Memorandum

To:	Geoff Ediss Neil Horner	Tony Kerr Dan Koller	Gene Lauria	Sri Srikanth
cc:	John Webber	Charles Cunningham		
From:	John Effland Greg Morris			
Date:	2005-02-17			

Revisions:

1.0	2005-01-26	Jee & Gm	Initial
2.1	2005-01-28	Jee	Added Charles Cunningham's corrections
2.2	2005-02-17	Jee	Included Charles Cunningham's remeasurements of Mirror 2

Subject: Comparison of Calculated and Measured Data for Mirrors used in ALMA Band 6 Cartridges

1. Introduction

A sidelobe on the order of 15 dB below the beam peak has been observed in patterns measured for the Band 6 Cartridge as documented in Dan Koller's report[1]. In an attempt to find the source of this sidelobe, the surfaces of both mirrors in the Band 6 Cartridge were measured to confirm their shape meets design requirements. Mirror geometry and the coordinate systems for the mirror surface measurements are given in Figure 1 for Mirror 1 and Figure 2 for Mirror 2. As summarized in Table 2, Mirror 1 has a worst case discrepancy of 78 µm and Mirror 2 deviates at most 360 µm from the theoretical design.

The mirror surfaces are generated from ellipsoids with semi-major axis (a) and semi-minor axis (b). A segment of the ellipse is rotated about the semi-major axis to form an ellipsoid defined by the following equation:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{b^2} = 1$$

2. Mirror 2 Definition Discrepancies

A discrepancy exists in the mechanical drawing used to fabricate Mirror 2 as provided to J&E Precision Tool Inc., Southampton, MA. In that drawing (Figure 2), the ellipse's semi-major and semi-minor axis lengths as dimensioned (summarized on Table 1, Line 1) do not yield the mirror endpoint coordinates shown on the drawings. The ellipse shape actually defined in the AutoCAD file has essentially the correct geometry (specified in Line 2 of Table 1), so the dimensions as drawn in Figure 2 are incorrect but the ellipse definition in the drawing file is

[1] D. Koller, "Cartridge #1 Update - Measurements through 12/08/04," posted internally at \\Cvfiler\cv-cdl-sis\CartTstRpts\Cartridge1_Preliminary_Test_Report_no5_12_08_04.pdf

correct. Because J&E fabricated the mirrors using the AutoCAD file, rather than the paper drawing, they used the correct ellipse definition as input to their milling machine.

Given the correct ellipse geometry, a discrepancy remains in selecting the endpoints of the elliptical segment used for Mirror 2. That is, the upper endpoints for the mirror segment specified in Figure 2 don't fall on the ellipse. Consequently, there is some uncertainty in how J&E selected the endpoints of the ellipse, but the analysis below demonstrates that these endpoint differences are insignificant.

Geoff Ediss recently rechecked the Mirror 2 ellipse dimensions against the requirements given in Carter's preliminary optics report[2] and found a slightly different ellipse geometry than the ellipse drawn in Figure 2 and used to fabricate the mirrors. The corrected dimensions are specified in Table 1, Line 3 and the differences from the values used for fabrication are thought to be insignificant.

Table 1: Ellipse Geometry Summary for Mirror 2

Line	Description	a (mm)	b (mm)
1	Dimensions drawn on machine-shop drawing (Figure 2)	208.291	171.816
2	Dimensions of ellipse defined in AutoCAD drawing	208.916	171.816
3	Dimensions recalculated by Ediss on 2005-01-13	208.922	171.818

3. HIA Measured Mechanical Data

Charles Cunningham of the Herzberg Institute of Astrophysics (HIA) in Victoria, Canada kindly provided measurements of the mirror surfaces and their results are shown in

Table 3: HIA Measured Data for Mirror 1 Measured 2005-01-10

and Table 4. HIA measured the height of the mirror surface in the z direction using the geometric center of the mirror as the origin.

The coordinate systems we requested that HIA employ for their measurements are defined in Figure 1 and Figure 2 with the positive direction of each axis shown by an arrow on the axis.

Original comparisons of HIA's measurements to design values showed large discrepancies on the order of 600 µm, and Geoff Ediss suggested that HIA or J&E might have interchanged the X and Y axis when measuring or fabricating the mirrors. This appears to be the case with the data measured on 2005-01-10, and the comparisons presented in this memo were made after swapping HIA's X and Y measurements. The X and Y coordinate labels in

Table 3: HIA Measured Data for Mirror 1 Measured 2005-01-10

and Table 4 have been swapped.

Charles Cunningham carefully remeasured Mirror 2 on 2005-01-31 and his measurements are tabulated in Table 5.

HIA measured the mirrors with a Nikon system:

- MM40 microscope

[2] M. Carter, *et. al.*, "ALMA Front End Optics," Table 10 in Draft dated 2004-04-16 and posted on ALMA EDM at http://almaedm.tuc.nrao.edu/forums/alma/dl.cgi/89e7d4bc9d0cecf77367bd303eae40e1/OpticsReportFinal20040801%20_2_.pdf

- 4X4 stage
- SC213 readout

The software used in HIA's system is:

- E Max Data Pro

HIA found the center of each mirror by measuring the mirror diameters and dividing them by two, this coincided with the center of the machining marks. They estimate the center errors are on the order of a few 10's of microns.

The measurements were made by focusing light on the mirror surface and the relative error is of the order of a few microns.

4. Comparison to Measured Data

AutoCAD was used to measure the theoretical design distance from the mirror face to the mirror surface. New drawings were created independently of Figure 1 and Figure 2 and details are given in "Appendix 1: Generation of Mirror Design Distances".

Figure 3 compares HIA's surface measurements for Mirror 1 to theoretical design depths with cuts along the x-axis using the coordinate system specified in Figure 1 . The left ordinate in the graph shows measured surfaces relative to the center of the mirror. The right ordinate shows differences between measured and calculated surfaces using the two approaches described in Appendix 1. Comparisons for the Y-axis cuts are shown in Figure 4.

Mirror 2's comparisons are shown in Figure 5 and Figure 6 and include calculated and measured distance comparisons for data measured at HIA on 2005-01-10 and 2005-01-31. Because there is uncertainty in the precise endpoints of the elliptical segment used by J&E to fabricate Mirror 2, both extremes were evaluated in Figure 6. That is, the curve labeled *Difference [Dim 205.226 holds]* was generated assuming that the *bottom* edge of the mirror is 205.226 mm from the semi-minor axis. The curve labeled *Difference [Dim 163.666 holds]* was generated assuming that the *top* edge of the mirror is 163.666 mm from the semi-minor axis. Both cases assume that the mirror is 85 mm in diameter, and that assumption was confirmed by mechanical measurements. Differences between measured and design distances for the two cases are only about 10 μm.

To determine if errors in locating the mechanical center of the mirror resulted in significant mirror surface errors, two additional cuts were made across the Mirror 1 model using *Inventor* to generate offsets which are ±150 μm from the center of the mirror. Cuts offset by +150 μm are compared to measured data in Figure 7 and Figure 8. Cuts offset by -150 μm are compared to measured data in Figure 9 and Figure 10. All cuts show negligible differences from cuts made through the center of the mirror.

The worst-case results for both mirrors are summarized in Table 2.

