Evaluation of the point source microscope (PSM)

1. Overview and brief summary

The following report lists all the data and used equations in the appendix while the different experiments are explained and summarized in separate chapters.

Over all the PSM is excellent to tip/tilt align optics which corresponds to a shift of the spot on the PSM camera. Aligning optical components along the optical axis of the PSM where only spot diameter can be used the accuracy decreases not a last because of the spot itself being less well defined (Raighley range). For the purpose of the GMT alignment additional measures need to be taken to get required axial accuracy where the proposed use of added astigmatism pared with the required software algorithm looks promising.

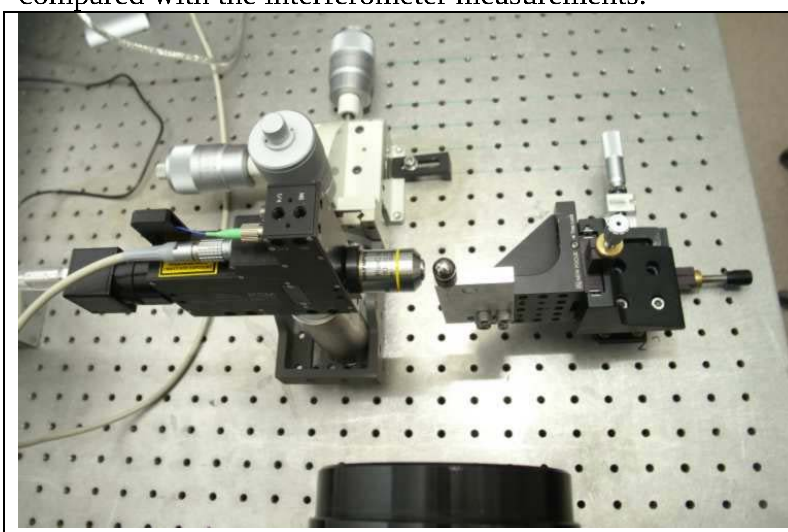
2. Software

The current version of the software is easy to use and programmed in LabView. Some of its drawbacks are that it’s not possible to save averaged frames for external data processing but only the current one. Further it would be appreciable when the peak irradiance in grey levels was continuously computed and the gray level at a certain cursor position was given without making sure that a certain window is the active one. The spot diameter is calculated wrong if it’s just a few pixels in size as the data below will show. The planned feature of auto scaling the gain is definitely going to be very valuable.

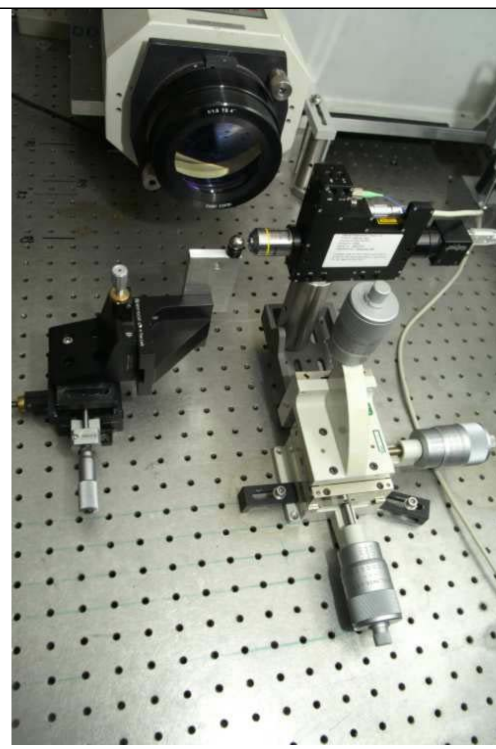
3. Lateral ball displacement test

3.1. Setup

The setup as shown in Figure 1 allows to test sensitivity and repeatability of the PSM regarding lateral displacements of the ball. The ball center was placed to be at the focus of the interferometer and then the PSM was aligned to focus at the center of the ball. Therefore the PSM measurements could be directly compared with the interferometer measurements.



a)



b)

Figure 1: a) The PSM is focused on the center of a ball and oriented 90° to the interferometer of which just the diverger lens is shown at the bottom of the picture. b) Same setup as a) from a different point of view

3.2. Repeatability

The repeatability test was performed by moving the ball lateral to the PSM that caused defocus in the interferometer and then tried to move it back to get the same reading with the PSM. The repeatability was limited by the mechanical adjustments of the stages. A comparison of the standard deviation measured by the PSM and the Interferometer are giving the repeatability of the PSM.

