X-RAY MICROSCOPE ASSEMBLIES

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Final Report and Metrology Report

LLL Subcontract 9936205

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1.0 INTRODUCTION

This is the Final Report and Metrology Report prepared under Lawrence Livermore Laboratory Subcontract 9936205, X-ray Microscope Assemblies. The purpose of this program was to design, fabricate, and perform detailed metrology on an axisymmetric grazing-incidence x-ray microscope (XRMS) to be used as a diagnostic instrument in the Lawrence Livermore Laser Fusion Program. The optical configuration chosen for this device consists of two internally polished surfaces of revolution: an hyperboloid facing the object; and a confocal, co-axial ellipsoid facing the image. This arrangement is known as the Wolter Type-I configuration. The grazing angle of reflection for both surfaces is approximately 1°. The general optical performance goals under this program were to achieve a spatial resolution in the object plane in the soft x-ray region of approximately 1 micron, and to achieve an effective solid collecting angle which is an appreciable fraction of the geometric solid collecting angle.

In the initial phases of this program, optical designs characterized by three different magnifications (9X, 22X, and 50X) were studied in various degrees of detail. The 9X optical design was extensively ray-traced in order to evaluate the adequacy of a baseline set of surface tolerances. In light of the ray tracing results, some of the baseline tolerances were modified and two additional tolerances were added to the set. Some ray tracing runs of the 50X design were performed to verify that the results of the 9X ray traces could be scaled to other magnifications. The 22X design was finally selected for fabrication in order to exploit the existing Lawrence Livermore diamond turning capabilities. That is, Lawrence Livermore Laboratory had previously diamond-turned x-ray microscopes to the 22X design, and an additional 22X unit in this series was produced for this program. In this way, a highly symmetrical surface shape and an accurate surface profile were established before any optical polishing and figuring were begun. It was then the purpose of the polishing and figuring to smooth the relatively rough local surface left by the diamond turning and to improve the accuracy of the surface profile shape.

The nominal optical parameters of the 22X design are listed as follows:

Object Distance: 300 mm

Image Distance: 6600 mm

Collecting Solid Angle (Geometrical): 4.2×10^{-4} steradians

Radius at the Hyperboloid-Ellipsoid Junction: 20.0617 mm

Grazing Angle of Reflection: 1.0°.

Other dimensions of the nominal design are shown in Figure 2.3.

The structural material of the diamond-turned unit supplied by LLL was No. 1018 cold rolled steel with a surface coating of electroless nickel. The final diamond turning, and the subsequent polishing and figuring, were all done within the electroless nickel layer.

Polishing and figuring were performed at Random Devices, Inc., Georgetown, Massachusetts. In the polishing and figuring phase, local profile errors left from the diamond-turning process were removed and the local surface finish was vastly improved. Local azimuthal slope errors were probably smoothed as well, although azimuthal measurements of the surface before polishing was begun were not made, so a clear comparison cannot be made. An attempt was made to correct the larger scale symmetry errors left from the diamond-turning process. This was not particularly successful because of the very slow rate of change of the symmetry shape which was achievable with the figuring methods that were used here, and because the primary emphasis was placed on improving the profile figure and the surface smoothness.

Preliminary x-ray measurements of the imaging properties of the unit delivered under this contract have been made at LLL. From verbal communications, these measurements indicate that the spatial resolution of this XRMS is several times better than any previous axisymmetric unit tested, and that the effective collecting solid angle (as indicated by the time required to make a given exposure) is about an order of magnitude improved over previous units.

In this report, Section 2 describes the ray tracing and tolerance study which was performed on the various optical designs considered under this program.

Section 3 briefly describes the Calibration Plan and the preliminary design of an x-ray calibration facility.

Section 4 describes the fabrication of the XRMS delivered under this program.

Section 5, the Metrology Report, describes the measurements made on the final optical surfaces, as well as the processing and interpretation of the metrology data. These measurements indicate that the effective collecting solid angle is limited by the variation in average slope ($\Delta R(\theta)$) tolerance and the axial slope (dS/dx) variations, whereas the spatial resolution is limited by the $\Delta R(\theta)$ variations alone.

2.0 RAYTRACING AND TOLERANCE STUDY

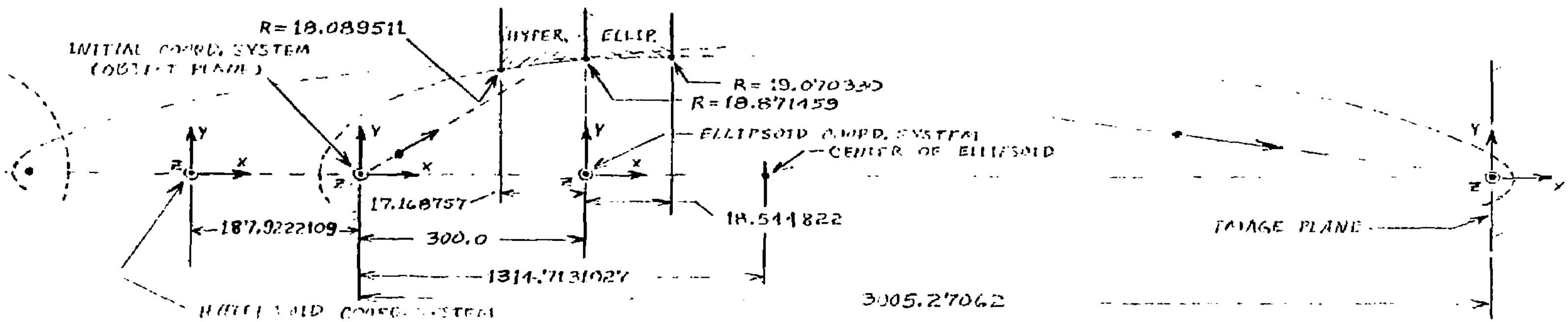
During the initial phase of this contract, an extensive series of optical ray tracing runs were made to determine the adequacy of the values assigned to the various optical surface tolerances and allowable misalignments. The raytracing was done using a computer program, RAYTRAC, which was in part developed under this contract. This program and its operation are described in detail in the RAYTRAC MANUAL, Visidyne Document Number VI-560, October, 1980.

The nominal optical design used for the tolerance study was that of a 9X unit shown in Figure 2.1. (All dimensions are in millimeters). Several runs were also made on the 50X design of Figure 2.2. Comparison of corresponding runs on the two designs showed that the aberration sizes in the image plane could be scaled in proportion to the image distance. Thus, the results of these raytracing runs can also be applied to the 22X unit, shown in Figure 2.3, which was ultimately delivered under this contract.

The initial set of optical surface tolerances used as a starting point for this study is listed in Column A of Table A, on page 21. This set of tolerances was provided to Visidyne, Inc. by LLL. In the course of approximately 50 raytracing runs, the effects on the imaging properties of surface errors within these tolerance limits were investigated. Generally, surface deformations or misalignments of the full amplitude listed in Column A and also of half that amplitude were used in these runs. In all cases, it was found that the overall size and also the RMS radius of the resulting image spot scaled linearly with the amplitude of a given deformation. For several of the deformations, the image size could be decreased by shifting the image plane. For these cases, multiple raytracing runs were made in order to locate the optimum image plane and minimum image spot size.

From the results of the raytracing runs, a set of Tolerance Summary Sheets, shown in Figures 2.4 through 2.14, were made up. (In the case of the $\Delta S(x)$ profile tolerance, both Figures 2.8 and 2.9 are applicable). In each of these diagrams, the form of the surface deformation and the dimensions used to quantify it appear in the upper left. Sketches of the form of the resulting image and a sample spot diagram from the RAYTRAC output are shown in the lower left. These spot diagrams come in either of two forms: a Calcomp plot in which the ray striking points are represented by small X's; and a line printer plot in which the number of rays striking in any given line printer bin is

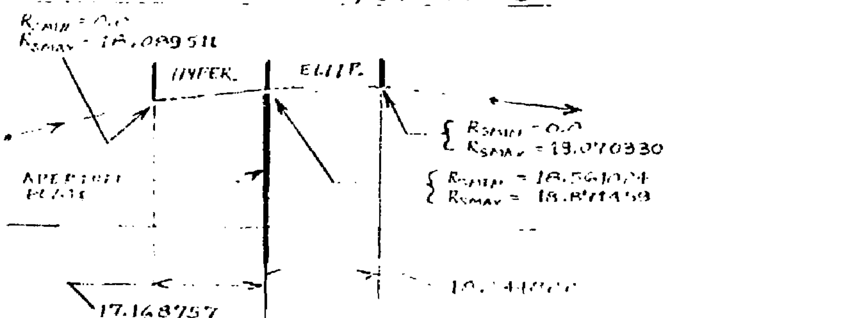
LLL 9X OPTICAL DESIGN, NOMINAL SYSTEM



EQUATION OF HYPERBOLOID: $X = [569.49456\,Y^2 + 569.49456\,Z^2 + 35252.855362]^{1/2}$

EQUATION OF ELLIPSOID: $X = -[-5131.4445\,Y^2 - 5131.4445\,Z^2 + 2858541.807079]^{1/2} + 1014.7131027$

STOPS AND APERTURES, SYSTEM C



STOPS AND APERTURES, SYSTEM D

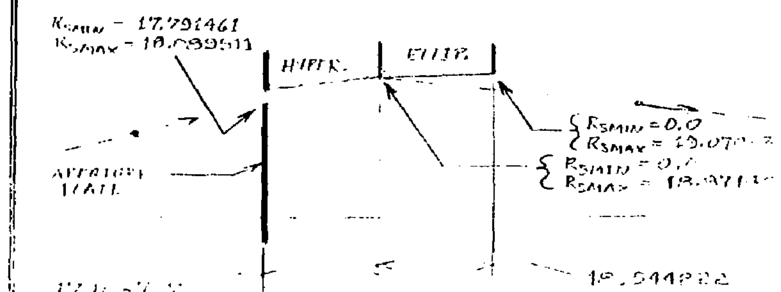


FIGURE 2.1

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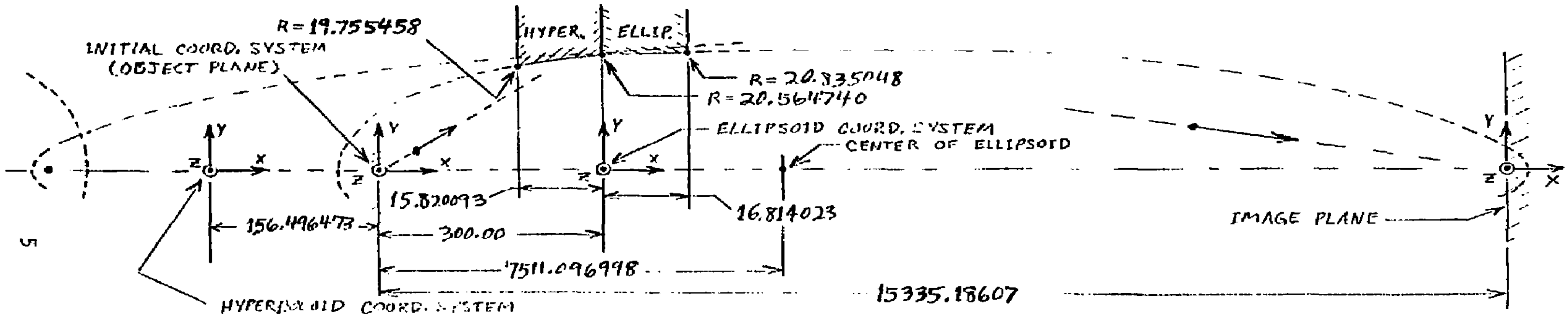
LLL 50X OPTICAL DESIGN, NOMINAL SYSTEM

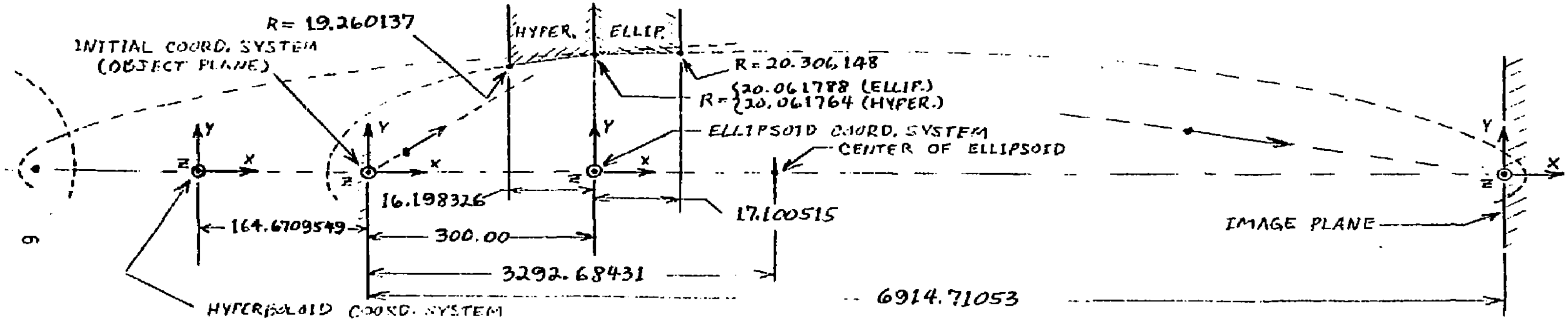


EQUATION OF HYPERBOLOID: $X = [434.973653\,Y^2 + 434.973653\,Z^2 + 24434.970299]^{1/2}$

EQUATION OF ELLIPSOID: $X = -[-21795.92\,Y^2 - 21795.92\,Z^2 + 61219192.23]^{1/2} + 7211.096998$

FIGURE 2.2

22X OPTICAL DESIGN, NOMINAL SYSTEM, LLL.



EQUATION OF HYPERBOLOID: $X = \left[469.24784\, Y^2 + 469.24784\, Z^2 + 27058.85907 \right]^{1/2}$

EQUATION OF ELLIPSOID: $X = -\left[-10346.4295\, Y^2 - 10346.4295\, Z^2 + 13120341.97374 \right]^{1/2} + 2992.68431$

$$M = \frac{6914.71053 - 300.00}{300.00} = 22.049\,X$$

FIGURE 2.3

given by an integer from 1 to 9 appearing in that bin. (If more than 9 rays strike a given bin, a letter of the alphabet is used, in accordance with the code given in the RAYTRAC Manual, page 69). On the right side of each Tolerance Summary Sheet is a plot of the RMS radius of the image and also of some characteristic image dimension (called Dimension A or Full Radius A) versus the amplitude of the surface error or misalignment. (In Figures 2.13 and 2.14, because of the form of the image, the full radius happens to be equal to the RMS radius). In the cases of Figures 2.6, 2.9, 2.11, and 2.12, an image plane shift was required to minimize the image size, and in these cases a companion plot of optimum image plane shift Δf versus amplitude of the surface error appears at the lower right.

The deformations or misalignments for the runs which are summarized in the Tolerance Summary Sheets were all applied to the ellipsoid alone. However, several other runs were made with deformations applied to the hyperboloid in order to verify that the effect on the form of the image was the same. Also, a run (Number 84) was made combining out-of-roundness, variation of ΔR with θ, and axial tilt of the ellipsoid to show the effects of superimposing several surface errors. The resulting RMS radius of the image, referenced back to the object plane, was 0.65 microns. This compares to a calculated RMS radius of 0.94 microns when the RMS radii for the separate deformations, found in earlier runs, were added in quadrature. The discrepancy is probably due to the fact that the effects of the three deformations are not entirely independent. The original output from Run Number 84 was previously supplied to LLL.

Raytracing runs were also made on the nominal, undeformed 9X optical design in order to verify that RAYTRAC would give the expected point image an axis and to investigate the imaging properties of the system for off-axis object points. Figure 2.15 on page 19 is a plot of the resulting RMS image radii (referenced back to the object plane) versus object point position, assuming a planar image surface. The blur sizes are mainly due to the effects of coma and field curvature.

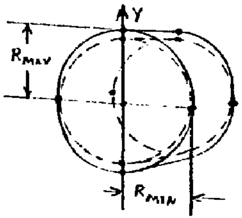
2.1 Revisions to the Tolerance Table

From the results of the raytracing, from discussions with LLL personnel, and from discussions with the optical fabricator, Random Devices, Inc., concerning what tolerance levels were feasible and what levels were not, a set of revised tolerances were arrived at. These are listed in Column B of

LLL 9X SYSTEM D

ROUNDNESS TOLERANCE

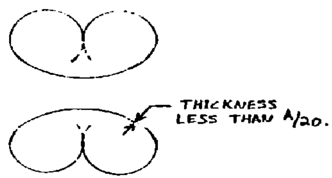
([$R_{MAX} - R_{MIN}$] IN PLANES NORMAL TO THE OPTICAL AXIS).



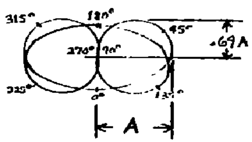
THIS TOLERANCE WAS MODELED BY MAKING THE ERROR IN RADIUS PROPORTIONAL TO Y^2.

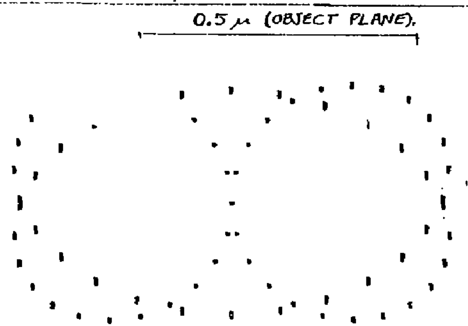
INITIAL VALUE: $(R_{MAX} - R_{MIN}) = 1.4\mu$

THE IMAGE CONSISTS OF TWO THIN LOOPS SUPERIMPOSED ON EACH OTHER.



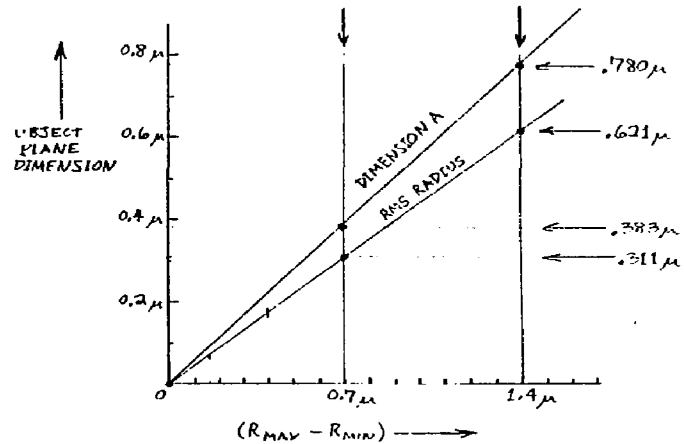
COMBINED LOOPS:





RUN # 51

$(R_{MAX} - R_{MIN}) = 0.7\mu$



(RMS RADIUS) ≈ .80 A

OTHER OUT-OF-ROUNDNESS RUNS: #31, #32, #50.

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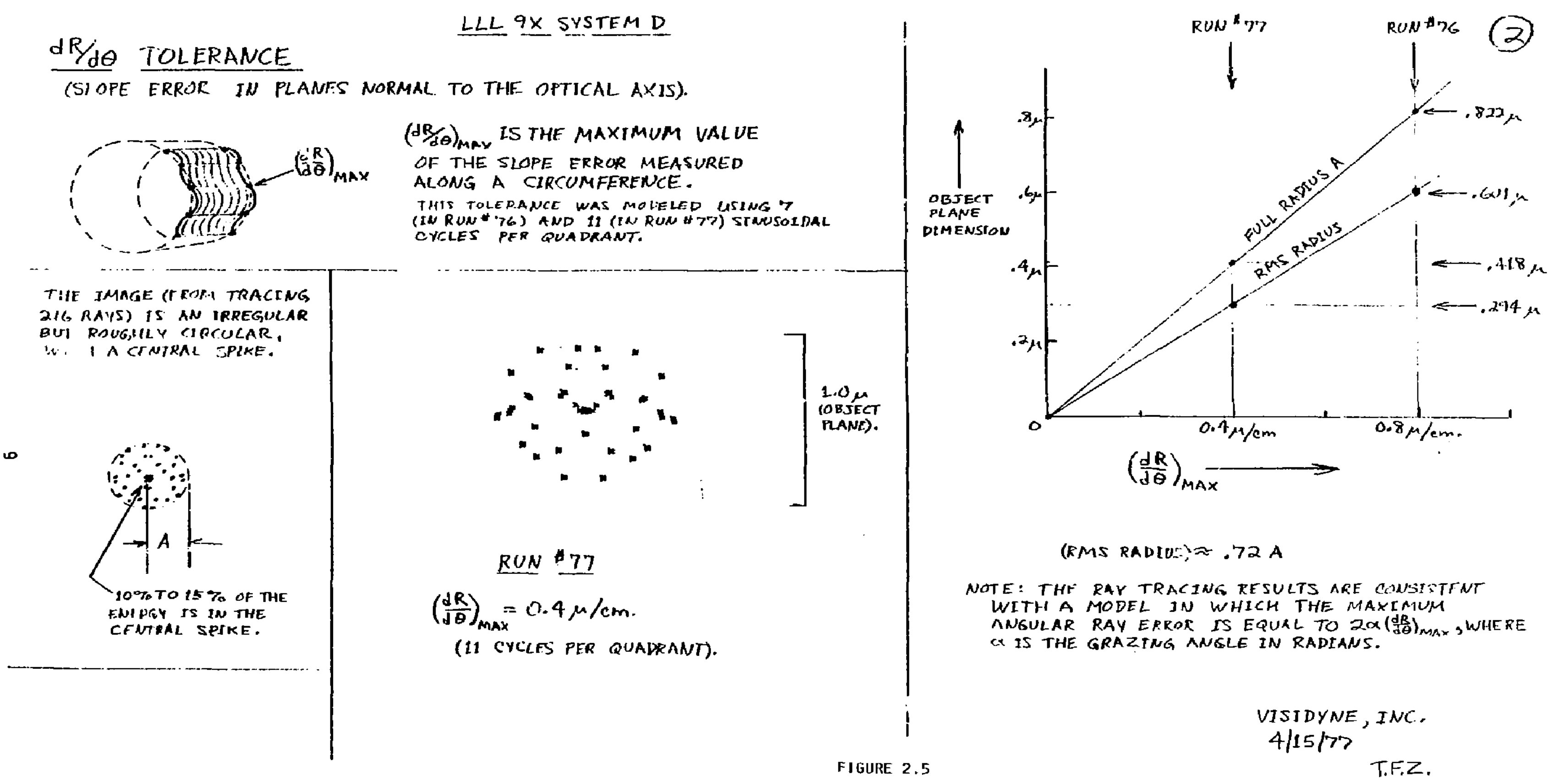
FIGURE 2.4



LLL 9X SYSTEM D
dR/dθ TOLERANCE
(SLOPE ERROR IN PLANES NORMAL TO THE OPTICAL AXIS).
$(dR/d\theta)_{MAX}$
$(dR/d\theta)_{MAX}$ IS THE MAXIMUM VALUE OF THE SLOPE ERROR MEASURED ALONG A CIRCUMFERENCE.
THIS TOLERANCE WAS MODELED USING 7 (IN RUN #76) AND 11 (IN RUN #77) SINUSOIDAL CYCLES PER QUADRANT.
THE IMAGE (FROM TRACING 216 RAYS) IS AN IRREGULAR BUT ROUGHLY CIRCULAR, A CENTRAL SPIKE.
A
10% TO 15% OF THE ENERGY IS IN THE CENTRAL SPIKE.
1.0μ (OBJECT PLANE).
RUN #77
$(dR/d\theta)_{MAX}$ = 0.4 μ/cm.
(11 CYCLES PER QUADRANT).
RUN #77
RUN #76
2
OBJECT PLANE DIMENSION
.8μ
.6μ
.4μ
.2μ
0
0.4μ/cm
0.8μ/cm.
$(dR/d\theta)_{MAX}$
FULL RADIUS A
RMS RADIUS
.822μ
.601μ
.418μ
.294μ
(RMS RADIUS) ≈ .72 A
NOTE: THE RAY TRACING RESULTS ARE CONSISTENT WITH A MODEL IN WHICH THE MAXIMUM ANGULAR RAY ERROR IS EQUAL TO $2\alpha(dR/d\theta)_{MAX}$, WHERE α IS THE GRAZING ANGLE IN RADIANS.
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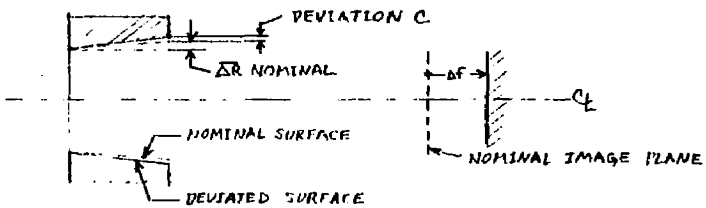
T.F.Z.

FIGURE 2.5

LLL 9X SYSTEM D

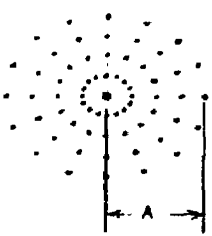
TOLERANCE ON $\overline{\Delta R}$

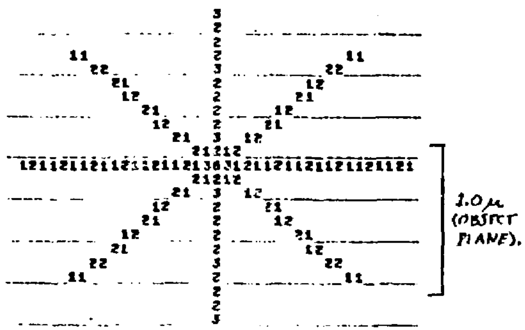
(THE DEVIATION OF THE AVERAGE AFT RADIUS MINUS THE AVERAGE FORE RADIUS FROM THE NOMINAL VALUE).



INITIAL VALUE: C = ±7μ

THE IMAGE IS A THIN RING WHICH CAN, BY REFOCUSSING, BE REDUCED TO A 1/r -TYPE ENERGY DISTRIBUTION.



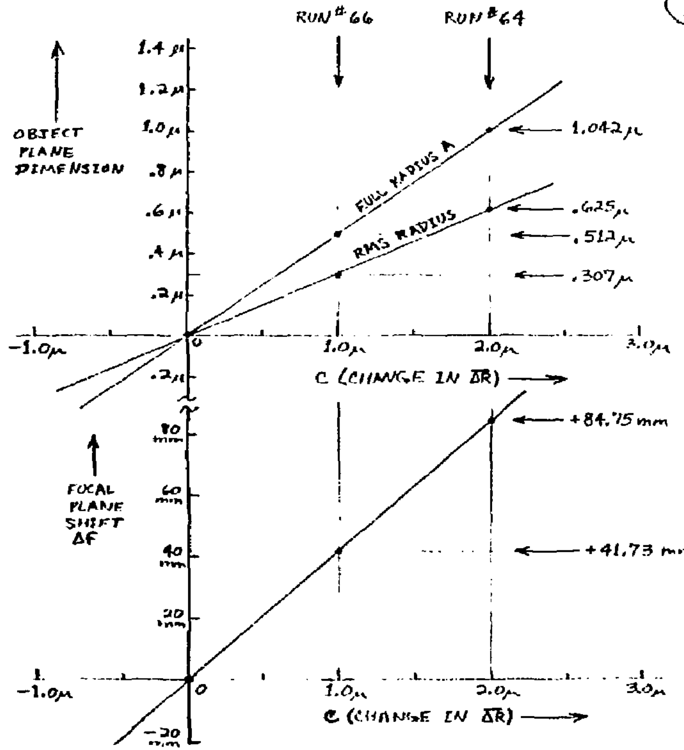


RUN #64

C = 2.0μ

ΔF = +84.75 mm.

FIGURE 2.6



(RMS RADIUS) ≈ .60A

OTHER $\overline{\Delta R}$ RUNS: #28, #29, #30, #62, #65.

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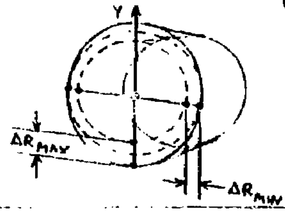
LLL 4X SYSTEM D

VARIATION OF ΔR WITH θ

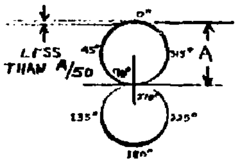
$(\Delta R_{MAX} - \Delta R_{MIN})$.

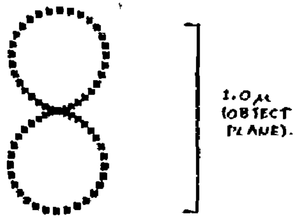


THIS TOLERANCE WAS MODELED BY MAKING THE ERROR IN ΔR PROPORTIONAL TO Y^2.

INITIAL VALUE: .033μ

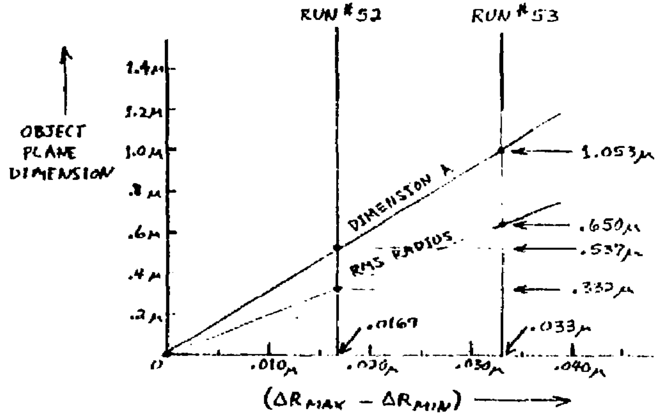
THE IMAGE CONSISTS OF A THIN FIGURE "8".





RUN #52

$\Delta R_{MAX} - \Delta R_{MIN} = .0169\mu$



(RMS RADIUS) ≈ .62 A

OTHER $(\Delta R_{MAX} - \Delta R_{MIN})$ RUN: #33

FIGURE 2.7

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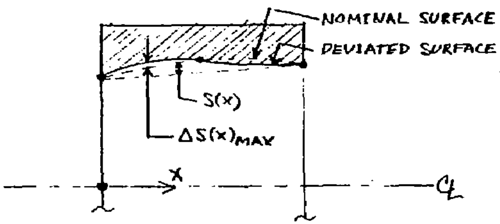
TOLERANCE ON S(x), FULL CYCLE

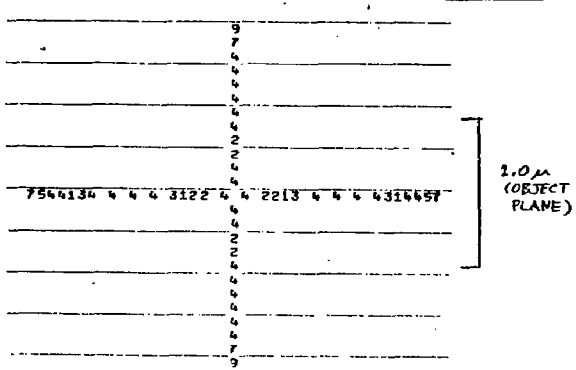
(THE DEVIATION OF THE SURFACE FROM NOMINAL IN PLANES WHICH CONTAIN THE OPTICAL AXIS).