Table 2: Measured Data Comparison			
Mirror	**Axis**	**Offset from Center (µm)**	**Discrepancy (Design – Measured Distance) (µm)**
1	X	0	-17 to +7
	Y	0	-46 to 53
2	X	0	-78 to +62
	Y	0	-360 to +300
1	X	+150	-17 to +8
	Y	+150	-45 to 54
1	X	-150	-17 to +8
	Y	-150	-46 to 53

Table 3: HIA Measured Data for Mirror 1 Measured 2005-01-10			
Point	**Y**	**X**	**Z**
1	0	-30.251	8.744
2	0	-23.946	5.309
3	0	-17.665	2.821
4	0	-11.39	1.152
5	0	-5.281	0.239
6	0	0.927	0.008
7	0	7.045	0.435
8	0	13.524	1.632
9	0	19.75	3.551
10	0	27.828	7.299
11	-28.281	0	7.014
12	-21.192	0	3.79
13	-14.909	0	1.817
14	-8.709	0	0.596
15	-2.463	0	0.039
16	5.715	0	0.285
17	12.053	0	1.238
18	18.297	0	2.858
19	24.599	0	5.232
20	29.564	0	7.678

Table 4: HIA Measured Data for Mirror 2 Measured 2005-01-10			
Point	**Y**	**X**	**Z**
1	-39.518	0	4.766
2	-33.433	0	3.418
3	-27.796	0	2.359
4	-23.119	0	1.63
5	-18.234	0	1.014
6	-13.305	0	0.536
7	-8.171	0	0.182
8	-0.502	0	0
9	5.036	0	0.063
10	9.542	0	0.279
11	14.047	0	0.628
12	18.583	0	1.111
13	23.577	0	1.794
14	28.341	0	2.613
15	32.888	0	3.55
16	38.685	0	4.962
17	0	0	0
18	0	38.189	4.992
19	0	32.083	3.503
20	0	25.84	2.261
21	0	19.544	1.287
22	0	13.367	0.588
23	0	7.05	0.142
24	0	0.921	0
25	0	-6.625	0.135
26	0	-12.989	0.574
27	0	-19.228	1.271
28	0	-25.448	2.23
29	0	-31.743	3.473
30	0	-38.988	5.271

Table 5: HIA Measured Data for Mirror 2 Measured 2005-01-31			
Point	X	Y	Z
17	-40.008	0	5.598
16	-35.002	0	4.305
15	-30.008	0	3.184
14	-25.004	0	2.247
13	-20.004	0	1.474
12	-15.004	0	0.877
11	-10.007	0	0.473
10	-5.004	0	0.198
1	0	0	0.143
2	5.003	0	0.229
3	10.005	0	0.496
4	15.002	0	0.948
5	20.005	0	1.546
6	25.004	0	2.323
7	30.002	0	3.248
8	35.004	0	4.415
9	40.008	0	5.738
33	-0.009	-40.001	5.57
32	-0.009	-35.004	4.271
31	-0.009	-30.005	3.162
30	-0.009	-25.008	2.232
29	-0.009	-19.995	1.483
28	-0.009	-15.007	0.918
27	-0.009	-10.001	0.485
26	-0.009	-5.002	0.24
18	-0.009	5.008	0.195
19	-0.009	10.003	0.407
20	-0.009	15.004	0.807
21	-0.009	20.003	1.336
22	-0.009	25.005	2.02
23	-0.009	30.005	2.833
24	-0.009	35.009	3.807
25	-0.009	40.002	4.956

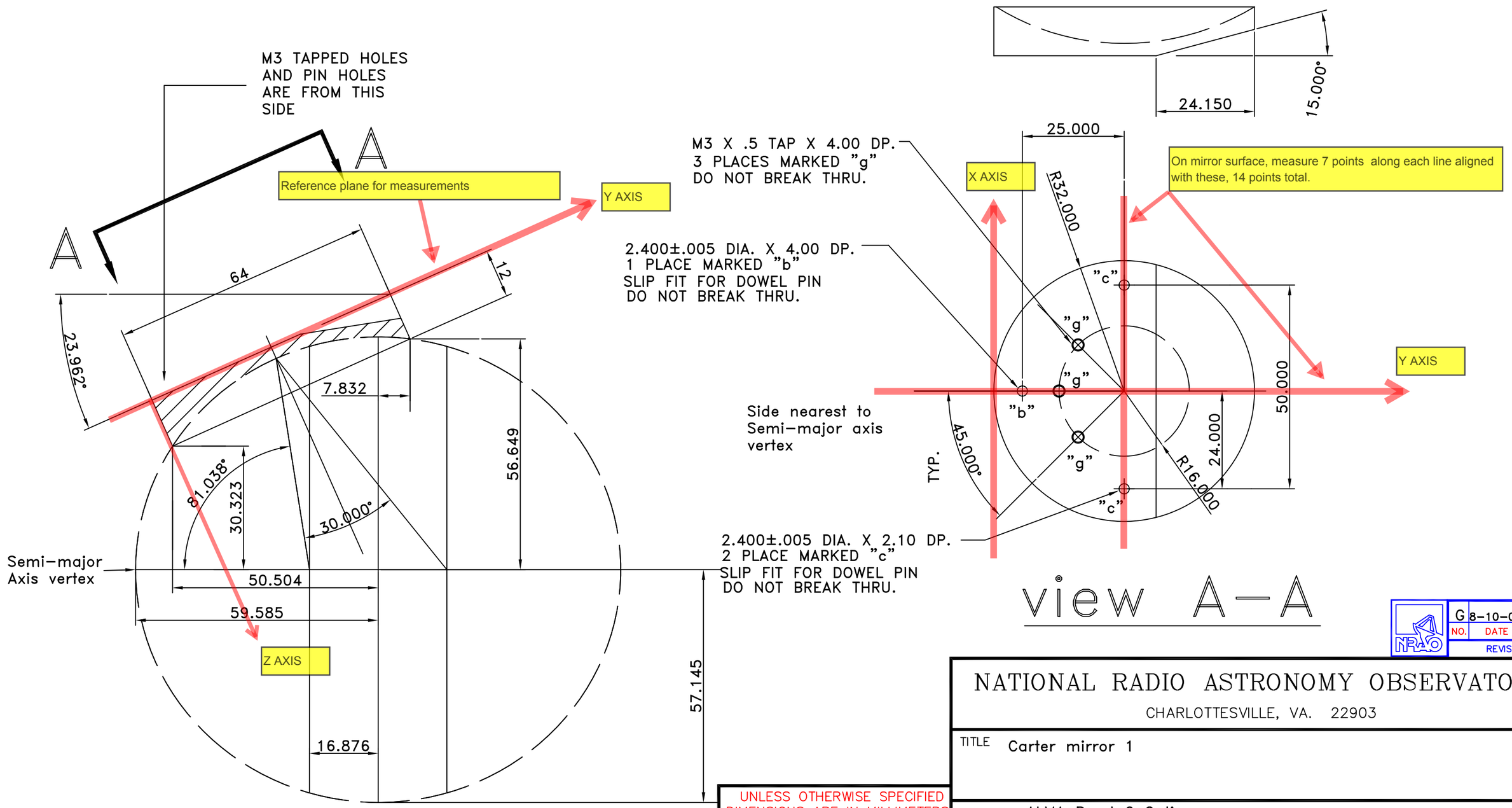


Figure 1: Mechanical Drawing for Carter Mirror 1

NO.	DATE	BY
G	8-10-04	GM

REVISIONS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
ANGLES ± 0.001°
3 PLACE DECIMALS (.xxx): ± 0.001
SURFACE ACCURACY: ± 0.005

MATERIAL: ALUMINUM (bare)

