Additional Testing of the 2.4-m Lick Primary Mirror

1. Determination of the test optic tetrafoil errors.

The procedure given in the Test Plan used to measure the figure of the mirror during final figuring and testing does not determine the values of errors that repeat in the **n4θ** angular orders. We assumed in that procedure that these errors reside completely in the mirror and not in the test optics, the assumption based on the low probability of bending 4θ errors into the test optics given their low stress mountings. However, by rotating the mirror 45 degrees with respect to one of the tests we can obtain a measure of the two lowest order tetrafoil terms of the Zernike polynomials.

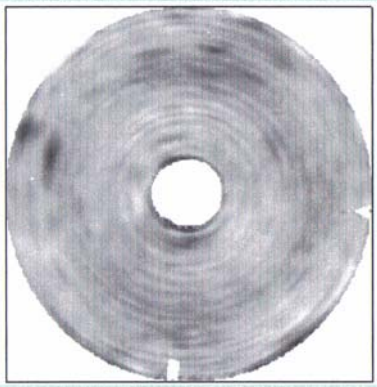
To perform the test the mirror was rotated 45 degrees with respect to the final test position of the last test performed that was at 270 degrees from our chosen 0 so the new test position was at 315 degrees. The result of the measurement is shown in Figure 1. No test optics have been subtracted, only tilt, focus, and coma.

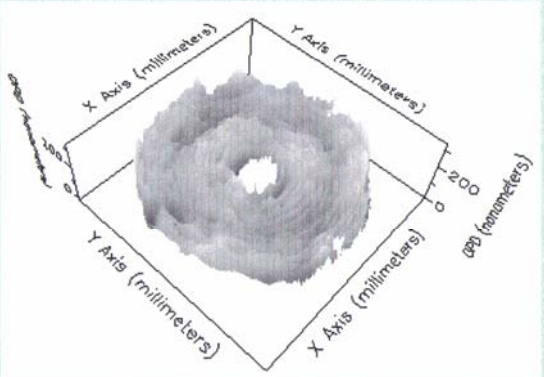
To obtain two estimates of the two pairs of coefficients of the 4θ terms this measurement was averaged with the measurements of the mirror at 270 degrees and 0 degrees. These averages will average out the 4θ contributions from the mirror and leave just the contributions from the test optics. These two averages are shown in Figures 2 and 3.

The final estimate of the coefficients is obtained by averaging the coefficients from the two averaged maps. The resulting coefficients and a phase map of their contribution to the test optics is shown in Figure 4. The contribution from this error is 2.6 nm rms of surface error.

Finally, this contribution was subtracted from the final test data and the result is shown in Figure 5. The resulting residual increased slightly from 23.6 nm rms to 24.1 nm rms of surface error.

FILE: 315 AVG	IntelliWave Report Sheet
Lick 2.4 M Primary Mirror	315 degree average
Surface Map	Surface Map



