Fabrication and Testing of the 1.2m SAO Primary Mirror

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Contents

1. Summary

Polishing of the SAO 1.2m primary mirror was completed on June 21st 2013. Final optical test measurements conducted June 24th through June 27th, yielded a measured surface figure of 11.3nm RMS after subtracting piston, tip/tilt, power and spherical aberration. The structure function specification has been met by a significant margin for the lower and mid spatial frequencies while the higher frequencies are at specification.

2. Coordinate system

The optical measurement coordinate system is defined such that the x-axis (0°) is aligned between cores B3 and C6 and the y-axis (90°) is aligned with core A5 as in Figure 1. (Note that the drawing in Figure 1 is the BOTTOM VIEW.). This coordinate system was used for the definition of optical axis centration and all optical surface maps in the report.

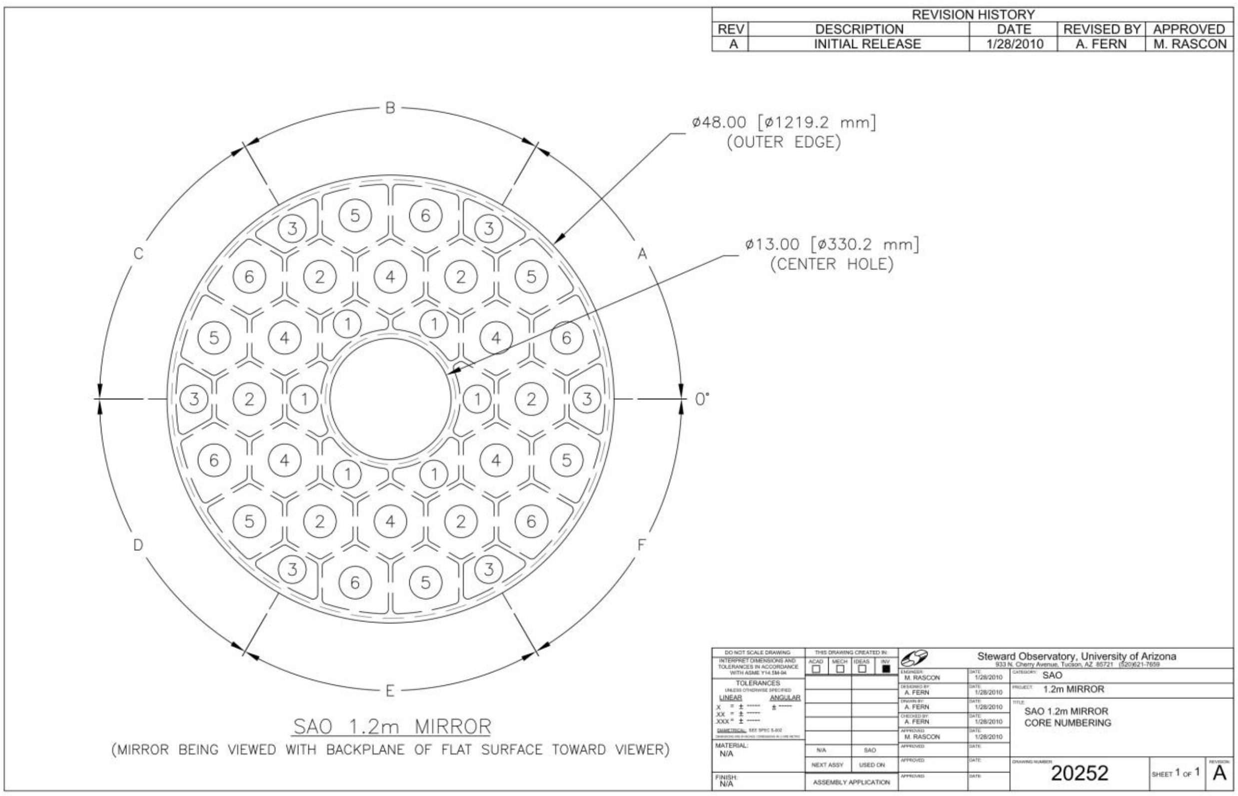


Figure 1. Drawing of SAO 1.2 m primary mirror

3. Mirror dimensions

The mean thickness of the facesheet and backsheet were measured in the surface generating stage using ultra sonic thickness measurement device. Both mean thickness of facesheet are out of specification and marked in red.

The outer edge thickness appears to be at the edge of its tolerance, but the measured radius of curvature shows that the mirror surface has the correct sag.

Table 1. Measured dimensions

Dimension	Nominal	Measured
Front facesheet		
Outer Diameter (mm)	1219.2 ± 1	1219.9
Inner Diameter (mm)	330.2 + 2	330.7
Mean Thickness (mm)	28.0±1	25.8
Backplate		
Outer Diameter (mm)	1219.2 ± 1	1219.9
Inner Diameter (mm)	330.2 + 2	330.4
Mean Thickness (mm)	25.4±1	27.1
Mirror thickness		
Vertex Thickness (mm)	166.4 ±2	166.98
Outer Edge Thickness (mm)	205.5±2	207.5
Wedge (TIR at OD; mm)	0.23	0.1

4. Mechanical and cosmetic quality

Document UASO 30125-TS-1 requires that all scratches that exceed 0.100 mm in width be catalogued. The document also requires that bubbles less than 10 mm in diameter must be treated. All catalogued scratches and bubbles that meet this criterion can be found in Table 2 and Table 3. (Full list of Table 3 is in Appendix B)

Table 2. Documented scratches in mirror clear aperture.

Location (Core #)	Length (mm)	Width (mm)	Comment
B1	50	0.1	*From grinding*
F6	7	0.1	*Bubble dressing*

Table 3. Partial list of bubbles in mirror clear aperture.

Location	Size(mm)	Area(mm^2)
A1	3.5	9.616
A1	2	3.140
A2	4	12.560
A2	2	3.140
A2	2	3.140
A2	2.5	4.906
A3	1.5	1.766

Location	Size(mm)	Area(mm^2)
C5	2.5	4.906
C6	2	3.140
C6	1.5	1.766
D1	4	12.560
D1	2	3.140
D1	2	3.140
D2	1	0.785

A total of 89 bubbles were catalogued. All bubbles were treated in effort to minimize their effect on the polishing process. The total area encompassed by the bubbles was calculated in an effort to demonstrate the net light loss to the clear aperture. These results can be found in Table 4.