THIS TOLERANCE WAS MODELED USING ONE SINUSOIDAL CYCLE WHICH EXTENDED ALONG THE FULL LENGTH OF THE SURFACE.

INITIAL VALUE: $\Delta S(x)_{MAX} = .011\mu$

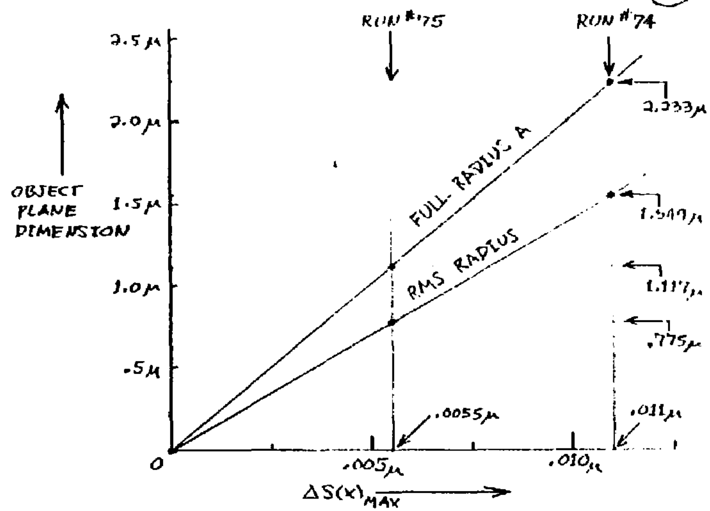
THE ENERGY DISTRIBUTION IN THE IMAGE HAS A CENTRAL PEAK AND AN INTENSIFIED CIRCULAR ZONE AT THE PERIPHERY.



RUN # 75

$\Delta S(x)_{MAX} = .0055\mu$.

(THE CENTRAL SPIKE IS NOT APPARENT BECAUSE OF THE SMALL NUMBER OF AZIMUTH POSITIONS IN THE INCIDENT RAY SET).



(RMS RADIUS) ≈ .69 A

NOTE: THE OBSERVED VALUE OF THE MAXIMUM RAY DEVIATION IN THE IMAGE PLANE IS VERY NEARLY EQUAL TO $2 I \delta_{MAX}$, WHERE I IS THE IMAGE DISTANCE AND δ_{MAX} IS THE MAXIMUM SURFACE SLOPE ERROR.

FIGURE 2.8

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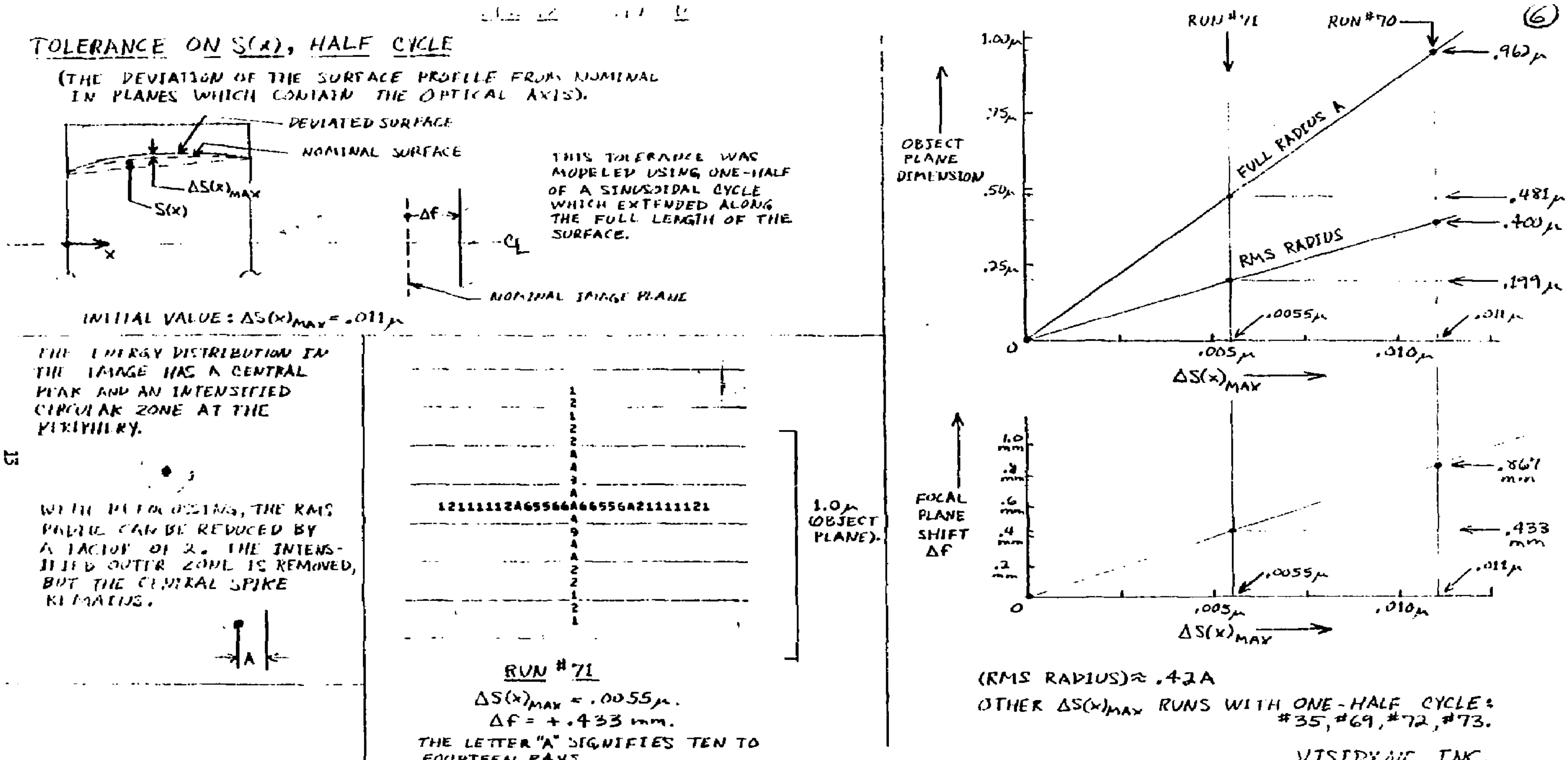

FIGURE 2.9

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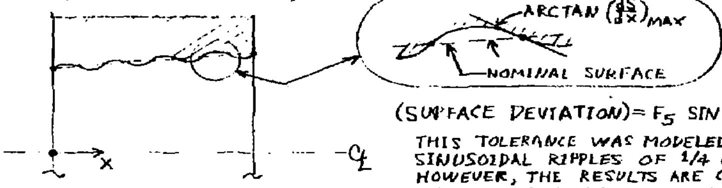
dS/dx TOLERANCE

(DEPARTURE OF THE LOCAL SLOPE FROM THE NOMINAL LOCAL VALUE IN PLANES CONTAINING THE OPTICAL AXIS).

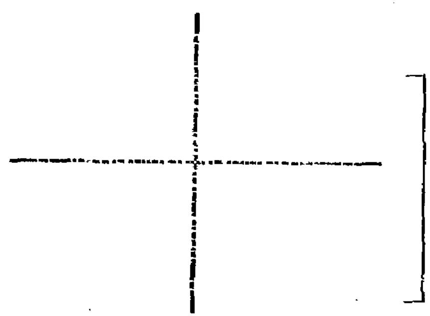


(SURFACE DEVIATION) = $F_5 \sin F_6 X$

THIS TOLERANCE WAS MODELED USING SINUSOIDAL RIPPLES OF 1/4 CYCLE/MM. HOWEVER, THE RESULTS ARE CONSISTENT WITH OTHER RUNS HAVING 1.0 CYCLE/MM AND 10 CYCLE/MM RIPPLES.

INITIAL VALUE = .022 μ/cm.

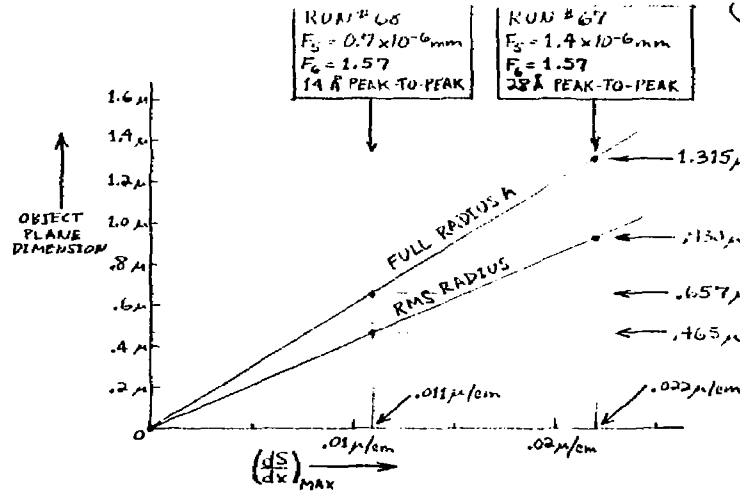
THE ENERGY DISTRIBUTION IN THE IMAGE HAS A CENTRAL PEAK AND AN INTENSIFIED CIRCULAR ZONE AT THE PERIPHERY.



RUN #68

$(\frac{dS}{dx})_{MAX}$ = .011 μ/cm at 1/4 cycle/mm.

(THE CENTRAL PEAK IS NOT APPARENT BECAUSE OF THE SMALL NUMBER OF AZIMUTH POSITIONS IN THE INCIDENT RAY SET).



(RMS RADIUS) ≈ .707A

OTHER dS/dx RUNS: #9, #12, #15-19, #36.

NOTE:

FOR A SURFACE DEVIATION OF THE FORM $F_5 \sin F_6 X$, THE MAXIMUM SLOPE ERROR IS $F_5 F_6$.

THE VARIOUS RAY TRACING RUNS SHOW THAT THE MAXIMUM RAY DEVIATION IN THE IMAGE PLANE IS $2F_5F_6I$, WHERE I IS THE IMAGE DISTANCE, AND THAT THE ENERGY DISTRIBUTION D(r) IN THE IMAGE PLANE CLOSELY FOLLOWS THE FORM:

$$D(r) = \frac{1}{\pi\sqrt{A^2 - r^2}}$$

WHERE r IS THE RADIAL DISTANCE FROM THE CENTER OF THE IMAGE.

FIGURE 2.10

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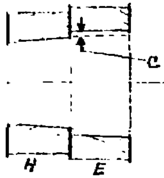
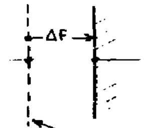
TOLERANCE ON CONSISTENCY OF RADII.

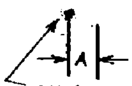
(THE RADIUS OF THE ELLIPSOID MINUS THE RADIUS OF THE HYPERBOLOID IN THE NOMINAL PLANE OF CONIC INTERSECTION).

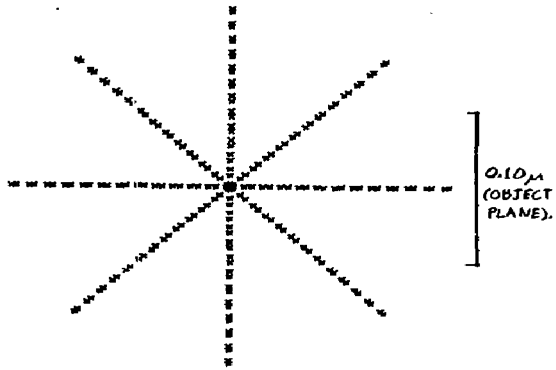




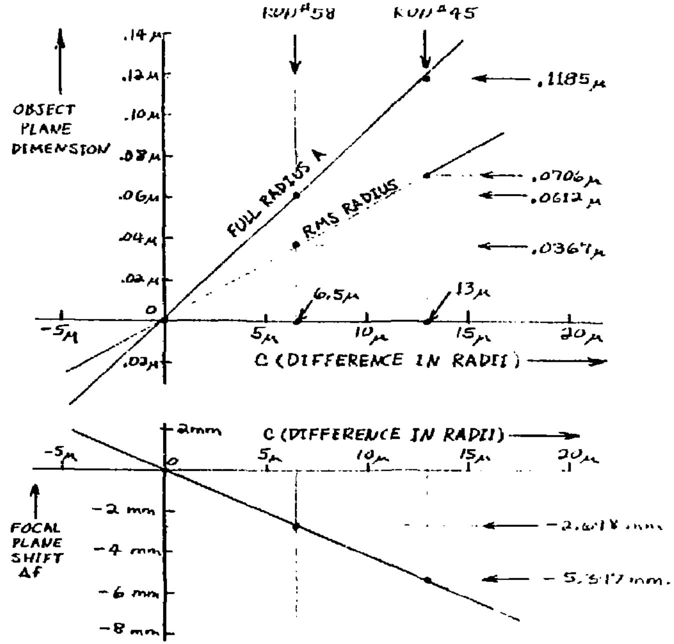
INITIAL VALUE: C = ±13μ.

THE IMAGE IS A THIN RING, WHICH CAN BE REDUCED, BY REFOCUSING, TO A 1/r -TYPE ENERGY DISTRIBUTION.





RUN #45
C = +13μ.
ΔF = −5.397 mm.



(RMS RADIUS) ≈ .60A

OTHER CONSISTENCY OF RADII RUNS: #41, #43, #44, #58A.

FIGURE 2.11

VISIDYNE, INC.
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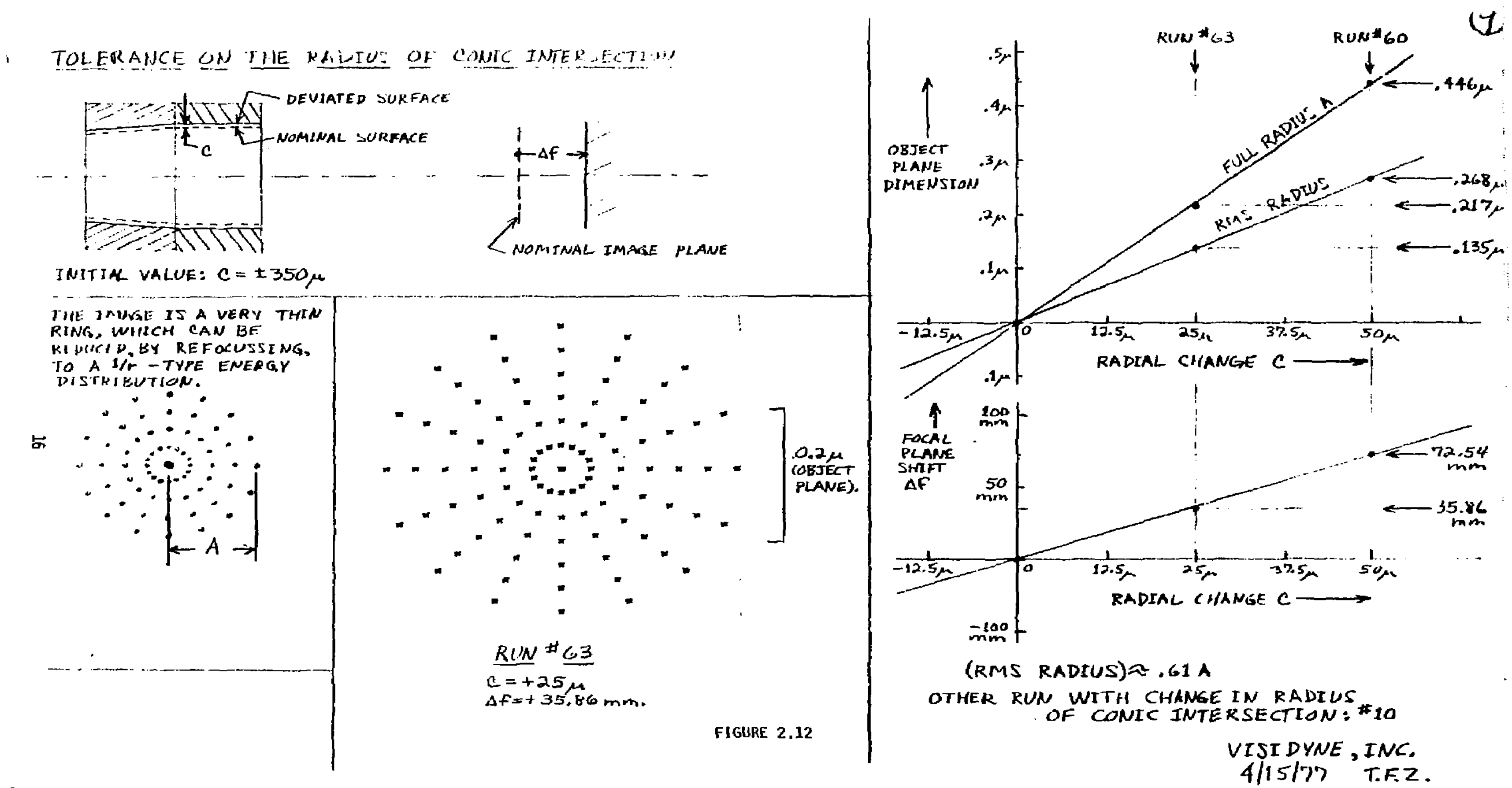
TOLERANCE ON THE RADIUS OF CONIC INTERSECTION
DEVIATED SURFACE
NOMINAL SURFACE
C
Δf
NOMINAL IMAGE PLANE
INITIAL VALUE: C = ± 350μ
THE IMAGE IS A VERY THIN RING, WHICH CAN BE REDUCED, BY REFOCUSSING, TO A 1/r - TYPE ENERGY DISTRIBUTION.
A
0.2μ (OBJECT PLANE).
RUN #63
C = +25μ
Δf = +35.86 mm.
RUN #63
RUN #60
OBJECT PLANE DIMENSION
.5μ
.4μ
.3μ
.2μ
.1μ
.1μ
FULL RADIUS, A
RMS RADIUS
.446μ
.268μ
.217μ
.135μ
-12.5μ
0
12.5μ
25μ
37.5μ
50μ
RADIAL CHANGE C
FOCAL PLANE SHIFT Δf
100 mm
50 mm
-100 mm
72.54 mm
35.86 mm
-12.5μ
0
12.5μ
25μ
37.5μ
50μ
RADIAL CHANGE C
(RMS RADIUS) ≈ .61 A
OTHER RUN WITH CHANGE IN RADIUS OF CONIC INTERSECTION: #10
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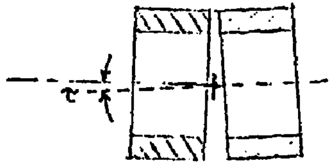
FIGURE 2.12

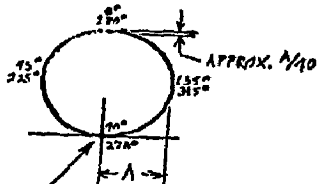
TILT TOLERANCE

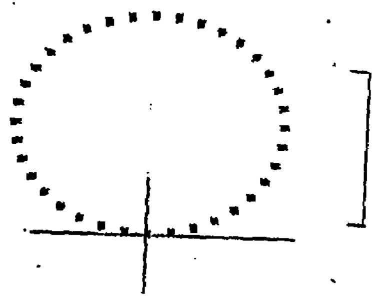
(TILT OF THE AXIS OF ONE COMPONENT WITH RESPECT TO THE OTHER).



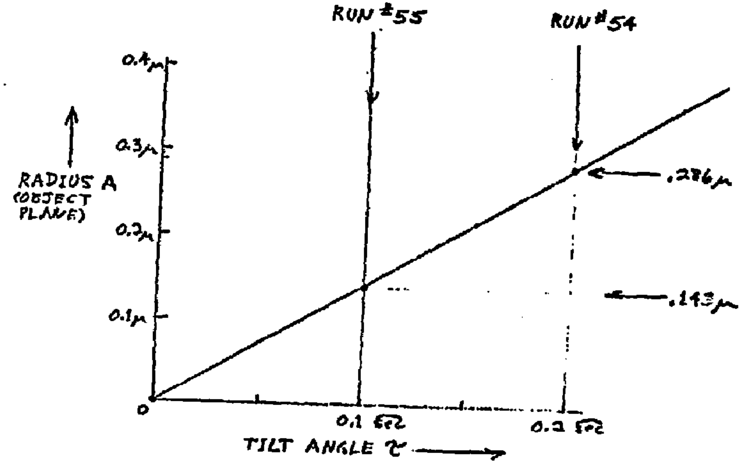
THIS TOLERANCE WAS MODELED BY ASSUMING THAT THE PIVOT POINT IS AT THE CENTER OF THE PLANE OF CONIC INTERSECTION.

THE IMAGE IS A THIN RING WITH THE OPTICAL AXIS ON THE PERIPHERY. THE RING CANNOT BE REDUCED IN SIZE BY REFOCUSSING, AS SHOWN IN RUN # 39.





RUN # 54
τ = 0.20 SEC.



(RMS RADIUS) = A

OTHER TILT RUNS: #37, #39.

FIGURE 2.13

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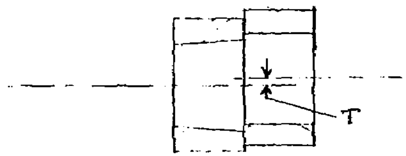
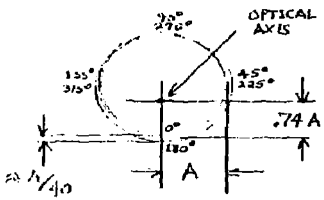
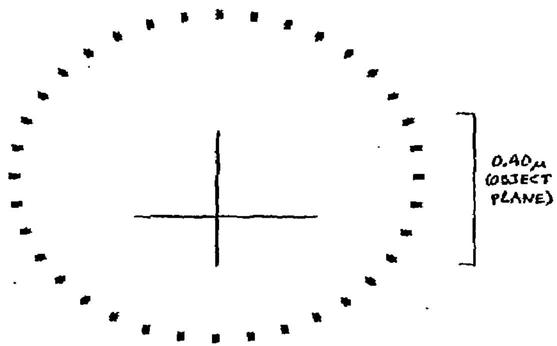
LATERAL TRANSLATION TOLERANCE

(DE-CENTERING OF ONE COMPONENT WITH RESPECT TO THE OTHER).



THE IMAGE IS A THIN RING THAT IS OFF CENTER WITH RESPECT TO THE OPTICAL AXIS. THE RING CANNOT BE REDUCED BY REFOCUSSING.

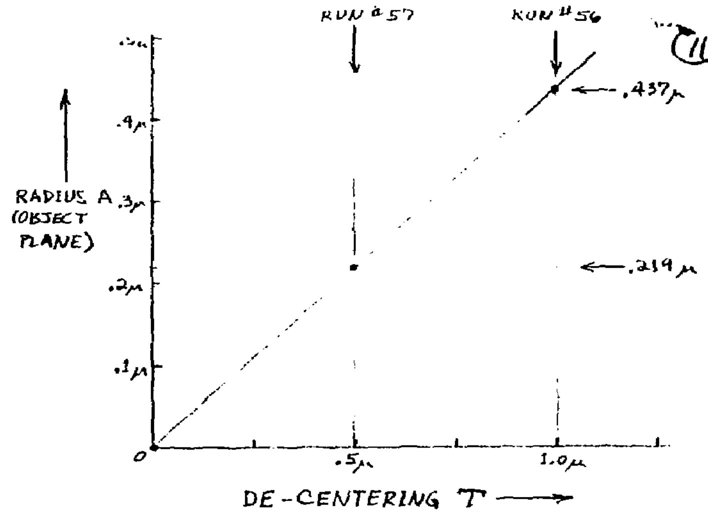




RUN #56

$T = 1.0\mu$.

FIGURE 2.14



(RMS RADIUS) = A

OTHER LATERAL TRANSLATION RUN: #38

VISIDYNE, INC.
4/15/77
T.F.Z.

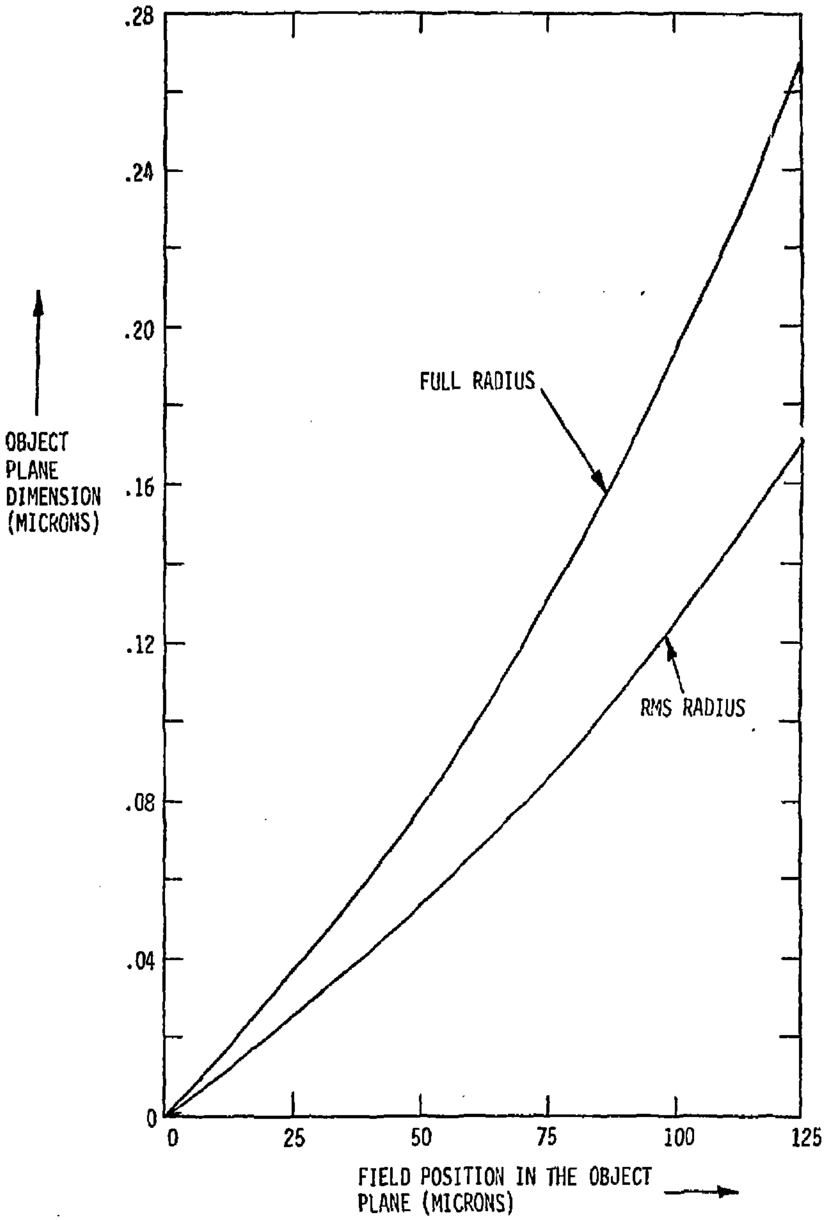


FIGURE 2.15 Imaging Performance of the Nominal 9X Optical Design

Table A. The first seven tolerances, the Optical Component Tolerances, refer to the ellipsoid and hyperboloid individually, whereas the last four, the Optical System Tolerances, refer to the matching and alignment of the ellipsoid and hyperboloid as a pair.

The first Optical Component Tolerance, the 1.4 micron out-of-roundness tolerance, was decreased to 0.5 microns in Column B because, at the 1.4 micron level, this tolerance would use up a substantial amount of the total tolerance budget (see Figure 2.4) and because the optical fabricator felt that there would be no problem holding to a substantially tighter roundness tolerance. The $dR/d\theta$ tolerance was left at 0.8 microns/cm because of uncertainty at the time of the level of smoothness in the azimuthal direction which could be achieved in practice. The $\overline{\Delta R}$ tolerance was tightened to ± 2.0 microns because the previous value of 7.0 microns would require a substantial shift in image plane position, and would, by itself, result in an RMS radius in the object plane in excess of 1.0 micron (see Figure 2.6). Also, the vendor felt that a tighter tolerance could be achieved. The tolerances on $\Delta R(\theta)$, $\Delta S(x)$, and dS/dx were left at their previous levels because these were considered to be near the limit of what could be achieved. The RMS surface roughness was left at 55 Å, with the agreement from the optical fabricator that he would attempt to do substantially better than this on a best effort basis.

The first of the Optical System Tolerances, on the consistency of radii, was left at ± 13 microns in order to allow the fabricator some freedom to remove material during lapping and polishing. Tightening this tolerance would have had little impact on the imaging performance, since the RMS radius corresponding to the full 13 micron allowable deviation is only .07 microns (see Figure 2.11). The tolerance on the radius of the conic intersection was tightened from ± 350 microns to 13 microns for mechanical rather than optical reasons. That is, it was felt that the absolute tolerance on the radius should be comparable to the 13 micron tolerance to which the radii of the two parts must match, rather than being much larger than that tolerance. Finally, from the results of the raytracing, it was felt necessary to add two more alignment tolerances: a tolerance on axial tilt of the ellipsoid with respect to the hyperboloid of 0.2 arc seconds; and a tolerance on the allowable lateral translation of the axis of the ellipsoid with respect to the axis of the hyperboloid of 0.2 microns.

	TOLERANCE DESCRIPTION	TOLERANCE MAGNITUDE			UNITS
		COLUMN A	COLUMN B	COLUMN C	
OPTICAL COMPONENT TOLERANCES	ROUNDNESS ($R_{MAX} - R_{MIN}$)	1.4	0.5	0.5	Microns
	$\frac{dR}{d\theta}$ (MAXIMUM SLOPE ERROR ABOUT A CIRCUMFERENCE)	0.8	0.8	0.4	Microns/cm
	$\overline{\Delta R}$ (DEVIATION OF THE AVERAGE AFT RADIUS MINUS THE AVERAGE FORE RADIUS FROM THE NOMINAL VALUE)	7.0	± 2.0	± 2.0	Microns
	$\Delta R(\theta)$ (VARIATION OF ΔR WITH θ; THAT IS, $\Delta R_{MAX} - \Delta R_{MIN}$)	.033	.033	.033	Microns
	$\Delta S(X)$ (DEVIATION OF THE ACTUAL SURFACE PROFILE FROM THE IDEAL PROFILE IN PLANES CONTAINING THE OPTICAL AXIS)	.011	.011	.011	Microns
	$\frac{dS}{dX}$ (DEPARTURE OF THE ACTUAL LOCAL SLOPE FROM THE IDEAL LOCAL SLOPE IN PLANES CONTAINING THE OPTICAL AXIS)	.022	.022	.022	Microns/cm
	RMS SURFACE ROUGHNESS	55	55	20	Å
OPTICAL SYSTEM TOLERANCES	CONSISTENCY OF RADII (ACTUAL DIFFERENCE IN THE RADII OF THE HYPERBOLOID AND ELLIPSOID IN THE NOMINAL PLANE OF INTERSECTION)	± 13	± 13	± 13	Microns
	RADIUS OF CONIC INTERSECTION (DEPARTURE OF THE ACTUAL RADIUS OF CONIC INTERSECTION FROM THE IDEAL VALUE)	± 350	13	13	Microns
	AXIAL TILT (TILT OF THE AXIS OF ONE COMPONENT WITH RESPECT TO THE OTHER)	None	0.2	0.2	Arc sec
	LATERAL TRANSLATION (TRANSLATION OF THE AXIS OF ONE COMPONENT FROM THE AXIS OF THE OTHER)	None	0.2	0.2	Microns

TABLE A. OPTICAL TOLERANCES

Later in the program, when final figuring and polishing were about to begin on the 22X unit which was delivered under this contract, two final changes to the tolerance table were made, as shown in Column C of Table A. The $dR/d\theta$ tolerance was tightened to 0.4 microns/cm because, by this time, it was recognized that azimuthal slope errors could impose an ultimate limit on the resolution by blunting the otherwise sharply peaked point spread function which would result if all the other tolerances were satisfied. The other change was to reduce the RMS surface roughness tolerance from 55 to 20 Å in order to decrease scattering and increase the effective collecting solid angle of the x-ray microscope. Both of the final changes were made on a best-effort basis.