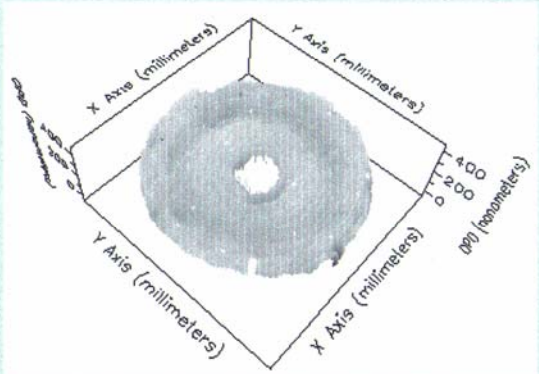


Data	OPD Statistics:	Value	Min	Max	QC (nanometer
Wavelength.....0.6328	PV.....	165.0891	-1.#QNB	0.0000	-
Waves/fringe.....0.5000	Peak.....	165.0891	-1.#QNB	0.0000	-
Image Size.....[640, 480]	Center.....	82.5445	-1.#QNB	0.0000	-
Data Aperture: Pos[320, 224] Size[413, 413]	Valley.....	0.0000	-1.#QNB	0.0000	-
Area Aperture: Pos[326, 240] Size[384, 384]	Average.....	199.6883	-1.#QNB	0.0000	-
Analysis Aper: Pos[320, 224] Size[413, 413]	RMS.....	30.3747	-1.#QNB	0.0000	-
Acquire	#Points.....	125904	0	0	-
#Interferograms: 5	Strehl.....	0.9131	-1.#QNB	0.0000	-
Microns/Volt....1.898402					
Unwrapping	RMS Fit:	Value	Min	Max	QC (nanometers)
Name.....[5B,S,MDA]	1	30.5033	0.0000	0.0000	-
Mod. Back.....0.0355	2	29.7381	0.0000	0.0000	-
	3	28.2658	0.0000	0.0000	-
Aberrations	4	24.1098	0.0000	0.0000	-
Name.....UofA	5	21.2175	0.0000	0.0000	-

1) Piston:	198.0312	0.0000	0.0000 -	19) X Trefoil:	8.2974	0.0000	0.0000 -
2) X Tilt:	2.1378	0.0000	0.0000 Removed	20) Y Trefoil:	-0.1240	0.0000	0.0000 -
3) Y Tilt:	3.0449	0.0000	0.0000 Removed	21) X Astig:	6.7839	0.0000	0.0000 -
4) Focus:	5.0032	0.0000	0.0000 Removed	22) Y Astig:	8.3232	0.0000	0.0000 -
5) X Astig:	10.3524	0.0000	0.0000 -	23) X Coma:	-10.6781	0.0000	0.0000 -
6) Y Astig:	12.2814	0.0000	0.0000 -	24) Y Coma:	-9.4207	0.0000	0.0000 -
7) X Coma:	-1.3385	0.0000	0.0000 Removed	25) Spherical:	-43.6774	0.0000	0.0000 -
8) Y Coma:	-1.7791	0.0000	0.0000 Removed	26) X Pentafoil:	-7.0371	0.0000	0.0000 -
9) Spherical:	-0.0445	0.0000	0.0000 -	27) Y Pentafoil:	17.1119	0.0000	0.0000 -
10) X Trefoil:	5.5654	0.0000	0.0000 -	28) X Tetrafoil:	22.2167	0.0000	0.0000 -
11) Y Trefoil.:	13.8685	0.0000	0.0000 -	29) Y Tetrafoil:	13.7777	0.0000	0.0000 -
12) X Astig:	-7.6154	0.0000	0.0000 -	30) X Trefoil:	0.2642	0.0000	0.0000 -
13) Y Astig:	-14.3543	0.0000	0.0000 -	31) Y Trefoil:	-2.2482	0.0000	0.0000 -
14) X Coma:	3.5901	0.0000	0.0000 -	32) X Astig:	1.4893	0.0000	0.0000 -
15) Y Coma:	-23.5419	0.0000	0.0000 -	33) Y Astig:	-16.0226	0.0000	0.0000 -
16) Spherical:	6.7682	0.0000	0.0000 -	34) X Coma:	4.8985	0.0000	0.0000 -
17) X Tetrafoil:	-9.7045	0.0000	0.0000 -	35) Y Coma:	-9.7286	0.0000	0.0000 -
18) Y Tetrafoil:	-14.2554	0.0000	0.0000 -	36) Spherical:	19.9734	0.0000	0.0000 -

Figure 1. Average of 30 measurements of the mirror at 315 degrees.