Table 4. Total area encompassed by bubbles in the clear aperture

Total number of bubbles	89
Total area from bubbles (mm^2)	319.84
Total area of mirror (mm^2)	1019636.50
Percent loss from bubbles (%)	0.03

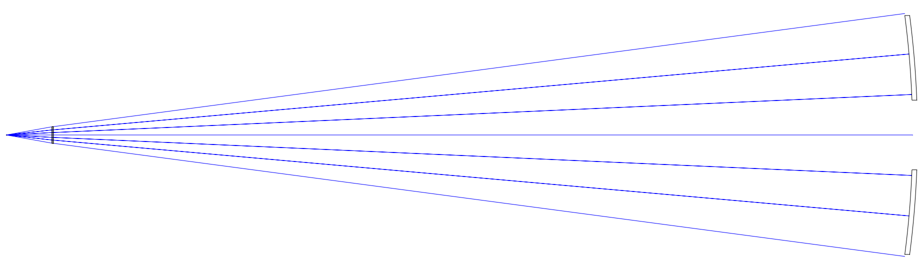
5. Surface figure at completion of polishing

5.1 Interferometric test and data processing

The final SAO mirror figure measurements were made on the polishing support which duplicated the force set of the telescope cell. The mirror was polished and measured with the telescopes circumferential load spreaders in place in order to account for their additional mass with respect to the mirror and the polishing support.

The mirror was allowed to thermally equilibrate for a total of 48 hours after the last polishing run. While in polishing, the mirror was given 14 to 16 hours for acclimation and the measurement repeatability was 5 to 8 nm RMS between measurements.

Optical layout of the interferometric testing set up is in Figure 2 and the actual configuration is shown in Figure 3. As shown in the photo the test set up consists of the 4020 Phasecam (4D Technology) and a computer-generated hologhram as a null corrector. The mirror was measured at 8 clocking orientations from 0° to 360° with 100 frames at each orientation. Then the measured data were averaged after matching the orientation in order to remove the artifacts created from the interferometer, CGH and environment.



Surf	Type	Comment	Radius	Thickness		Glass		Semi-Diameter		Conic
OBJ	Standard		Infinity	230.000				0.000		0.000
1	Standard		Infinity	0.000				41.246		0.000
2	Binary 2		Infinity	6.370		SILICA		41.246		0.000
3	Standard		Infinity	4320.000				41.823		0.000
*	Standard		-4590.870	-4320.000	P	MIRROR		610.000	U	-1.040
5	Standard		Infinity	-6.370	P	SILICA		41.328		0.000
6	Binary 2		Infinity	-230.000	P			40.750		0.000
IMA	Standard		Infinity	-				0.293		0.000

Figure 2. Optical layout

Figure 3. Interferometric testing set up

5.2 CGH wavefront error evaluation

The CGH used for the interferometric test of the SAO mirror is patterned in 6” substrate and the substrate error was evaluated under the Wyko 6000 interferometer as in the Figure 4.

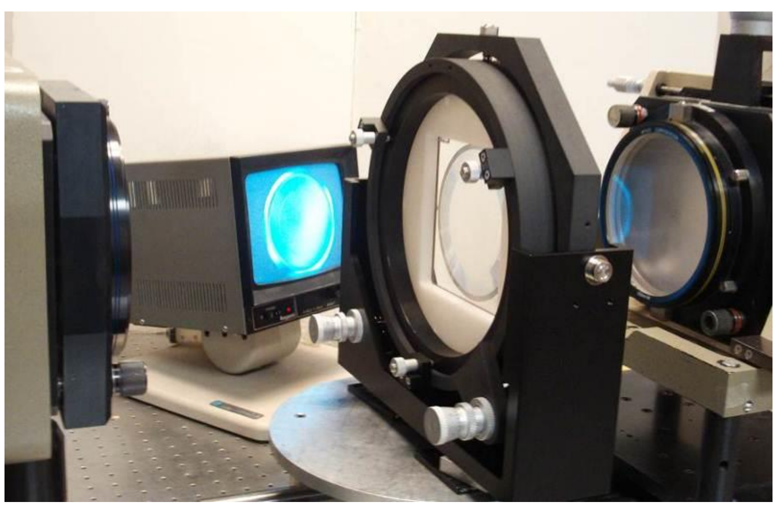


Figure 4. CGH wavefront error evaluation

Same as the mirror testing, the CGH wavefront map has been clocked to 8 different orientations by 45° and averaged. From the averaged map we observed error of 21.9nm RMS dominated mostly by power as in Figure 5. Note that all the artifacts from the fiducials in the CGH are masked out. The amount of power, 21.9 nm RMS, is yet small and it corresponds to less than 1.5 µm spacing change between the CGH and the mirror. Spherical aberration in the CGH is 0.26 nm RMS as in Figure 6 and it is negligible. After power and spherical aberration were removed, the residual wavefront error, which will be observed in surface figure, is 2.0 nm RMS and statistical evaluation is shown in Figure 7.

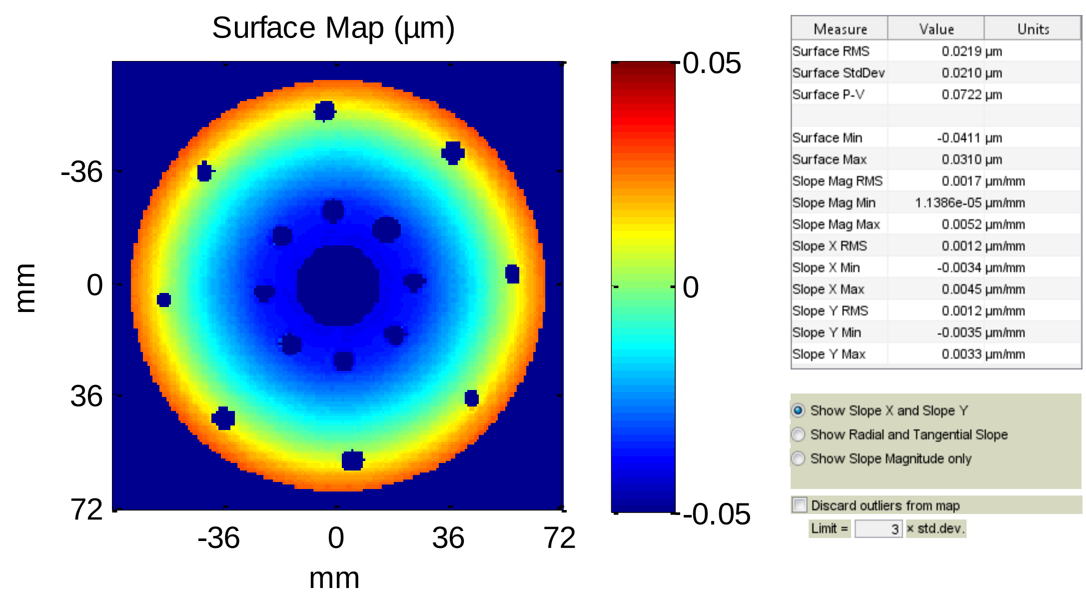


Figure 5. CGH Wavefront error map (Piston and tilt removed and fiducials in CGH are masked)