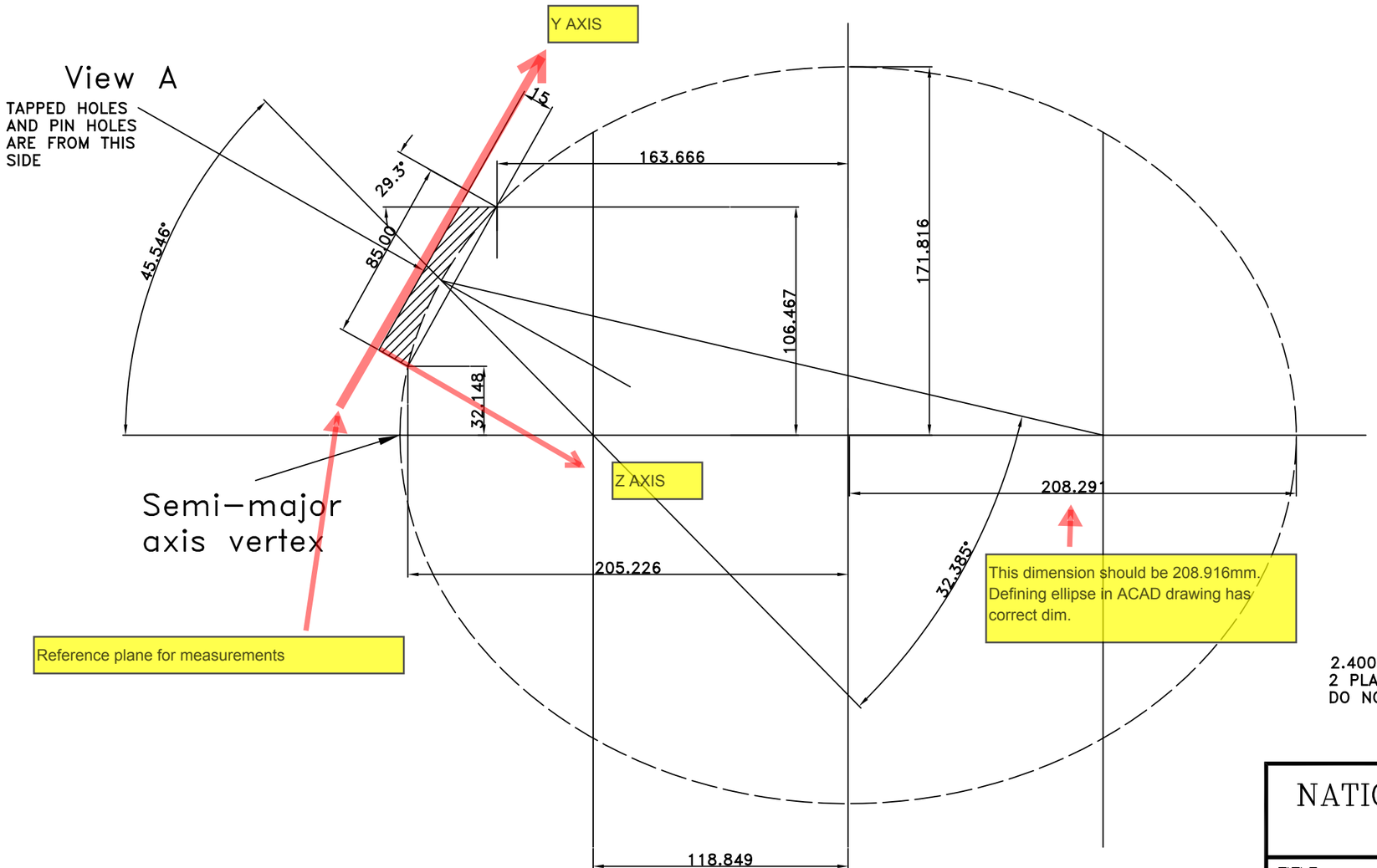
FINISH: 0.0025 MM RMS

NATIONAL RADIO ASTRONOMY OBSERVATORY
CHARLOTTESVILLE, VA. 22903

TITLE Carter mirror 1

PROJECT ALMA Band 6 Optics

DESIGN	MC/GAE		COMPUTER DRAWING	mattmirror1.dwg
DRAWN	GAE	10/10/2002	MATERIAL	Aluminum
SHEET	1/1		FINISH	Polish ellipse surface
SCALE	1:1 MM's		DWG. NO.	FEND-40.02.06.01-002-G-DWG
			REVISION	G



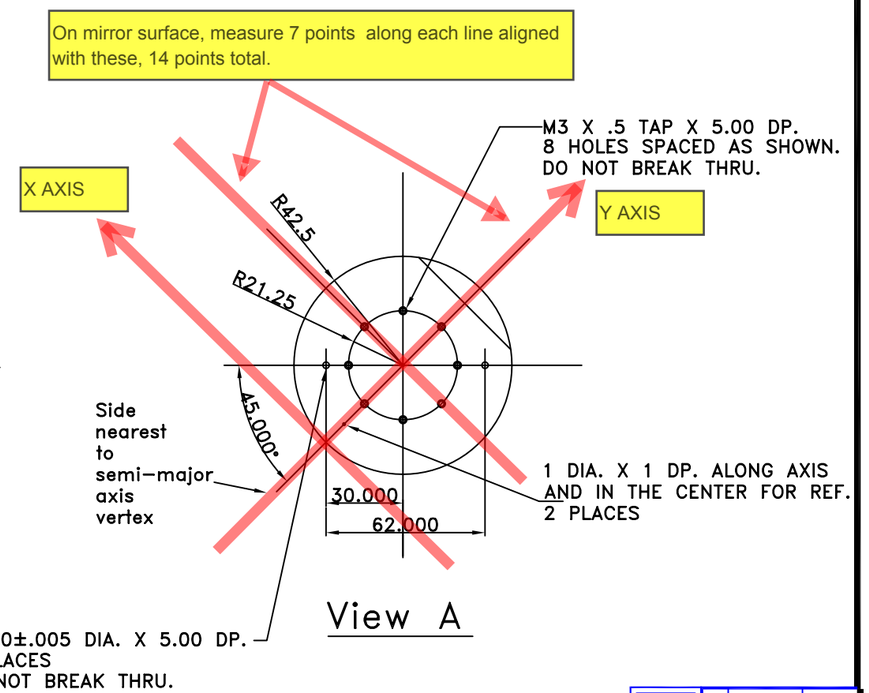


Figure 2: Mechanical Drawing for Carter Mirror 2

NO.	DATE	BY
E	5-5-04	GM

REVISIONS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS

TOLERANCES:
ANGLES ± 0.001°
3 PLACE DECIMALS (.xxx): ± 0.001
SURFACE ACCURACY: ± 0.005

MATERIAL: ALUMINUM (bare)

FINISH: 0.0025 MM RMS

NATIONAL RADIO ASTRONOMY OBSERVATORY
CHARLOTTESVILLE, VA. 22903

TITLE Carter mirror 2

PROJECT ALMA Band 6 Optics

DESIGN	MC/GAE		COMPUTER DRAWING	mattmirror2.dwg
DRAWN	GAE	11/13/2002	MATERIAL	Aluminum
SHEET	1/1		FINISH	Polish ellipse surface
SCALE	1:1 MM's		DWG. NO.	FEND-40.02.06.01-003-E-DWG
			REVISION	E