FILE: 0,315 AVERAGE	IntelliWave Report Sheet
Lick 2.4 M Primary Mirror	Average of 0 and 315
Surface Map	**Surface Map**

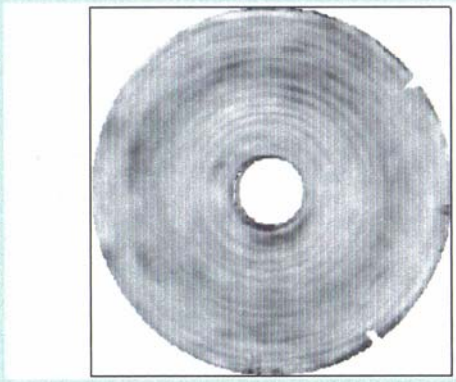


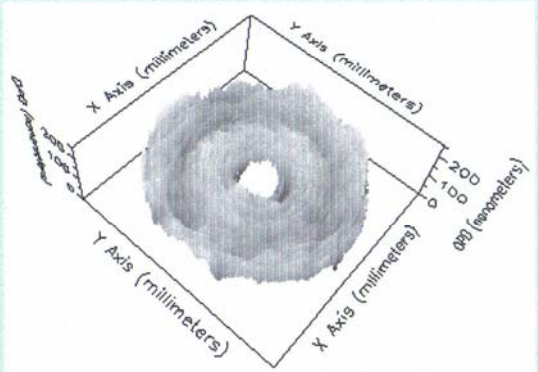
Data	OPD Statistics:	Value	Min	Max	QC (nanometer
Wavelength.....0.6328	PV.....	135.2670	-1.#QNB	0.0000	-
Waves/fringe.....0.5000	Peak.....	135.2670	-1.#QNB	0.0000	-
Image Size.....[640, 480]	Center.....	67.6335	-1.#QNB	0.0000	-
Data Aperture: Pos[322, 223] Size[413, 413]	Valley.....	0.0000	-1.#QNB	0.0000	-
Area Aperture: Pos[326, 240] Size[384, 384]	Average.....	98.6926	-1.#QNB	0.0000	-
Analysis Aper: Pos[322, 223] Size[413, 413]	RMS.....	25.5628	-1.#QNB	0.0000	-
Acquire	#Points.....	125806	0	0	-
#Interferograms: 5	Strehl.....	0.9376	-1.#QNB	0.0000	-
Microns/Volt....1.898402					
Unwrapping	RMS Fit:	Value	Min	Max	QC (nanometers)
Name.....[5B,S,MDA]	1	26.7024	0.0000	0.0000	-
Mod. Back.....0.0414	2	26.2970	0.0000	0.0000	-
	3	25.1338	0.0000	0.0000	-
Aberrations	4	20.2758	0.0000	0.0000	-
Name.....UofA	5	19.5702	0.0000	0.0000	-

1)	Piston:	238.3145	0.0000	0.0000 -	19)	X Trefoil:	2.7869	0.0000 0.0000 -
2)	X Tilt:	-0.7889	0.0000	0.0000 Removed	20)	Y Trefoil:	9.0853	0.0000 0.0000 -
3)	Y Tilt:	-0.3795	0.0000	0.0000 Removed	21)	X Astig:	-3.0723	0.0000 0.0000 -
4)	Focus:	3.4887	0.0000	0.0000 Removed	22)	Y Astig:	4.3889	0.0000 0.0000 -
5)	X Astig:	-1.7406	0.0000	0.0000 -	23)	X Coma:	-16.8152	0.0000 0.0000 -
6)	Y Astig:	8.4272	0.0000	0.0000 -	24)	Y Coma:	5.4148	0.0000 0.0000 -
7)	X Coma:	-4.8124	0.0000	0.0000 Removed	25)	Spherical:	-45.0962	0.0000 0.0000 -
8)	Y Coma:	0.1285	0.0000	0.0000 Removed	26)	X Pentafoil:	0.4512	0.0000 0.0000 -
9)	Spherical:	1.3792	0.0000	0.0000 -	27)	Y Pentafoil:	2.2304	0.0000 0.0000 -
10)	X Trefoil:	5.3453	0.0000	0.0000 -	28)	X Tetrafoil:	5.2152	0.0000 0.0000 -
11)	Y Trefoil.:	11.2229	0.0000	0.0000 -	29)	Y Tetrafoil:	3.2324	0.0000 0.0000 -
12)	X Astig:	13.7010	0.0000	0.0000 -	30)	X Trefoil:	2.3041	0.0000 0.0000 -
13)	Y Astig:	-9.3692	0.0000	0.0000 -	31)	Y Trefoil:	-7.5640	0.0000 0.0000 -
14)	X Coma:	5.0731	0.0000	0.0000 -	32)	X Astig:	5.1556	0.0000 0.0000 -
15)	Y Coma:	-18.6994	0.0000	0.0000 -	33)	Y Astig:	-3.1449	0.0000 0.0000 -
16)	Spherical:	8.0689	0.0000	0.0000 -	34)	X Coma:	3.0023	0.0000 0.0000 -
17)	X Tetrafoil:	-1.1073	0.0000	0.0000 -	35)	Y Coma:	0.5798	0.0000 0.0000 -
18)	Y Tetrafoil:	-8.6396	0.0000	0.0000 -	36)	Spherical:	16.2940	0.0000 0.0000 -