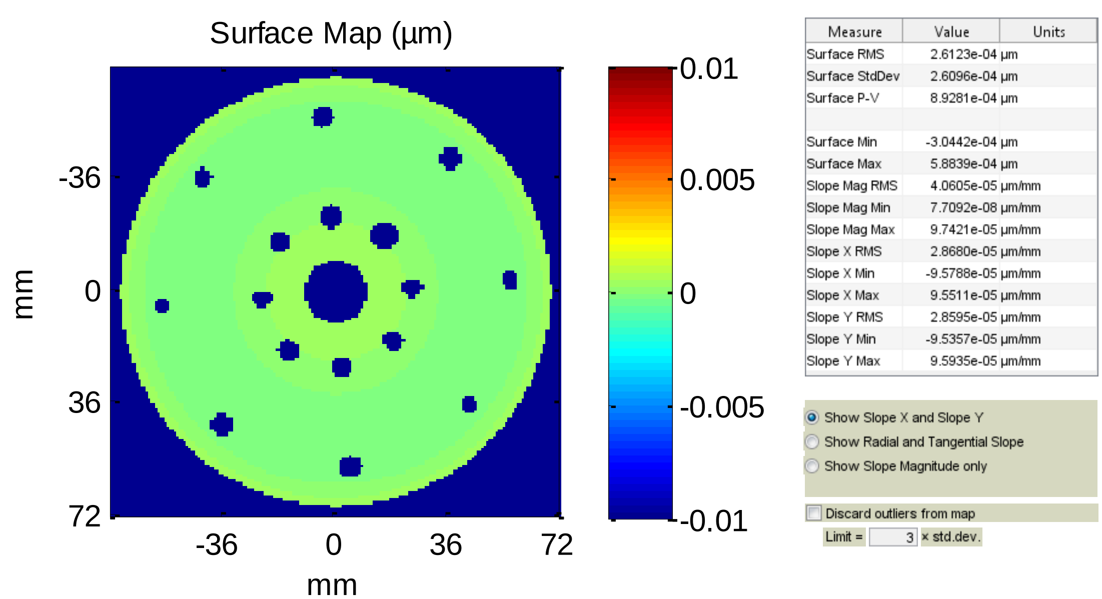


Figure 6. Spherical aberration in CGH

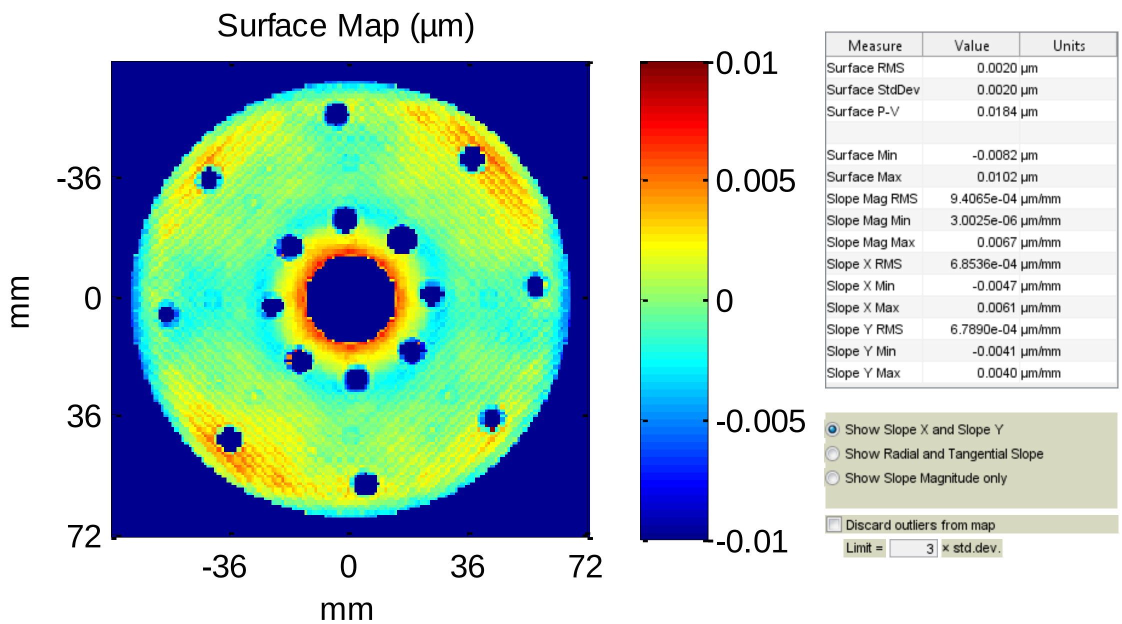


Figure 7. Residual CGH wavefront error map (Piston, tilt, power and spherical aberration removed)

5.3 Distortion correction and clear aperture verification

Verification of the clear aperture of the mirror was accomplished through the use of fiducials and proper distortion correction. To correct imaging distortion of the testing, fiducials were layed out on the optical surface of the mirror as in Figure 8 and the locations of each fiducial were measured using a laser tracker as in the Figure 9.