Table 1 shows the that the PSM essentially measures the same uncertainty as the interferometer. The detailed data are given in Appendix 6.3 and how they were processed are given in Appendix 6.2.

	Interferometer	PSM
	[µm]	[µm]
mean	2.1	-0.02
std	0.35	0.31

Table 1: Comparing the repeatability of the ball placement lateral to the PSM measured with the PSM to Interferometer measurements

3.3. Sensitivity

The test was done by moving the ball forth and back measuring its motion with the interferometer and the PSM and comparing the measurements in Figure 2 with the Interferometer measurement. It can be seen that the relation is linear but the interferometer measures different distances. If the settings in the PSM were right it should calculate the ball shift properly. One needs to check if that discrepancy comes from an improper setting like selecting the wrong objective or a software bug. The PSM shows here about twice as much ball motion as the interferometer but in the repeatability test that was not the case but would have been expected since the settings remained unchanged (or at least it is believed that they remained unchanged)).

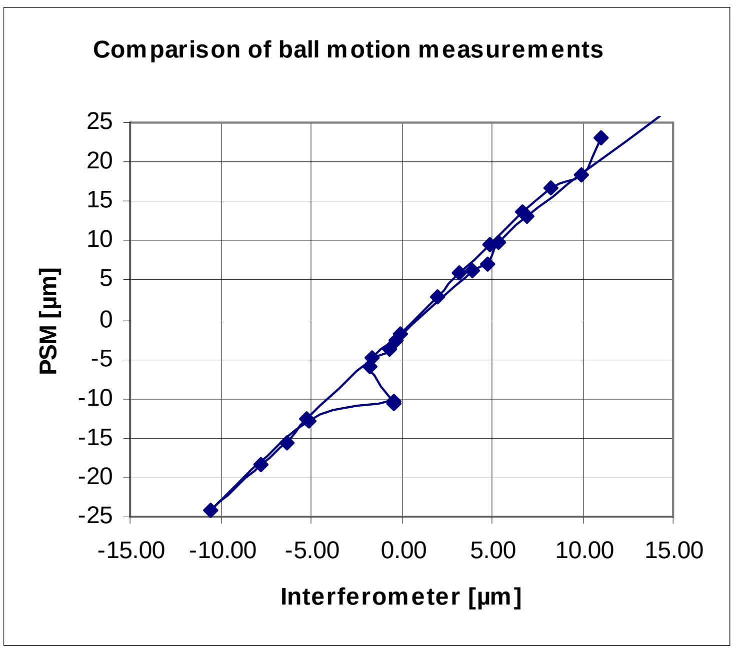


Figure 2: Comparing between the ball motion measurements of the PSM with the Interferometer measurement. The two outliers are probably from inappropriate recording in the notebook since they are off by exactly a factor of 10.

4. Axial ball displacement test

4.1. Setup

In order to check sensitivity and repeatability of the PSM for motions of the ball along the optical axis of the PSM the test was setup as shown in Figure 3.

