4µm, corresponding to 3.1mm and 3.8mm, respectively. The defocus of the instrument is therefore approximately 1.7mm at F/5. This corresponds to a WFE RMS of 2.4µm.

Astigmatism:

- The effect of the SM8A rotation on the theoretical system is only visible on the two astigmatism coefficients: ΔZ4 = 6.98µm and ΔZ5 = 8.01µm. All other coefficients are equal to within 0.04µm.
- The measured Astigmatism values are in good agreement with the theoretical system. The mean values of Z4 and Z5 are within 0.1µm and 3.65µm, respectively, of the theoretical values. The difference in Z5 value are probably due to differential errors between radii of toroidal surfaces and astigmatic deformations of some mirrors, as evoked for the photometer.

Coma:

- Both measured paths show non-negligible amounts of coma whereas the theoretical instrument contains very little of this. A sensitivity analysis indicates that this is not easily introduced by misalignments. Interferometric measurements of the mirror SM12A shows that this mirror suffers from 0.9µm of Zernike coma on the mirror surface. Since this mirror is very close to the pupil and at 45º incidence, this translates into a Zernike coma on the reflected wavefront of $0.9\mu m*2\sqrt{2} = 2.5\mu m$. As seen in Figure 3, none of the two measurements reported in Table 2 are seen by SM12A. Unless the A and B mirrors have been exchanged during assembly, SM12A cannot therefore be the culprit. However, it shows that coma can be generated during the fabrication process. The mirrors SM8A and SM11A and B, as well as the four flat mirrors used in the SMEC tool roof-top assembly have not been tested and are prime suspects.

Spherical aberration:

- Spherical aberration is also present at a mean level of Z8 = 1.2µm. Again, misalignment cannot be considered a source for this amount of aberration. It turns out from the interferometric measurement report [RD1] that both SM9A and SM9B suffers from spherical aberration, with surface Zernike coefficients of 0.74µm and 0.67µm, respectively. Used not far from normal incidence, the wavefront errors induced are close to the double of these numbers, ie 1.5µm and 1.3µm, respectively, in good agreement with the measured results.

Other terms:

- Non-negligible coefficients for trefle (Tri5) and 5th order coma (Coma5) are also present. Similar error sources are probable, but the measurement report does not include these aberration terms.

Table 2. Zernike coefficients in µm for the three measurements effectuated on the spectrometer, compared with the theoretical Zernike coefficients.

Zname	Number	SynoZ	BolSp509h	BolSp509h	STM	STM
			InstrOnly	SM8A = 2.5º	SLW_SBS1	SLW_SBS2
cTiltX	Z1	ZS2	1.63	1.59	-10.60	-7.17
cTiltY	Z2	ZS1	1.05	0.95	9.26	10.16
cFocus	Z3	ZS3	-4.56	-4.51	-7.74	-9.35
cAstX	Z4	ZS4	-1.71	5.27	6.07	4.67
cAstY	Z5	ZS5	3.09	11.10	14.51	15.00
cComaX	Z6	ZS7	-0.82	-0.80	-5.23	-4.80
cComaY	Z7	ZS6	0.53	0.48	1.26	1.59
cSph	Z8	ZS8	0.04	0.04	1.00	1.32
cTri5X	Z9	ZS10	1.73	1.78	0.29	0.71
cTri5Y	Z10	ZS9	-0.42	-0.37	-1.81	-2.45
cAst5X	Z11	ZS11	0.27	0.27	0.25	0.10
cAst5Y	Z12	ZS12	0.12	0.12	-0.43	0.15
cComa5X	Z13	ZS14	0.01	0.01	1.18	0.82
cComa5Y	Z14	ZS13	0.00	0.00	-0.71	-0.54

4. Conclusion

Table 3 compares RMS contributions for each aberration type for each of the theoretical models (as designed and including a 2.5º rotation of SM8A) and the two optical paths measured by the Hartmann test. These numbers include the inherent defocus of the theoretical model and the residual astigmatism error due to SM8A. Still, both measured paths are well within the total instrument error budget allocation of WFE RMS = 10.7µm.

Table 3. Comparison of RMS coefficients, total RMS wavefront error,
and corresponding Strehl ratio at 250µm for the raytracing models and for the as-built STM.

Aberration	**BolSp509h InstrOnly**	**BolSp509h SM8A = 2.5°**	**STM SLW_SBS1**	**STM SLW_SBS2**
Focus	2.64	2.61	4.47	5.40
Astigmatism	1.44	5.02	6.42	6.41
Coma	0.35	0.33	1.90	1.79
SphAb	0.02	0.02	0.45	0.59
Tri5	0.63	0.64	0.65	0.90
Ast5	0.09	0.09	0.16	0.06
Coma5	0.00	0.00	0.40	0.28
WFE RMS	**3.09**	**5.70**	**8.10**	**8.64**
Strehl 250um	**0.994**	**0.979**	**0.959**	**0.953**