Figure 2. Average of the 315 deg measurement and the 0 degree measurement.

FILE: 270,315 AVERAGE	IntelliWave Report Sheet
Lick 2.4 M Primary Mirror	Average of 270 and 315
Surface Map	Surface Map





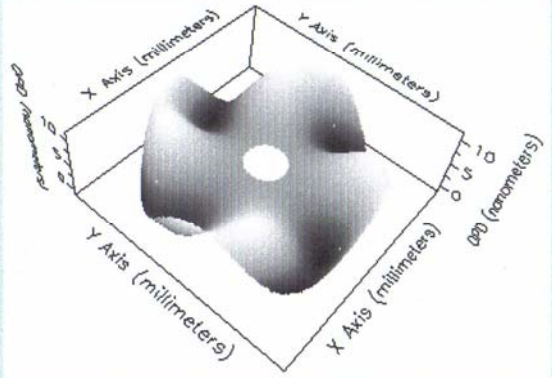
Data	OPD Statistics:	Value	Min	Max	QC (nanometer
Wavelength.....0.6328	PV.....	112.9643	-1.#QNB	0.0000	-
Waves/fringe.....0.5000	Peak.....	112.9643	-1.#QNB	0.0000	-
Image Size.....[640, 480]	Center.....	56.4821	-1.#QNB	0.0000	-
Data Aperture: Pos[322, 223] Size[413, 413]	Valley.....	0.0000	-1.#QNB	0.0000	-
Area Aperture: Pos[326, 240] Size[384, 384]	Average.....	170.2161	-1.#QNB	0.0000	-
Analysis Aper: Pos[322, 223] Size[413, 413]	RMS.....	23.3784	-1.#QNB	0.0000	-
Acquire	#Points.....	126047	0	0	-
#Interferograms: 5	Strehl.....	0.9475	-1.#QNB	0.0000	-
Microns/Volt....1.898402					

Unwrapping	RMS Fit:	Value	Min	Max	QC (nanometers)
Name.....[5B,S,MDA]	1	23.7351	0.0000	0.0000	-
Mod. Back.....0.0414	2	22.5450	0.0000	0.0000	-
	3	21.5211	0.0000	0.0000	-
Aberrations	4	17.1307	0.0000	0.0000	-
Name.....UofA	5	15.7259	0.0000	0.0000	-