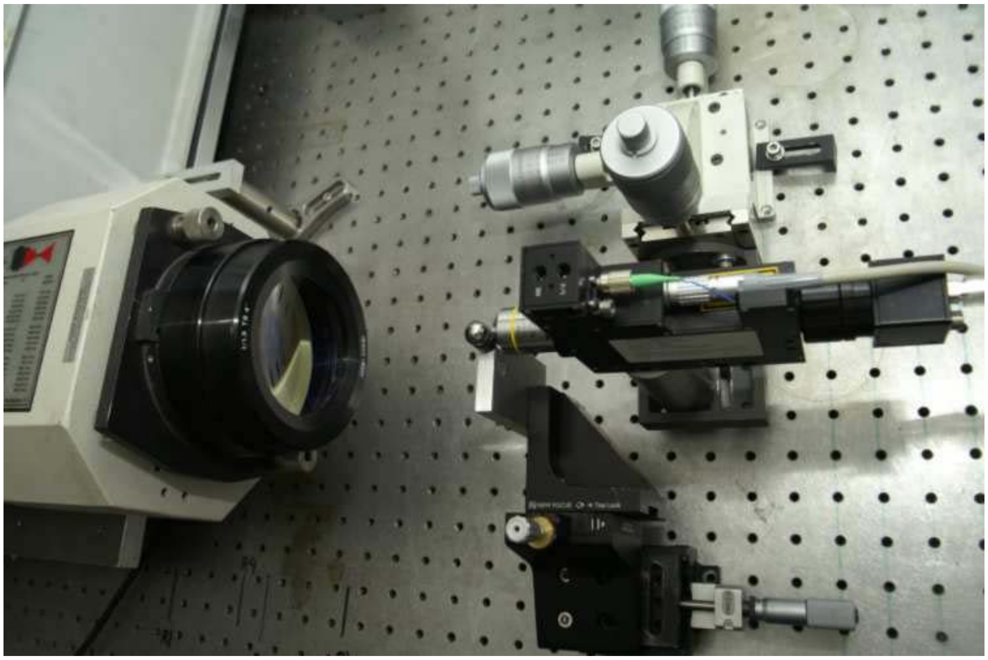


Figure 3: The picture shows the setup to test axial sensitivity and repeatability for a ball at the common focus of the PSM and interferometer

4.2. Repeatability

The ball was moved out of the PSM focus and back and then the position was determined with the interferometer. Any unintended lateral motion of the ball due to mechanical properties of the stages was not corrected. Since the PSM software returned negative values for the spot diameter that calculation was not trusted and the best focus position was obtained by visual estimation. Doing so the interferometer determined an uncertainty as given in Table 2.

Mean	**-0.7**	**[µm]**
Std	**2.03**	**[µm]**

Table 2: Mean and uncertainty for axial ball repeatability

Figure 4 shows that there was no way to use spot diameter to determine best focus position. The diameters are averaged values.

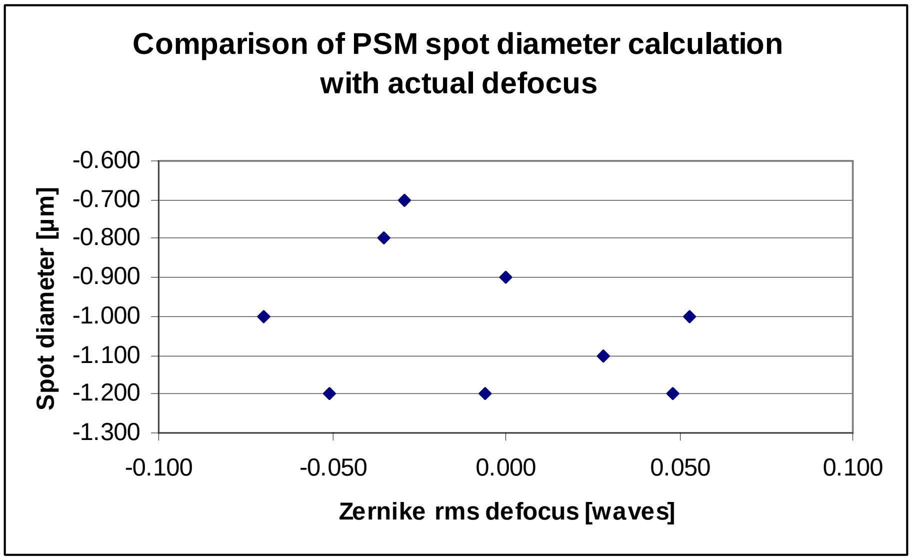


Figure 4: There is no relation between calculated spot diameter with actual ball motion visible for small ball motions

Figure 5 shows an example spot at best focus from a single frame.

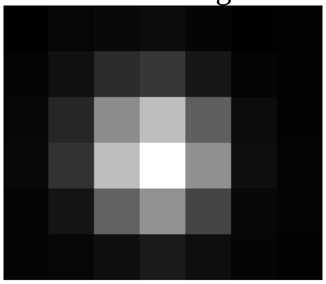


Figure 5: Example spot at best focus (one single frame, no average, processed for proper displaying in this document)

4.3. Through focus sensitivity

Moving the ball through best focus influences the return spot size as shown in Figure 6. Where it becomes obvious that an accurate determination of the defocus position by measured spot diameter is not possible. Again, the spot diameters were calculated being negative and therefore the values need to be questioned.