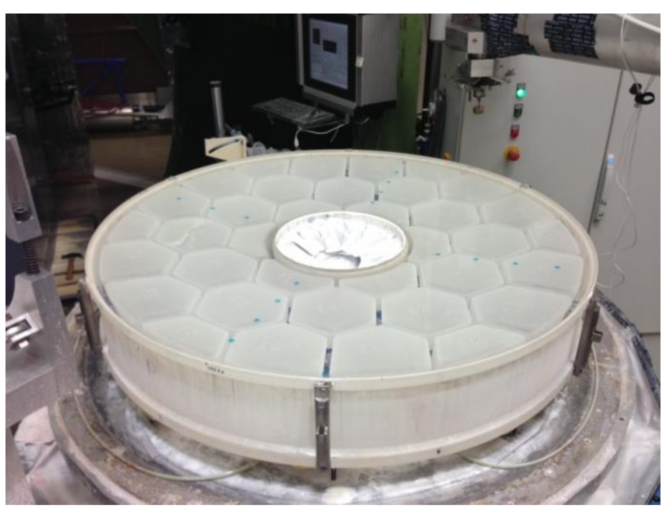


Figure 8. SAO mirror and fiducials

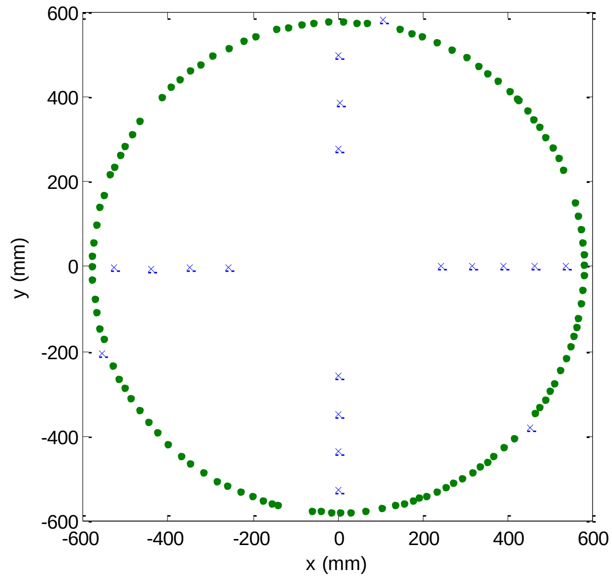


Figure 9. SAO mirror fiducial layout for distortion correction

To verify clear aperture three fiducials are placed on the circle of 1200 mm diameter as in Figure 10.

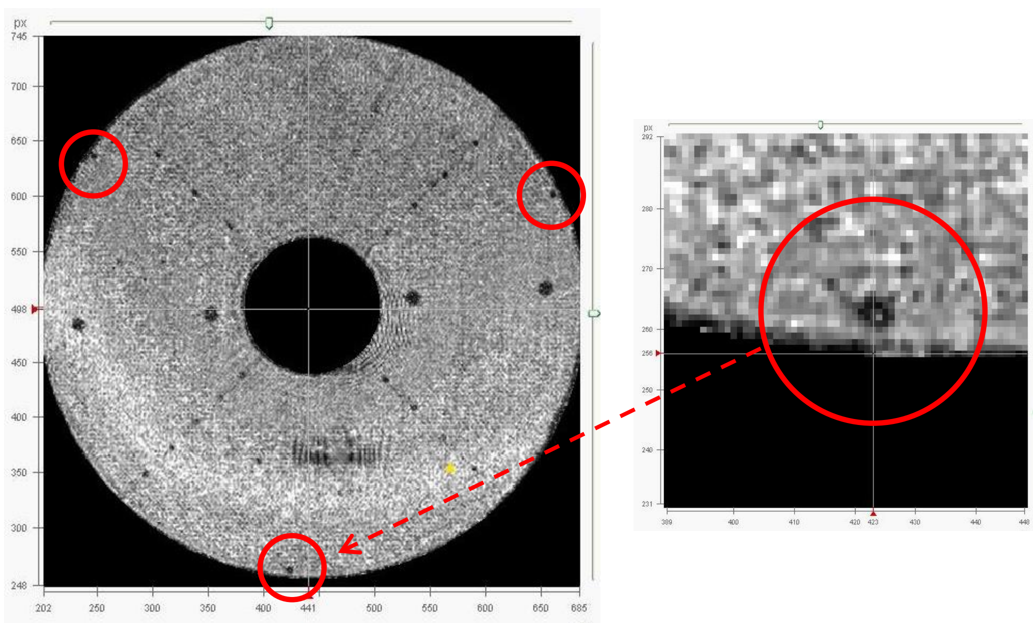


Figure 10. Modulation map shows three fiducials to verify clear aperture

5.4 Optical surface figure

The figure of the SAO 1.2m mirror is shown in Figure 11. The aperture defined has a 1200mm outer and 356mm inner diameter. The surface map indicated in Figure 11 has Piston, Tip/Tilt, Focus, Spherical and Coma subtracted. The amount of coma present in the mirror will later be related to the amount of decenter between the optical axis and mechanical axis. This value of decenter was found to be within specification; therefore Coma does not need to be included in the surface RMS calculation. The map is an average of 8 angular orientations rotated by 45°. The optical test was conducted after an acclimation period of 48 hours. Air handlers in the vicinity of the mirror were shut off in an effort to reduce air turbulence in the optical path. The mirror surface error is 11.3 nm RMS.

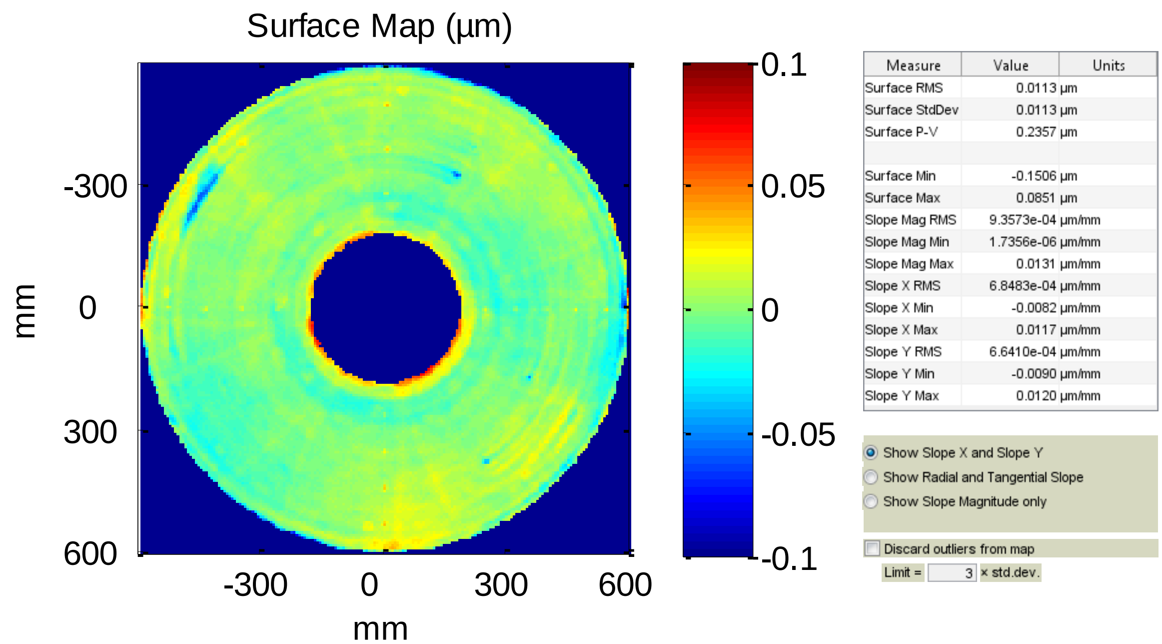


Figure 11. SAO 1.2 m mirror surface figure

5.5 Encircled energy and structure function

Figure 12 shows the surface map, point spread function and encircled energy at 500 nm for the actual mirror in perfect seeing and same quantity in 0.25 arcsec seeing. It is calculated over the clear aperture and 80% of the light is contained in a diameter of 0.32 arcsec.