3.0 CALIBRATION PLAN AND PRELIMINARY DESIGN OF CALIBRATION FACILITY

An x-ray calibration plan, previously supplied to LLL, was formulated during this program. The purpose of the Calibration Plan was to devise a way to measure the shape of the point spread function in the soft x-ray region for several field positions within the field of view, and to devise a method for measuring effective reflection efficiency (or effective collecting solid angle) at several energies in the soft x-ray range. In addition, preliminary drawings of a x-ray calibration facility were made, and a scanning electron microscope, to serve as a point x-ray source, was purchased. These items have been previously delivered to LLL.

4.0 FABRICATION

The 22X unit which was delivered under this contract was originally diamond-turned at Lawrence Livermore Laboratory, and then polished and figured at Random Devices, Inc., Georgetown, Massachusetts. A special measuring system, called the Scanner, was used at Random Devices for in-process monitoring of the surface figure and smoothness. The Scanner is described in Section 4.1, and the figuring and polishing process is described in Section 4.2.

4.1 Description of the Scanner

The Scanner makes measurements of the profiles of optical surfaces by detecting small displacements in the position of a HeNe laser beam reflected from the optical surface as that surface is moved past the laser beam. The input beam is fixed, and, ideally, the mechanical mounting of the piece under test is arranged so that the output beam is also fixed when the desired surface profile has been achieved. Thus, the Scanner gives a null measurement or nearly a null measurement for the correct surface figure.

As shown schematically in the plan view of Figure 4.1, the laser beam first passes through a set of beam defining components: lens L_1 and apertures A_1, A_2, and A_3. It is then focussed down to a 50 micron diameter spot on the optical surface under test by lens L_2. A weak lens L_3 can be translated along the laser beam axis to make fine adjustments in this focus. A set of small planar mirrors M_1, M_2, and M_3 mounted within the fixed Optical Probe Assembly are used to deliver the beam to the optical surface, and then to extract the reflected beam and direct it toward the detectors. A cylindrical lens L_5 may be placed as shown to compensate for the beam divergence normal to the plane of the diagram due to the strong azimuthal curvature of the surface under test. L_5 was used for some measurements, and deleted for others.

To make a profile measurement along a path approximately parallel to the optical axis (that is, to make an axial scan), the piece under test is moved along a very shallow circular arc defined by the two linear air bearings. This circular arc, which is a portion of a figure called the best fit slope circle, is produced by deliberately misaligning the linear air bearings from their nominal plane-parallel orientation, as shown. The radius and position of the center of the best fit slope circle are chosen so as to minimize the angular excursions of the reflected laser beam as the optical surface is moved through an axial scan. (The best fit slope circle is an approximation

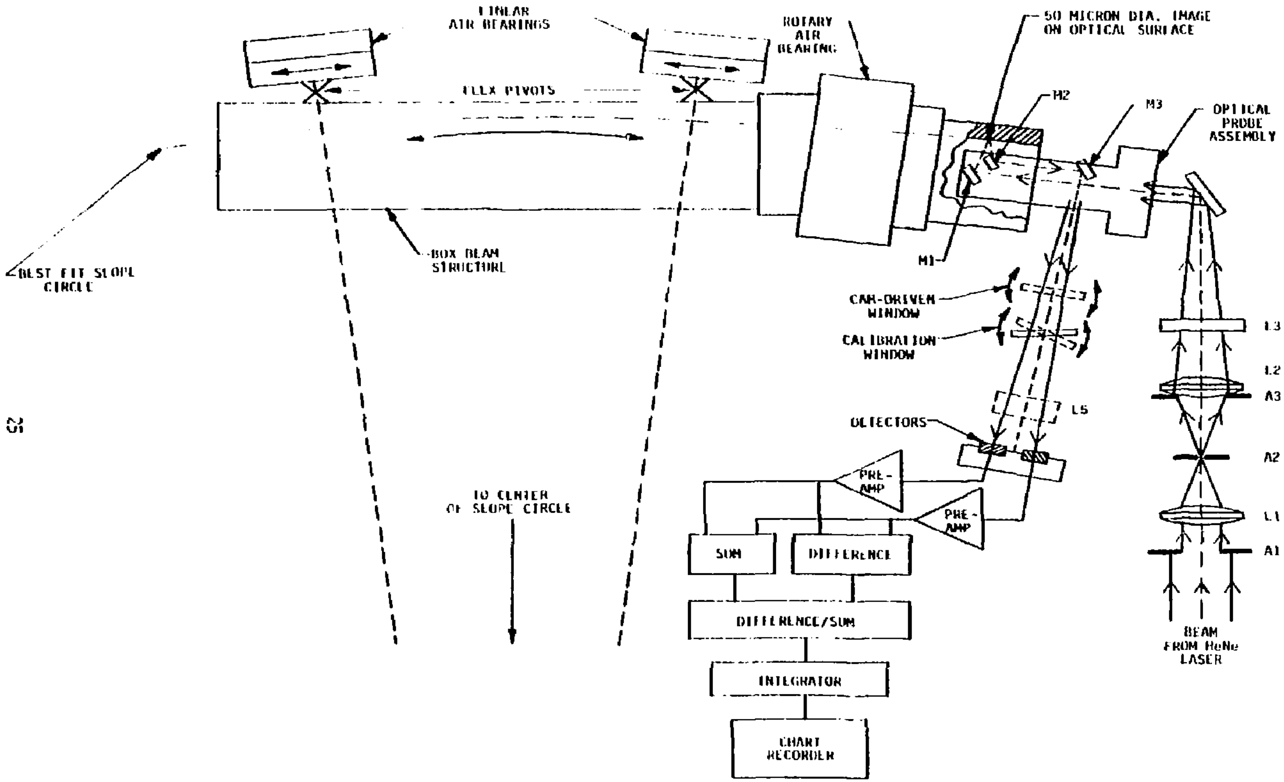


FIGURE 4.1 Schematic Diagram of the Scanner System

to the profile of the optical surface in which the slope differences, rather than the linear displacements, have been minimized. The calculated radii of the best fit slope circles for the 22X unit are 67.109 meters and 62.025 meters for the ellipsoid and hyperboloid, respectively. Minor rotations of the box beam structure with respect to the air bearings as the beam moves in the required arc are permitted by means of the flex pivots, as shown. By making the box beam relatively long and spacing the linear air bearings far apart, the system was made insensative to the irregularities and variations in clearance in the ways of the air bearings, because, with the air bearings widely spaced, such irregularities would produce only very small angular tilts of the optical surface. The box beam and rotary air bearing are supported in the vertical direction (normal to the diagram) by a set of air bearing cushions, which are not shown.

The box beam structure was driven along the slope circle by a lead screw, which was flexibly coupled to the box beam. The position of the box beam, and thus of the optical surface, was detected by a linear variable transformer, the signal from which was used to drive the abscissa coordinate of the chart recorder on which the scans were plotted.

Small angular motions of the reflected beam in the plane of Figure 4.1 were detected by pairs of discrete silicon detectors in the detector plane. Later in this program, the discrete detectors were replaced with a silicon quadrant detector, with the outputs of the quadrants tied together in pairs. In either case, the output signals, after passing through preamplifiers, were differenced and also summed in analog circuits. The difference was then normalized by dividing by the sum. The resulting signal as a function of time was a measure of the changes in slope of the optical surface as it was moved past the laser beam focus. This signal was integrated in an analog circuit to give the surface profile, which was then plotted on a chart recorder. Typical plots produced with the Scanner are shown in Section 5. The magnification was on the order of 300,000X, so that 0.3 inches on a Scanner trace in the ordinate direction represents an optical surface feature about 1 microinch high.

The calibration window shown in Figure 4.1 was used to measure the magnification of the Scanner. This glass window, which was .022 inches thick, could be tilted through an angle of 10°, resulting in a lateral translation of the reflected laser beam of .0013 in. in the detector plane. Over the 10.25 in. optical lever arm from the optical surface to the detector plane, a .0013 in. displacement corresponds to an angular shift in the laser beam of 26.2 arc sec, or to an angular change on the optical surface of 13.1 arc sec. Thus, by tilting this window, the angular sensativity of the Scanner was measured, and, by integration, the scale sizes or magnifications of the profile scans were determined from the calibration ramps which accompany the various sets of scans.

Another thin plate, the cam-driven window shown in Figure 4.1, could be inserted into the reflected beam to give a null measurement even if the desired profile of the optical surface could not be adequately approximated by the slope circle arc. The tilt of the plate was varied as the axial scan was made by means of a cam which was linked to the axial motion of the test piece, thereby laterally displacing the beam with time in a controlled way. By properly contouring the cam, deviations of the ideal surface from the best fit slope circle could be compensated for, giving a null measurement (that is, a straight line plot) when that ideal surface profile was achieved. For this program, the ellipsoid and hyperboloid profiles were adequately approximated by their respective slope circles, and this window was not required.

In addition to axial scans, the Scanner could also make scans in the azimuthal direction in order to measure the roundness profile. This was done by rotating the detector assembly 90° in order to detect reflected beam motions normal to the plane of Figure 4.1. Then, with the box beam fixed, the rotary air bearing was driven in rotation, while the chart recorder pen moved at constant speed in the abscissa direction. The rotary position of the test piece was recorded on these scans by a set of tic marks which were added to the scans using an optical rotation sensor which detected the passage of a set of reference marks located on the periphery of the air bearing. Typical azimuthal scans are also reproduced in Section 5. The magnification of these scans is about 20,000X.

In the course of this program, many modifications and improvements were made to the Scanner. In any future program, the following modifications would be desirable:

1. Replacement of the present laser with one having a stable output beam, or, alternatively, provision for an effective system to stabilize a time-varying beam.

2. Replacement of the present electronics with a stable set of output electronics, preferably based on digital logic, with some capability for real time data reduction.

3. Provision for an optical reference surface of known profile which could conveniently be moved into position and scanned whenever calibration of the overall curvature (sagittal depth) of the Scanner traces was desired.

4.2 Figuring and Polishing

The figuring and polishing process was laborious, with many setbacks and unexpected problems. Progress was irregular, with periods of weeks when there was no measurable progress or when the surface figure or polish actually seemed to deteriorate. Much ingenuity and patience was necessary at Random Devices, Inc., to overcome these difficulties and eventually produce a successful unit.

In order to figure and polish the diamond turned unit supplied by LLL, a special lap-mounting mechanism was devised and built. The purpose of this mechanism was to position the polishing lap properly on optical surface and oscillate it in a controlled way in the axial direction as the x-ray microscope rotated on the rotary air bearing of the Scanner. The oscillations were adjustable in length, speed, and axial position. The lap pressure was also adjustable. The mechanism was designed so that the lap could rotate with the optical surface about the optical axis (that is, in the azimuthal direction) for a small distance at the ends of the strokes. However, the mechanism was very stiff with respect to azimuthal rotations of the lap relative to the arm to which it was attached, so that very narrow laps could be used without the lap tipping sideways. Finally, a controlled moment could be applied to the lap to concentrate the polishing action at the fore or aft end of the lap, in order to correct the slope symmetry errors of the surface. This moment could be automatically varied with azimuthal position by means of an adjustable cam mechanism.

After receipt from LLL, the diamond turned 22X unit was mounted on the air bearing of the Scanner, where it remained until finished. (An advantage of the Scanner design is that the work piece does not have to be removed when changing from the polishing mode to the measurement mode). Initial scans showed that the local surface was relatively rough, with .05 to .07 micron local irregularities.

The ellipsoid was figured and polished first. In the course of this operation, all of the numerous degrees of freedom available to the optical fabricator were called into play. The hardness and composition of the lap were varied frequently to achieve various effects on the surface. The shape and width of the lap was changed often. The lap pressure and lap moment were varied. Various polishing compounds pressed into the lap in various ways were used, although for the ellipsoid a standard .06 micron polishing compound was used most frequently. Occasionally, the Scanner would give unrepeatable or suspect results, and re-alignment or modification was required. Figuring was finally completed when the Scanner traces indicated that the ΔS deviations had been reduced to .0035 microns (or .0070 microns, peak-to-peak), and the surface was smooth to at least 20Å, as averaged over the Scanner spot size.

Although experience with the ellipsoid no doubt aided in figuring the hyperboloid, the hyperboloid presented some new problems of its own. Some of these problems were probably related to the fact that, because of the much steeper average cone half-angle for the hyperboloid compared to the ellipsoid (2.8° vs 0.8°), the rate of change of the azimuthal curvature encountered by the polishing lap is much greater as it is translated axially within the hyperboloid. At one point in the process, further improvement in the local surface finish ceased entirely. The problem was believed to be caused by excessive acidity of the .06 micron polishing solution, promoting uncontrollable chemical removal of material faster than the more controllable mechanical removal. The pH of the solution was varied, and other polishing compounds (Tizox 1300 and two grades of Ludox) were tried at various pH levels before progress resumed.

Polishing was terminated on the hyperboloid when the Scanner traces indicated that the surface profile was within .010 microns, peak-to-peak. At this point, the ellipsoid was again polished briefly to bring its surface smoothness up to the level of the hyperboloid.

The results of the final surface measurements on this unit are reported in Section 5.

5.0 METROLOGY REPORT

After completion of figuring and polishing, a series of axial and azimuthal scans were made on the ellipsoid and hyperboloid. These are reproduced in Figures 5.2 through 5.20. For reference pruposes, two scans were also made on an LLL-Supplied cylindrical mirror from a Kirkpatrick-Baez x-ray microscope, as reproduced in Figure 5.1. The apparent sagittal depth of this K-B mirror over an 0.5 inch baseline is .32 ± .08 microinches, as measured from one of these traces. (The error brackets come from an estimate of the uncertainty in the sagitta due to the apparent noise in the trace). This trace was made while the Scanner was set to the ellipsoid slope circle, whose radius is 67.109 meters. Over the same 0.5 inch baseline, the calculated sagitta of this slope circle is 11.83 microinches. Then, assuming that the Scanner was in fact set perfectly to the nominal slope circle radius, the measured sagitta of the K-B mirror is 11.83 + .32 = 12.15 ± 08 microinches, which corresponds to a radius of curvature of 65.3 ± 0.4 meters. This value should be compared to the radius of curvature of this mirror measured by other means.

Figures 5.2 through 5.5 are the axial scans of the ellipsoid at the 0°, 90°. 180°, and 270° azimuthal positions, respectively. Figure 5.6 is a repeat of the 0° position to check reproducibility. Figures 5.7 through 5.9 are the azimuthal scans of the ellipsoid at the small end, mid-plane, and large end, respectively. Figures 5.10 through 5.13 are the axial scans of the hyperboloid at 0°, 90°, 180°, and 270°, respectively. In Figure 5.14, these scans are repeated in a different order. Figures 5.15 through 5.17 are the azimuthal scans of the hyperboloid at the small end, mid-plane, and large end, respectively. Finally, in Figures 5.18 through 5.20, these azimuthal scans are repeated at higher vertical and horizontal magnifications.

In this report, Figures 5.1 through 5.20 have been reduced somewhat from their original sizes. The original scale can be reconstructed from the reference lengths found in the margins of Figure 5.1. All subsequent scan dimensions found in this report apply to the scans in their original, unreduced size.

A total of 91 of these scans were selected to be used in further analysis. These are the ones marked with an arrow and a rectangular box containing a scan identification number ranging from 0100 to 8302. These selected scans were digitized by Envirodata Corporatiton, Chelmsford, Mass., and the coordinates of the digitized data points were recorded on a 9 track magnetic tape in

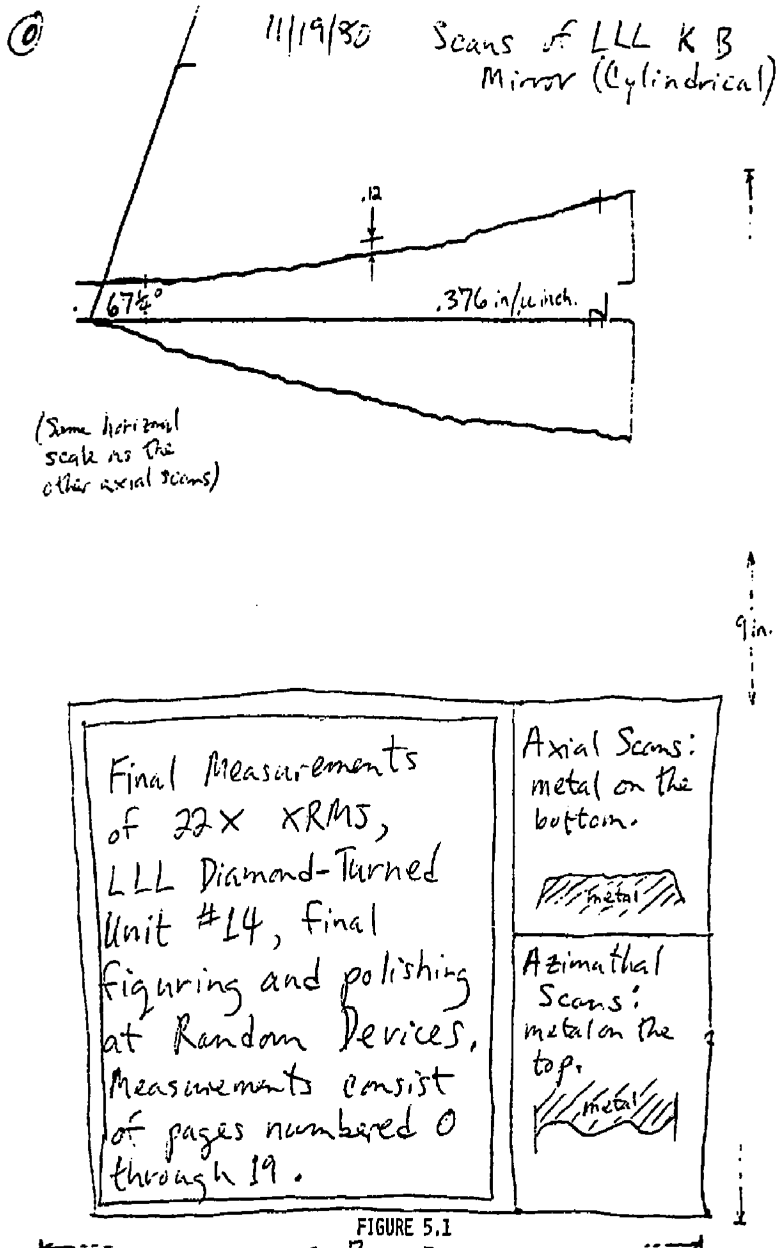

0
11/19/80 Scans of LLL K B Mirror (Cylindrical)
.12
67¼°
.376 in/μ inch.
(Same horizontal scale as the other axial scans)
9 in.
Final Measurements of 22X XRMS, LLL Diamond-Turned Unit #14, final figuring and polishing at Random Devices. Measurements consist of pages numbered 0 through 19.
Axial Scans: metal on the bottom.
metal
Azimuthal Scans: metal on the top.
metal
7 in.

FIGURE 5.1

① (Scanner was not re-centered during ① thru ④) 11/19/80

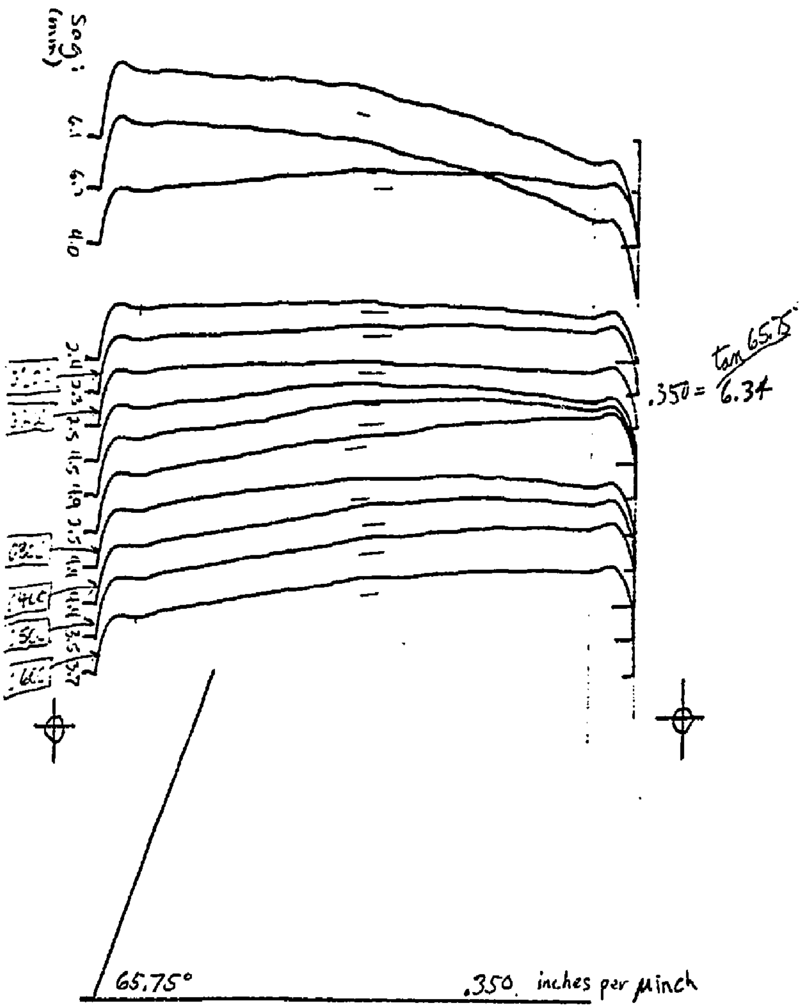


FIGURE 5.2

Scans 4-13:
Mean Sag. = 3.5 mm. = .39 μin.
RMS Dev. = .96 mm. = .11 μin.

Azimuth = 0°
Ellipsoid

② 11/19/80

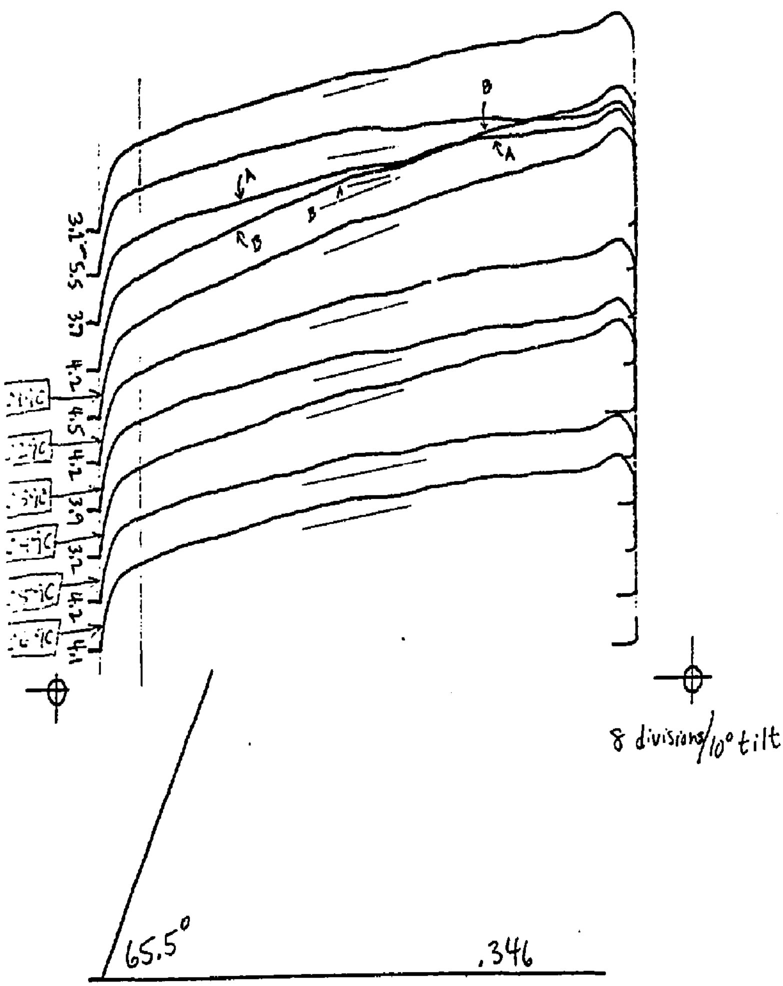
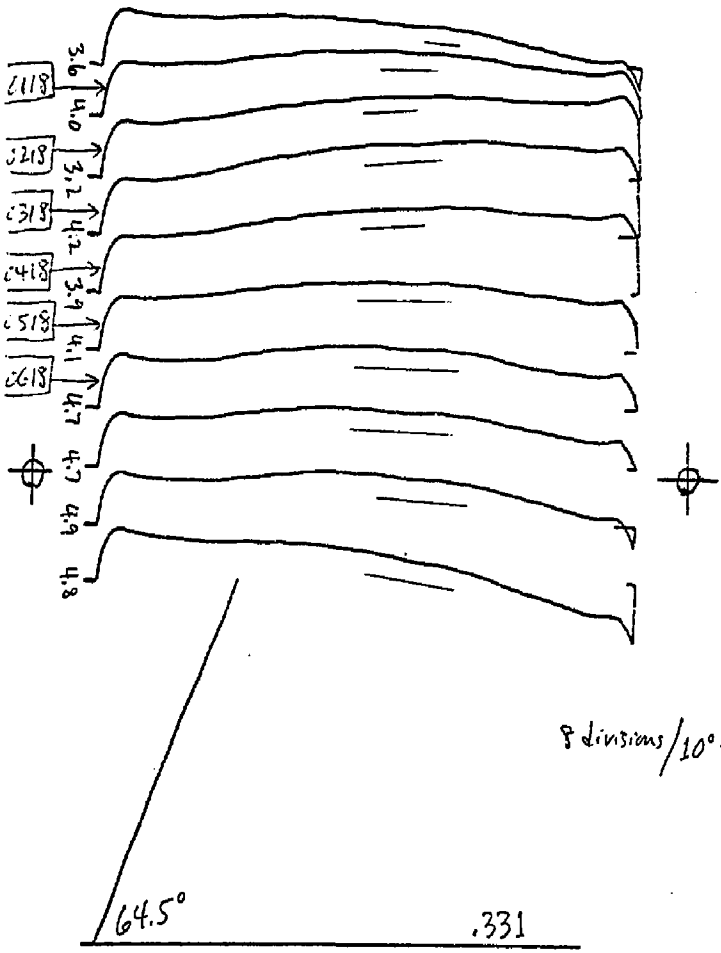


FIGURE 5.3

Scans 1-10:
Mean Sag. = 4.1 mm = .46 μin.
RMS Dev. = .65mm = .07 μin.

Azimuth = 90°
Ellipsoid

③ 11/19/80



Scans 1-10;
Mean Sag = 4.2 mm. = .50 μin.
RMS Dev. = .53 mm. = .06 μin.

FIGURE 5.4

Azimuth = 180°
Ellipsoid

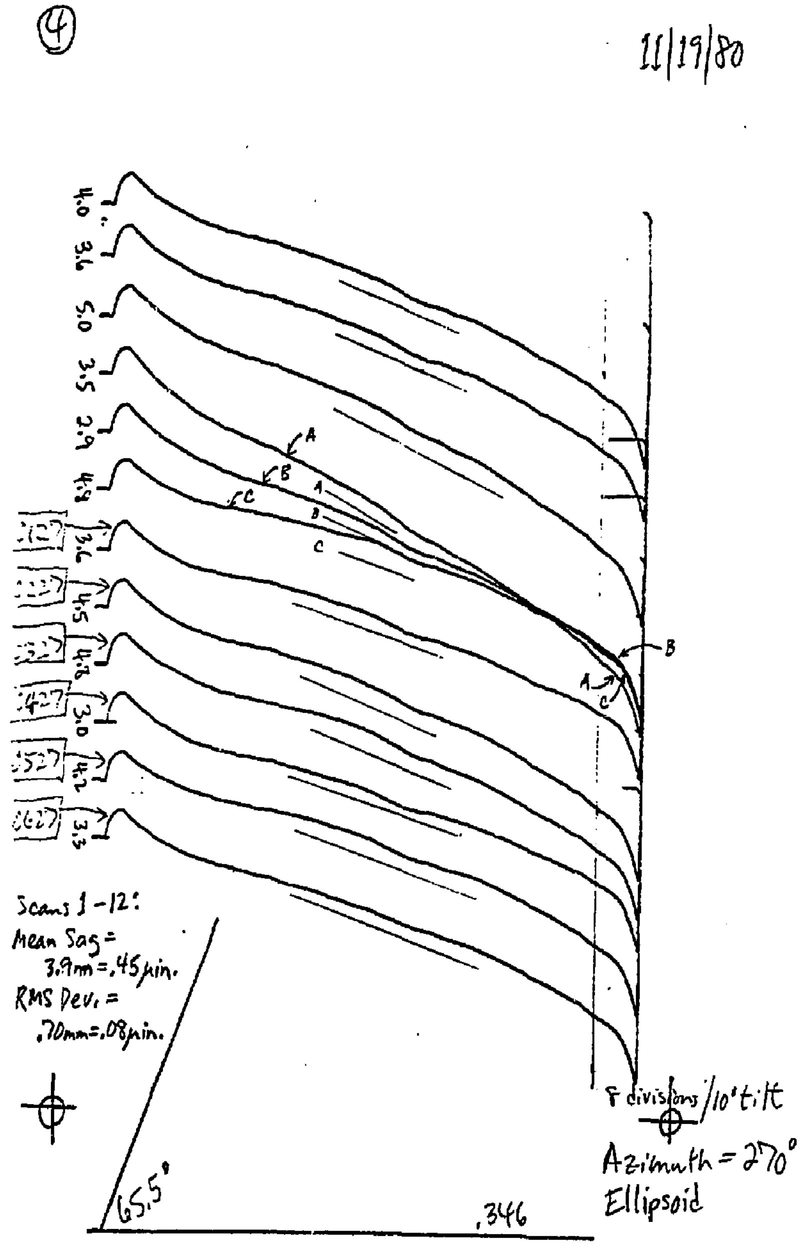

④
11/19/80
4.0
3.6
5.0
3.5
2.9
4.9
3.6
4.5
4.8
3.0
4.2
3.3
A
B
C
Scans 1-12:
Mean Sag =
3.9mm = .45 µin.
RMS Dev. =
.70mm = .08 µin.
65.5°
.346
8 divisions / 10" tilt
Azimuth = 270°
Ellipsoid

FIGURE 5.5

(5) (Scanner re-centered here, less than 1 div. on slope meter). 11/19/80

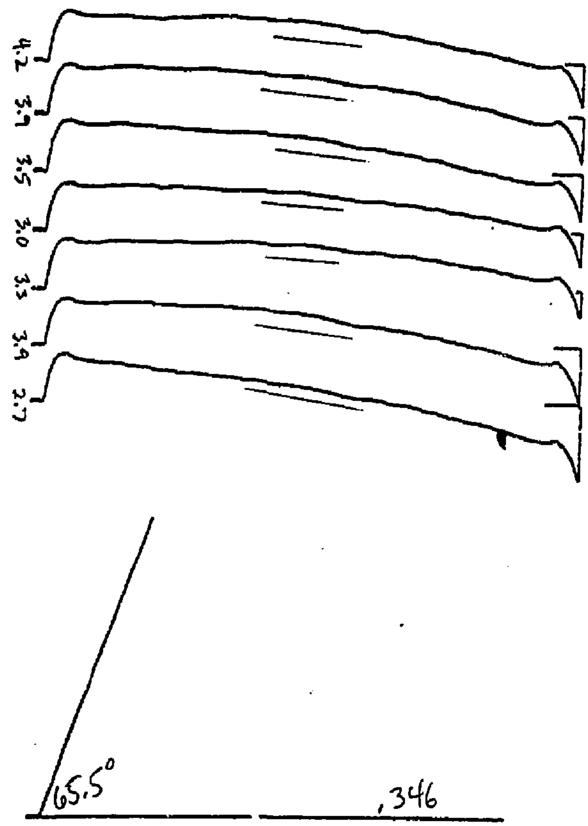


FIGURE 5.6

Repeat at 0° Azimuth Ellipsoid.