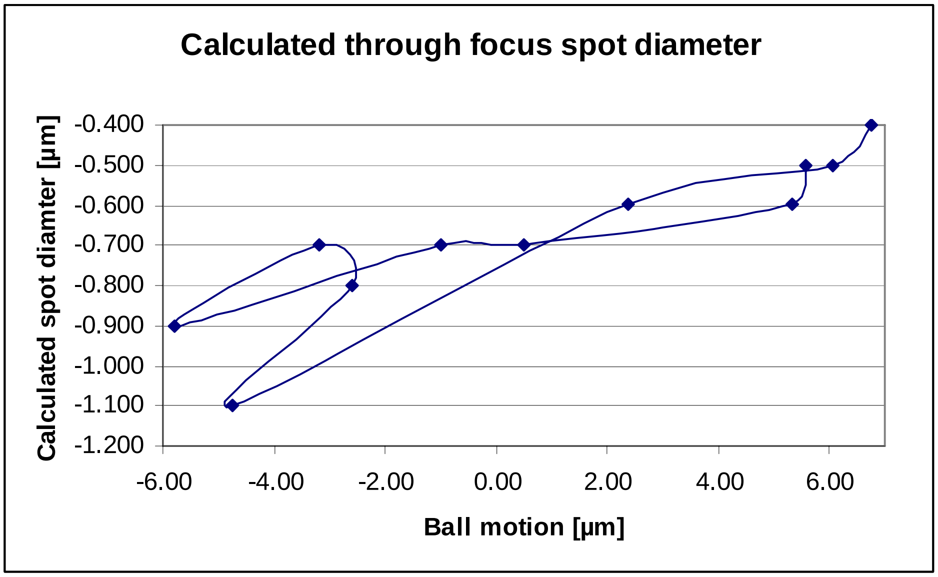


Figure 6: Spot diameter versus ball position through focus. A trend is visible but it would not be possible to use the spot diameter to calculate an accurate defocus position

5. Axial alignment of a mirror

5.1. Setup

In order to get some data how repeatability of aligning a mirror axially depends on the R/# of the mirror the setup in Figure 7 was used. With the same setup and one given R/# a through focus scan was done.

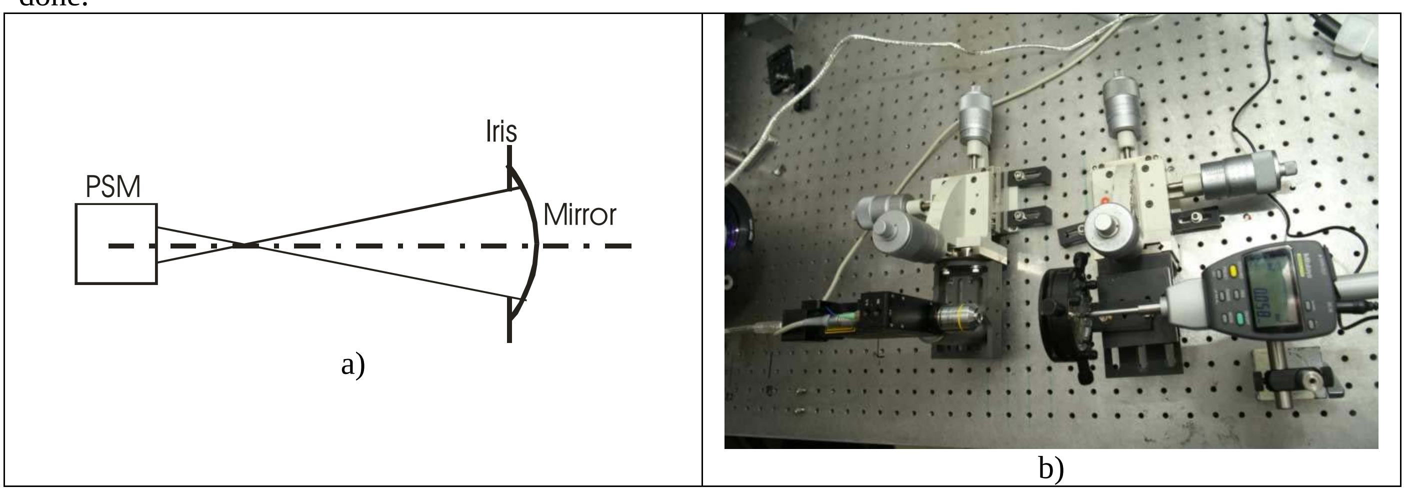


Figure 7: a) Sketch of the cross section of the setup showing the PSM illuminating a concave mirror and an Iris that allows to adjust the R/# of the mirror. b) A picture of the setup that in addition shows an indicator measuring motions of the mirror along the optical axis of the PSM

5.2. Axial Repeatability

For a small R/# significant astigmatism in the mirror surface helped finding the best focus visually. When the system was stopped down the astigmatism was not visible any more which made it much more difficult to find the best focus. Table 3 shows the repeatability of the axial alignment.