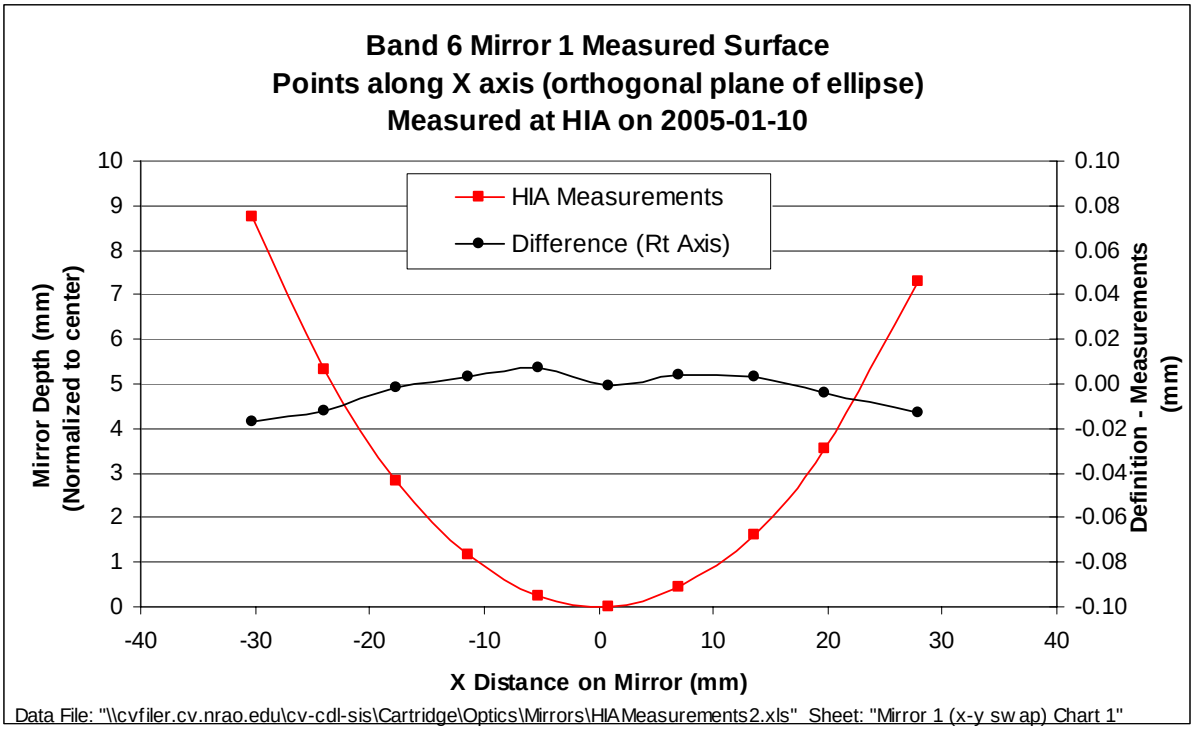


Figure 3: Measured vs. Design Data - Mirror 1, X axis

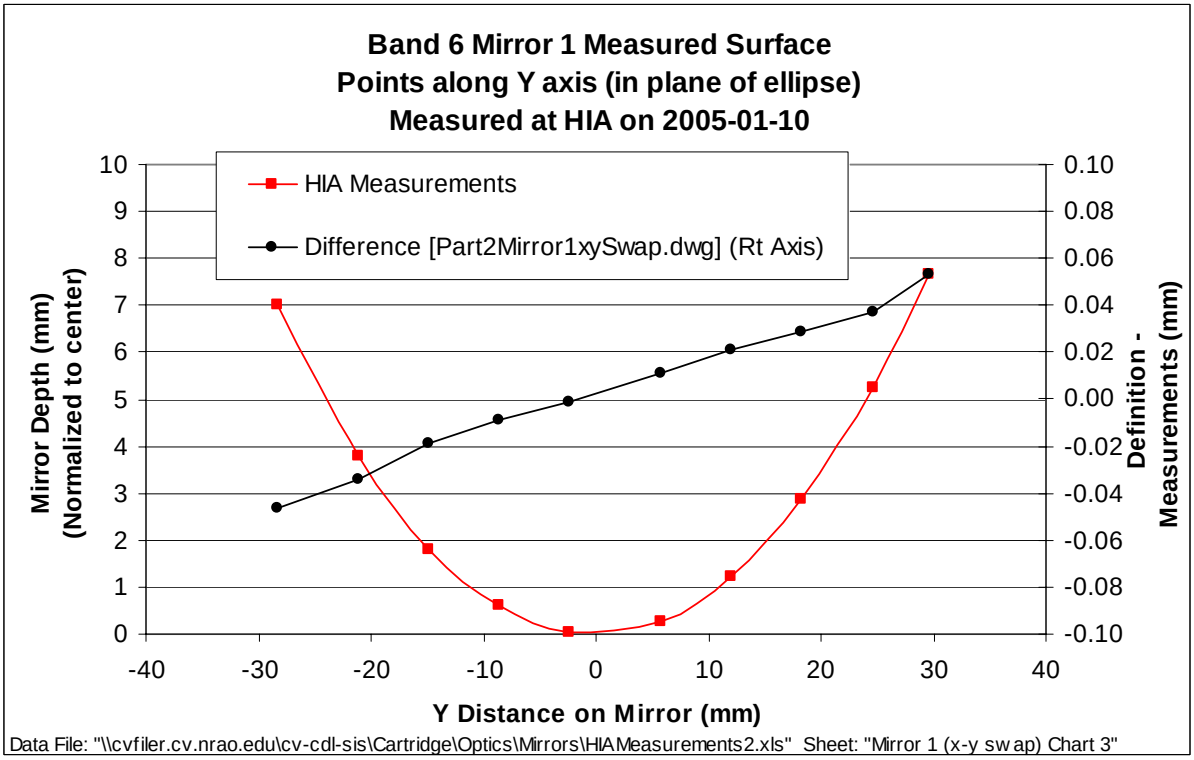


Figure 4: Measured vs. Design Data - Mirror 1, Y axis

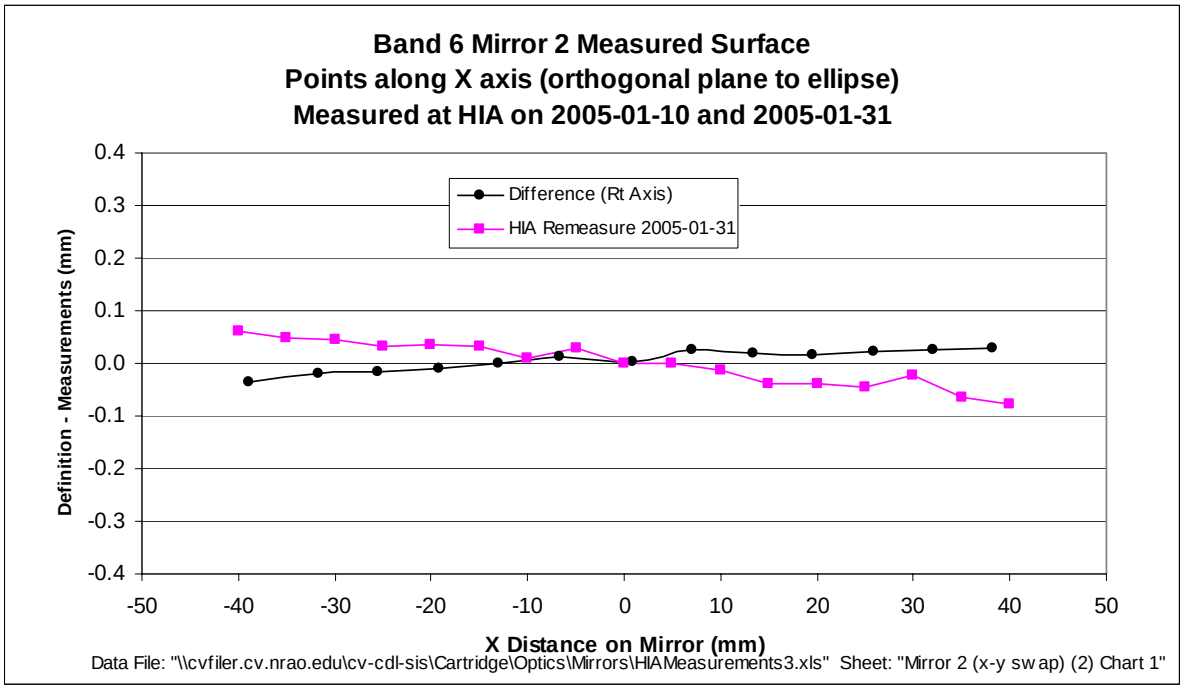


Figure 5: Measured vs. Design Data - Mirror 2, X axis

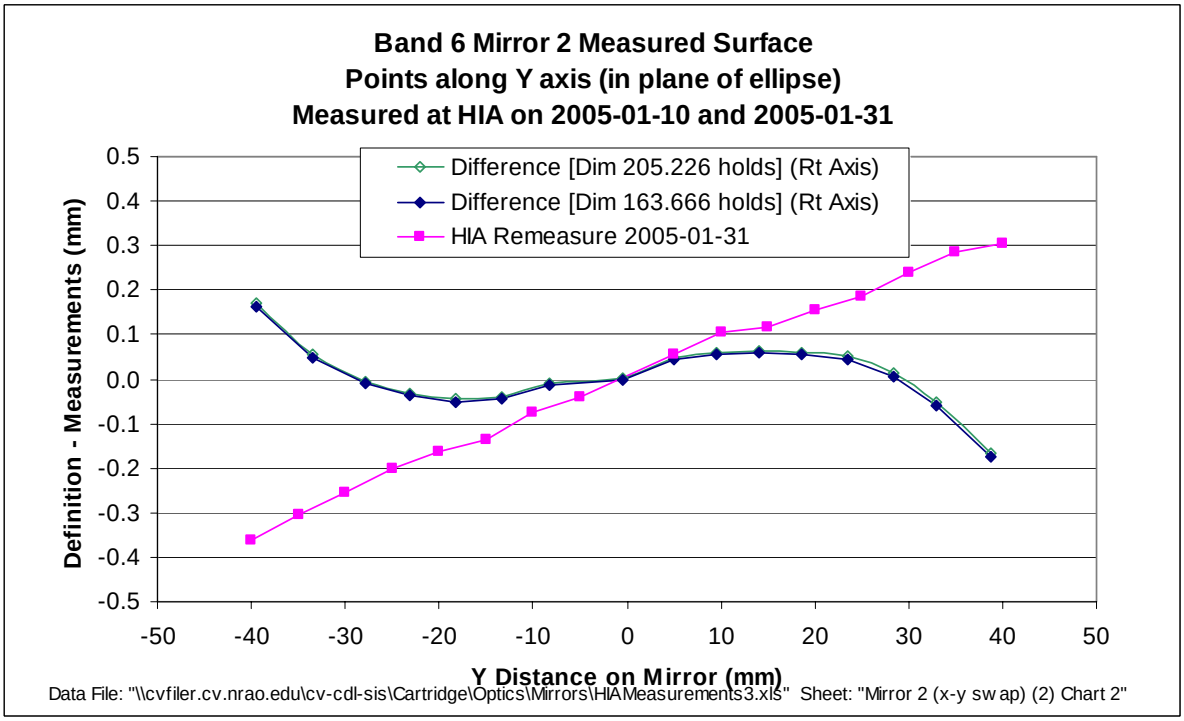