Scans 1-7:
Mean Sag = 3.5 mm = .40 μin.
RMS Dev. = .50 mm = .06 μin.

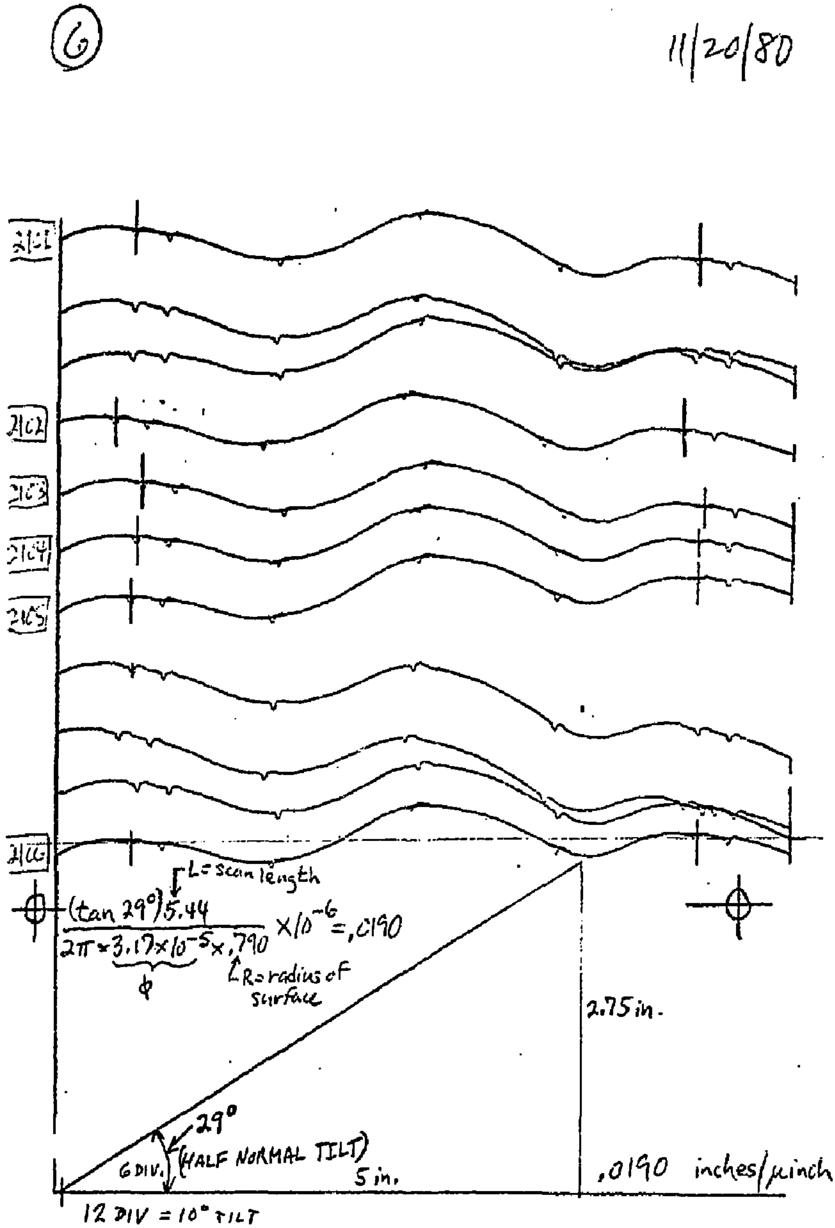


FIGURE 5.7

Ellipsoid, 0.10 inch in from Small End

⑦ 11/20/80

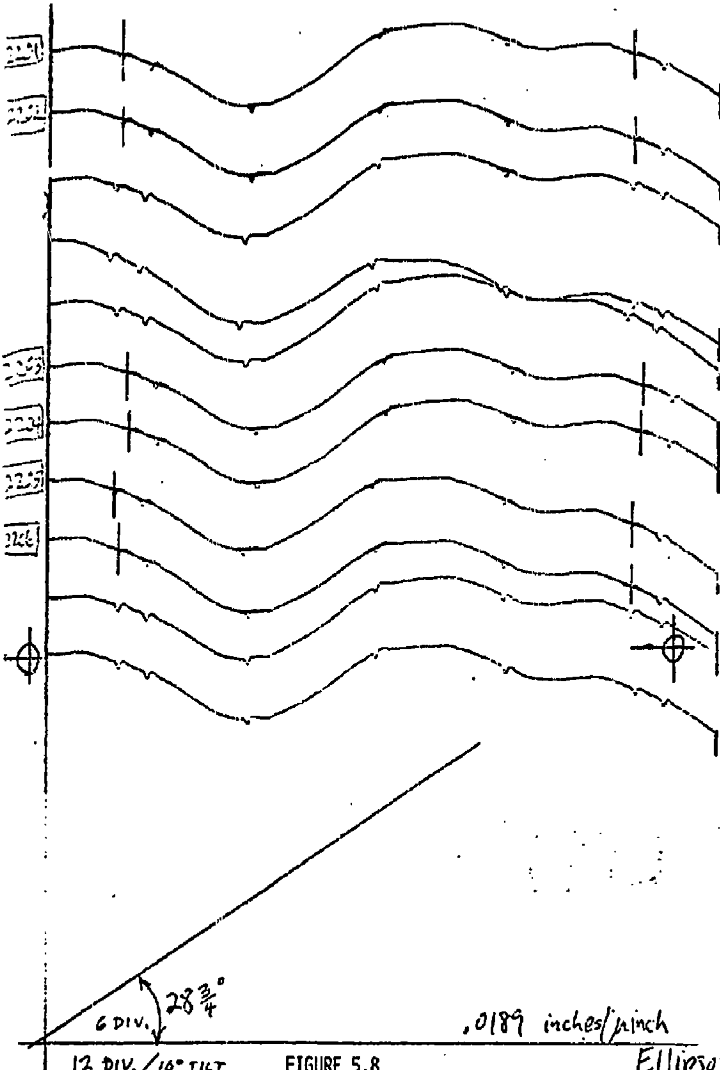


FIGURE 5.8

Ellipsoid Middle

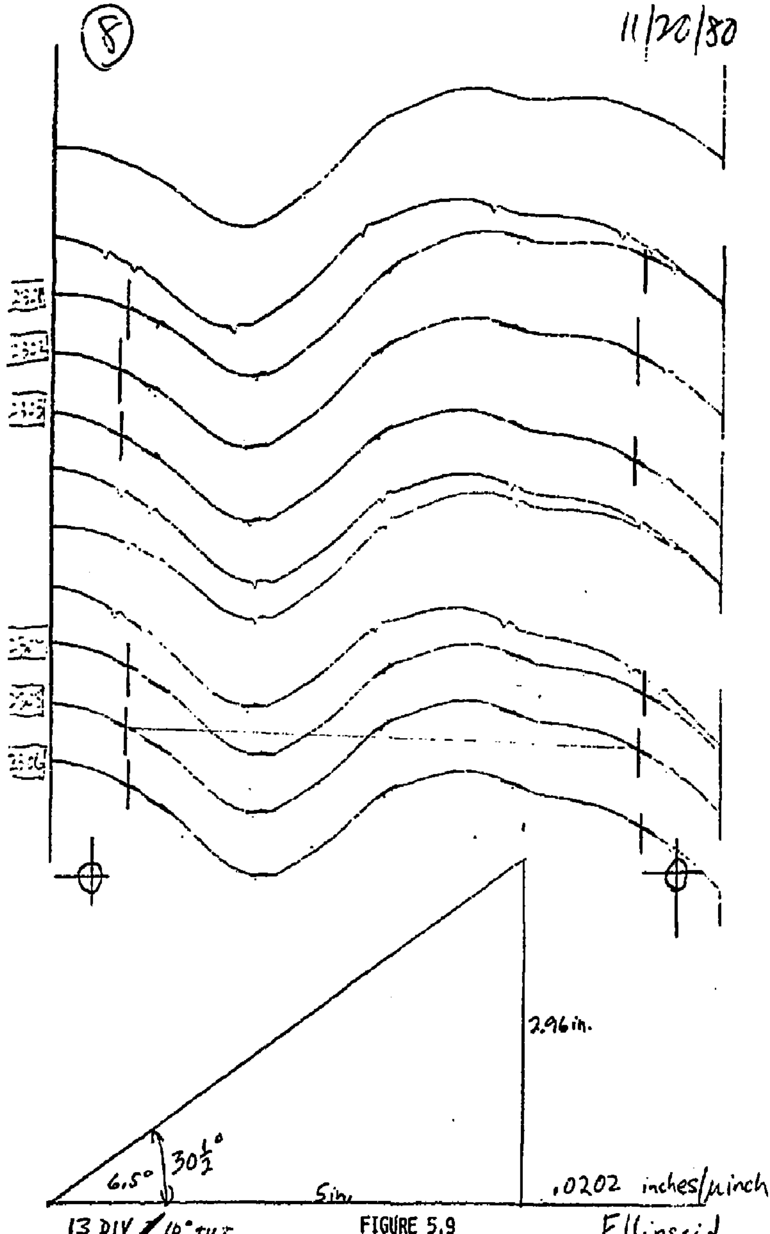


FIGURE 5.9 Ellipsoid 0.10 inch in from Large End

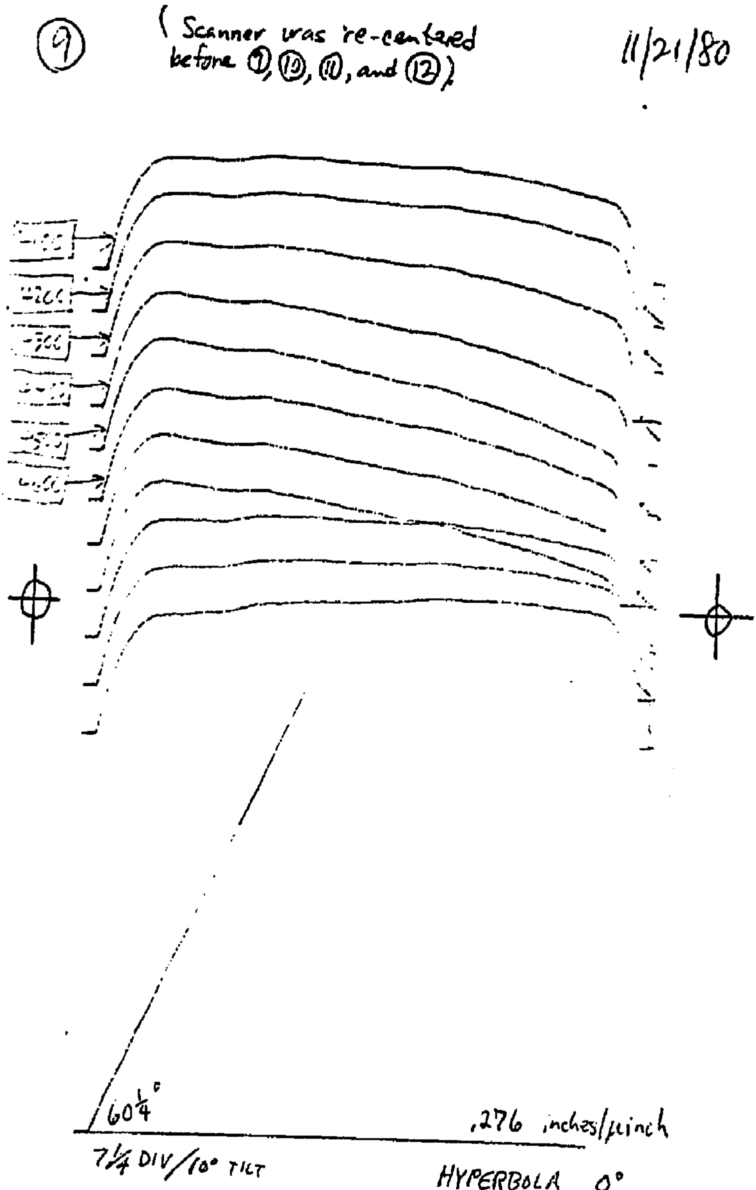

9
(Scanner was re-centered before 9, 10, 11, and 12)
11/21/80
60¼°
.276 inches/μinch
7¼ DIV/10° TILT
HYPERBOLA 0°

FIGURE 5.10

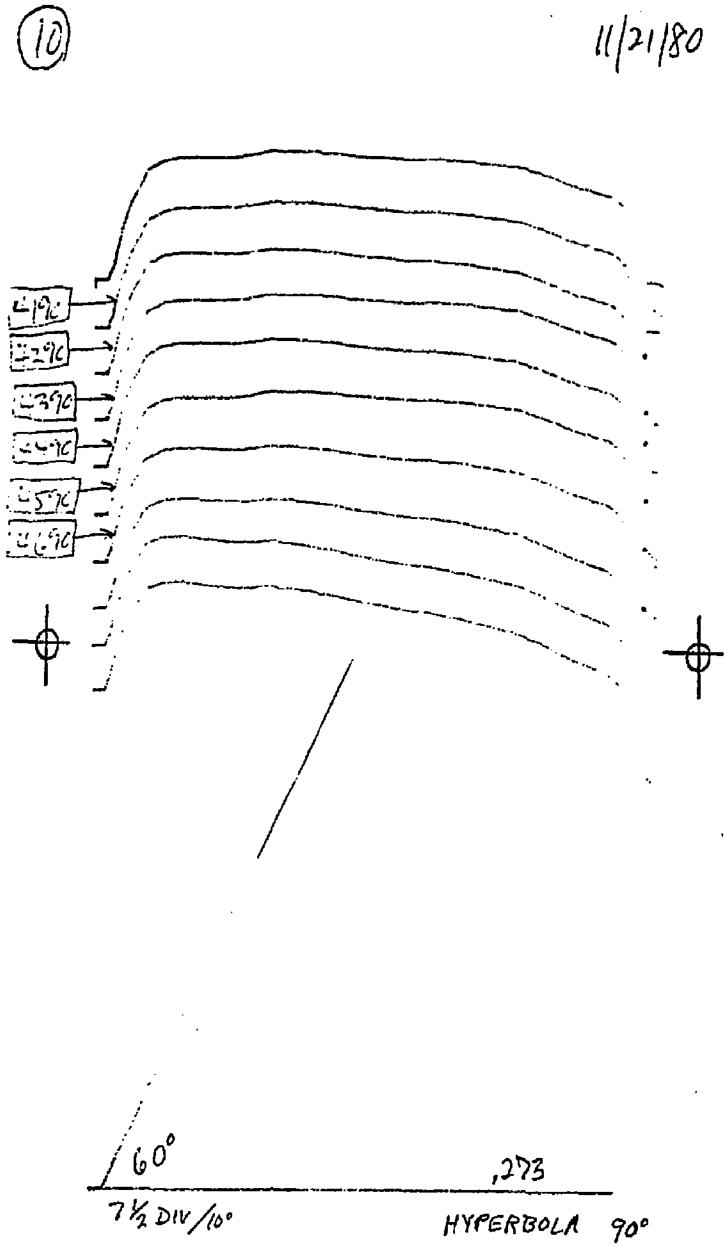
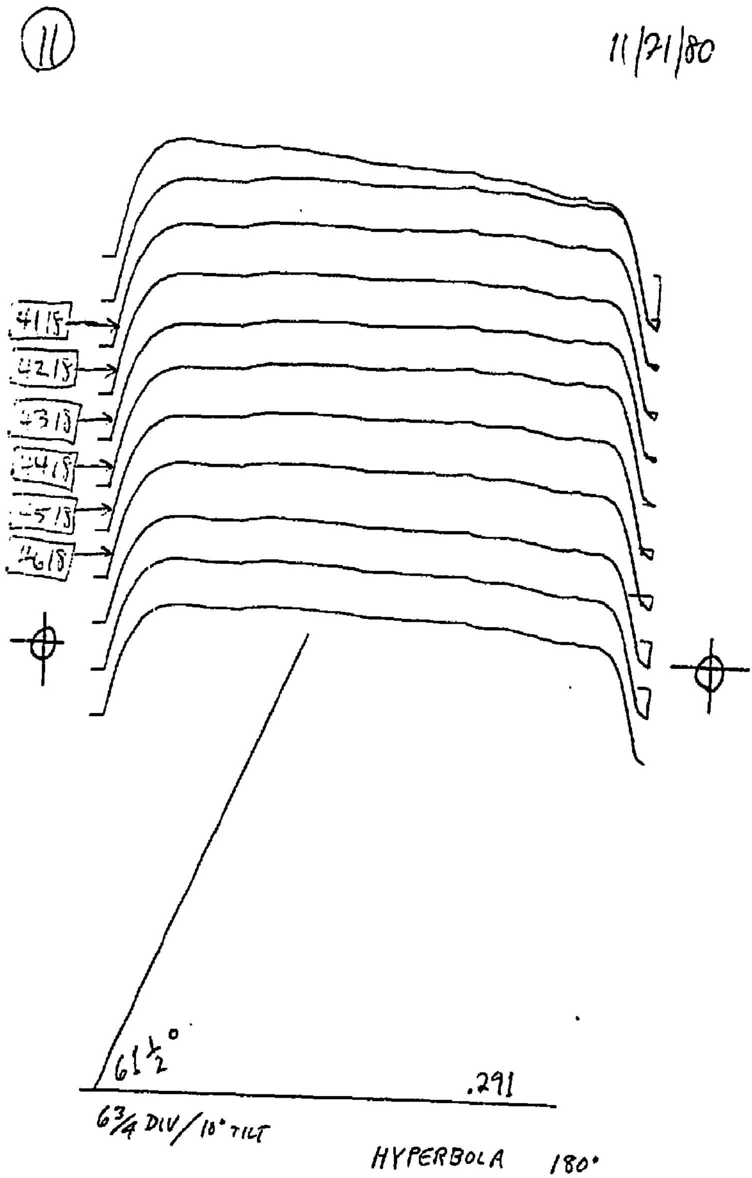


FIGURE 5.11



(11)
11/21/80
4118
4218
4318
4418
4518
4618
61½°
.291
6¾ DIV/10° TILT
HYPERBOLA
180°

FIGURE 5.12

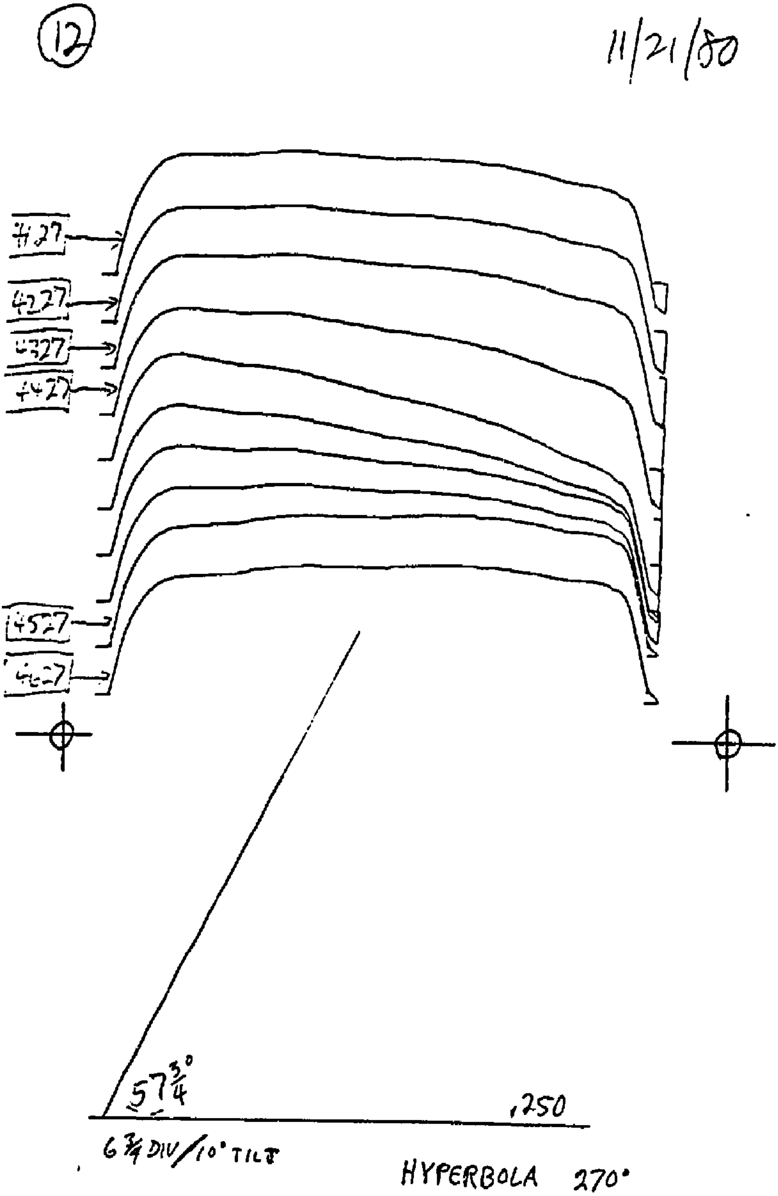
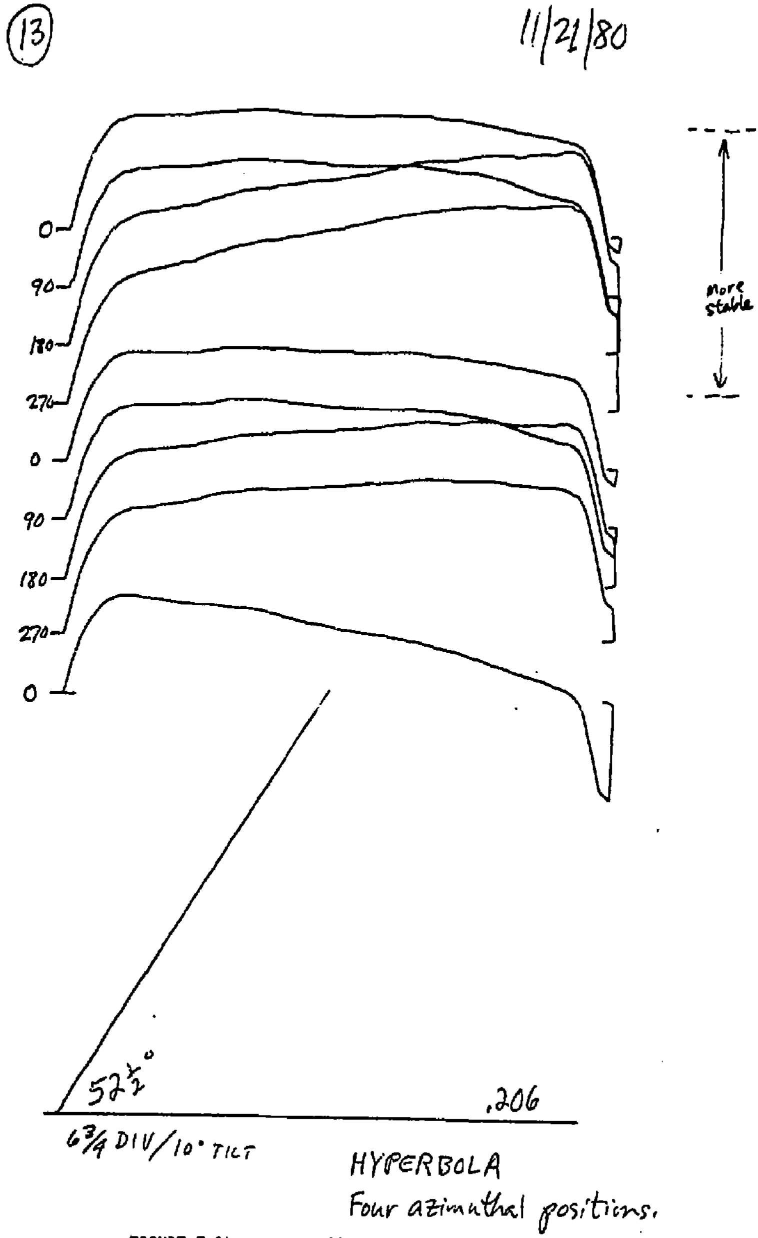

12
11/21/80
4127
4227
4327
4427
4527
4627
57 3/4°
.250
6 3/4 DIV/10° TILT
HYPERBOLA 270°

FIGURE 5.13



13
11/21/80
0
90
180
270
0
90
180
270
0
more stable
52½°
.206
6¾ DIV/10° TILT
HYPERBOLA
Four azimuthal positions.

FIGURE 5.14

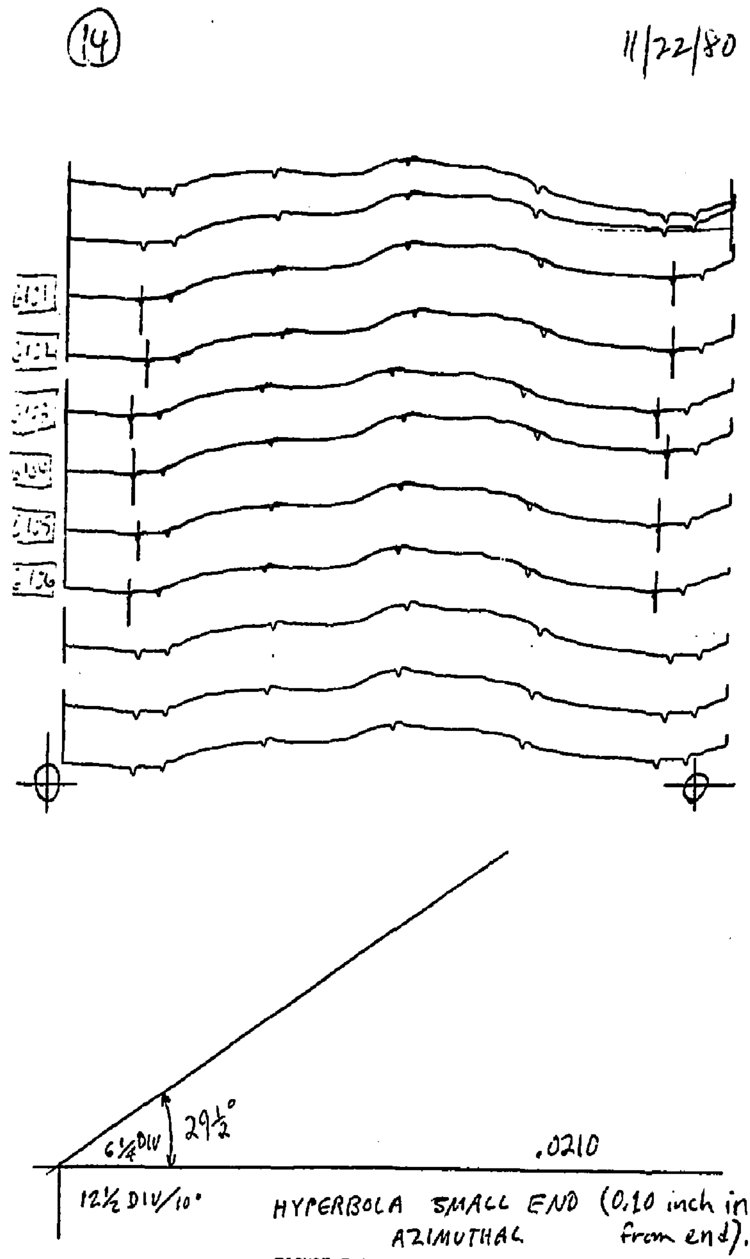

14
11/22/80
6¼ DIV
29½°
.0210
12½ DIV/10°
HYPERBOLA SMALL END (0.10 inch in
AZIMUTHAL from end).