1) Piston:	126.3134	0.0000	0.0000 -	19) X Trefoil:	-0.5592	0.0000	0.0000 -
2) X Tilt:	-0.0376	0.0000	0.0000 Removed	20) Y Trefoil:	-2.9997	0.0000	0.0000 -
3) Y Tilt:	-0.8227	0.0000	0.0000 Removed	21) X Astig:	7.5126	0.0000	0.0000 -
4) Focus:	4.5898	0.0000	0.0000 Removed	22) Y Astig:	3.0127	0.0000	0.0000 -
5) X Astig:	16.7674	0.0000	0.0000 -	23) X Coma:	-14.7721	0.0000	0.0000 -
6) Y Astig:	6.8623	0.0000	0.0000 -	24) Y Coma:	0.8660	0.0000	0.0000 -
7) X Coma:	-2.5904	0.0000	0.0000 Removed	25) Spherical:	-41.6561	0.0000	0.0000 -
8) Y Coma:	-0.6724	0.0000	0.0000 Removed	26) X Pentafoil:	-10.2952	0.0000	0.0000 -
9) Spherical:	-0.9385	0.0000	0.0000 -	27) Y Pentafoil:	-1.4047	0.0000	0.0000 -
10) X Trefoil:	12.8587	0.0000	0.0000 -	28) X Tetrafoil:	4.8763	0.0000	0.0000 -
11) Y Trefoil.:	6.1162	0.0000	0.0000 -	29) Y Tetrafoil:	3.9459	0.0000	0.0000 -
12) X Astig:	-6.1700	0.0000	0.0000 -	30) X Trefoil:	1.0010	0.0000	0.0000 -
13) Y Astig:	-3.3910	0.0000	0.0000 -	31) Y Trefoil:	-2.9008	0.0000	0.0000 -
14) X Coma:	-4.4224	0.0000	0.0000 -	32) X Astig:	-8.2175	0.0000	0.0000 -
15) Y Coma:	-17.5244	0.0000	0.0000 -	33) Y Astig:	-9.5487	0.0000	0.0000 -
16) Spherical:	8.6425	0.0000	0.0000 -	34) X Coma:	8.9540	0.0000	0.0000 -
17) X Tetrafoil:	0.9279	0.0000	0.0000 -	35) Y Coma:	-8.9478	0.0000	0.0000 -
18) Y Tetrafoil:	-3.9136	0.0000	0.0000 -	36) Spherical:	15.9094	0.0000	0.0000 -

Figure 3. Average of the 315 and 270 degree measurements.

FILE: TEST OPTICS TETRAFOIL	IntelliWave Report Sheet
Lick 2.4 M Primary Mirror	Test optics tetrafoil
Surface Map	Surface Map



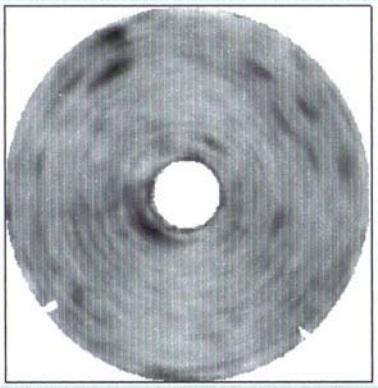
Data	OPD Statistics:	Value	Min	Max	QC (nanometer
Wavelength.....0.6328	PV.....	9.9091	-1.#QNB	0.0000	-
Waves/fringe.....-1.0000	Peak.....	9.9091	-1.#QNB	0.0000	-
Image Size.....[640, 480]	Center.....	4.9545	-1.#QNB	0.0000	-
Data Aperture: Pos[320, 224] Size[413, 413]	Valley.....	0.0000	-1.#QNB	0.0000	-
Area Aperture: Pos[320, 224] Size[413, 413]	Average.....	142.3470	-1.#QNB	0.0000	-
Analysis Aper: Pos[320, 224] Size[413, 413]	RMS.....	2.6243	-1.#QNB	0.0000	-
Acquire	#Points.....	127288	0	0	-
#Interferograms: 5	Strehl.....	0.9993	-1.#QNB	0.0000	-
Microns/Volt....1.898402					