Figure 6: Measured vs. Design Data - Mirror 2, Y axis

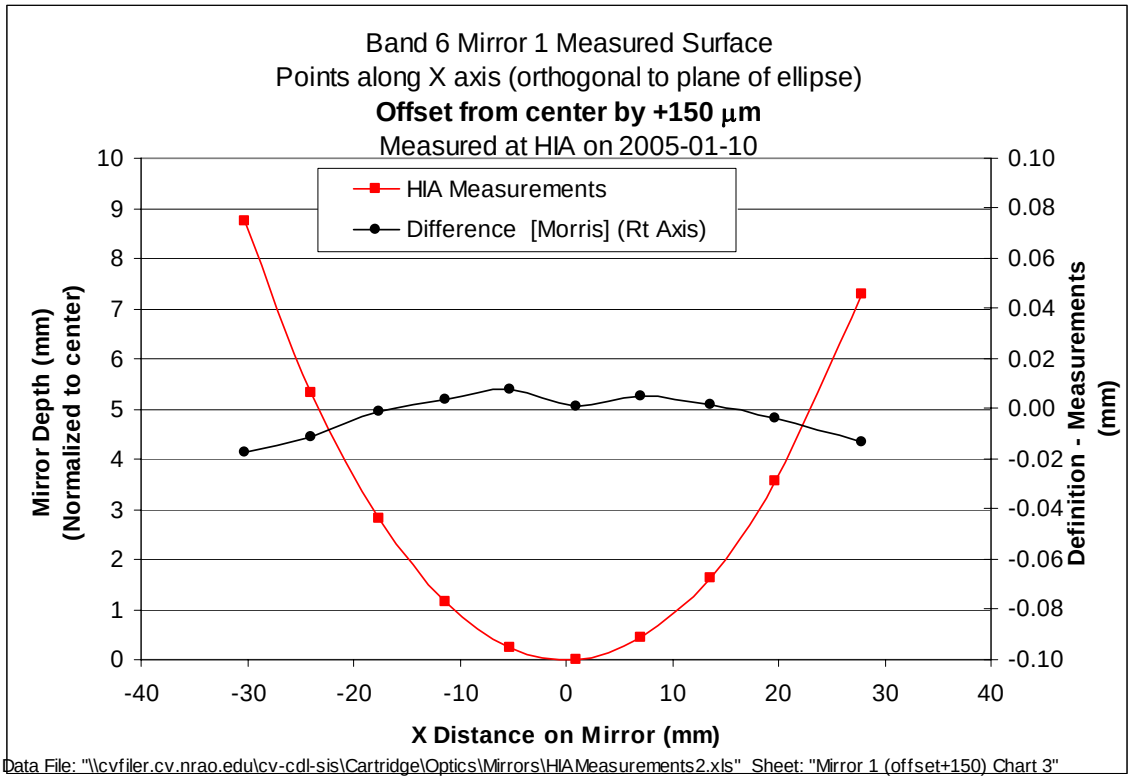


Figure 7: Measured vs. Design Data - Mirror 1, X axis offset from center by +150 µm

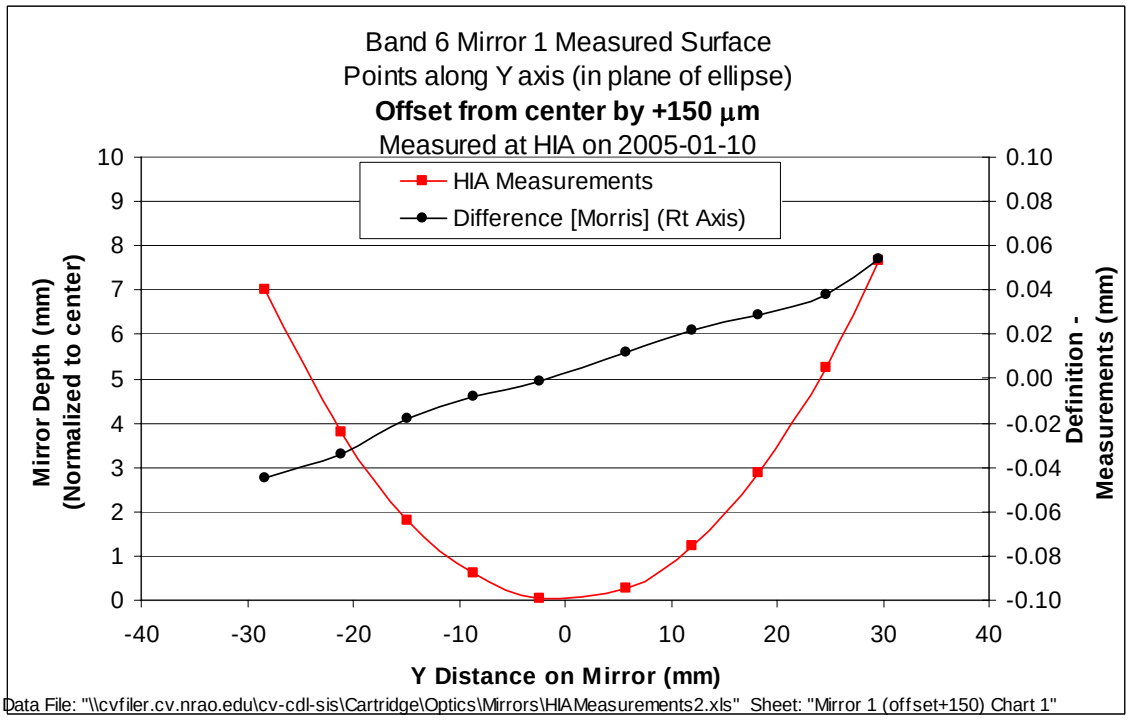


Figure 8: Measured vs. Design Data - Mirror 1, Y axis offset from center by +150 µm