FIGURE 5.15

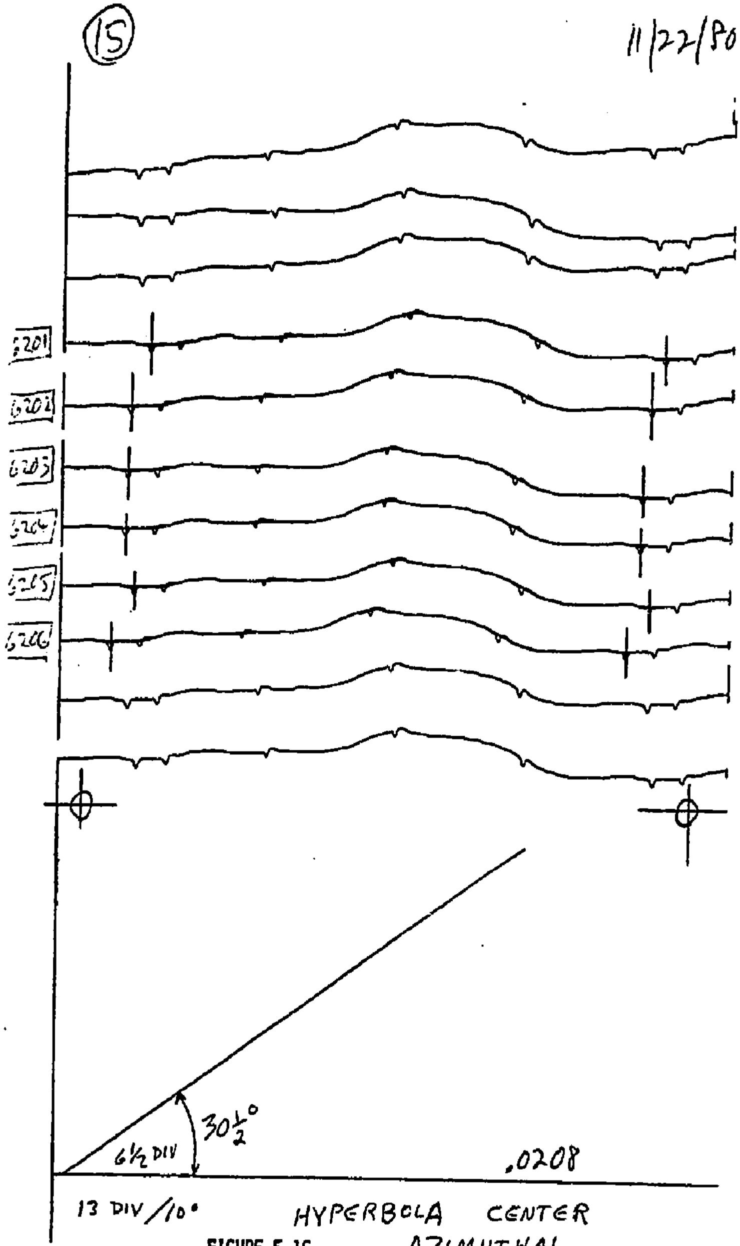
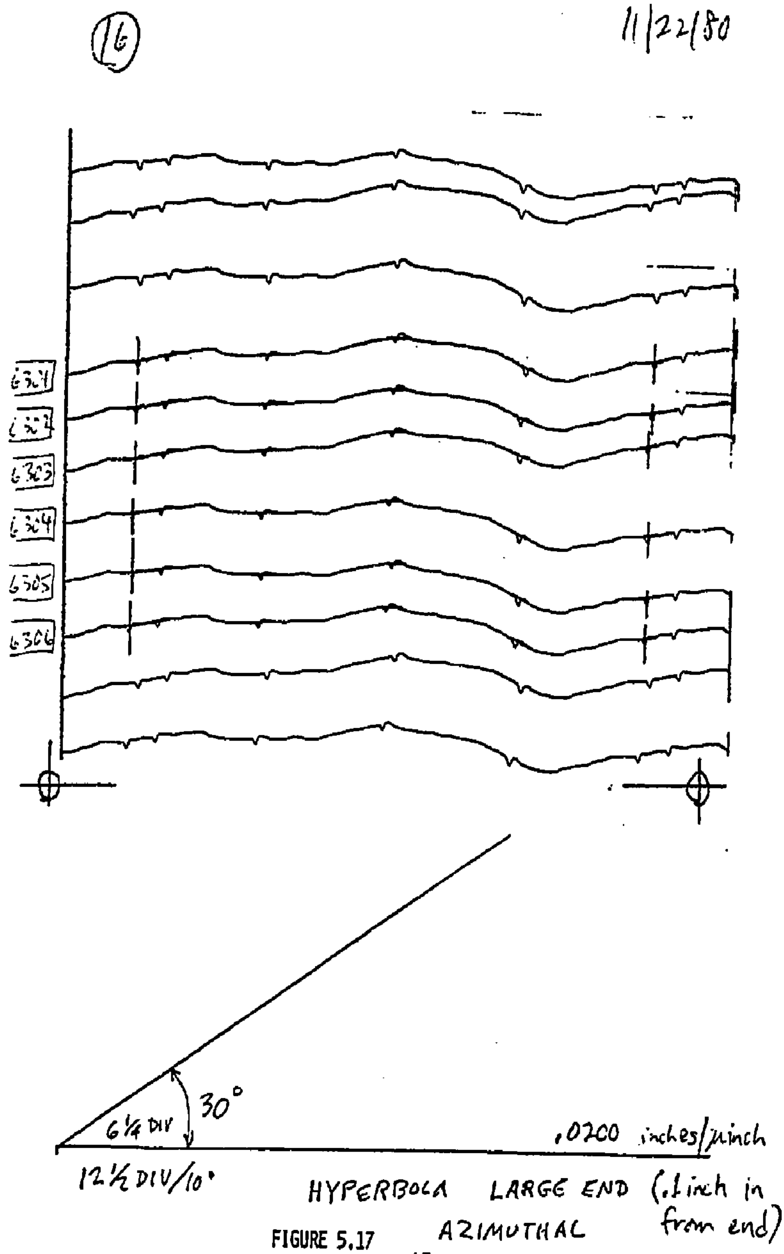

15
11/22/80
6201
6202
6203
6204
6205
6206
30½°
6½ DIV
.0208
13 DIV/10°
HYPERBOLA CENTER
AZIMUTHAL

FIGURE 5.16



16
11/22/80
6301
6302
6303
6304
6305
6306
30°
6¼ DIV
12½ DIV/10°
.0200 inches/μinch
HYPERBOLA LARGE END (.1 inch in from end)
AZIMUTHAL

FIGURE 5.17

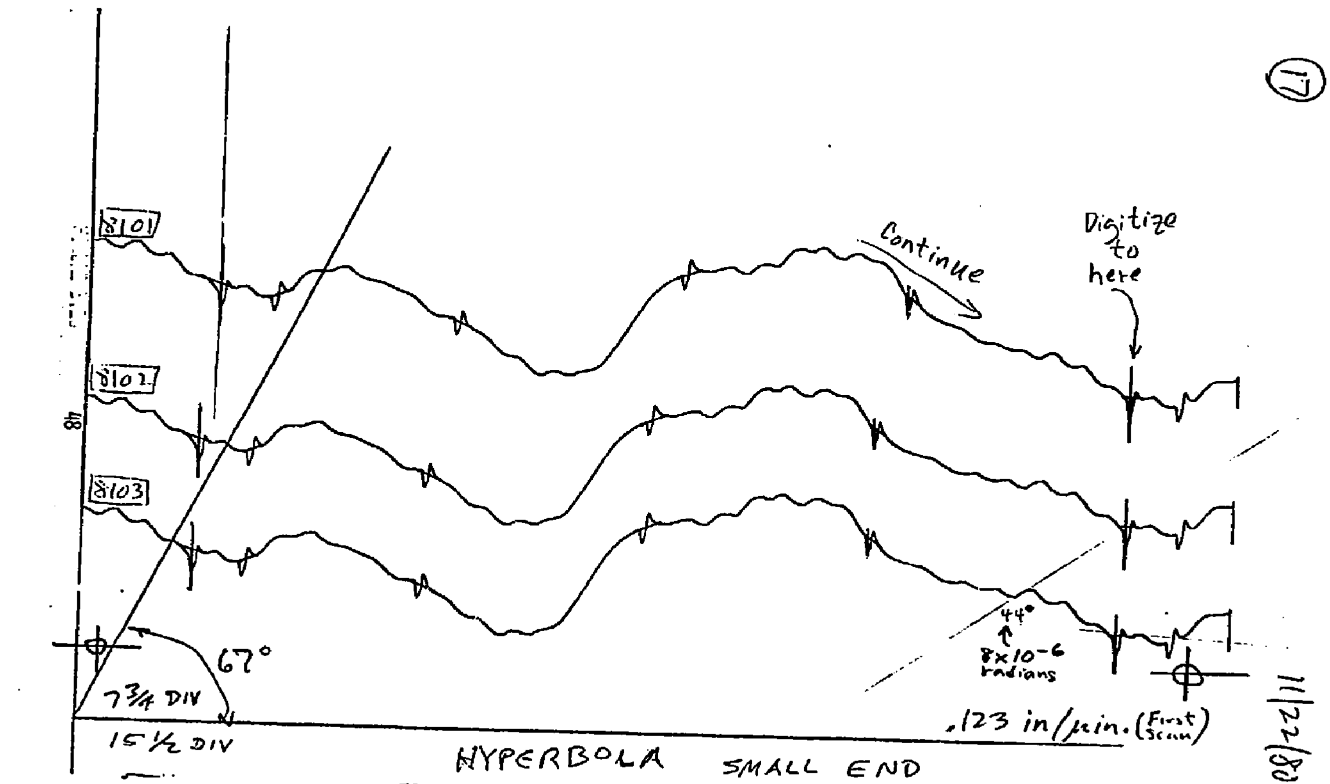

17
δ101
δ102
δ103
Continue
Digitize to here
67°
7 3/4 DIV
15 1/2 DIV
44°
8x10-6 radians
.123 in/μin. (First Scan)
11/22/80
HYPERBOLA SMALL END
Higher gain

FIGURE 5.18

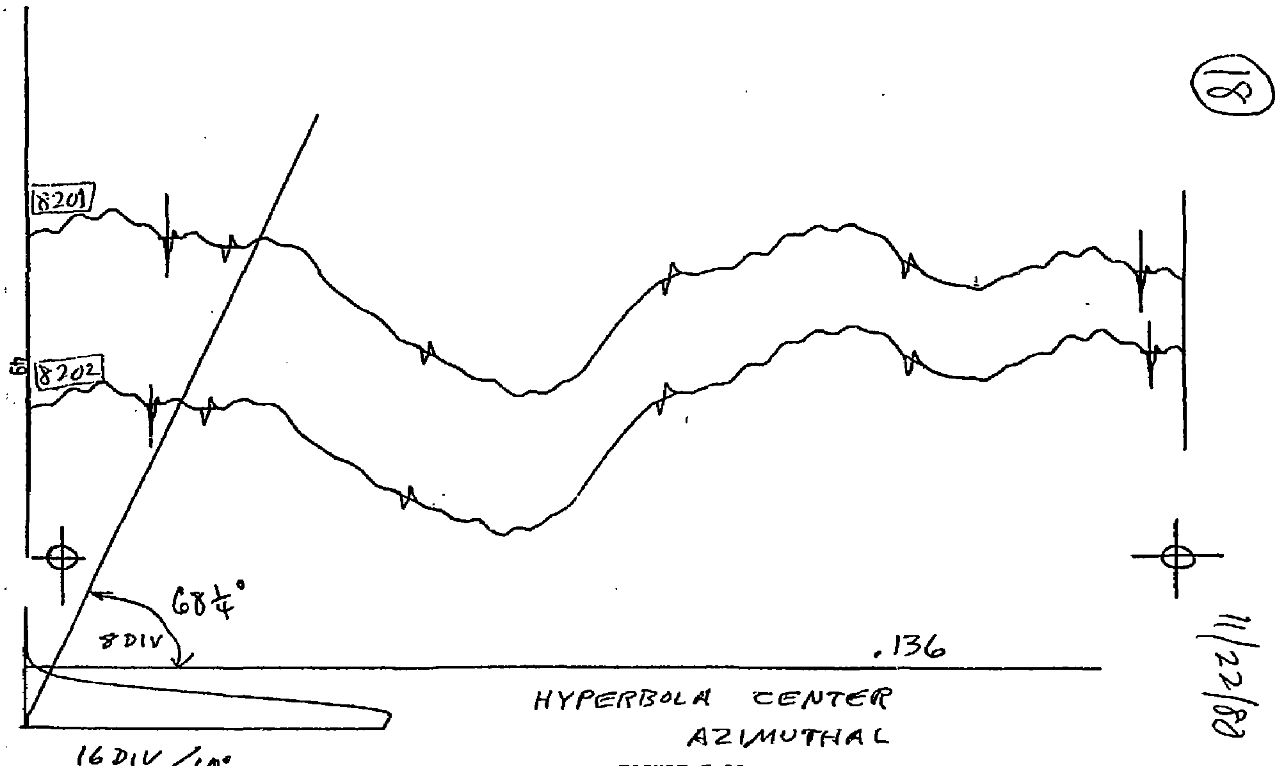

18
8201
8202
68¼°
8 DIV
16 DIV/10°
.136
HYPERBOLA CENTER
AZIMUTHAL
11/22/80

FIGURE 5.19

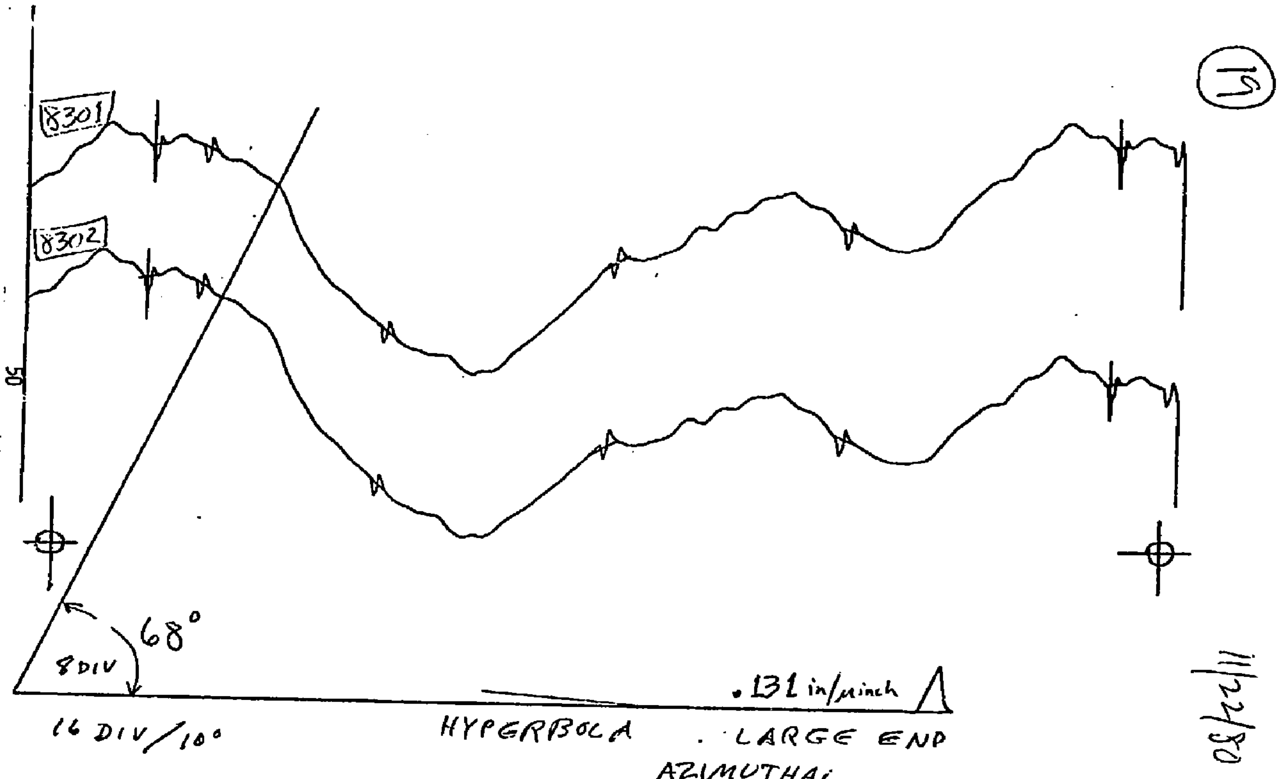

19
11/22/80
8301
8302
50
68°
8 DIV
16 DIV/10°
.131 in/μinch
HYPERBOLA
. LARGE END
AZIMUTHAL

FIGURE 5.20

the EBCDIC Code at 800 BPI. This tape was then used as the data file which was read by the programs and subroutines described below in course of replotting and extracting statistical data from the metrology scans.

Digitizing began and ended at the dot marks for the axial scans, and at the crosses for the azimuthal scans.

5.1 The Metrology Computer Programs

Initial reduction and replotting of the metrology data was performed using two computer programs: SCANNAX, for the axial scans; and SCANNAZ for the azimuthal scans. Both programs incorporate three subroutines, ENVIRDT, FSTSCN, and SCANRD, which are used to read, unpack, scale, and store in the central memory data from selected regions of the data tape. The subroutines, as used with both SCANNAX and SCANNAZ, are identical except for their dimension statements.

Program listings for SCANNAX, SCANNAZ, and the three subroutines are contained in Appendices A and B of this report. The operation of the subroutines is explained within their respective listings. The general operation of SCANNAX and SCANNAZ is described below.

5.2 Description of Program SCANNAX

Referring to the program listing for SCANNAX in Appendix A, the input quantities from the data deck are read in the section between program lines 5 and 30. These quantities are described in the program between lines 35 and 85. On line 32 a three digit number, equal to 111, and called IND for Indicator, is printed out. Similar numbers are printed throughout the program, and are used to indicate where the program stopped if the calculation was terminated because of an error. The selected region of the data tape is then read at line 89, using the three subroutines, and the X (abscissa) and Y (ordinate) coordinates of the data points on the selected scans are stored in arrays XA and YA. The region of the tape to be read is specified by the input quantities LMIN and LMAX, which are four digit scan identification numbers found in the rectangular boxes next to the original SCANNER traces. The Reorder Routine beginning on line 110 is used to rearrange the order of the scans in the XA and YA register if the all the axial scans at a given azimuthal angle were made and digitized as a group. If, on the other hand, the azimuthal angles were alternated (that is, 0°, 90°, 180°, 270°, 0°, 90°, 180°, etc.), the Reorder Routine is bypassed by means of the input quantity REODR. Beginning on line 165, the empty regions of arrays XA and YA are filled by repeating the data a second time if only half of a data set (24 axial scans instead of 48) is available. Beginning at line 180, the scans are zeroed in the X (abscissa) direction by subtracing the X coordinate XMIN of the first digitized data point on a scan from the X coordinates of all the other points along that scan.

Lines 200 to 390 of SCANNAX contain a series of routines which are used to shift corresponding scans into alignment in the X direction so that they may be co-added properly. In this section, the First Interpolation routine calculates an evenly-spaced set of points along each scan from the original unevenly-spaced set, and stores them in register YB. The interpolated scans are then leveled and filtered to remove the low spatial frequencies. Then, cross correlations are calculated for various pairs of corresponding scans as a function of relative X position as one curve of each pair is slid past the other. The X position corresponding to the maximum of each of these cross correlation functions is then found. It is then used to shift the corresponding scan, which is still stored in original form in arrays XA and YA, into proper register in the X direction. If the cross correlation routine does not work properly with a given data set (see Section 5.4) and/or if the Scanner traces are in proper alignment to begin with, the entire section from program lines 204 through 397 can be bypassed using the input parameter CCOR. (See line 203).

The Second Interpolation routine, beginning on line 395, computes a new set of evenly-spaced points from the original unevenly-spaced set for each of the now-aligned traces, and stores these sets in array YB. Beginning on line 425, the least squares best fit straight line for each trace is found. These best fit lines are then used to reduce all scans to zero average slope and zero average Y position between program lines 455 and 470. The scans at this point are finally ready to be averaged and inter-compared. Corresponding scans are averaged point-by-point between lines 480 and 495. Then, from lines 495 through 525, the RMS deviation of each scan from its corresponding average scan is computed, point by point, and also the six largest individual deviations, ERROR(IJ, NA, NB), of the given scan from the average scan are found and stored. In lines 530 through 555, similar quantities are computed with respect to the corresponding average scans from the first half of the data set (first day) and from the second half (second day).

In SCANNAX lines 560 through 620, local slope distribution histograms are computed and printed out from the leveled, interpolated, averaged scans. The local slopes are computed in arc seconds over baselines of 1, 2, and 4 of the interpolation intervals DELTA. For all runs, DELTA was set equal to .020 inches on the Scanner trace, which is approximately .002 inches measured along the surface. These calculated local slope values are then distributed among the bins in the slope distribution histogram, depending on their absolute magnitudes. The number in each bin is counted and printed out in the Slope Distribution Tables, along with a running total of the number in all previous bins. To increase the angular range of the Slope Distribution Tables, the bin widths are increased in a regular manner from a minimum of 0.15 arc seconds to a maximum of 8.3 arc sec as the maximum of the slope goes from 0.0 to 79.6 arc seconds.

In lines 620 through 640, the average scans are prepared for plotting by scaling them to the nominal magnification of the LLL Cleavite Surface Analyzer and by adding in the best fit slope circle curvature which had been mechanically subtracted out of the original traces by the Scanner mechanism. In lines 650 through 730, the computed scan statistics (RMS deviations and largest individual deviations) and various other computed quantities and input parameters are printed out. Finally, in lines 730 through 785, the six averaged scans are plotted using the Control Data Corporation UNIPLOT routine.

5.3 Description of Program SCANNAZ

SCANNAZ performs processing and plotting of the azimuthal scans which is quite similar to that performed on the axial scans by SCANNAX. For this reason, only the major ways in which SCANNAZ differs from SCANNAX will be described here. The program listing for SCANNAZ is found in Appendix B.

The first major difference is found in lines 75 through 95 of SCANNAZ. Here, the azimuthal scans are re-arranged within arrays XA and YA in order to group them correctly for further processing. This is necessary because the three subroutines which read the data tape were designed for use with SCANNAX, and therefore arrange the scans in 12 groups (NB=1 through 12) of 4 scans each (NA=1 through 4). However, the azimuthal scans consist of 6 groups (NB=1 through 6) of 6 scans each (NA=1 through 6).

At lines 120 through 135, the azimuthal scans are stretched or compressed in the X direction to match the length of the first scan, as well as being zeroed in the X direction. The amount of stretch is inversely proportional to the length of the original scan as measured between the first and last tic marks. This is necessary because the speed of the rotary air bearing was not well controlled, whereas the X translation of the chart recorder pen was a constant.

The next major difference is the absence of the Cross Correlation Routines and the associated First Interpolation, Leveling, and Shifting Routines. These are not needed because the digitizing of each azimuthal scan was begun at the first reference tic mark on each scan. Thus, once the X coordinate of this first digitized point in each scan is subtracted from the X coordinates of the other points in that scan, all scans are moved into proper alignment.

In lines 260 through 290, the amplitude AMP and phase angle PHSE of the best fit sinusoid to each of the average scans is found. The best fit sinusoids are then subtracted away from the average scans before computing the scan statistics which compare the first half of the data (first day) to the second half (second day). They are also subtracted in preparing the scans for final plotting. This is necessary because the true azimuthal surface shape would otherwise be masked by the sinusoid resulting from imperfect centering of the piece on the air bearing. It is justifiable because it is, in fact, equivalent to properly centering the piece.

In lines 335 through 360, the final averaged scans are re-scaled and transformed to polar form in order to match them to the format of the LLL Indiround Traces.

5.4 Results of the SCANNAX and SCANNAZ Computer Runs

The results of the metrology data computer runs are shown in Tables B through L and in Figures 5.21a through 5.27c.

During the initial runs of Program SCANNAX on the Scanner traces for this unit, it was found that the cross correlation routine was not working properly. The routine did find reasonable shifts in the X direction for a few of the traces. Generally, however, the cross correlation functions increased or decreased very slowly and monotonically across the entire cross correlation interval, and therefore the routine selected the largest possible positive or negative shifts. Since the cross correlation routine had been tested and had worked properly in the past, the problem was believed originate in Scanner

PROGRAM SUMMARY [illegible] K1= 274 K2= 20 K3= 152 (FACTOR 1)=1.0000 (FACTOR 2)=1.0000

X SCALE= [illegible] X OFFSET= [illegible] Y SCALE = [illegible] Q1= [illegible] Q2= -2.65[illegible] Y OFFSET= 1.5[illegible] SMAG=330600.C

INTERVALS [illegible] XMAG= [illegible]

SCAN GROUP	AZIMUTH (DEGREES)	XSTR	XBREAK (START)	XBREAK (END)	AVERAGE SLOPE	RMS DEV	SIX LARGEST DEVIATIONS
		(((INCHES ON SCANNER TRACES)))				((((((((((MICRONS ON THE OPTICAL SURFACE))))))	
1 A	[illegible]	.466[illegible]	[illegible]	[illegible]	-.03895	.00120	.0025 .0025 .0024 .0024 .0024 .0024
2 A	[illegible]	.4580	[illegible]	[illegible]	-.01406	.00120	.0046 .0046 .0045 .0043 .0041 .0039
3 A	[illegible]	.437[illegible]	[illegible]	[illegible]	.04161	.00116	-.0031-.0031-.0030-.0030-.0030-.0029
4 A	[illegible]	.4540	[illegible]	[illegible]	.08056	.00124	-.0033-.0032-.0031-.0029-.0028-.0028
5 A	[illegible]	.4736	[illegible]	[illegible]	.09057	.00037	.0013 .0012 .0012-.0010 .0009 .0009
6 A	[illegible]	.4247	[illegible]	[illegible]	.07806	.00037	-.0008 .0007-.0007-.0007 .0007-.0007
1 B	[illegible]	.4660	[illegible]	0.000	.06895	.00120	.0025 .0025 .0024 .0024 .0024 .0024
2 B	[illegible]	.4580	[illegible]	[illegible]	-.01406	.00120	.0046 .0046 .0045 .0043 .0041 .0039
3 B	[illegible]	.437[illegible]	[illegible]	[illegible]	.04161	.00116	-.0031-.0031-.0030-.0030-.0030-.0029
4 B	[illegible]	.4540	[illegible]	[illegible]	.08056	.00124	-.0033-.0032-.0031-.0029-.0028-.0028
5 B	[illegible]	.4236	[illegible]	[illegible]	.09057	.00037	.0013 .0012 .0012-.0010 .0009 .0009
6 B	[illegible]	.4247	[illegible]	[illegible]	.07806	.00037	-.0008 .0007-.0007-.0007 .0007-.0007
1 A	90.0	.4860	[illegible]	[illegible]	.28859	.00059	.0015 .0015 .0015 .0015 .0015 .0014
2 A	90.0	.4880	[illegible]	[illegible]	.19255	.00041	.0011 .0011 .0011 .0011 .0010 .0010
3 A	90.0	.4430	[illegible]	[illegible]	.16576	.00068	.0020 .0020 .0019-.0018 .0018-.0018
4 A	90.0	.4740	[illegible]	[illegible]	.21510	.00079	.0016 .0016 .0016 .0016 .0016 .0016
5 A	90.0	.4761	[illegible]	[illegible]	.14030	.00056	-.0015-.0015-.0015-.0015-.0014-.0014
6 A	90.0	.4640	[illegible]	[illegible]	.14932	.00064	-.0019-.0019-.0018-.0018-.0018-.0016
1 B	90.0	.4860	[illegible]	0.000	.28859	.00059	.0015 .0015 .0015 .0015 .0015 .0014
2 B	90.0	.4880	[illegible]	0.000	.19255	.00041	.0011 .0011 .0011 .0011 .0010 .0010
3 B	90.0	.4400	[illegible]	0.000	.16575	.00068	.0020 .0020 .0019-.0018 .0018-.0018
4 B	90.0	.4740	[illegible]	0.000	.21510	.00079	.0016 .0016 .0016 .0016 .0016 .0016
5 B	90.0	.4761	[illegible]	[illegible]	.14030	.00056	-.0015-.0015-.0015-.0015-.0014-.0014
6 B	90.0	.4660	[illegible]	0.000	.14932	.00064	-.0019-.0019-.0018-.0018-.0018-.0016
1 A	180.0	.6660	[illegible]	0.000	.00083	.00027	.0008 .0008 .0007 .0007 .0006 .0006
2 A	180.0	.6720	[illegible]	0.000	.05208	.00081	.0027 .0026 .0025 .0024 .0023 .0022
3 A	180.0	.6640	[illegible]	[illegible]	.07458	.00054	-.0015-.0015-.0014-.0013-.0013-.0012
4 A	180.0	.6640	[illegible]	0.000	.05657	.00035	-.0009-.0008-.0008 .0008 .0008 .0008
5 A	180.0	.6560	[illegible]	[illegible]	.01176	.00038	-.0010-.0010-.0010-.0009-.0009-.0009
6 A	180.0	.6660	[illegible]	0.000	-.00606	.00102	-.0020-.0020-.0020-.0020-.0019-.0019
1 B	180.0	.6660	[illegible]	[illegible]	.00083	.00027	.0008 .0008 .0007 .0007 .0006 .0006
2 B	180.0	.6720	[illegible]	[illegible]	.05208	.00081	.0027 .0026 .0025 .0024 .0023 .0022
3 B	180.0	.6640	[illegible]	0.000	.07458	.00054	-.0015-.0015-.0014-.0013-.0013-.0012
4 B	180.0	.6640	[illegible]	[illegible]	.05657	.00035	-.0008-.0008-.0008 .0008 .0008 .0008
5 B	180.0	.6560	[illegible]	[illegible]	.01176	.00038	-.0010-.0010-.0010-.0009-.0009-.0009
6 B	180.0	.6660	[illegible]	[illegible]	-.00606	.00102	-.0020-.0020-.0020-.0020-.0019-.0019
1 A	270.0	.4830	[illegible]	[illegible]	-.26508	.00102	.0031 .0030 .0030 .0028 .0027 .0025
2 A	270.0	.4960	[illegible]	[illegible]	-.31616	.00093	-.0021-.0021-.0021-.0020-.0020-.0019
3 A	270.0	.4960	[illegible]	[illegible]	-.29885	.00123	.0028 .0027 .0027 .0027 .0026 .0025
4 A	270.0	.4930	[illegible]	[illegible]	-.25231	.00142	.0036 .0036 .0035 .0035 .0035 .0034
5 A	270.0	.4960	[illegible]	[illegible]	-.26457	.00092	-.0028-.0028-.0027-.0026-.0025-.0023
6 A	270.0	.4960	0.000	0.000	-.27665	.00099	-.0023-.0023-.0023-.0022-.0022-.0022
1 B	270.0	.4830	[illegible]	0.000	-.26508	.00102	.0031 .0030 .0030 .0028 .0027 .0025
2 B	270.0	.4960	[illegible]	[illegible]	-.31616	.00093	-.0021-.0021-.0021-.0020-.0020-.0019
3 B	270.0	.4960	[illegible]	[illegible]	-.29880	.00123	.0028 .0027 .0027 .0027 .0026 .0025
4 B	270.0	.4930	[illegible]	0.000	-.25231	.00142	.0036 .0036 .0035 .0035 .0035 .0034
5 B	270.0	.4960	[illegible]	[illegible]	-.26457	.00092	-.0028-.0028-.0027-.0026-.0025-.0023
6 B	270.0	.4960	[illegible]	[illegible]	-.27656	.00099	-.0023-.0023-.0023-.0022-.0022-.0022

TABLE B

traces themselves. Specifically, the traces for this unit were believed to be too smooth and featureless for the routine to produce meaningful cross correlation maxima. At the time this problem arose, it was also noted that, because of the order in which the traces were made and digitized, they were already in good alignment in their original form. Therefore, it was decided to bypass the Cross Correlation Routine and its associated routines by setting the input parameter CCOR in SCANNAX to 0.0.

Table B lists various input parameters and results from the SCANNAX run on the axial scans of the ellipsoid. Most of the input parameters listed in the top three lines of this table are described in the program listing. FACTOR 1 and FACTOR 2 are both equal to unity because only one half of a nominal data set was taken, and consequently the data set for the "first day" was identically equal to that for the "second day". X SCALE and Y SCALE, which are used to scale the Scanner traces up to the size of the Cleavite Surface Analyzer traces, are calculated from the measured scales (XMAG and SMAG) of the Scanner and from the nominal scale factors of the Cleavite system which had been used during previous measurements of other x-ray microscopes. The values of C1 and C2, which are constants used in adding the slope circle curvature back into the final plots, were calculated from the known radius and position of the center of the slope circle and the nominal scale factors of the Cleavite system. SMAG, the Y magnification of the Scanner traces, was calculated from the expression:

$$SMAG = \frac{XMAG \tan \Omega}{\theta}$$

Here, XMAG is the X magnification of the Scanner (found by dividing the length of the trace by the length of the optical surface), Ω is the measured slope angle of the relevant calibration ramp, and θ is the angle on the optical surface which corresponds to Ω. That is, θ is the actual slope on the optical surface of a feature which would have the same slope on the Scanner trace that the calibration ramp has. The angle θ is equal to 6.34×10^{-5} radians, which is one half the angle subtended by the .0013 inch sideways displacement of the laser beam produced by tilting calibration window through 10°, divided by the optical lever arm length of 10.25 inches. (The lever arm length is the distance from the optical surface to the detectors, measured along the optical path). If a particular calibration ramp corresponds to a window tilt of only 5" instead of 10", a value for θ of 3.17×10^{-5} radians was used instead.