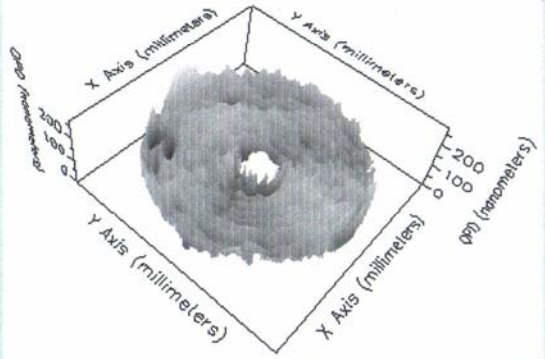
Unwrapping	RMS Fit:	Value	Min	Max	QC (nanometers)
Name.....[5B,S,MDA]	1	2.5807	0.0000	0.0000	-
Mod. Back.....0.0414	2	2.5807	0.0000	0.0000	-
	3	2.5807	0.0000	0.0000	-
Aberrations	4	1.6435	0.0000	0.0000	-
Name.....UofA	5	0.0000	0.0000	0.0000	-

1) Piston:	5.5583	0.0000	0.0000	-	19) X Trefoil:	-0.0000	0.0000	0.0000 -
2) X Tilt:	-0.0000	0.0000	0.0000	-	20) Y Trefoil:	-0.0000	0.0000	0.0000 -
3) Y Tilt:	-0.0000	0.0000	0.0000	-	21) X Astig:	-0.0000	0.0000	0.0000 -
4) Focus:	0.0000	0.0000	0.0000	-	22) Y Astig:	-0.0000	0.0000	0.0000 -
5) X Astig:	0.0000	0.0000	0.0000	-	23) X Coma:	0.0000	0.0000	0.0000 -
6) Y Astig:	-0.0000	0.0000	0.0000	-	24) Y Coma:	-0.0000	0.0000	0.0000 -
7) X Coma:	0.0000	0.0000	0.0000	-	25) Spherical:	0.0000	0.0000	0.0000 -
8) Y Coma:	0.0000	0.0000	0.0000	-	26) X Pentafoil:	-0.0000	0.0000	0.0000 -
9) Spherical:	-0.0000	0.0000	0.0000	-	27) Y Pentafoil:	-0.0000	0.0000	0.0000 -
10) X Trefoil:	0.0000	0.0000	0.0000	-	28) X Tetrafoil:	5.0116	0.0000	0.0000 -
11) Y Trefoil.:	-0.0000	0.0000	0.0000	-	29) Y Tetrafoil:	3.5698	0.0000	0.0000 -
12) X Astig:	-0.0000	0.0000	0.0000	-	30) X Trefoil:	-0.0000	0.0000	0.0000 -
13) Y Astig:	0.0000	0.0000	0.0000	-	31) Y Trefoil:	-0.0000	0.0000	0.0000 -
14) X Coma:	-0.0000	0.0000	0.0000	-	32) X Astig:	-0.0000	0.0000	0.0000 -
15) Y Coma:	-0.0000	0.0000	0.0000	-	33) Y Astig:	-0.0000	0.0000	0.0000 -
16) Spherical:	0.0000	0.0000	0.0000	-	34) X Coma:	-0.0000	0.0000	0.0000 -
17) X Tetrafoil:	-0.1154	0.0000	0.0000	-	35) Y Coma:	-0.0000	0.0000	0.0000 -
18) Y Tetrafoil:	-6.2907	0.0000	0.0000	-	36) Spherical:	-0.0000	0.0000	0.0000 -

Figure 4. Test optic tetrafoil.

FILE: LICK FINAL MAP	IntelliWave Report Sheet
Lick 2.4 M Primary Mirror	Test optics tetrafoil subtracted
Surface Map	**Surface Map**