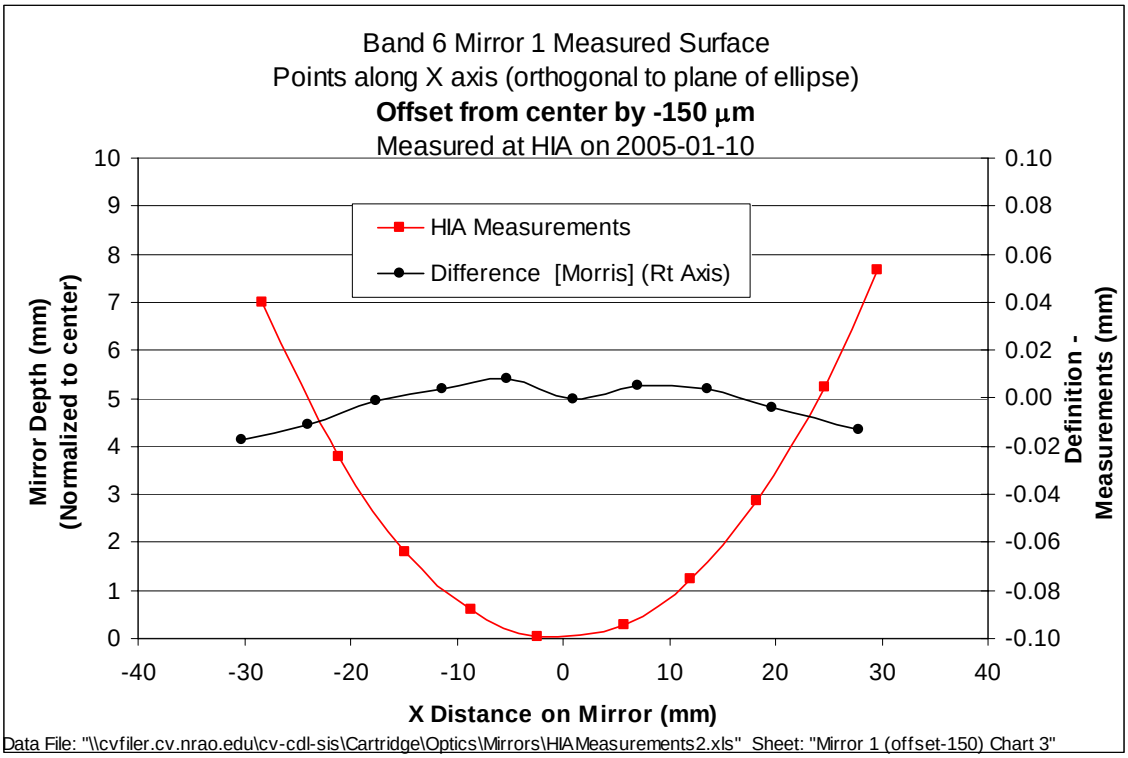


Figure 9: Measured vs. Design Data - Mirror 1, X axis offset from center by -150 µm

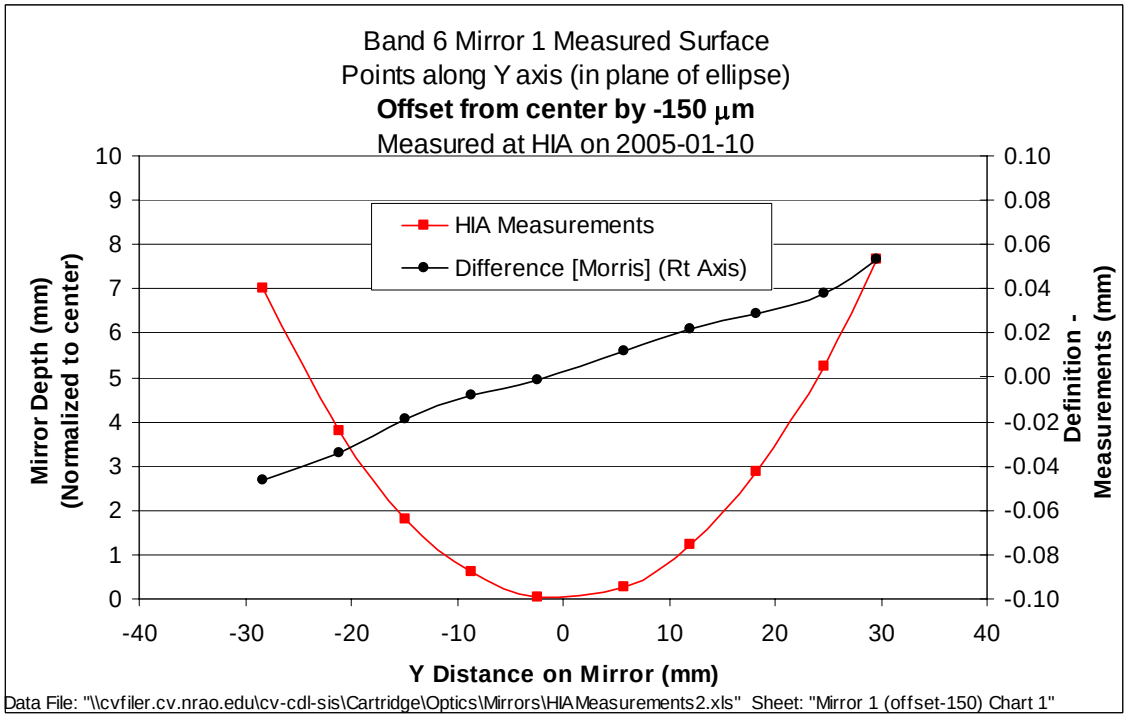


Figure 10: Measured vs. Design Data - Mirror 1, Y axis offset from center by -150 µm

Appendix 1: Generation of Mirror Design Distances

Several approaches were used to determine the theoretical mirror design depth, *i.e.* the distance from the mirror face to the mirror surface, at the same locations as measured by HIA. Greg Morris used Autodesk's *Inventor* to generate a 3-D representation of the mirrors (Figure 11 and Figure 12) and generate cross sections from it. The cross-sectional drawings were exported to AutoCAD (see Figure 13) where appropriate User Coordinate System (UCS) translations to the center of the mirror face allowed mirror depth measurements. The UCS was translated and rotated to the center of the mirror face to allow convenient measurement of the distances from face to the mirror surface using the x and y coordinates specified by HIA. To measure the distance in AutoCAD, the x-coordinate of the construction line was changed to each center offset distance used by HIA and the aligned dimension was repositioned along the construction line to give the distance perpendicular to the mirror face. Figure 14 is a representative cross-section with construction lines drawn at the same distances from the center of the mirror face as those measured by HIA.

To confirm that the *Inventor* files and their conversion to AutoCAD were sufficiently accurate, AutoCAD was used to measure independently Mirror 1's design depths. The defining ellipse is drawn in Figure 15 and the mirror face was drawn on the figure from the dimensions given in Figure 1. Aligning the UCS to the bisecting line across the face of the mirror allowed measurement of mirror depths with the same coordinates as used by HIA.

AutoCAD's surface command was used to generate a 3D version of the mirror surface so that distances could be measured in the rotational plane, *i.e.* orthogonal to the plane of the defining ellipse. Figure 16 shows the mirror surface formed by rotating a section of the defining ellipse about the semi-major axis. The plane of the mirror face was determined from the dimensions given in Figure 1. Changing AutoCAD's view to the x-z plane defined in Figure 1 and translating and rotating the UCS to lie along the line bisecting the mirror face allowed measurement of depths at the same distances measured by HIA. Figure 17 shows lines originating on the mirror face and passing through the surface. Each line is located at the same distance from the center along the x-axis as HIA's measurements. The intersection of each line and the mirror surface was determined by zooming in and visually finding the intersection to within a few tenths of a micron.