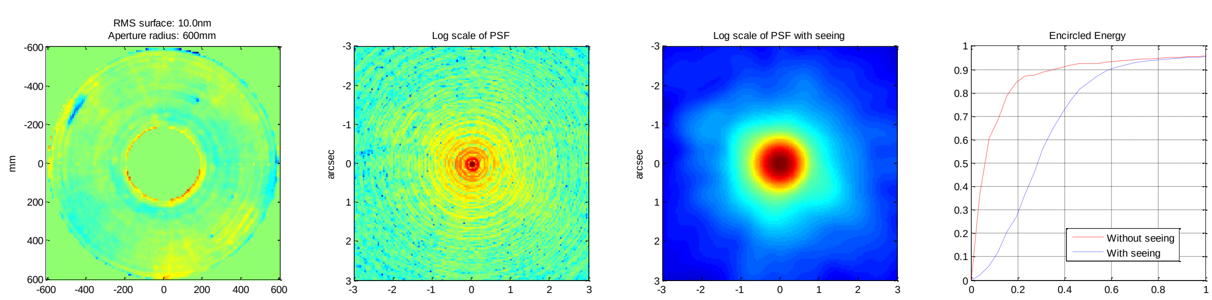


Figure 12. Encircled energy

The specification for the SAO primary mirror corresponds to 0.12 arc second seeing and 2% scattering loss at 500 nm per the document UASO 30125-TS-1. Structure function has been evaluated using the final processed map in Figure 11 and the results are in Figure 13.

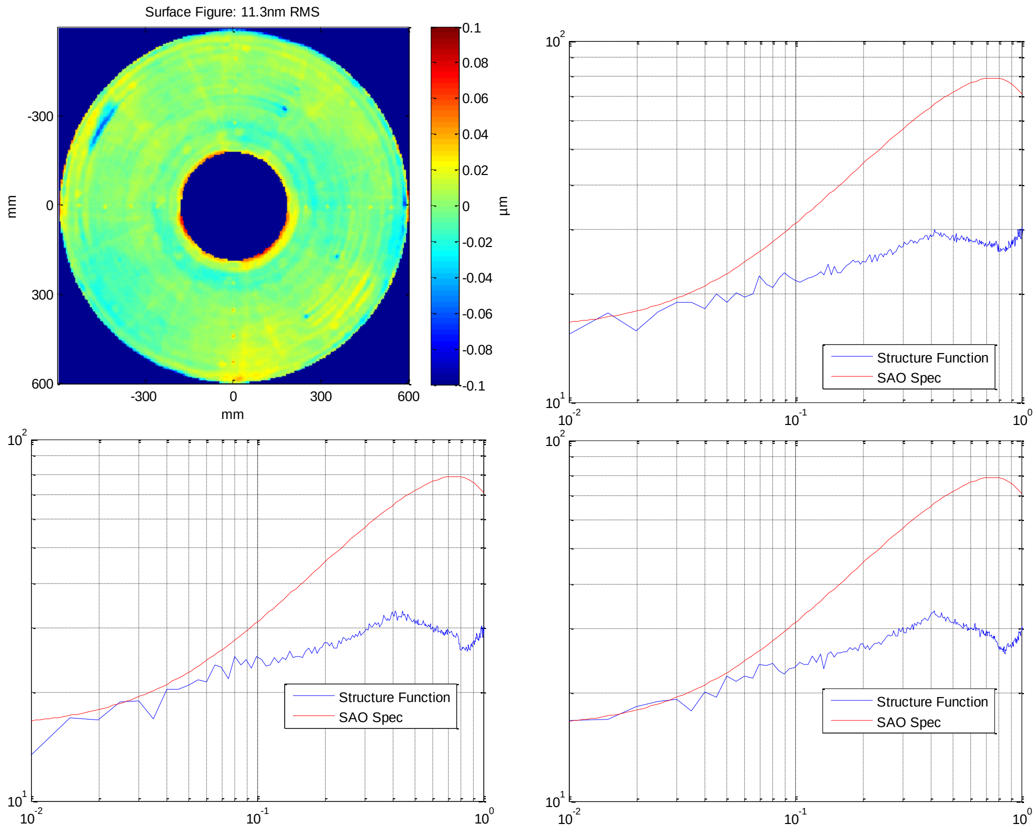


Figure 13. Structure function analysis of SAO mirror. (Three iterations were conducted to demonstrate repeatability.)

5.6 Optical surface finish

The optical surface finish of the SAO 1.2m mirror was measured with the MicroFinish Topographer (MFT) instrument in order to determine the microroughness down to the angstrom level. The MFT instrument, pictured in Figure 14, is essentially an interferometer with a small FOV of 1.1mm × 8mm. This tool is very effective at resolving microscopically small surface structure. Document UASO 30125-TS-1 requires that the SAO 1.2m mirror surface finish be 20Å RMS or better.

Figure 14. MFT instrument used for measuring surface microroughness

The SAO mirror's optical surface finish was measured in 6 locations, each with a different radial or clocking location. The measurement locations are depicted in Figure 15 where the cores A1, A2, A3, E2 and rib sections D1-D2, D2-D3 were sampled. The selected radial locations allow for a sample point every 75mm radially. Outer most and inner most sample locations were approximately 50mm from their respective edge relative to the ID or OD of the mirror. Measurement results indicate that the SAO mirror currently meets the microroughness specification of 20Å with an average microroughness of 17Å.