The main body of Table B lists various characteristics of the individual axial scans of the ellipsoid. The first two columns identify the individual scans, with the first digit (1 through 6) giving the number of the scan within its scan group (there are 12 scan groups, total), the letter A or B designating whether the scan is part of the data from the "first day" or the "second day", and the azimuth column indicating the angular position at which the scan was made. Since the data for the first and second days are identically equal here, note that corresponding pairs of lines in this table are identical. For instance, the line for Scan 1A at 0.0° is the same as Scan 1B at 0.0°.

XMIN is the amount each scan was shifted in the X direction in the initial registration, where the X coordinate of the first digitized point in the scan was subtracted from the X coordinates of all the other points. The two XPEAK columns tabulate the positions of the peaks of the cross correlation functions at the beginning and ends of the scans. Since the cross correlation routines were bypassed here, these columns are zero. The AVERAGE SLOPE Column lists the slope of the best fit straight line for each scan before the scan was leveled.

The final seven columns in Table B list the RMS Deviations in microns of each separate scan from the average of all six scans within the corresponding scan group, and also the six largest individual deviations which were found. These statistics illustrate the repeatability of the Scanner traces. The RMS Deviations are typically less than .0010 microns, or 10Å, with the largest value in this column being .00142 microns, or about 14Å. The six largest deviations are typically 2 to 4 times larger than the corresponding RMS value. The largest single deviation found is .0046 microns. Thus, in terms of scan-to-scan repeatability, Table B indicates that the Scanner performance is quite adequate for the purposes of this project.

Table C is a comparison of the average scans of the "first day" to those of the "second day" for the axial measurements of the ellipsoid. Since the two data sets were identical, the differences are all zero, as expected. This table is reproduced only to indicate that certain parts of the SCANNAX program were functioning correctly. The entries in the corresponding tables for the azimuthal scans of the ellipsoid and the axial and azimuthal scans of the hyperboloid were all found to be zero as well, and are not reproduced here.

TABLE C

COMPARISON OF AVERAGE FIRST DAY SCANS WITH AVERAGE SECOND DAY SCANS

AZIMUTH	RMS DEV(MICRONS)	SIX LARGEST DEV (MICRONS)
0.0	0.0000	0.00000.00000.00000.00000.00000.0000
90.0	0.0000	0.00000.00000.00000.00000.00000.0000
180.0	0.0000	0.00000.00000.00000.00000.00000.0000
270.0	0.0000	0.00000.00000.00000.00000.00000.0000

SLOPE DISTRIBUTION TABLES

XXXXXXX	DATA SET 1			XXXXXXXX	DATA SET 3			XXXXXXXX	INTERVAL= 1
SLOPE(SEC)	NBR	TOTAL	NORM NBR	SLOPE	NBR	TOTAL	NORM NBR	SLOPE(SEC)	
0.000	181	181	1206.667	0.000	181	181	1206.667	0.000	
.153	208	389	1386.667	.153	208	389	1386.667	.153	
.330	169	558	1017.844	.330	169	558	1110.844	.330	
.467	155	713	431.798	.467	155	713	431.798	.467	
.654	141	854	578.982	.654	141	854	578.982	.654	
.861	69	923	298.166	.861	69	923	298.066	.861	
1.033	17	940	65.967	1.033	17	940	65.967	1.033	
1.351	8	947	31.296	1.351	9	949	31.296	1.351	
1.638	7	956	21.839	1.638	7	956	21.839	1.638	
1.953	0	956	0.000	1.953	0	956	0.000	1.953	
2.316	0	956	0.000	2.316	0	956	0.000	2.316	
2.714	0	956	0.000	2.714	0	956	0.000	2.714	
3.158	0	956	0.000	3.158	0	956	0.000	3.158	
3.653	0	956	0.000	3.653	0	956	0.000	3.653	
4.204	0	956	0.000	4.204	0	956	0.000	4.204	
4.813	0	956	0.000	4.813	0	956	0.000	4.813	
5.514	0	956	0.000	5.514	0	956	0.000	5.514	
6.267	0	956	0.000	6.267	0	956	0.000	6.267	

TABLE D. AXIAL SLOPE DISTRIBUTION TABLE FOR ELLIPSOID FOR INTERVAL EQUALS 1

XXXXXXX DATA SET A XXXXXXX DATA SET B XXXXXXX INTERVAL= 2

SLOPE(SEC)	NOR	TOTAL	NORM NOR	SLOPE	NOR	TOTAL	NORM NOR	SLOPE(SEC)
0.000				0.000				0.000
	186	186	[illegible]		186	186	1240.000	
.151				.151				.151
	221	387	[illegible]		221	387	1340.000	
.300				.302				.303
	164	551	[illegible]		164	551	350.938	
.467				.467				.467
	173	724	928.394		173	724	928.394	
.654				.654				.654
	141	865	578.882		141	865	578.882	
.861				.861				.851
	56	921	241.999		56	921	241.909	
1.093				1.093				1.093
	23	944	89.142		23	944	89.142	
1.351				1.351				1.351
	4	948	13.909		4	948	13.909	
1.679				1.678				1.639
	8	956	24.959		8	956	24.959	
1.959				1.953				1.959
	0	956	[illegible]		0	956	0.000	
2.716				2.315				2.316
	0	956	0.000		0	956	0.000	
2.714				2.714				2.714
	0	956	0.000		0	956	0.000	
3.158				3.159				3.159
	0	956	0.000		0	956	0.000	
3.653				3.653				3.653
	0	956	0.000		0	956	0.000	
4.204				4.204				4.204
	0	956	0.000		0	956	0.000	
4.819				4.919				4.813
	0	956	0.000		0	956	0.000	
5.534				5.504				5.594
	0	956	0.000		0	956	0.000	
6.267				6.267				6.267
	0	956	[illegible]		0	956	0.000	
7.113				7.118				7.119
	0	956	0.003		0	956	0.000	
8.066				8.065				8.065
	0	956	0.000		0	952	0.000	
9.123				9.123				9.123
	0	956	0.000		0	956	0.000	
10.301				10.301				10.331
	0	956	[illegible]		0	956	0.000	
11.615				11.615				11.615
	0	956	0.000		0	956	0.000	
13.078				13.078				13.075
	0	956	[illegible]		0	956	0.000	

TABLE E. AXIAL SLOPE DISTRIBUTION TABLE FOR ELLIPSOID FOR INTERVAL EQUALS 2

XXXXXXX DATA [illegible] XXXXXXX DATA [illegible] XXXXXXX INTERVAL= 4

SLOPE(SEC)	NBR	TOTAL	NORM NBR	SLOPE(SEC)	NBR	TOTAL	NORM NBR	SLOPE(SEC)
0.000				0.000				0.000
	19	19	1266.667		19	19	1266.667	
.150				.150				.150
	[illegible]	333	1353.333		[illegible]	333	1353.333	
.303				.303				.303
	167	561	994.681		167	561	994.681	
.457				.457				.457
	163	724	901.562		163	728	901.562	
.654				.654				.654
	151	879	727.329		151	879	727.329	
.861				.861				.861
	48	927	267.350		48	927	267.350	
1.093				1.093				1.093
	18	945	63.763		18	945	63.763	
1.351				1.351				1.351
	5	950	17.386		5	950	17.396	
1.638				1.638				1.638
	4	954	12.479		4	954	12.479	
1.959				1.959				1.959
	2	956	5.598		2	956	5.598	
2.316				2.316				2.316
	0	956	0.000		0	956	0.000	
2.714				2.714				2.714
	0	956	0.000		0	956	0.000	
3.158				3.158				3.158
	0	956	0.000		0	956	0.000	
3.653				3.653				3.653
	0	956	0.000		0	956	0.000	
4.204				4.204				4.204
	0	956	0.000		0	956	0.000	
4.819				4.819				4.819
	0	956	0.000		0	956	0.000	
5.504				5.534				5.534
	0	956	0.000		0	956	0.000	
6.267				6.267				6.267
	0	956	0.000		0	956	0.000	
7.118				7.118				7.118
	0	956	0.000		0	956	0.000	
8.065				8.066				8.065
	0	956	0.000		0	956	0.000	
9.123				9.123				9.123
	0	956	0.000		0	956	0.000	
10.301				10.301				10.301
	0	956	0.000		0	956	0.000	
11.615				11.615				11.615
	0	956	0.000		0	956	0.000	
13.078				13.078				13.078
	0	956	0.000		0	956	0.000	
14.713				14.713				14.713
	0	956	0.000		0	956	0.000	
16.528				16.528				16.528
	0	956	0.000		0	956	0.000	
18.554				18.554				18.554
	0	956	0.000		0	956	0.000	

TABLE F. AXIAL SLOPE DISTRIBUTION TABLE FOR ELLIPSOID FOR INTERVAL EQUALS 4

Tables D, E, and F are the slope distribution tables for the axial scans of the ellipsoid in which the slopes are computed over one interpolation interval (.020 inches on the scanner trace), two intervals, and four intervals, respectively. These tables were made up from the Scanner traces after they had been interpolated, leveled, and averaged. The turned-down edges at the two ends of the optical surface were deleted from the sampling area for these tabulations. Here, the columns labeled NBR contain the number of calculated slope values falling within each slope bin, the TOTAL column gives the running total, and in the NORM NBR column the number NBR has been divided by the angular bin width to give a measure of the normalized contribution within that bin. The similarity of the three tables for 1, 2, and 4 intervals indicates that the characteristic wavelengths of the surface features on the averaged scans were long compared to the interpolation interval. No surface slope errors greater than 2.3 arc seconds were found. These results are discussed further in Section 5.5.

The corresponding results of the SCANNAX run on the axial scans of the hyperboloid are found in Tables G through J. The RMS Deviation and Largest Deviations listed in Table G are of the same order of magnitude as the corresponding statistics for the ellipsoid, although values are noticeably smaller here, indicating that the Scanner was probably more stable during the scans of the hyperboloid. The largest RMS Deviation found is .00084 microns, and the largest single deviation is .0040 microns. The axial slope distributions for the hyperboloid in Tables H, I, and J have slightly narrower central peaks then those of the ellipsoid, but also have significantly longer tails, with the largest slope errors which are listed approaching 10 arc seconds.

The averaged axial Scanner traces of the ellipsoid and hyperboloid, scaled to the nominal magnification of the LLL Cleavite System and with the slope circle curvatures added in, are plotted in Figures 5.21 and 5.22, respectively. Figures 5.21a through 5.21d are the ellipsoid scans corresponding to the 0°, 90°, 180°, and 270° azimuthal positions, respectively. (These position angles are referenced to the x-ray microscope mounting hole pattern in Figure 5.23). The horizontal magnification with respect to the optical surface for the original version of these plots is 19.46 X and the vertical magnification is 98960 X. For this report, these plots have been reduced somewhat. On the originals, the divisions on the abscissa and ordinate scales were 1 cm apart. One division on the abscissa scale equals 0.1037 cm on the optical

PROGRAM SCANNAX SURFAC[illegible] [illegible] DELTA= [illegible] K1= 27[illegible] K2= [illegible] K3= 15[illegible] (FACTOR 1)=1.[illegible] (FACTOR 2)=1.[illegible]

X SCALE= 2.[illegible]59[illegible] X OFFSET= .25[illegible] Y SCALE= .377[illegible] C1= .0179 C2= -2.44[illegible] Y OFFSET= 1.5[illegible] SMAG=26230[illegible].

INTERVAL= 1 XMAG= 9.64.

SCAN GROUP	AZIMUTH (DEGREES)	XMIN	XPEAK (START)	XPEAK (END)	AVERAGE SLOPE	RMS DEV	SIX LARGEST DEVIATIONS
		(((INCHES	ON SCANNER	TRACES)))		(((((((((	MICRONS ON THE OPTICAL SURFACE)))))))
1 A	[illegible]	.7C2[illegible]	[illegible]	0.[illegible]	-.[illegible]4057	.00[illegible]84	.0[illegible]4[illegible] .[illegible]036 .0032 .[illegible]25 .0020 .0019
2 A	[illegible]	.6921	[illegible]	[illegible]	-.[illegible]4866	.[illegible]0159	.[illegible]015 .0[illegible]14 .[illegible]013 .0[illegible]13 .0[illegible]13 .0012
3 A	[illegible]	.686[illegible]	[illegible]	[illegible]	-.[illegible]9[illegible]86	.00[illegible]45	-.[illegible]013-.[illegible]012-.0[illegible]11-.[illegible]-.001[illegible]-.[illegible]
4 A	[illegible]	.668[illegible]	[illegible]	[illegible]	-.13765	.[illegible]0[illegible]74	-.[illegible]33-.[illegible]33-.[illegible]32-.[illegible]31-.[illegible]31-.0029
5 A	[illegible]	.6860	[illegible]	[illegible]	-.16407	.00[illegible]57	-.0017-.0[illegible]16-.0016-.[illegible]16-.0015-.0014
6 A	[illegible]	.68[illegible]	[illegible]	[illegible]	-.13435	.[illegible]0[illegible]66	-.[illegible]018-.[illegible]017-.0017-.0016-.[illegible]015-.0014
1 B	0.0	.7020	0.[illegible]	0.000	-.[illegible]4057	.00[illegible]84	.0040 .0036 .0032 .0[illegible]25 .0020 .0019
2 B	[illegible]	.692[illegible]	0.[illegible]00	[illegible]	-.[illegible]4866	.[illegible]0159	.[illegible]015 .0[illegible]14 .0013 .0[illegible]13 .0013 .0012
3 B	[illegible]	.6860	0.[illegible]	0.000	-.[illegible]9[illegible]86	.[illegible]0[illegible]45	-.[illegible]13-.[illegible]12-.[illegible]11-.[illegible]
4 B	[illegible]	.668[illegible]	0.[illegible]	[illegible]	-.13765	.[illegible]0[illegible]74	-.[illegible]33-.[illegible]33-.0032-.0031-.0031-.0029
5 B	0.0	.6860	0.[illegible]00	0.000	-.16437	.00[illegible]57	-.0017-.0016-.0016-.0016-.0015-.0014
6 B	0.0	.6803	0.000	0.00[illegible]	-.13435	.00[illegible]66	-.0018-.0017-.0017-.[illegible]016-.0015-.0014
1 A	90.0	.6163	[illegible].000	0.000	-.[illegible]393[illegible]	.[illegible]0[illegible]61	-.0021-.0[illegible]19-.[illegible]18-.0[illegible]16-.[illegible]015-.0015
2 A	9[illegible].0	.60[illegible]8[illegible]	0.[illegible]	0.000	-.[illegible]5117	.00063	.0022 .0022 .0[illegible]22 .0021 .0020 .0019
3 A	90.0	.6[illegible]20	0.[illegible]	0.000	-.[illegible]2741	.00[illegible]58	.0025 .0021 .0[illegible]21 .0017 .0016-.0011
4 A	9[illegible].0	.615[illegible]	0.0[illegible]	0.000	-.[illegible]4786	.[illegible]0[illegible]67	-.0021-.[illegible]20-.0018-.[illegible]017-.0017-.0016
5 A	90.0	.614[illegible]	[illegible].000	0.000	-.[illegible]3231	.[illegible]0[illegible]67	-.0013-.[illegible]13-.0012-.[illegible]012-.[illegible]012-.0012
6 A	9[illegible].0	.616[illegible]	0.[illegible]	0.000	-.[illegible]6016	.[illegible]0[illegible]5[illegible]	.0013 .0012 .0012 .0011 .0011 .0011
1 B	90.0	.616[illegible]	0.000	0.000	-.[illegible]3930	.00061	-.0021-.0019-.0018-.0016-.0015-.0015
2 B	90.0	.60[illegible]	[illegible].0[illegible]	0.000	-.[illegible]5117	.00063	.0022 .[illegible]022 .0022 .0021 .0020 .0019
3 B	9[illegible].0	.6[illegible]2[illegible]	0.[illegible]	0.0[illegible]	-.[illegible]2741	.[illegible]0[illegible]58	.0025 .[illegible]21 .0[illegible]2[illegible] .[illegible]17 .[illegible]16-.0011
4 B	9[illegible].0	.61[illegible]	0.[illegible]	[illegible]	-.[illegible]4786	.00[illegible]67	-.0021-.[illegible]20-.0018-.0017-.0017-.0016
5 B	90.0	.6140	[illegible].00[illegible]	0.000	-.[illegible]3231	.00067	-.0013-.0013-.0012-.0012-.0012-.0012
6 B	90.0	.6163	0.000	0.000	-.[illegible]6016	.[illegible]0054	.0013 .0012 .0012 .0011 .0011 .0011
1 A	180.0	.638[illegible]	0.000	0.000	-.[illegible]0764	.0005[illegible]	-.0016-.0[illegible]14 .0014 .[illegible]013 .0013-.[illegible]013
2 A	18[illegible].0	.646[illegible]	[illegible]	0.0[illegible]	-.[illegible]0915	.[illegible]0[illegible]58	-.0014-.0013-.0013-.0013-.0013-.0012
3 A	18[illegible].0	.6503	[illegible].[illegible]00	[illegible]	.[illegible]0466	.00[illegible]47	.0022 .0022 .0017 .0014 .0012 .0011
4 A	180.0	.64[illegible]	[illegible]	[illegible].000	.[illegible]0559	.00047	-.[illegible]015-.[illegible]14-.0013-.0012-.0012-.0011
5 A	18[illegible].0	.650[illegible]	[illegible].000	0.000	-.[illegible]0892	.00068	.0023 .0022 .0021 .0019 .0019 .0018
6 A	180.0	.6460	0.00[illegible]	0.000	-.[illegible]2165	.[illegible]0061	-.0014-.0013-.0013-.0013-.0012 .0012
1 B	180.0	.6383	0.000	[illegible].000	-.[illegible]0764	.[illegible]0059	-.0016-.0014 .0014 .0013 .0013-.0013
2 B	180.0	.646[illegible]	0.0[illegible]	0.00[illegible]	-.[illegible]0915	.00059	-.[illegible]14-.0013-.[illegible]13-.[illegible]13-.[illegible]13-.[illegible]12
3 B	18[illegible].0	.65[illegible]	[illegible]	[illegible]	.[illegible]0466	.00[illegible]47	.0022 .0022 .0017 .0014 .0012 .0011
4 B	18[illegible].0	.6483	[illegible].000	0.000	.[illegible]0559	.00[illegible]47	-.0015-.0014-.0013-.[illegible]012-.[illegible]012-.0011
5 B	180.0	.6509	[illegible].000	0.000	-.[illegible]0892	.00068	.0023 .0022 .0021 .[illegible]019 .0019 .0018
6 B	180.0	.6463	[illegible].[illegible]00	0.000	-.[illegible]2165	.00061	-.0014-.0013-.0013-.[illegible]13-.[illegible]12 .[illegible]12
1 A	27[illegible].0	.502[illegible]	[illegible]	0.000	-.[illegible]3747	.00[illegible]48	-.0021-.0020-.0018-.0018-.0016-.0014
2 A	27[illegible].0	.498[illegible]	[illegible]	0.0[illegible]	-.[illegible]5182	.00[illegible]56	.[illegible]013 .[illegible]12-.0012-.[illegible]11 .0011 .0011
3 A	270.0	.490[illegible]	[illegible]	0.000	-.[illegible]6552	.[illegible]0041	-.0011-.[illegible]11-.0011-.[illegible] .0009 .0009
4 A	27[illegible].0	.486[illegible]	[illegible]	[illegible].000	-.11793	.[illegible]0061	-.0015-.0014-.0014-.0012-.0012-.0012
5 A	27[illegible].0	.4822	[illegible]	0.0[illegible]	.[illegible]1259	.[illegible]0[illegible]53	-.0014-.0013-.[illegible]012-.0011-.0011 .0011
6 A	270.0	.476[illegible]	0.0[illegible]	[illegible].000	.[illegible]1462	.00057	-.0014-.0014-.[illegible]014 .0013 .0[illegible]13-.0013
1 B	270.0	.5029	0.00[illegible]	[illegible].000	-.[illegible]3747	.00[illegible]48	-.0021-.0020-.0018-.0018-.0016-.0014
2 B	27[illegible].0	.4982	[illegible].[illegible]0[illegible]	0.000	-.[illegible]5182	.00[illegible]56	.0013 .[illegible]12-.[illegible]12-.[illegible]11 .[illegible]11 .[illegible]11
3 B	27[illegible].0	.49[illegible]	[illegible].00[illegible]	0.000	-.[illegible]6552	.[illegible]0041	-.0011-.[illegible]11-.0011-.[illegible] .[illegible]09 .0009
4 B	27[illegible].0	.4865	0.00[illegible]	.000	-.11793	.[illegible]0061	-.0015-.[illegible]14-.0014-.0012-.[illegible]12-.0012
5 B	270.0	.4822	0.000	0.000	.[illegible]1259	.[illegible]0053	-.0014-.0013-.0012-.[illegible]11-.0011 .0011
6 B	27[illegible].0	.476[illegible]	0.[illegible]	[illegible].00[illegible]	.[illegible]1462	.[illegible]0057	-.[illegible]014-.0[illegible]14-.0014 .0013 .0013-.0013

TABLE G

SLOPE DISTRIBUTION TABLES

XXXXXXX	DATA SET A			XXXXXXXX	DATA SET B			XXXXXXXX INTERVAL= 1
SLOPE(SEC)	NBR	TOTAL	NORM NBR	SLOPE	NBR	TOTAL	NORM NBR	SLOPE(SEC)
[illegible]				[illegible]				[illegible]
	191	191	1273.333		191	191	1273.333	
.154				.154				.154
	163	354	1086.667		163	354	1086.667	
.310				.310				.331
	155	509	927.106		155	509	927.106	
.467				.467				.467
	122	611	547.377		122	611	547.377	
.654				.654				.654
	68	679	327.404		68	679	327.404	
.861				.861				.861
	73	752	315.345		73	752	315.345	
1.093				1.093				1.093
	76	828	294.555		76	828	294.555	
1.351				1.351				1.351
	34	862	118.228		34	862	118.228	
1.638				1.638				1.638
	19	881	59.277		19	881	59.277	
1.959				1.959				1.959
	14	895	39.187		14	895	39.167	
2.316				2.316				2.316
	12	907	30.136		12	907	30.136	
2.714				2.714				2.714
	5	912	11.266		5	912	11.266	
3.158				3.158				3.158
	1	913	2.022		1	913	2.022	
3.653				3.653				3.653
	7	920	12.696		7	921	12.696	
4.204				4.204				4.204
	5	925	8.136		5	925	8.136	
4.819				4.819				4.819
	6	931	8.761		6	931	8.761	
5.504				5.504				5.504
	2	933	2.627		2	933	2.628	
6.267				6.267				6.267
	5	938	5.876		5	938	5.876	
7.118				7.118				7.118
	3	941	3.163		3	941	3.163	
8.066				8.066				8.066
	2	943	1.892		2	943	1.892	
9.123				9.123				9.123
	1	944	.849		1	944	.849	
10.301				10.301				10.301
	0	944	[illegible]		0	944	[illegible]	
11.615				11.615				11.615
	0	944	[illegible]		0	944	[illegible]	
13.[illegible]				13.[illegible]				13.[illegible]
		944	[illegible]		0	944	[illegible]	

TABLE H. AXIAL SLOPE DISTRIBUTION TABLE FOR HYPERBOLOID FOR INTERVAL EQUALS 1.

SLOPE(SEC)	NBR	TOTAL	NORM NBR	SLOPE	NBR	TOTAL	NORM NBR	SLOPE(SEC)
[illegible]				[illegible]				[illegible]
	194	194	1293.333		194	194	1293.333	
.151				.151				.151
	173	367	1153.333		173	367	1153.333	
.301				.301				.301
	149	516	891.218		149	516	891.218	
.467				.467				.467
	95	611	509.812		95	611	509.812	
.654				.654				.654
	62	673	298.515		62	673	298.515	
.861				.861				.861
	83	756	354.543		83	756	354.543	
1.093				1.093				1.093
	72	828	279.052		72	828	279.052	
1.351				1.351				1.351
	34	862	118.228		34	862	118.228	
1.638				1.638				1.638
	20	882	62.396		20	882	62.396	
1.959				1.959				1.959
	15	897	41.987		15	897	41.987	
2.316				2.316				2.316
	12	909	30.136		12	909	30.136	
2.714				2.714				2.714
	3	912	6.76[illegible]		3	912	6.76[illegible]	
3.158				3.158				3.158
	5	917	10.108		5	917	10.108	
3.653				3.653				3.653
	4	921	7.255		4	921	7.255	
4.204				4.204				4.204
	7	928	11.391		7	928	11.391	
4.819				4.819				4.819
	3	931	4.38[illegible]		3	931	4.38[illegible]	
5.504				5.504				5.504
	4	935	5.24[illegible]		4	975	5.24[illegible]	
6.267				6.267				6.267
	5	940	5.876		5	940	5.876	
7.118				7.119				7.118
	3	943	3.163		3	943	3.163	
8.066				8.066				8.066
	0	943	0.000		0	943	0.000	
9.123				9.123				9.123
	1	944	.849		1	944	.849	
10.361				10.361				10.361
	0	944	0.000		0	944	0.000	
11.615				11.615				11.615
	0	944	0.000		0	944	0.000	
13.078				13.078				13.078
	0	944	0.000		0	944	0.000	
14.710				14.710				14.710
	0	944	0.000		0	944	0.000	
16.528				16.528				16.528
	0	944	0.000		0	944	0.000	
18.554				18.554				18.554
	0	944	0.000		0	944	0.000	
20.813				20.813				20.813
	0	944	0.000		0	944	0.000	
23.331				23.331				23.331
	0	944	0.000		0	944	0.000	

TABLE I. AXIAL SLOPE DISTRIBUTION TABLE FOR HYPERBOLOID FOR INTERVAL EQUALS 2

XXXXXXX		DATA SET A		XXXXXXXX		DATA SET B		XXXXXXXX	INTERVAL= 4
SLOPE(SEC)	NOR	TOTAL	NORM NOR	SLOPE	NOR	TOTAL	NORM NOR	SLOPE(SEC)	
[illegible]				[illegible]				[illegible]	
	199	199	1326.667		199	199	1326.667		
.150				.150				.150	
	175	374	1166.667		175	374	1166.667		
.300				.300				.300	
	140	514	837.346		140	514	837.346		
.467				.467				.467	
	99	613	531.278		99	613	531.278		
.654				.654				.654	
	72	685	346.667		72	685	346.667		
.861				.861				.861	
	78	763	336.944		78	763	336.944		
1.093				1.093				1.093	
	72	835	279.052		72	835	279.052		
1.351				1.351				1.351	
	32	867	111.273		32	867	111.273		
1.638				1.638				1.638	
	21	888	65.516		21	888	65.516		
1.959				1.959				1.959	
	21	909	56.781		21	909	56.781		
2.316				2.316				2.316	
	3	912	7.534		3	912	7.534		
2.714				2.714				2.714	
	6	918	13.519		6	918	13.519		
3.158				3.158				3.158	
	4	922	8.086		4	922	8.086		
3.653				3.653				3.653	
	3	925	5.441		3	925	5.441		
4.294				4.294				4.294	
	7	932	11.391		7	932	11.391		
4.819				4.819				4.819	
	3	935	4.380		3	935	4.380		
5.504				5.504				5.504	
	5	940	6.550		5	940	6.550		
6.267				6.267				6.267	
	2	942	2.350		2	942	2.350		
7.118				7.118				7.118	
	2	944	2.109		2	944	2.109		
8.066				8.066				8.066	
	[illegible]	944	[illegible]		0	944	[illegible]		
9.123				9.123				9.123	
	[illegible]	944	[illegible]		0	944	[illegible]		
10.301				10.301				10.301	
	[illegible]	944	[illegible]		0	944	[illegible]		
11.615				11.615				11.615	
	[illegible]	944	[illegible]		0	944	[illegible]		
13.078				13.078				13.078	
	[illegible]	944	[illegible]		0	944	[illegible]		
14.710				14.710				14.710	

TABLE J. AXIAL SLOPE DISTRIBUTION TABLE FOR HYPERBOLOID FOR INTERVAL EQUALS 4

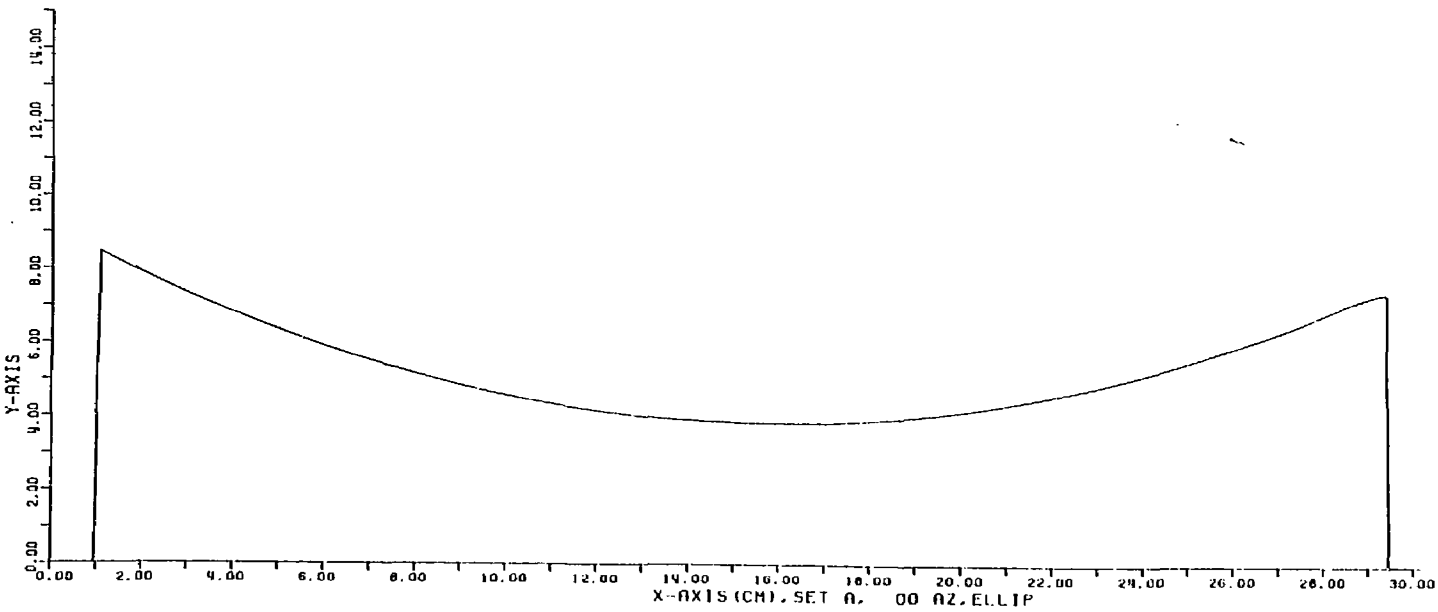
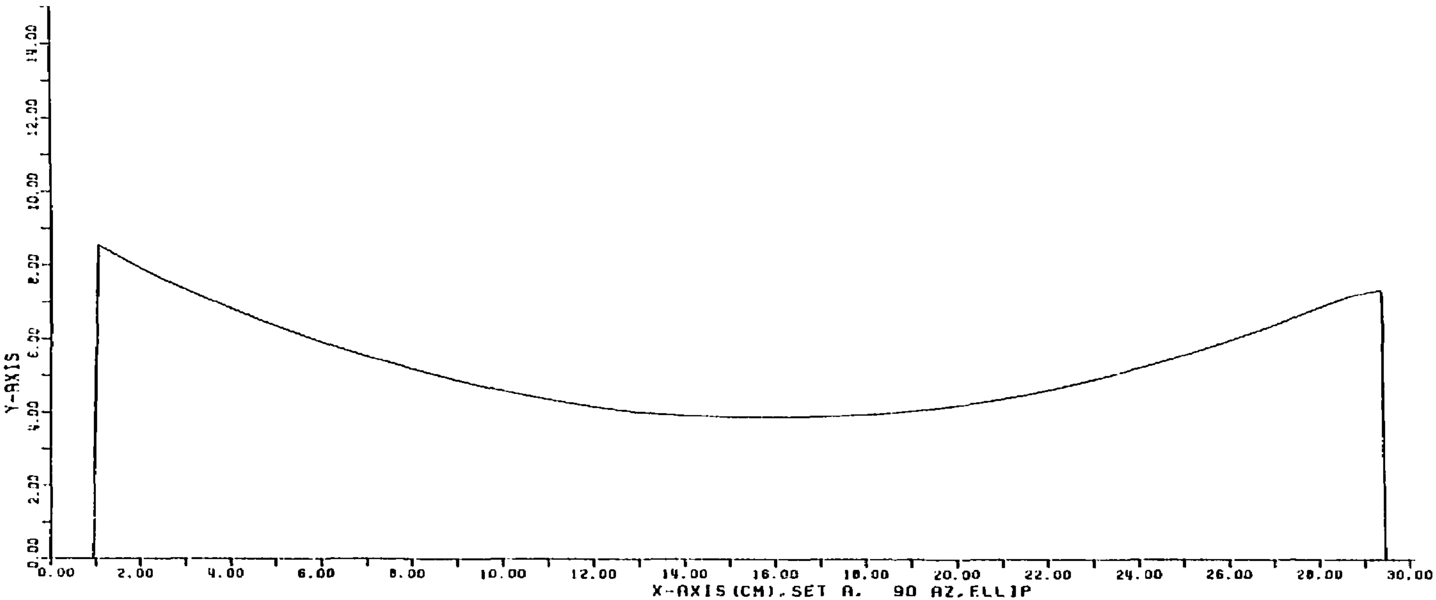