	R/2	R/5	R/10
Mean [µm]	-3.8	-14.7	-17.2
Std [µm]	2.0	5.2	16.4

Table 3: Repeatability of the mirror alignment

5.3. Through focus scan

Here the mirror was shifted through focus from –150µm to +150µm and back in steps of 5µm. The calculated spot diameter was recorded. At each position one frame of the actual spot was saved for off line processing. Since the gain was not always adjusted to have the maximum gray level being at 255 the calculated spot diameter decreases with increasing defocus due to the light spreading out and mostly falling below the threshold set for the grey level.

There has no post processing been done on that aspect yet.

6. Appendix

6.1. Hardware settings

The setting for the PSM are listed in Table 4 and the ones for the interferometer in Table 5.

Property	Value
Intensity threshold	50
Min. Area	1
# to Average (moving averaged of calculated statistical values, not statistical values of averaged frames)	25
Objective	M10x0.25 (f/2)
Max intensity	230 [grey level]

Table 4: PSM settings

Property	Value
Diverger lens	F/1.5
Wedge factor	½
# averaged phases per measurement	4 [*1]

Table 5: Settings of the interferometer. [*1] not listed in the notebook but recalled from memory

6.2. Conversion from rms Zernike defocus [λ] to [µm] ball motion

The interferometer returned the ball position in terms of rms Zernike defocus in units of λ. The conversion was done in two steps. First the defocus term W020 in µm was calculated by

$$W_{020} = 2\sqrt{3} Zern_{def,rms} 0.06328 \frac{\mu m}{\lambda}$$

Equation 1: Zernike rms defocus to W020 conversion

In the second step the defocus term was converted into ball motion by

$$\Delta z = 8\,(f/\#)^2\, W_{020}$$

Equation 2: Converting W020 to Δz ball motion

6.3. Repeatability data for lateral ball motion

Table 6 shows the measured data for the ball repeatability experiment and the statistical evaluation of them.

Interferometer f/1.5			**PSM f/2**		
Zernike rms coefficients					
Tiltx [waves]	**Tilty [waves]**	**def [waves]**	**d [µm]**	**x [µm]**	**y [µm]**
-0.089	0.192	0.059	-0.7	0.5	-0.6
-0.106	0.192	0.045	-0.9	0.1	-0.7
-0.096	0.194	0.07	-0.9	-0.3	-0.6
-0.064	0.119	0.045	-0.9	-0.3	-0.5
-0.067	0.105	0.062	-0.9	0.5	-0.2
-0.117	-0.143	0.05	-0.6	-0.3	-0.2
-0.123	0.131	0.053	-0.7	-0.1	0
-0.145	0.153	0.044	-0.5	-0.2	0
-0.131	0.127	0.045	-1	0.1	0.1
-0.135	0.123	0.049	-0.5	-0.2	0
	mean	0.0522		**-0.02**	**-0.27**
	std	0.0088		**0.31**	**0.30**
	W020	**[µm]**			
	mean	0.1144			
	std	0.0193			
	[µm ball shift]				
	mean	**2.1**			
	std	**0.35**			

Table 6: Measured data for lateral ball placement repeatability

6.4. Sensitivity data for lateral ball motion

Table 7 shows the measured data for the lateral ball motion sensitivity. In the experiment the ball was shifted just along the intended axis and no corrections were made for any unintended motion along other axis causes by the mechanical properties of the stages.