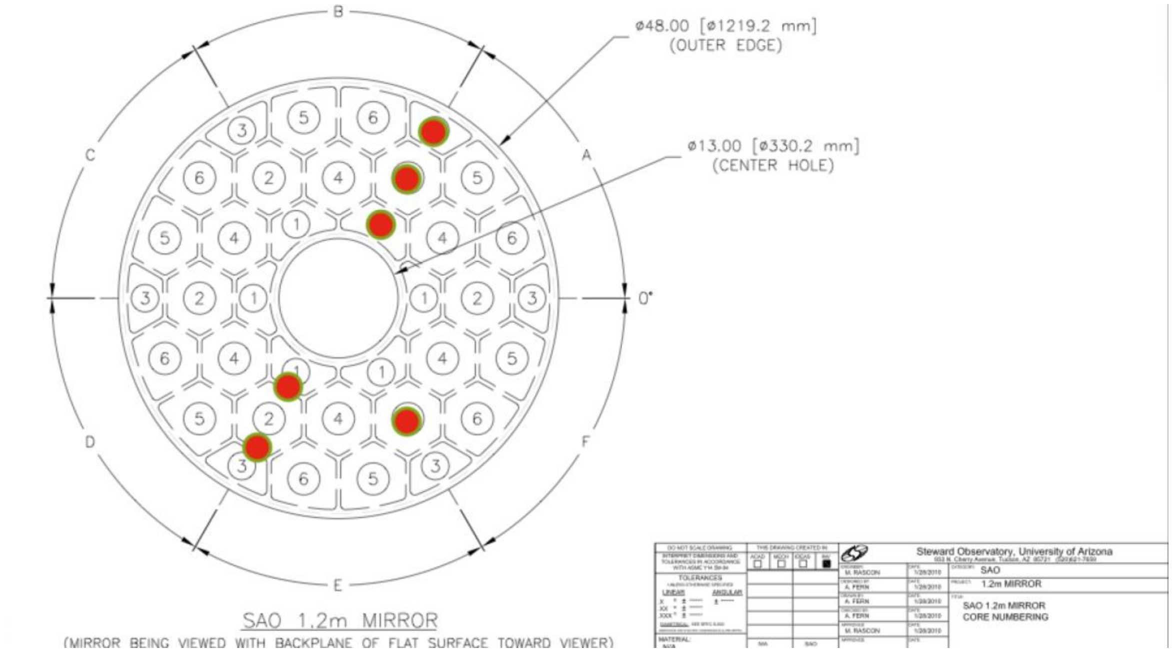


Figure 15. Microroughness measurement locations on SAO mirror

The surface roughness values for each measurement location are listed in Table 5. The results were a random distribution indicating that no particular radial zone on the mirror was more polished than any other. These results are consistent with the surface microroughness typically expected from a cerium oxide polishing compound and 64-pitch combination.

Table 5. Surface roughness measurement

Core	Surface RMS (Å)
A1	15.8
A2	18.5
A3	18.1
D1/D2	18.2
D2/D3	13.8
E2	15.0
Average	16.6

In Figure 16 a topographical map of the surface microroughness is depicted for the highest and lowest values, which were found in core A2 and rib D2/D3 respectively.

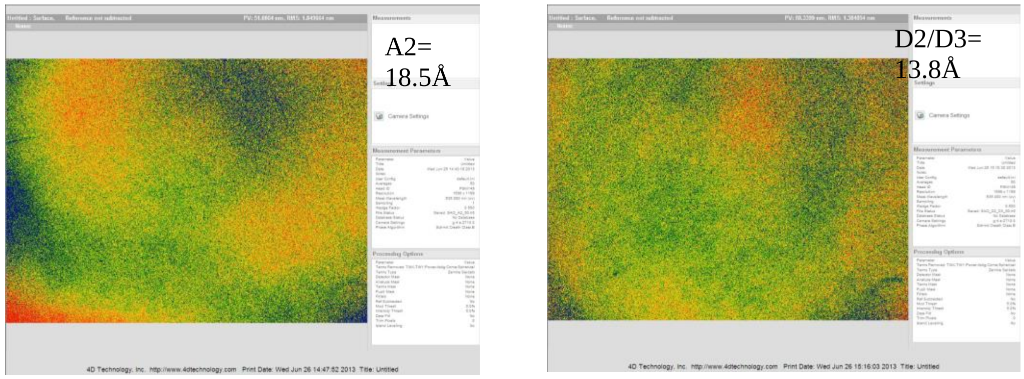


Figure 16. MFT measurements of surface roughness analyzed in 4Sight 2.4

6. Mirror geometry

6.1 Radius of curvature

The spacing between the CGH and the mirror was measured using T3 laser tracker with 0.5" sphere mounted retroreflector (SMR) as in Figure 17. The measured spacing is 4317.538 mm with 50 µm uncertainty. The spacing between the focus of interferometer and the CGH was not measured but evaluated using power in alignment pattern in the CGH. With the measured value, reoptimization was performed with the optical model in Zemax and the Radius of Curvature of 4590.244mm was obtained.