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 00 AZ, ELLIP

FIGURE 5.21a



Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00 2.00 4.00 6.00 8.00 10.00 12.00 14.00 16.00 18.00 20.00 22.00 24.00 26.00 28.00 30.00
X-AXIS (CM), SET A. 90 AZ, ELLIP

FIGURE 5.21b

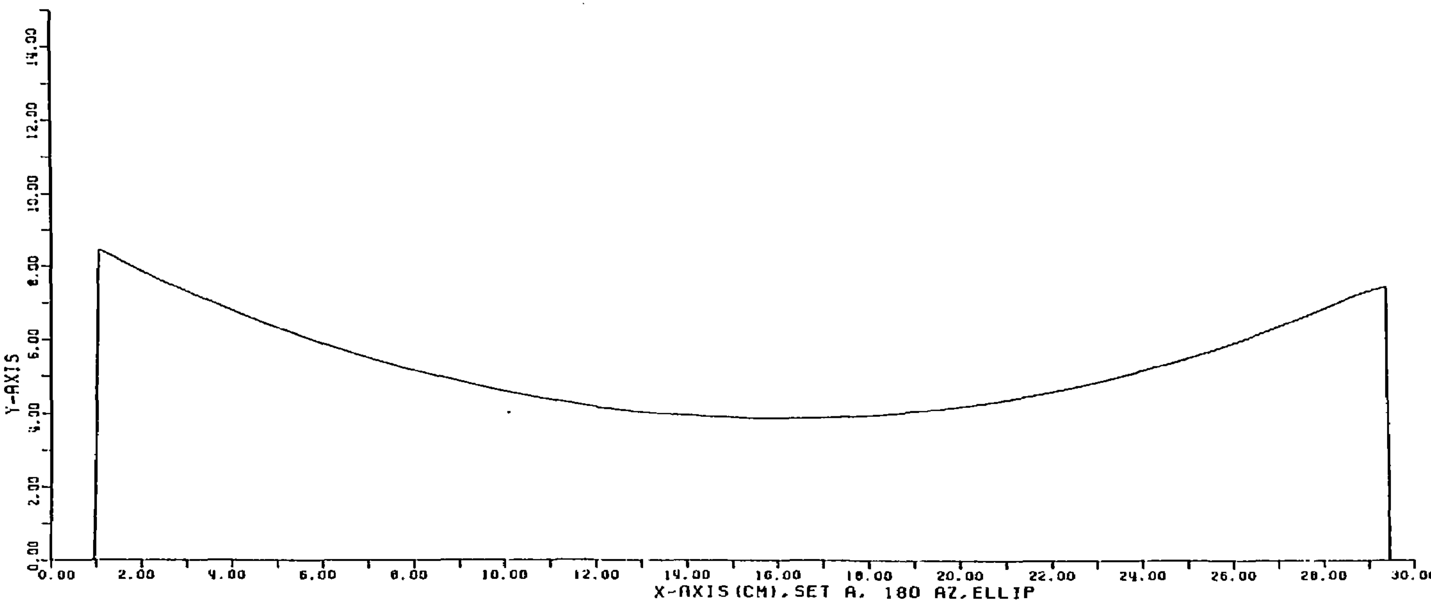

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM),SET A, 180 AZ,ELLIP

FIGURE 5.21c

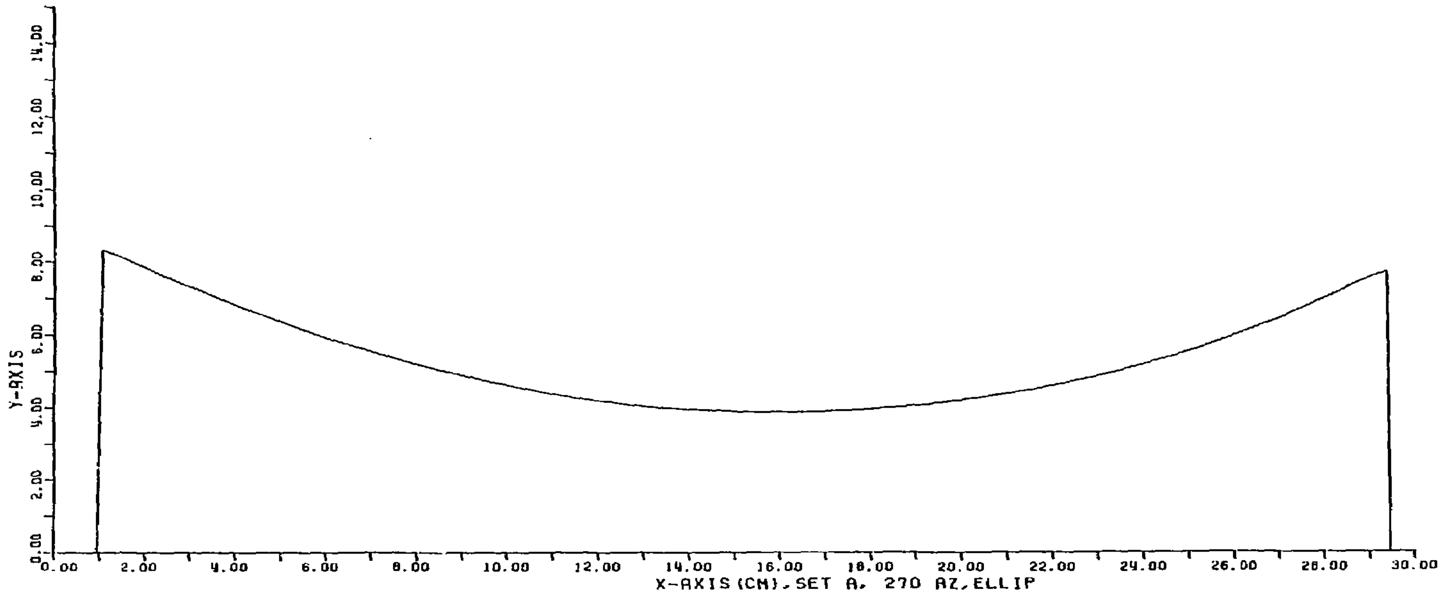

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 270 AZ, ELLIP

FIGURE 5.21d

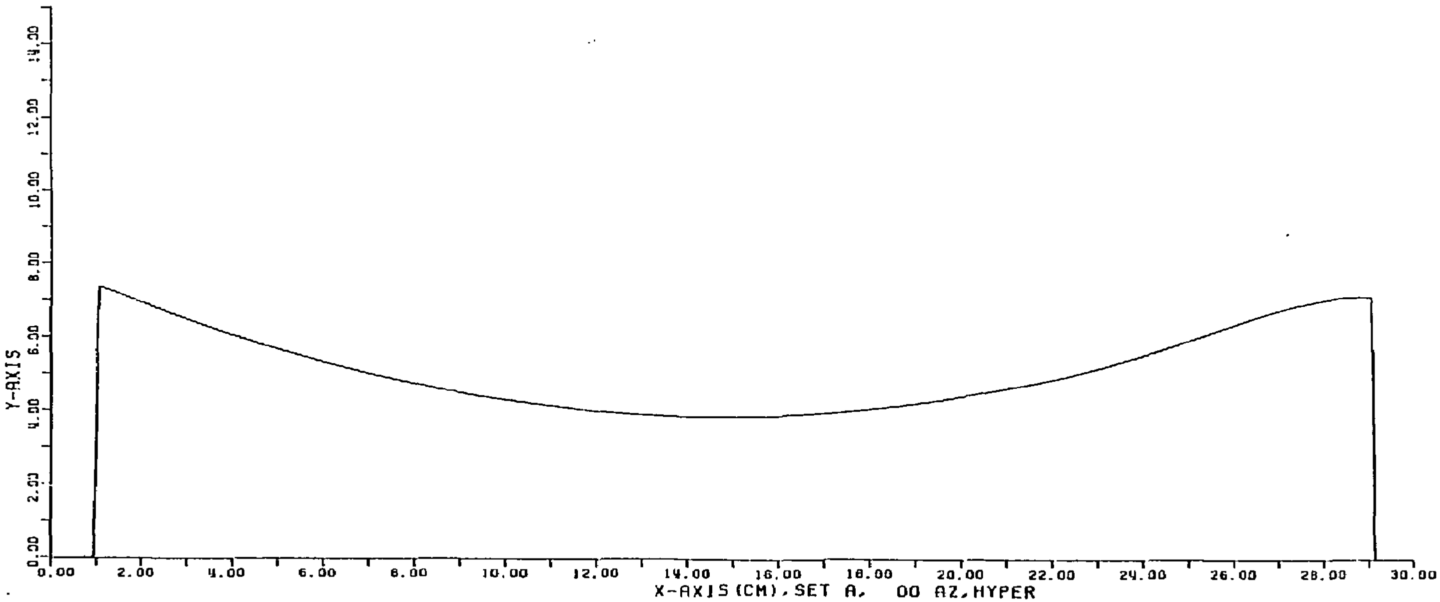

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 00 AZ,HYPER

FIGURE 5.22a

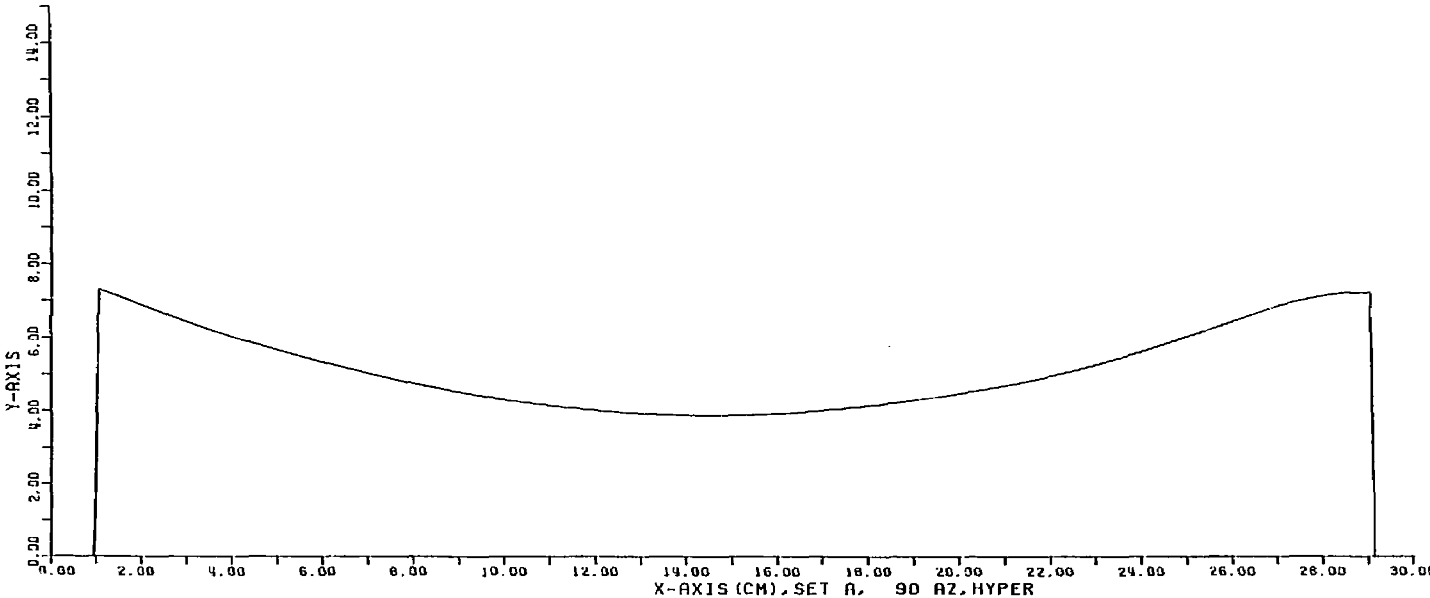

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00 2.00 4.00 6.00 8.00 10.00 12.00 14.00 16.00 18.00 20.00 22.00 24.00 26.00 28.00 30.00
X-AXIS (CM), SET A, 90 AZ, HYPER

FIGURE 5.22b

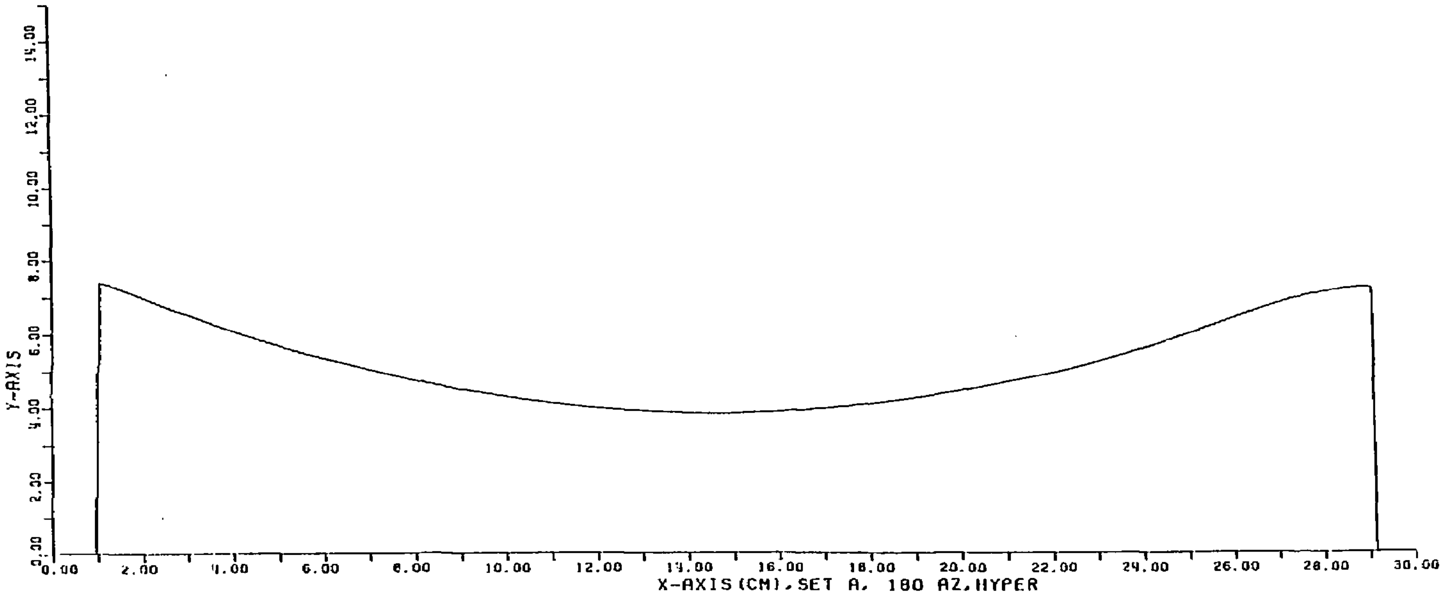

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 180 AZ, HYPER

FIGURE 5.22c

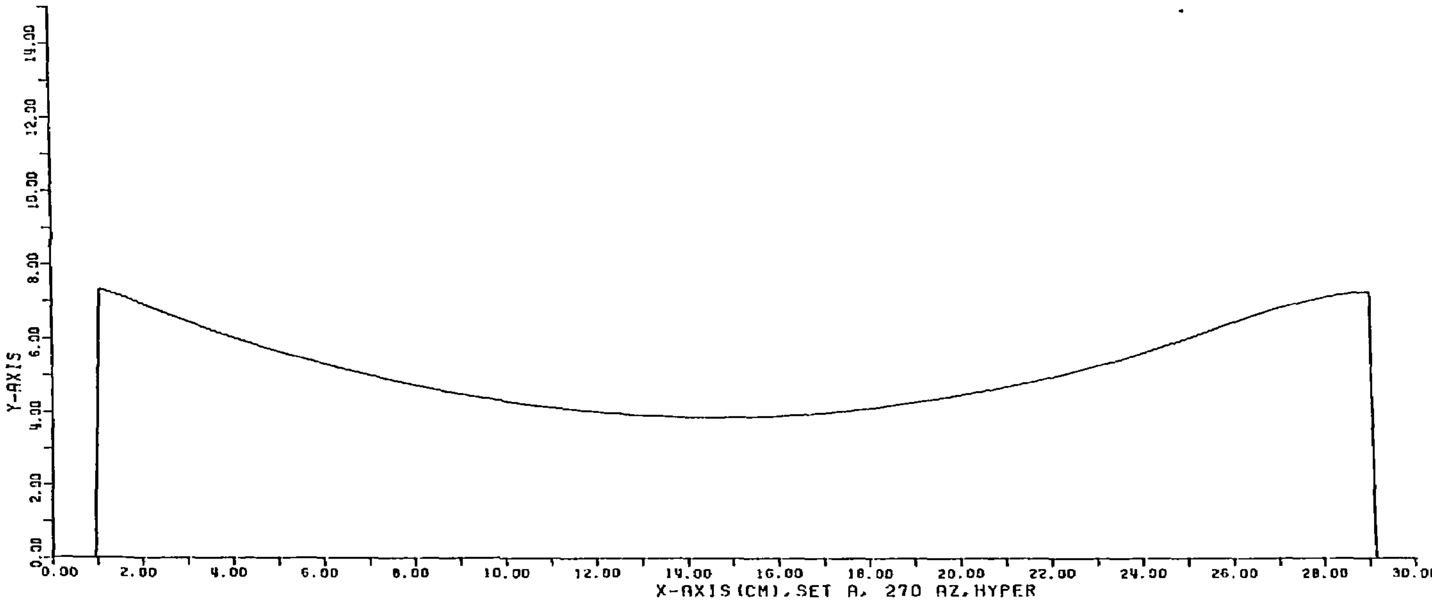

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 270 AZ, HYPER

FIGURE 5.22d

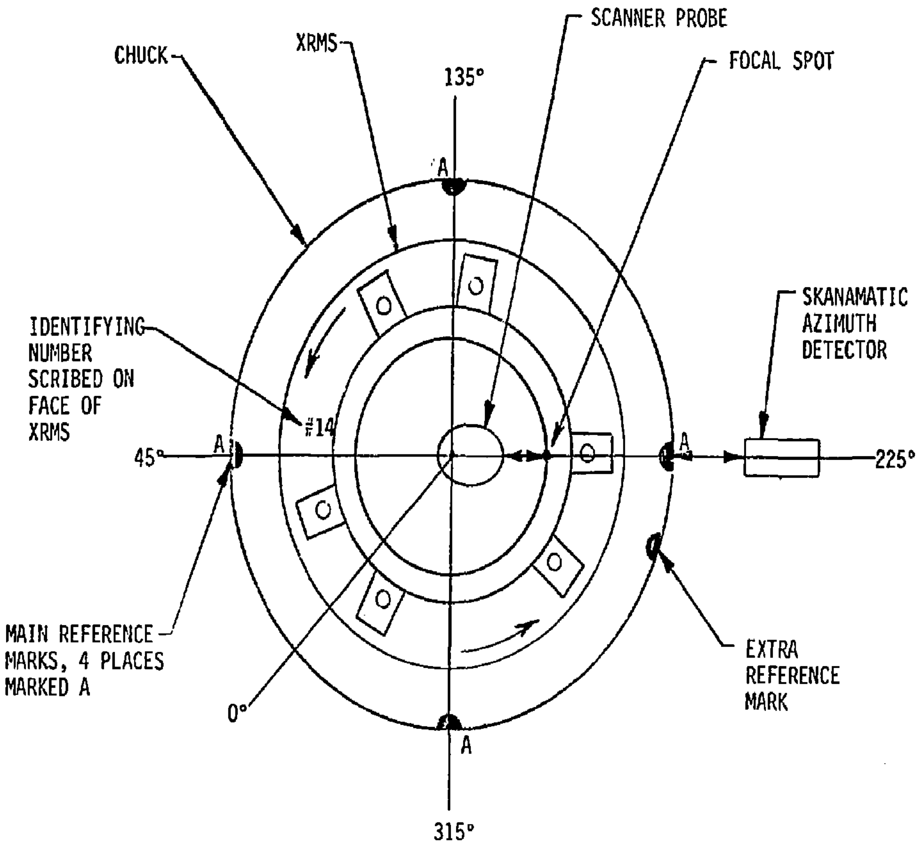


FIGURE 5.23 Orientation of the Piece on the Rotary Air Bearing of Scanner, as Viewed from the Large End. Rotation was Counter - Clockwise.

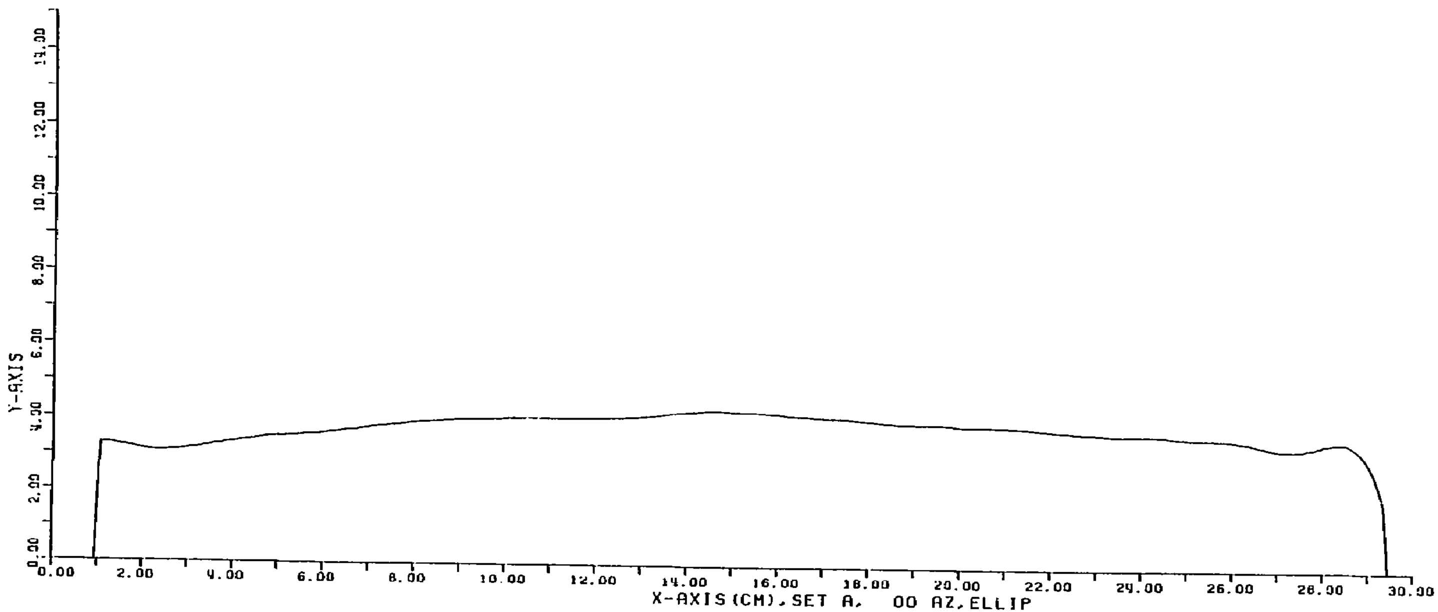
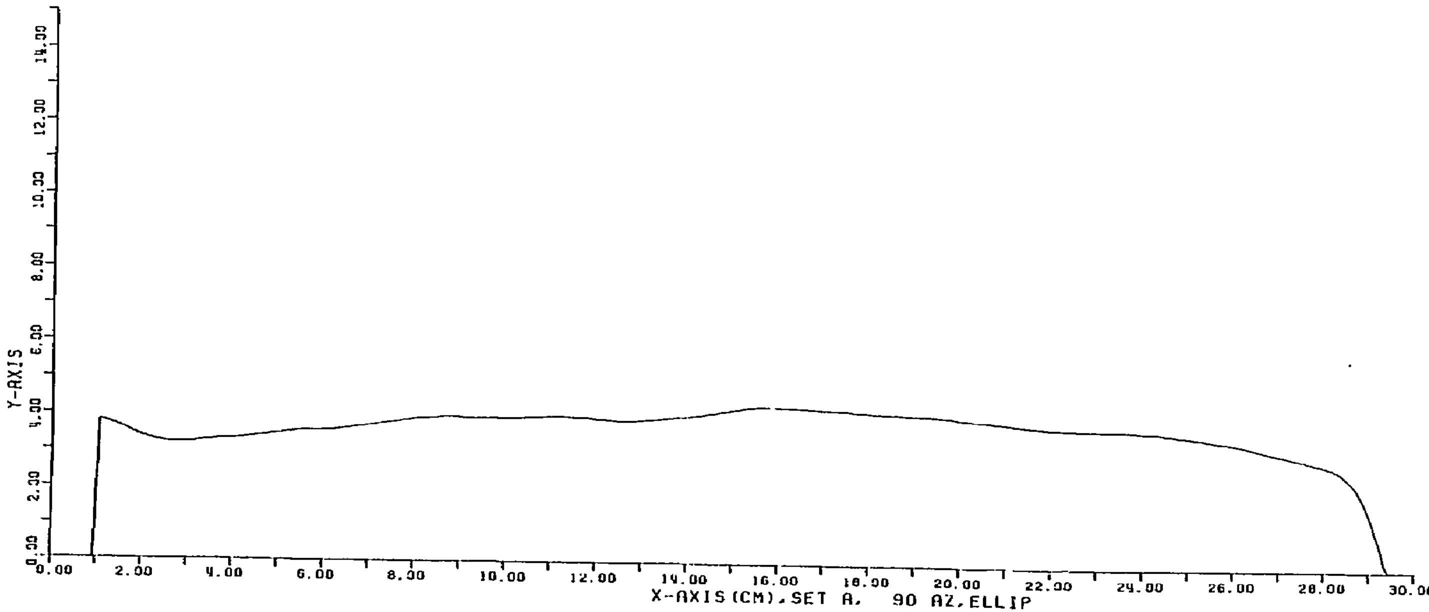
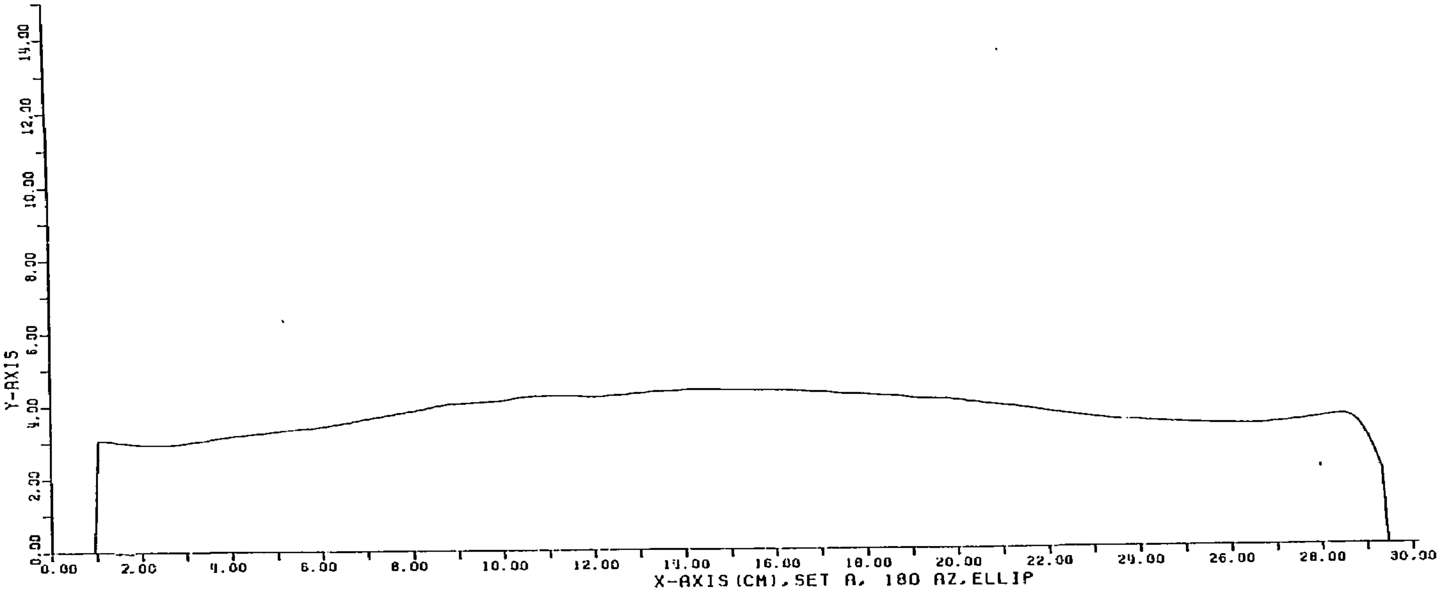

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS (CM), SET A, 00 AZ, ELLIP

FIGURE 5.24a



Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS (CM), SET A, 90 AZ, ELLIP

FIGURE 5.24b



Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS (CM), SET A, 180 AZ, ELLIP