Data	OPD Statistics:	Value	Min	Max	QC (nanometer
Wavelength.....0.6328	PV.....	125.3789	-1.#QNB	0.0000	-
Waves/fringe.....0.5000	Peak.....	125.3789	-1.#QNB	0.0000	-
Image Size.....[640, 480]	Center.....	62.6894	-1.#QNB	0.0000	-
Data Aperture: Pos[322, 223] Size[413, 413]	Valley.....	0.0000	-1.#QNB	0.0000	-
Area Aperture: Pos[326, 240] Size[384, 384]	Average.....	114.0152	-1.#QNB	0.0000	-
Analysis Aper: Pos[322, 223] Size[413, 413]	RMS.....	24.0677	-1.#QNB	0.0000	-
Acquire	#Points.....	125222	0	0	-
#Interferograms: 5	Strehl.....	0.9445	-1.#QNB	0.0000	-
Microns/Volt....1.898402					
Unwrapping	RMS Fit:	Value	Min	Max	QC (nanometers)
Name.....[5B,S,MDA]	1	24.1534	0.0000	0.0000	-
Mod. Back.....0.0414	2	23.2622	0.0000	0.0000	-
	3	20.2464	0.0000	0.0000	-
Aberrations	4	18.3368	0.0000	0.0000	-
Name.....UofA	5	16.5406	0.0000	0.0000	-

1) Piston:	119.2115	0.0000	0.0000	-	19) X Trefoil:	-6.5125	0.0000	0.0000 -
2) X Tilt:	1.7644	0.0000	0.0000	Removed	20) Y Trefoil:	12.8439	0.0000	0.0000 -
3) Y Tilt:	0.1443	0.0000	0.0000	Removed	21) X Astig:	-14.0917	0.0000	0.0000 -
4) Focus:	5.7872	0.0000	0.0000	Removed	22) Y Astig:	0.8086	0.0000	0.0000 -
5) X Astig:	-15.3098	0.0000	0.0000	-	23) X Coma:	-5.1201	0.0000	0.0000 -
6) Y Astig:	-3.2003	0.0000	0.0000	-	24) Y Coma:	-4.3913	0.0000	0.0000 -
7) X Coma:	0.1724	0.0000	0.0000	Removed	25) Spherical:	-5.5183	0.0000	0.0000 -
8) Y Coma:	-1.2544	0.0000	0.0000	Removed	26) X Pentafoil:	14.4625	0.0000	0.0000 -
9) Spherical:	-7.4148	0.0000	0.0000	-	27) Y Pentafoil:	-9.3149	0.0000	0.0000 -
10) X Trefoil:	-8.3047	0.0000	0.0000	-	28) X Tetrafoil:	-16.1481	0.0000	0.0000 -
11) Y Trefoil.:	-6.8662	0.0000	0.0000	-	29) Y Tetrafoil:	-8.1732	0.0000	0.0000 -
12) X Astig:	16.6912	0.0000	0.0000	-	30) X Trefoil:	4.0266	0.0000	0.0000 -
13) Y Astig:	-6.2730	0.0000	0.0000	-	31) Y Trefoil:	-2.7460	0.0000	0.0000 -
14) X Coma:	10.1175	0.0000	0.0000	-	32) X Astig:	12.2585	0.0000	0.0000 -
15) Y Coma:	-21.1976	0.0000	0.0000	-	33) Y Astig:	2.6043	0.0000	0.0000 -
16) Spherical:	20.6568	0.0000	0.0000	-	34) X Coma:	0.3523	0.0000	0.0000 -
17) X Tetrafoil:	14.9632	0.0000	0.0000	-	35) Y Coma:	2.2499	0.0000	0.0000 -
18) Y Tetrafoil:	11.3706	0.0000	0.0000	-	36) Spherical:	6.7083	0.0000	0.0000 -

Figure 5. Final mirror data with test optic tetrafoil subtracted.

2. Scattering near the center hole.

We inspected the region near the center hole that retains some residual gray that contributes to increased scattering in the region. We looked at the region with a bright light and find that the gray follows what the scattering measurements showed earlier. From the center hole out to about 50 mm from the center hole the gray is the worst but rapidly decreases from there out to about 120 mm. The gray is very fine and is undoubtedly a remnant of the final stage of fine grinding. The surface looks polished to the naked eye but the gray becomes visible under bright illumination. We believe the high bulk scatter from the Astro-Sital contributed to our not noticing the remaining gray when we made our surface inspections during fabrication. We certainly agree with Jerry Nelson that this was indeed sloppy work and we certainly will not let this happen again when using this material.