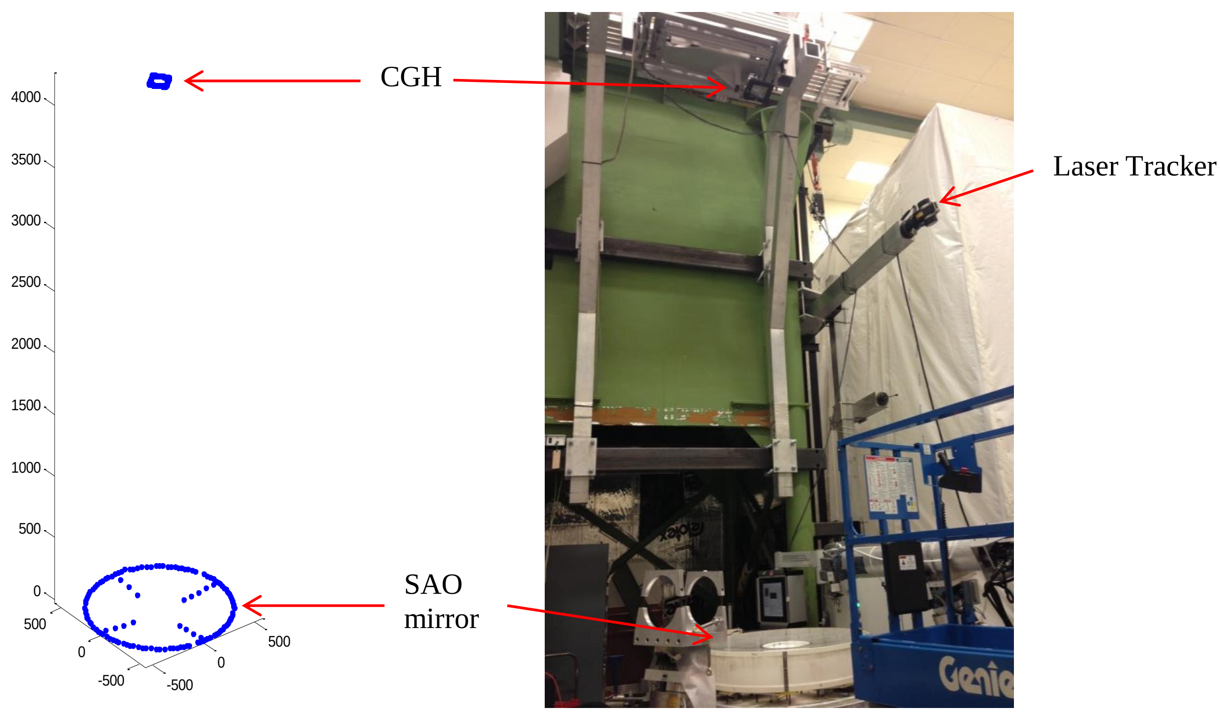


Figure 17. Spacing measurement using a laser tracker

6.2 Conic constant

The Conic constant was evaluated from the residual 3rd order spherical aberration, -0.0019 µm from the measurement, which is expressed as $S(6\rho^4 - 6\rho^2 + 1)$, where $\rho = r/(D/2)$ is the normalized radius and S is the Zernike coefficient for surface error. The relation between S and conic error Δk is

$$\Delta k = 6144 f^3 \frac{S}{D},$$

where f=1.91 is the focal ratio and D =1200 mm. The resulting conic error from residual spherical aberration in measurement, Δk is -0.000068.

An error in radius of curvature also introduces an error in the conic constant determined from the null test. The relation between radius of curvature error and conic error is

$$\frac{\Delta k}{k} = -\frac{\Delta R}{R},$$

where measured ΔR = -0.626 mm and nominal k = -1.040231. The resulting conic error from radius curvature error, Δk is -0.00014.

Therefore the conic constant error of the SAO mirror is -0.000072 and the estimated conic constant, k is -1.040303.

6.3 Centration of optical axis

In order to evaluate the amount of decenter between the mechanical OD and optical axis of the mirror, the Coma coefficients that measured at 0° and 180° were used. The first step of the measurement process is to center the mechanical OD of the mirror relative to rotary table axis. This is accomplished using conventional dial indicator metrology. We found that the mechanical OD was decentered from the turntable axis by 75 microns toward 329° in the mirror coordinate system. We included this displacement in the calculation of the decenter of the optical axis.

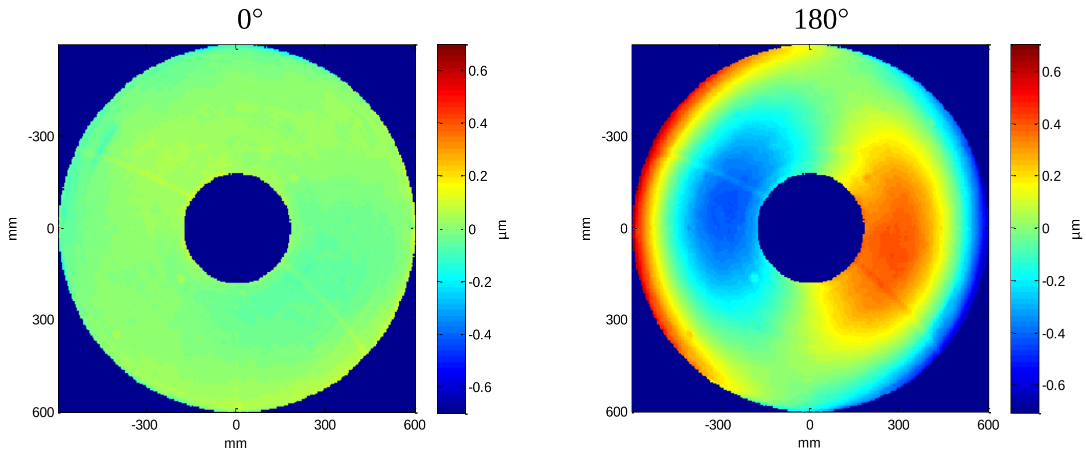
The relation between decenter of the optical axis and coma is

$$\Delta x = 384 f^3 C_0$$

$$\Delta y = 384 f^3 C_{90}$$

where C_0 and C_{90} are the Zernike coefficients for the 2 components of coma in the surface, and the 2 polynomials are $(3\rho^3 - 2\rho^2)\cos\theta$ and $(3\rho^3 - 2\rho^2)\sin\theta$ for normalized polar coordinates (ρ, θ) on the mirror.

Figure 18 shows the measurements at 0° and 180° and corresponding Zernike Coma coefficients.



C_0= -0.020
C_{90}= 0.016

C_0= -0.232
C_{90}= 0.053

Figure 18. Measured Coma at 0° and 180°

Due to the large 180° rotational change, the tilt fringe density in the optical measurement reached a level in which phase unwrapping errors. To mitigate this problem, the interferometer was decentered and the effect of decentering the interferometer led to a 100 nm uncertainty in the coma coefficients. This amount of uncertainty in Coma was translated to ±0.30 mm in decenter uncertainty.

The evaluated optical axis decenter is shown in Table 6.

Table 6. Optical axis location reference to the OD of mirror

Decenter in x	0.37	±0.30	mm
Decenter in y	-0.16	±0.30	mm
Net decenter	0.40	±0.45	mm
Direction	-23.4		degrees

The Coma measurement indicates that the mechanical axis and optical axis are aligned to each other within the required specification of ±1.00mm. These measurements were repeated 3 times and yielded variability in net decenter of less than 50 µm.

7. Compliance Matrix

The compliance matrix of the SAO 1.2m mirror is listed in Table 7 in accordance with document UASO 30125-TS-1 and Drawing 20253 Rev E.