Interferometer f/1.5				PSM f/2		
Tiltx [waves]	**Tilty [waves]**	**def [waves]**	**[µm ball motion] *1**	**d [µm]**	**X *2 [µm]**	**y [µm]**
0.015	-0.053	0.361	14.24	-0.1	25.8	5.3
-0.029	-0.041	0.176	6.94	0.2	13.2	7.4
-0.024	-0.041	0.137	5.41	0.1	9.7	7.7
-0.037	-0.051	0.122	4.81	0	7.1	8.1
-0.002	-0.051	0.098	3.87	0	6.2	8.1
-0.011	-0.075	-0.009	-0.36	0.1	-2.5	8.3
-0.003	-0.082	-0.016	-0.63	0.1	-3.6	8.5
-0.008	-0.071	-0.044	-1.74	-0.1	-6	8.8
-0.021	-0.092	-0.01	-0.39	-0.1	-10.5	9.1
-0.011	-0.09	-0.01	-0.39	-0.8	-10.3	9.3
-0.03	-0.101	-0.13	-5.13	-0.8	-12.9	9.4
-0.019	-0.11	-0.268	-10.57	-1	-24.1	9.4
-0.024	-0.067	-0.1962	-7.74	-0.8	-18.3	9.3
-0.018	-0.072	-0.161	-6.35	-0.7	-15.5	9.5
0.012	-0.061	-0.133	-5.25	-0.7	-12.6	9.5
0.009	-0.029	-0.041	-1.62	-0.5	-4.9	9.3
0.003	-0.014	-0.003	-0.12	-1	-1.8	9.4
0.018	-0.019	0.05	1.97	-0.8	3	9.5
0.004	-0.021	0.08	3.16	-0.6	6	9.5
-0.013	-0.061	0.123	4.85	-1.2	9.4	9.9
-0.012	-0.066	0.168	6.63	-0.8	13.7	10.1
-0.023	-0.046	0.209	8.25	-0.8	16.6	10.2
-0.052	0.006	0.252	9.94	-0.7	18.5	10.2
-0.043	-0.027	0.279	11.01	-0.5	23	10.2

Table 7: Data for the lateral sensitivity test of the PSM. *1: Ball motion calculated from defocus using equations in section 6.2. *2: Direction of primary ball motion

6.5. Repeatability for axial ball placement

Table 1 lists all the measured data.

Interferometer f/1.5			PSM f/2			
Zernike rms coefficients						
Tiltx	**Tilty**	**def**	**d**	**x**	**y**	**File[*1]**
[waves]	**[waves]**	**[waves]**	**[µm]**	**[µm]**	**[µm]**	
-0.171	-0.008	-0.006	-1.200	-0.800	-0.400	AxB01
-0.161	-0.022	0.028	-1.100	-0.900	-0.400	AxB02
-0.319	-0.003	-0.106	-1.200	0.100	0.600	AxB03
-0.320	-0.026	-0.051	-1.200	0.100	0.600	AxB04
-0.338	-0.020	-0.035	-0.800	0.000	0.900	AxB05
-0.334	-0.031	0.053	-1.000	0.100	0.700	AxB06
-0.296	-0.050	-0.029	-0.700	-0.400	1.000	AxB07
-0.298	-0.068	-0.070	-1.000	-0.800	1.600	AxB08
-0.265	-0.060	0.000	-0.900	-1.000	1.600	AxB09
-0.400	0.131	0.048	-1.200	-0.100	0.500	AxB10
	mean	-0.0168				
	std	0.0515				
	W020	**[µm]**				
	mean	-0.0368				
	std	0.1130				
	[µm ball shift]					
	mean	**-0.7**				
	std	**2.03**				

Table 8: Measured data for axial ball repeatability test with some statistical evaluation.
[*1] Name of the file where the frame is saved.

6.6. Sensitivity data for axial ball motion

The data collected by testing how sensitive the calculated spot diameter is to a motion of the ball along the optical axis of the PSM are listed in Table 9

Interferometer f/1.5				PSM f/2			
Zernike rms coefficients							
Tiltx	**Tilty**	**def**		**d**	**x**	**y**	**File**
[waves]	**[waves]**	**[waves]**	**[µm ball motion]**	**[µm]**	**[µm]**	**[µm]**	
0.005	0.110	0.171	6.75	-0.400	-4.000	3.000	AxThF01
0.012	0.126	0.154	6.08	-0.500	-4.000	3.000	AxThF02
0.012	0.126	0.060	2.37	-0.600	-4.200	3.300	AxThF03
-0.015	0.120	-0.120	-4.73	-1.100	-4.500	3.400	AxThF04
-0.024	0.120	-0.066	-2.60	-0.800	-4.900	3.800	AxThF05
-0.013	0.126	-0.081	-3.20	-0.700	-5.000	3.800	AxThF06
-0.008	0.129	-0.147	-5.80	-0.900	-5.300	4.400	AxThF07
0.008	0.147	-0.025	-0.99	-0.700	-5.000	3.800	AxThF08
0.041	0.167	0.013	0.51	-0.700	-5.000	3.800	AxThF09
0.056	0.188	0.135	5.33	-0.600	-5.000	3.500	AxThF10
0.041	0.173	0.141	5.56	-0.500	-5.100	3.700	AxThF11

Table 9: Data showing how the measured spot diameter changes as the ball is moved through best focus

6.7. Repeatability data for axial mirror alignment

The data collected by testing how repeatable a mirror can be aligned with respect to the PSM in axial direction are listed in Table 10.