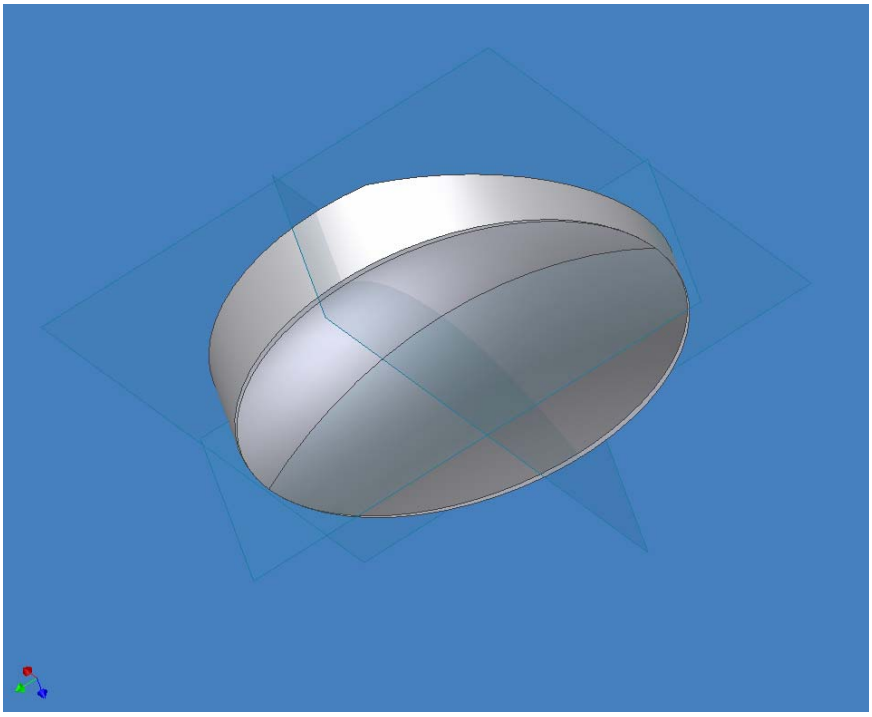


Figure 11: Mirror 1 rendering from *Inventor*

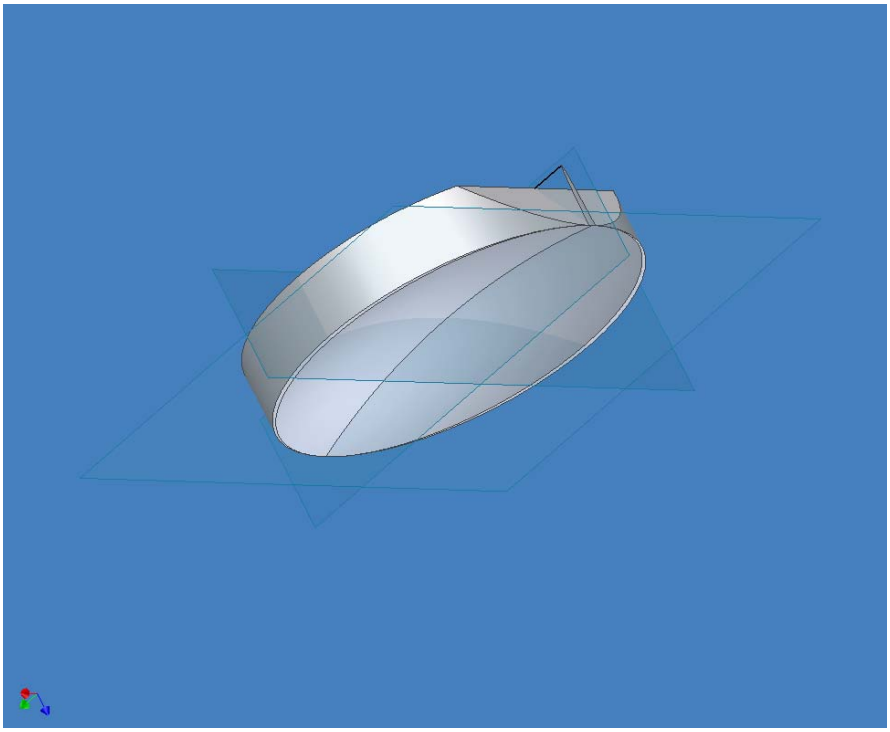


Figure 12: Mirror 2 rendering from *Inventor*

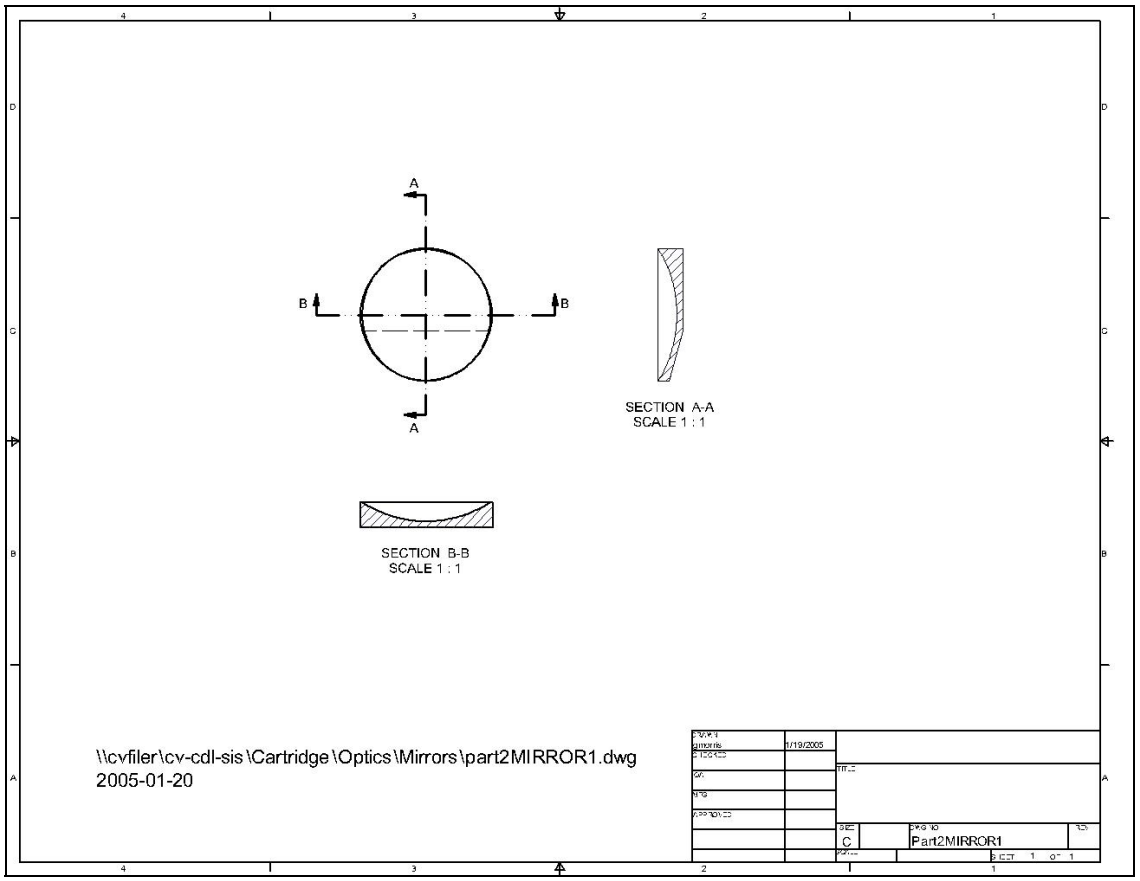


Figure 13: ACAD drawing of Mirror 1 imported from *Inventor* showing cross-sectional views. Section A-A lies in the plane of the defining ellipse and section B-B is lies in the rotational plane.