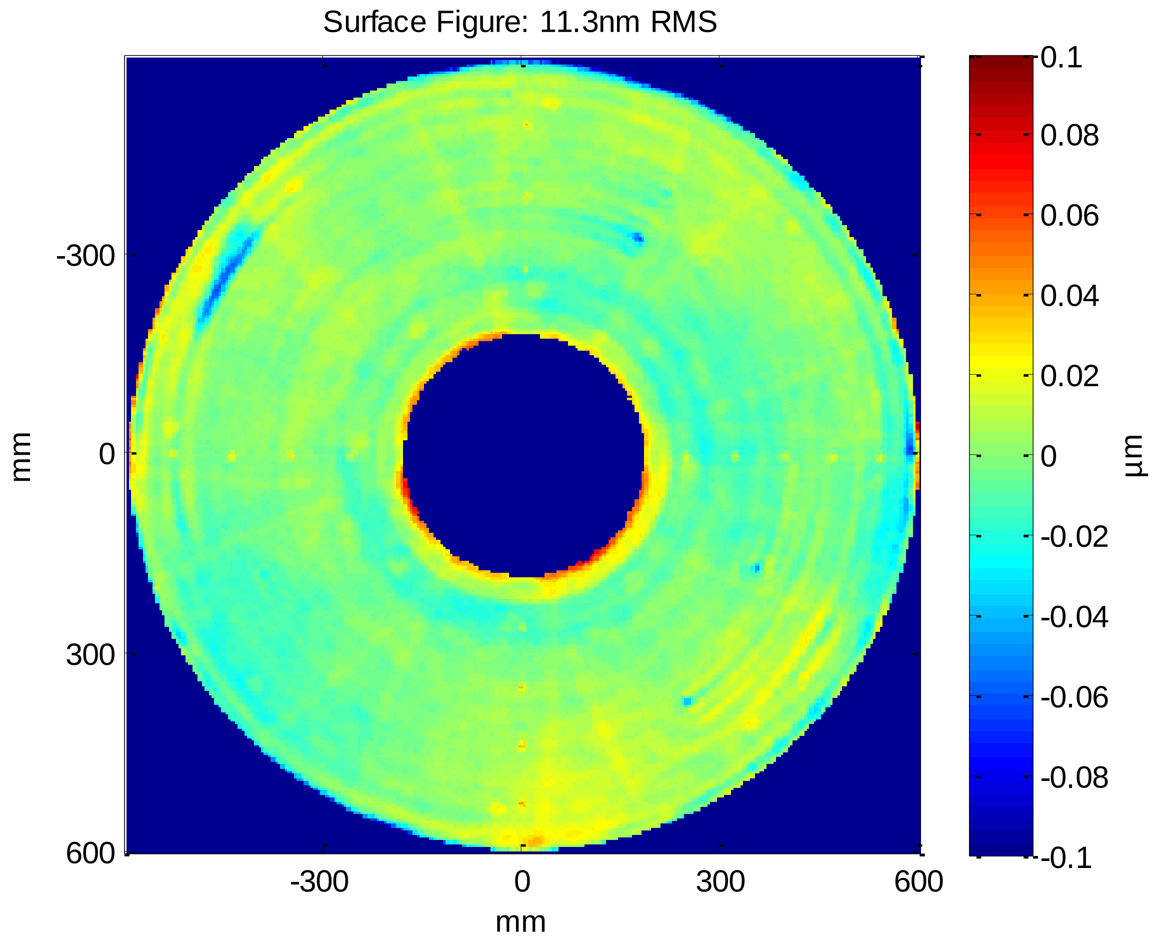
Table 7. Compliance matrix

Item	Specification (Tolerance)	As-Built (Uncertainty)	Compliance
Radius of Curvature, *R*	4590.870(±1.0mm)	4590.244mm (50µm)	YES
Conic Constant, *k*	-1.040231(±0.0002)	-1.040303 (0.00001)	YES
Clear Aperture (OD/ID)	1194mm/356mm	1200mm/356mm	YES
Surface Figure	See Structure Function Chart	See Structure Function Chart	YES
Surface Finish	20Å RMS	17Å RMS	YES
OA Centration	1mm	0.4mm (±0.42mm)	YES

References

1. Technical Specifications of SAO 1.2m Mirror (UASO 30125-TS-1)
2. Drawing of SAO 1.2m Mirror (DWG 20253 Rev E)

Appendix A: Surface map



Appendix B: Table 3. Full list of bubbles in mirror clear aperture

Location	Size(mm)	Area(mm^2)	Location	Size(mm)	Area(mm^2)
A1	3.5	9.616	C5	2.5	4.906
A1	2	3.140	C6	2	3.140
A2	4	12.560	C6	1.5	1.766
A2	2	3.140	D1	4	12.560
A2	2	3.140	D1	2	3.140
A2	2.5	4.906	D1	2	3.140
A3	1.5	1.766	D2	1	0.785
A3	2	3.140	D2	1.5	1.766
A3	1.5	1.766	D4	1.5	1.766
A4	0.7	0.385	D4	1	0.785
A4	1.5	1.766	D4	2	3.140
A5	3.5	9.616	D4	0.7	0.385
A5	2.5	4.906	D4	2	3.140
A5	2.5	4.906	D5	1	0.785
A5	2.5	4.906	D5	1	0.785
A6	2	3.140	D6	1	0.785
A6	2.5	4.906	D6	1	0.785
B1	1	0.785	D6	1	0.785
B1	1	0.785	D6	3	7.065
B1	2.5	4.906	D6	2	3.140
B2	2	3.140	E1	1.5	1.766
B2	2.5	4.906	E2	1	0.785
B2	0.5	0.196	E2	1	0.785
B2	3.5	9.616	E2	1.5	1.766
B2	2	3.140	E2	0.7	0.385
B2	2	3.140	E2	1	0.785
B3	3	7.065	E2	3	7.065
B3	0.7	0.385	E4	1.5	1.766
B4	0.7	0.385	E5	2.5	4.906
B4	3	7.065	E5	4	12.560
B6	2.5	4.906	E5	3	7.065
B6	2	3.140	F1	1.5	1.766
C1	4	12.560	F2	2	3.140
C2	1.5	1.766	F2	2	3.140
C2	2	3.140	F4	4	12.560
C2	2	3.140	F4	4	12.560
C2	1.5	1.766	F4	2	3.140
C2	1	0.785	F5	1.5	1.766
C2	1	0.785	F5	1.5	1.766
C2	2	3.140	F5	2.5	4.906
C4	2	3.140	F5	1.5	1.766
C4	1.5	1.766	F5	2	3.140
C4	1.5	1.766	F6	2.5	4.906
C4	1	0.785	F6	1.5	1.766
C5	0.7	0.385	F6	2	3.140