	R/2		R/5		R/10	
Trial	**Indicator [µm]**	**spot dia. [pixel]**	**Indicator [µm]**	**spot dia. [pixel]**	**Indicator [µm]**	**spot dia. [pixel]**
1	0	-0.9	-14	1.4	-18	7.2
2	-2	-0.8	-19	1.5	-10	7.1
3	-2	-0.8	-6	1.3	5	7.2
4	-5	-0.8	-14	1.4	-3	7.3
5	-4	-0.5	-12	1.7	-4	7.2
6	-3	-0.8	-11	1.5	-49	7.0
7	-6	-0.5	-26	1.5	-18	7.2
8	-6	-0.6	-16	1.5	-12	7.2
9	-4	-0.6	-14	1.3	-36	7.2
10	-6	-0.8	-15	1.5	-27	7.1
mean	**-3.8**	**-0.71**	**-14.7**	**1.46**	**-17.2**	**7.17**
std	**2.0**	**0.1**	**5.2**	**0.1**	**16.4**	**0.1**

Table 10: Collected data from the repeatability test for different R/#s' of the mirror

6.8. Through focus data of the mirror

Table 11 shows the data collected from the scan through focus.

File	Indicator [µm]	spot dia. [pixel]	File	Indicator [µm]	spot dia. [pixel]	File	Indicator [µm]	spot dia. [pixel]	File	Indicator [µm]	spot dia. [pixel]
001	-150	5.1	032	5	7.2	062	145	4.4	092	-5	7.3
002	-145	5.3	033	10	7.2	063	140	4.4	093	-10	7
003	-140	5.6	034	15	7.1	064	135	4.6	094	-15	7.2
004	-135	5.7	035	20	7.1	065	130	4.8	095	-20	7.2
005	-130	5.8	036	25	6.9	066	125	5.1	096	-25	7.2
006	-125	6.1	037	30	7	067	120	5.3	097	-30	7.1
007	-120	6.1	038	35	6.9	068	115	5.6	098	-35	7.1
008	-115	6.3	039	40	6.9	069	110	5.9	099	-40	7.1
009	-110	6.4	040	45	7	070	105	6	100	-45	7.1
010	-105	6.5	041	50	6.8	071	100	6.1	101	-50	7.2
011	-100	6.5	042	55	6.9	072	95	6.3	102	-55	6.9
012	-95	6.7	043	60	6.8	073	90	6.3	103	-60	6.9
013	-90	6.7	044	65	6.6	074	85	6.5	104	-65	7.1
014	-85	6.8	045	70	6.7	075	80	6.5	105	-70	6.9
015	-80	6.9	046	75	6.6	076	75	6.6	106	-75	7
016	-75	6.9	047	80	6.6	077	70	6.8	107	-80	6.9
017	-70	6.9	048	85	6.5	078	65	6.7	108	-85	6.8
018	-65	7	049	90	6.4	079	60	6.9	109	-90	6.7
019	-60	6.9	050	95	6.1	080	55	6.8	110	-95	6.8
020	-55	7	051	100	6	081	50	6.9	111	-100	6.7
021	-50	7.2	052	105	5.8	082	45	6.9	112	-105	6.6
022	-45	7.1	053	110	5.8	083	40	7	113	-110	6.5
023	-40	7	054	115	5.6	084	35	7.1	114	-115	6.4
024	-35	7.1	055	120	5.3	085	30	7.1	115	-120	6.2
025	-30	7.1	056	125	5	086	25	7.1	116	-125	6
026	-25	6.9	057	130	4.9	087	20	7.1	117	-130	5.8
027	-20	7.3	058	135	4.6	088	15	7.1	118	-135	5.7
028	-15	7	059	140	4.2	089	10	7.2	119	-140	5.5
029	-10	7.1	060	145	4	090	5	7.1	120	-145	5.3
030	-5	7.1	061	150	3.6	091	0	7.2	121	-150	5
031	0	7									

Table 11: Data collected from the through focus scan by moving the concave mirror. The file number corresponds to a saved frame