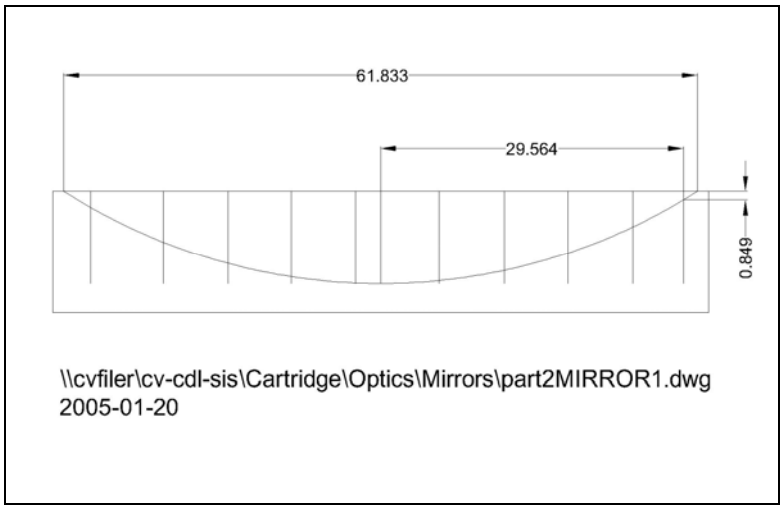


Figure 14: Close-up of Section B-B in Figure 13 showing how distances were measured from the mirror face to the mirror surface.

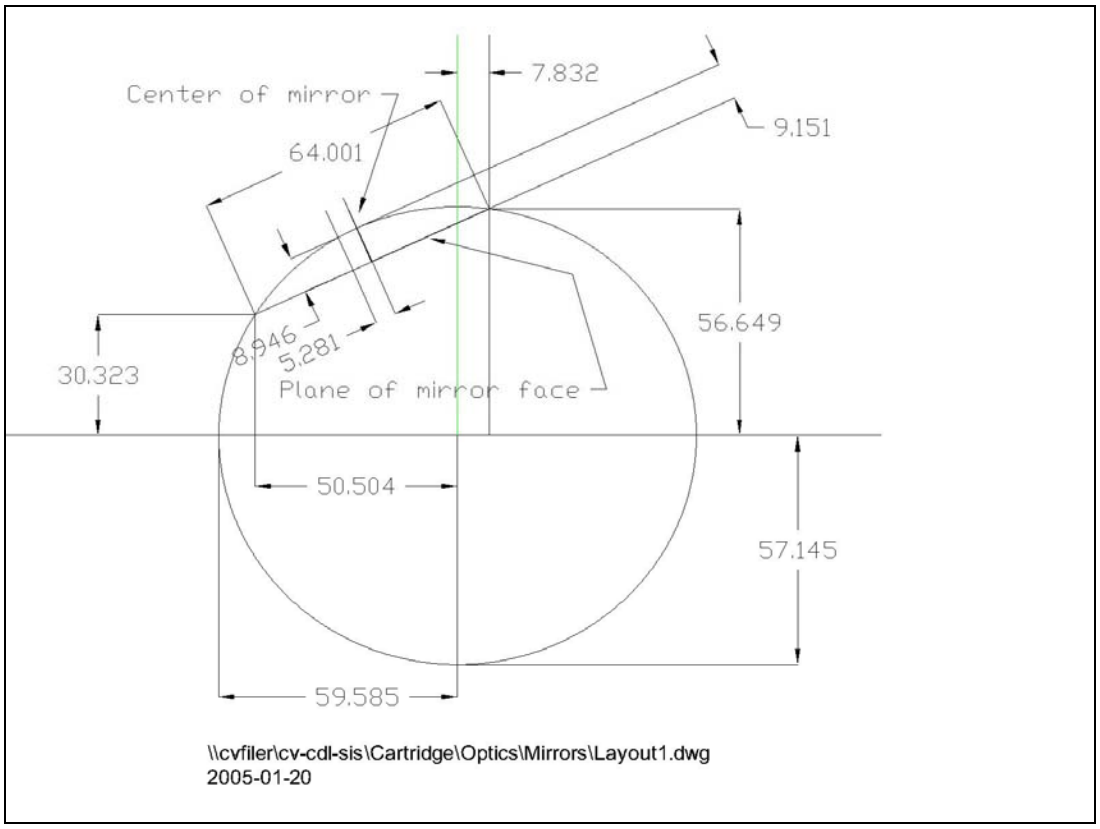


Figure 15: ACAD drawing of Mirror 1 using ellipse definition to measure mirror depth in the plane of the defining ellipse

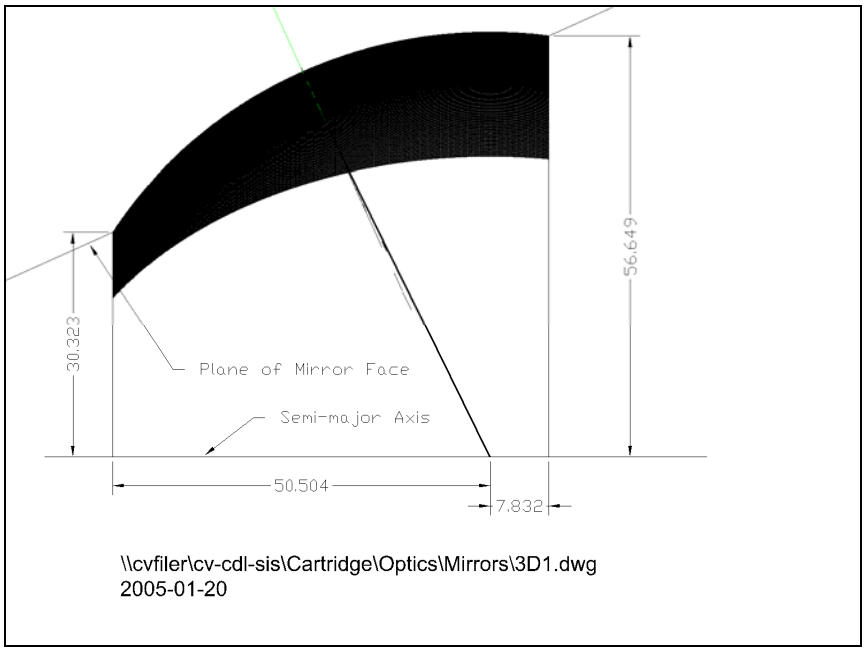


Figure 16: Mirror 1 defined with ACAD surface command. Ellipse segment was rotated about the semi-major axis.

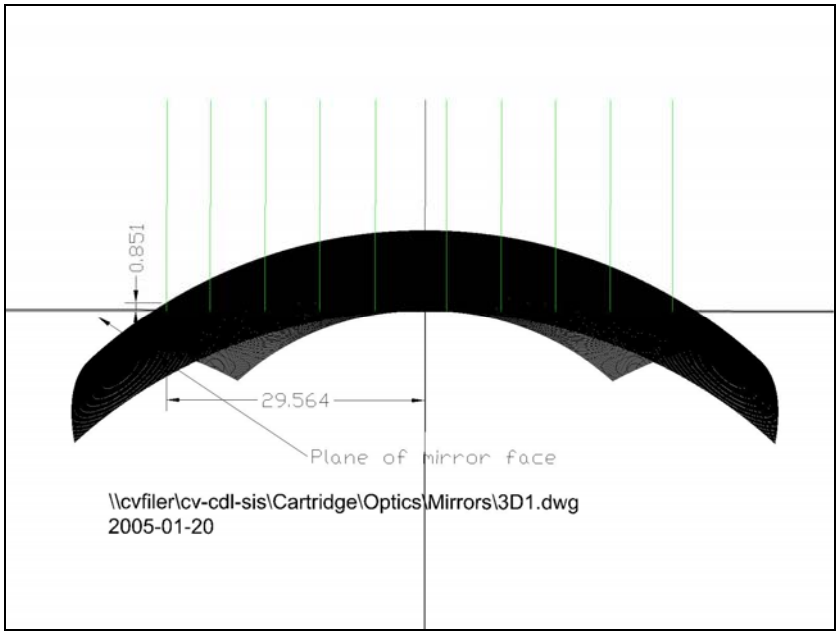


Figure 17: View of Figure 16 in x-z plane (defined in Figure 1) showing how depth of mirror was measured at same distances from mirror center line used by HIA. Each line depicts location of HIA measurement along x-axis.