FIGURE 5.24c

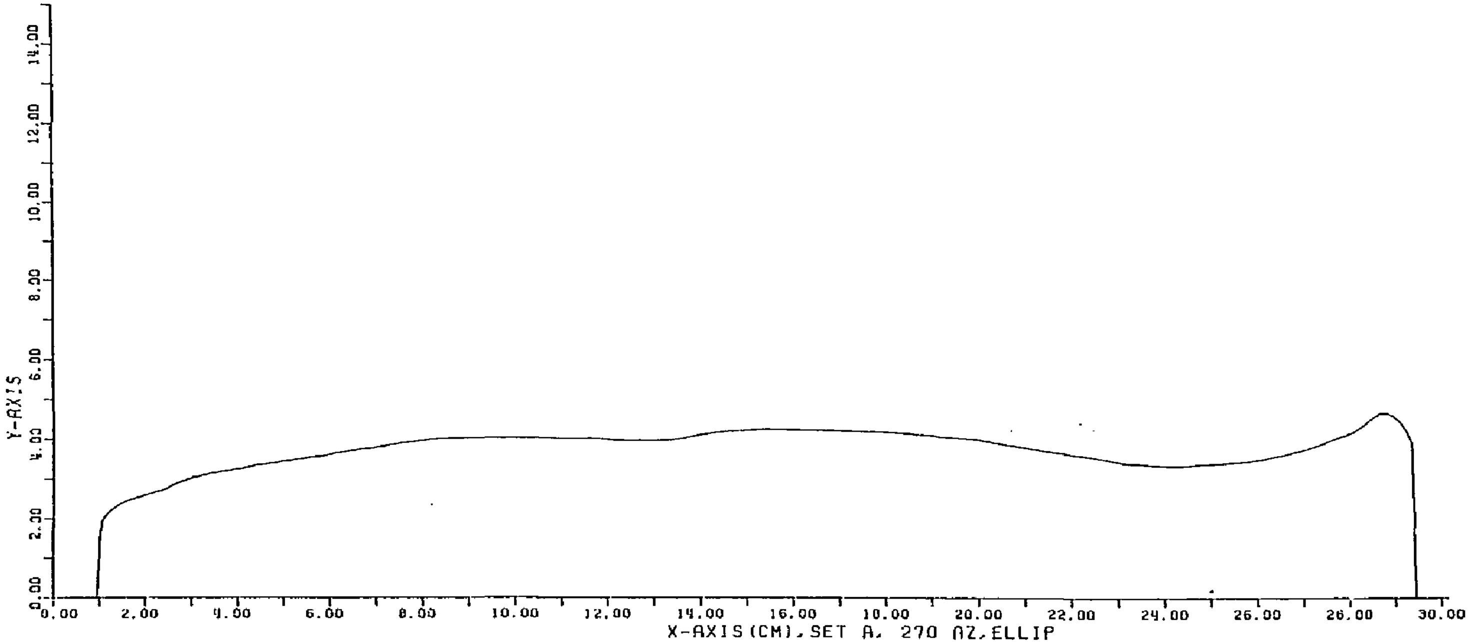

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00 2.00 4.00 6.00 8.00 10.00 12.00 14.00 16.00 18.00 20.00 22.00 24.00 26.00 28.00 30.00
X-AXIS(CM),SET A, 270 AZ,ELLIP

FIGURE 5,24d

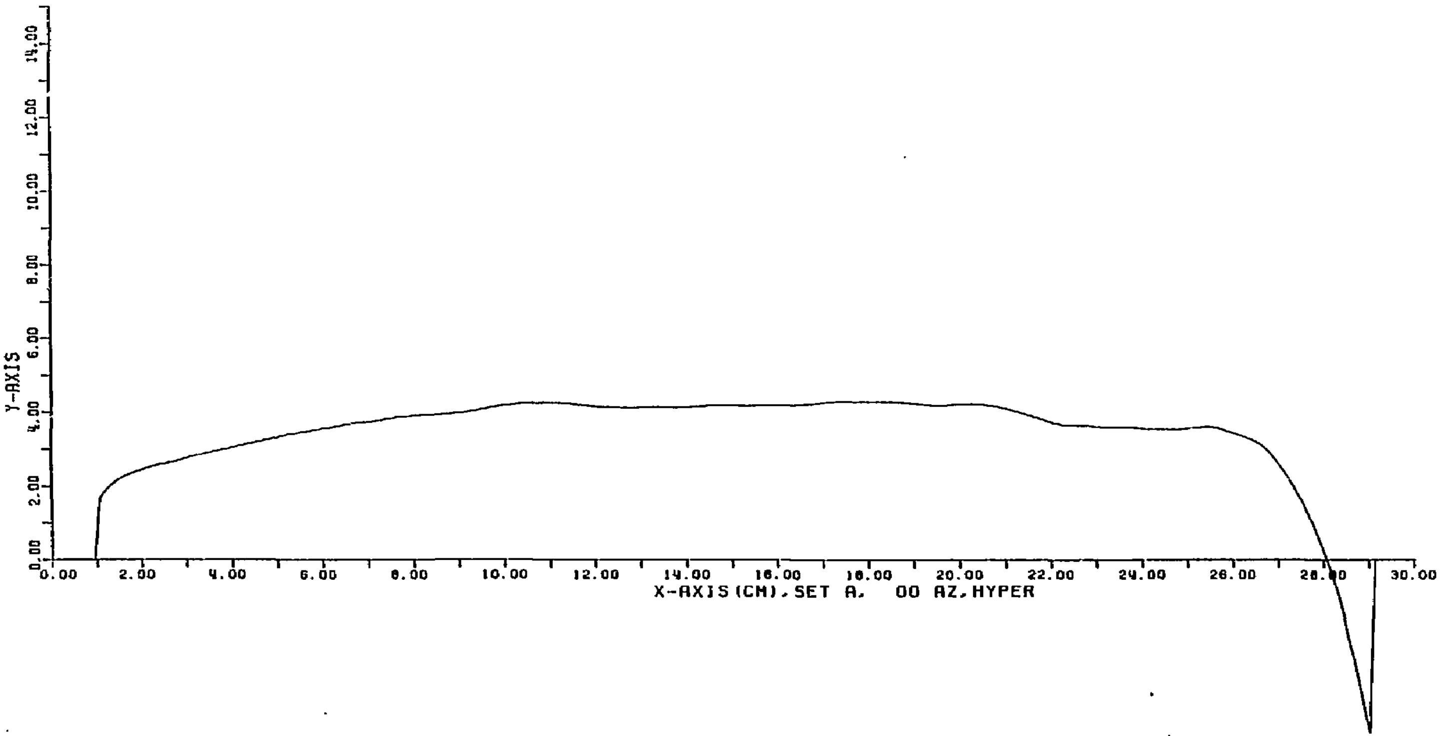

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 00 AZ, HYPER

FIGURE 5.25a

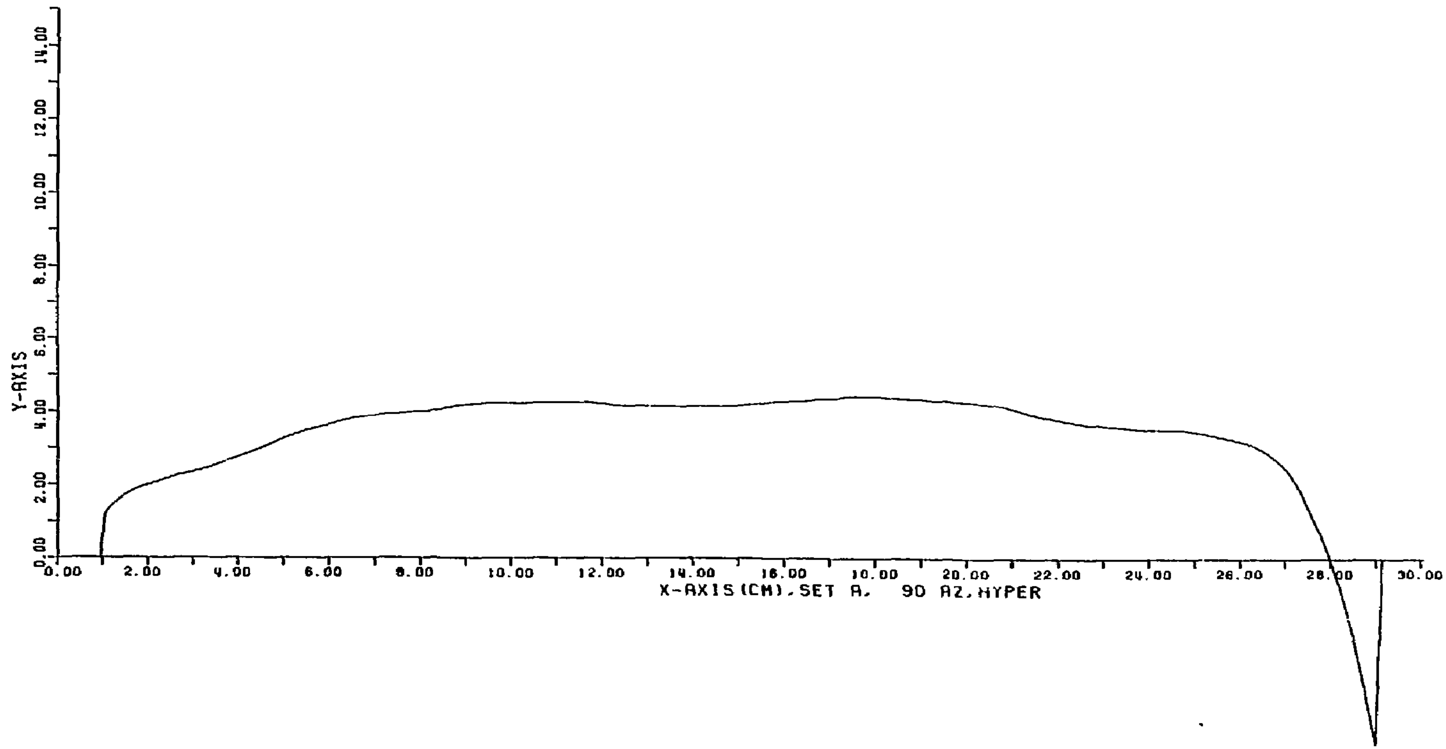
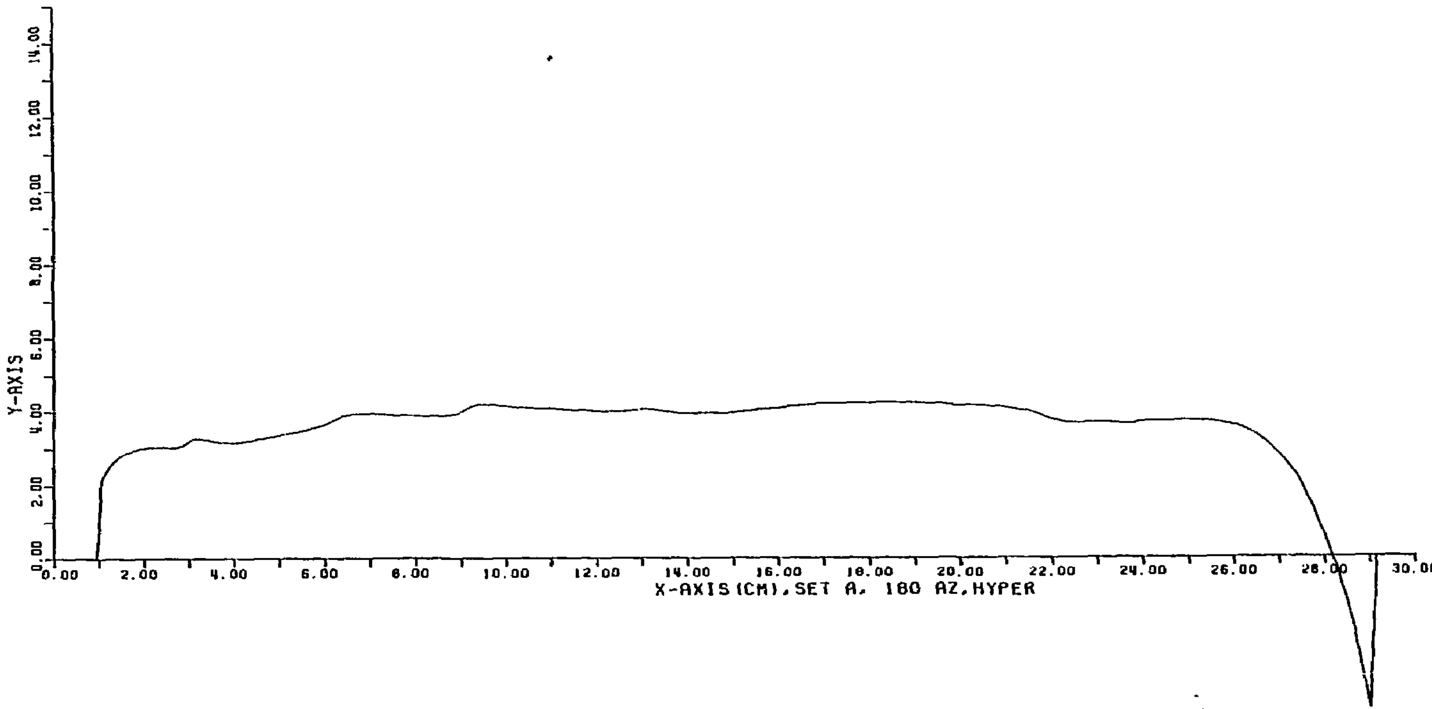

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 90 AZ, HYPER

FIGURE 5.25b



Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM), SET A, 180 AZ, HYPER

FIGURE 5.25c

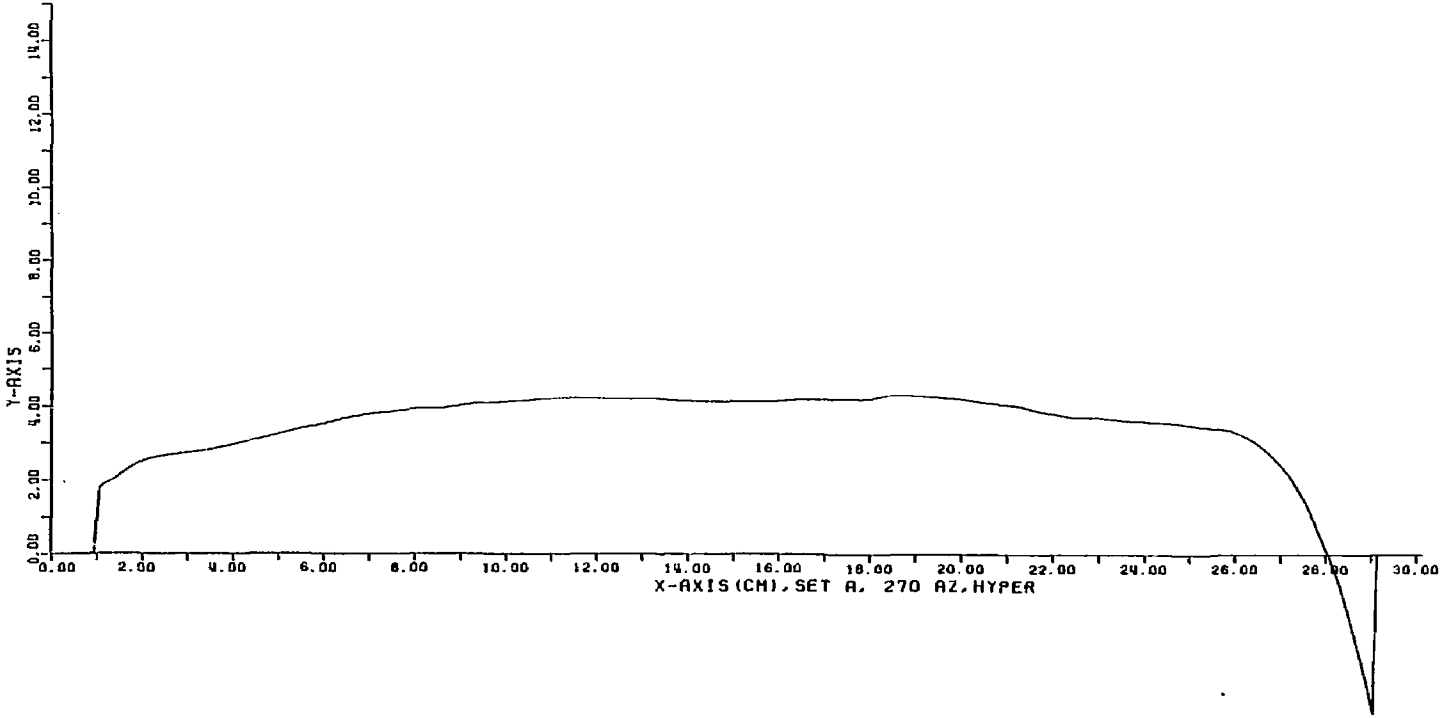

Y-AXIS
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
30.00
X-AXIS(CM),SET A, 270 AZ,HYPER

FIGURE 5.25d

surface, and one division on the ordinate scale equals 0.101 microns on the optical surface. For all of the axial plots, the large diameter of the surface is on the left and the small diameter is on the right. With the exception of the turned-down edges these plots are quite featureless. This is to be expected, since the original Scanner traces show that the local irregularities are only a few tenths of a microinch in height, which would be a few tens of mils on these plots. The magnification in the vertical direction could, of course, simply be increased. However, at a magnification high enough to bring out the local surface features, the plots would be badly distorted by the highly exaggerated slope circle curvatures. Instead, the axial scans have been replotted in Figures 5.24a through 5.25d at a higher magnification, 1×10^6X on the original plots, and the slope circle curvature has been removed. Thus, one ordinate division here equals .01 microns on the optical surface.

The results of the SCANNAZ processing of the azimuthal scans of the ellipsoid are listed in Table K. Among the quantities tabulated at the top of this table, FCTR1 through FCTR6 are scale factors to compensate for variations in the Scanner magnification normal to the optical surface from scan group to scan group. X SCALE is the azimuthal scale factor, chosen to scale the length of the processed Scanner traces to the approximate circumference of a typical LLL Indiround trace. Y SCALE is used to adjust the Scanner magnification normal to the optical surface to that of the Indiround device. SMAG once again is the Y magnification of the Scanner traces with respect to the optical surface. The AMPLITUDES and PHASES are those of the best fit sinusoids which were fitted to, and then subtracted from, the averaged traces during the course of the computer run.

The first column in Table K list the scan group number. The traces in Scan Group 1 were are made 0.10 inches from the small end of the ellipsoid. The Group 2 traces were made at the mid-plane. The Group 3 traces were made 0.10 inches from the large end. In Groups 4, 5, and 6, the data for Groups 1, 2, and 3 were simply repeated. The RMS deviations and the six largest deviations for each scan are listed in the last seven columns of this table. The RMS deviations are typically about .012 microns, and the largest individual deviation which was found is .045 microns.

The corresponding listing for the azimuthal scans of the hyperboloid is found in Table L. Once again, scan Groups 1, 2, and 3 were made 0.10 inches from the small end, at the mid-plane, and 0.10 inches from the large end of the hyperboloid, respectively.

PROGRAM SCANNAZ SURFACE ELLIPSE DELTA= .0200 (FCTR1 THRU FCTR6)= 1.0000 1.0170 .9530 1.0000 1.0170 .9530

X SCALE= 1.50000 X OFFSET= 2.500 Y SCALE=2.61000 Y OFFSET= 2.300 SMAG= 19170.0

AMPLITUDES= .1309 .2971 .4447 .1309 .2971 .4447 PHASES= 2.0109 2.8887 3.0602 2.0109 2.8887 3.0602

SCAN GROUP (NB)	SCAN NUMBER (NA)	NUMBER OF INTRPOLATO POINTS	RMS DEVIATION	SIX LARGEST DEVIATIONS ((((((((((MICRONS ON THE OPTICAL SURFACE))))))
1	1	273	.01413	.0262 .0256 .0251 .0246 .0240 .0233
1	2	273	.01083	-.0310-.0308-.0296-.0287-.0284-.0279
1	3	273	.01423	.0282 .0281 .0277 .0268 .0259 .0251
1	4	273	.00676	.0185 .0180 .0177 .0168 .0155 .0153
1	5	273	.01886	-.0395-.0390-.0386-.0383-.0376-.0376
1	6	273	.01127	-.0366-.0354-.0343-.0329-.0317-.0299
2	1	273	.00811	.0185 .0179-.0177-.0171-.0170 .0166
2	2	273	.01028	.0329 .0328 .0319 .0301 .0281 .0278
2	3	273	.00951	-.0244-.0225-.0218-.0211-.0211-.0210
2	4	273	.00905	-.0225-.0224-.0223-.0222-.0219-.0217
2	5	273	.01754	.0449 .0446 .0442 .0441 .0438 .0433
2	6	273	.01171	-.0273-.0272-.0272-.0263-.0259-.0258
3	1	273	.00802	-.0173-.0169-.0165-.0163 .0161-.0156
3	2	273	.01261	-.0337-.0336-.0332-.0321-.0312-.0307
3	3	273	.00986	.0281 .0279 .0243 .0239 .0237 .0231
3	4	273	.01165	-.0266-.0265-.0263-.0251-.0251-.0250
3	5	273	.00687	.0192 .0192 .0187 .0180 .0178 .0169
3	6	273	.01225	.0296 .0295 .0290 .0287 .0286 .0285
4	1	273	.01413	.0262 .0256 .0251 .0246 .0240 .0233
4	2	273	.01083	-.0310-.0300-.0296-.0287-.0284-.0279
4	3	273	.01423	.0282 .0281 .0277 .0268 .0259 .0251
4	4	273	.00676	.0185 .0180 .0177 .0168 .0155 .0153
4	5	273	.01886	-.0395-.0390-.0386-.0383-.0376-.0376
4	6	273	.01127	-.0366-.0354-.0343-.0329-.0317-.0299
5	1	273	.00811	.0185 .0179-.0177-.0171-.0170 .0166
5	2	273	.01028	.0329 .0328 .0319 .0301 .0281 .0278
5	3	273	.00951	-.0244-.0225-.0218-.0211-.0211-.0210
5	4	273	.00905	-.0225-.0224-.0223-.0222-.0219-.0217
5	5	273	.01754	.0449 .0446 .0442 .0441 .0438 .0433
5	6	273	.01171	-.0273-.0272-.0272-.0263-.0259-.0258
6	1	273	.00802	-.0173-.0169-.0165-.0163 .0161-.0156
6	2	273	.01261	-.0337-.0336-.0332-.0321-.0312-.0307
6	3	273	.00986	.0281 .0279 .0243 .0239 .0237 .0231
6	4	273	.01165	-.0266-.0265-.0263-.0251-.0251-.0250
6	5	273	.00687	.0192 .0192 .0187 .0180 .0178 .0169
6	6	273	.01225	.0296 .0295 .0290 .0287 .0286 .0285

TABLE K

PROGRAM SCANNA7 SURFACE HYPERBOLA DELTA= .02[illegible] (FCTR1 THRU FCTR6)= 1.0000 .9803 1.0210 1.0000 [illegible] 1.0210

X SCALE= 1.5600 X OFFSET= 2.300 Y SCALE=2.3800 Y OFFSET= 2.300 SMAG= 21000.0

AMPLITUDES= .1549 .1317 .1246 .1549 .1317 .1046 PHASES= 1.5698 1.7072 1.0201 1.5598 1.7072 1.0201

SCAN GROUP (NB)	SCAN NUMBER (NA)	NUMBER OF INTRPULATO POINTS	RMS DEVIATION	SIX LARGEST DEVIATIONS					
			(((((((((MICRONS ON THE OPTICAL SURFACE)))))))						
1	1	283	.00775	-.0217	-.0209	-.0200	-.0198	-.0187	-.0184
1	2	283	.01093	-.0299	-.0297	-.0295	-.0291	.0265	-.0265
1	3	283	.01523	-.0336	-.0321	-.0297	-.0289	-.0289	-.0288
1	4	283	.01977	.0421	.0406	.0385	.0381	.0365	.0363
1	5	283	.00535	.0176	.0173	.0155	.0134	.0134	-.0130
1	6	283	.01633	-.0273	-.0269	-.0265	-.0256	-.0246	-.0242
2	1	283	.01049	.0354	.0352	.0325	.0287	.0280	.0248
2	2	283	.00601	-.0184	-.0181	-.0155	-.0147	.0141	.0138
2	3	283	.00863	-.0188	-.0187	-.0177	-.0176	-.0174	-.0168
2	4	283	.00609	.0214	.0204	.0200	.0195	.0187	.0178
2	5	283	.00512	-.0131	-.0119	.0117	.0108	.0107	.0106
2	6	283	.00644	.0160	.0154	.0145	.0142	.0133	.0132
3	1	283	.00984	.0272	.0255	.0244	.0218	.0214	.0191
3	2	283	.01374	-.0304	-.0304	-.0301	-.0298	-.0297	-.0283
3	3	283	.01007	.0218	.0215	.0214	.0213	.0213	.0212
3	4	283	.01425	.0361	.0354	.0352	.0351	.0324	.0318
3	5	283	.02061	-.0419	-.0413	-.0399	-.0390	-.0383	-.0382
3	6	283	.01474	.0384	.0383	.0365	.0339	.0320	.0313
4	1	283	.00778	-.0217	-.0209	-.0200	-.0198	-.0187	-.0184
4	2	283	.01093	-.0299	-.0297	-.0296	-.0291	.0265	-.0265
4	3	283	.01523	-.0336	-.0321	-.0297	-.0289	-.0289	-.0288
4	4	283	.01937	.0421	.0405	.0385	.0391	.0365	.0363
4	5	283	.00535	.0176	.0173	.0155	.0134	.0134	-.0130
4	6	283	.01639	-.0273	-.0269	-.0266	-.0256	-.0246	-.0242
5	1	283	.01049	.0354	.0352	.0325	.0287	.0281	.0248
5	2	283	.00601	-.0184	-.0181	-.0155	-.0147	.0141	.0138
5	3	283	.00863	-.0188	-.0187	-.0177	-.0176	-.0174	-.0168
5	4	283	.00609	.0214	.0204	.0200	.0195	.0187	.0178
5	5	283	.00512	-.0131	-.0119	.0117	.0108	.0107	.0106
5	6	283	.00604	.0160	.0154	.0145	.0142	.0133	.0132
6	1	283	.00984	.0272	.0250	.0244	.0218	.0214	.0191
6	2	283	.01374	-.0304	-.0304	-.0301	-.0298	-.0297	-.0283
6	3	283	.01007	.0219	.0215	.0214	.0213	.0213	.0212
6	4	283	.01465	.0361	.0354	.0352	.0351	.0324	.0318
6	5	283	.02061	-.0418	-.0413	-.0399	-.0390	-.0383	-.0382
6	6	283	.01474	.0384	.0383	.0365	.0339	.0320	.0313

TABLE L

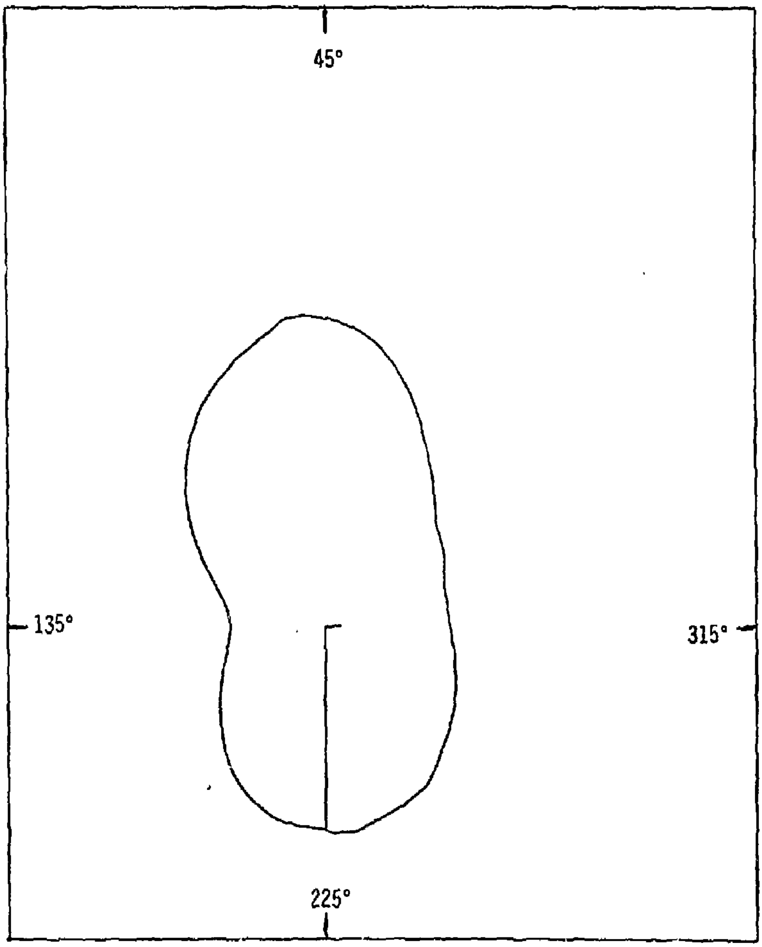


FIGURE 5.26a Azimuth Ellipsoid, Small End

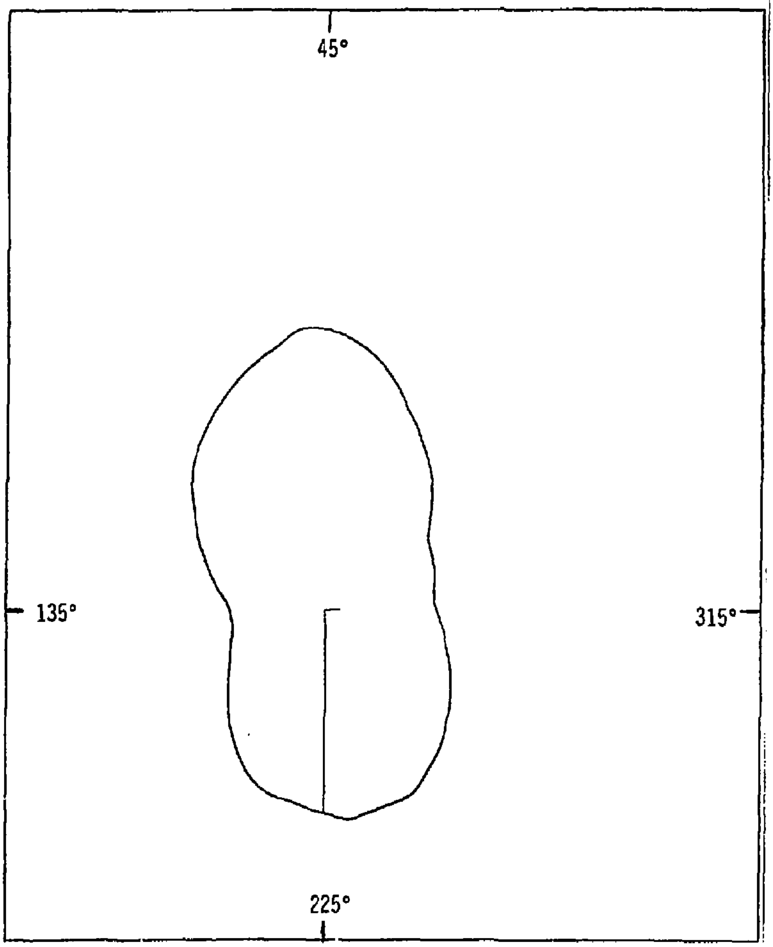


FIGURE 5.26b Azimuthal Ellipsoid, Midplane

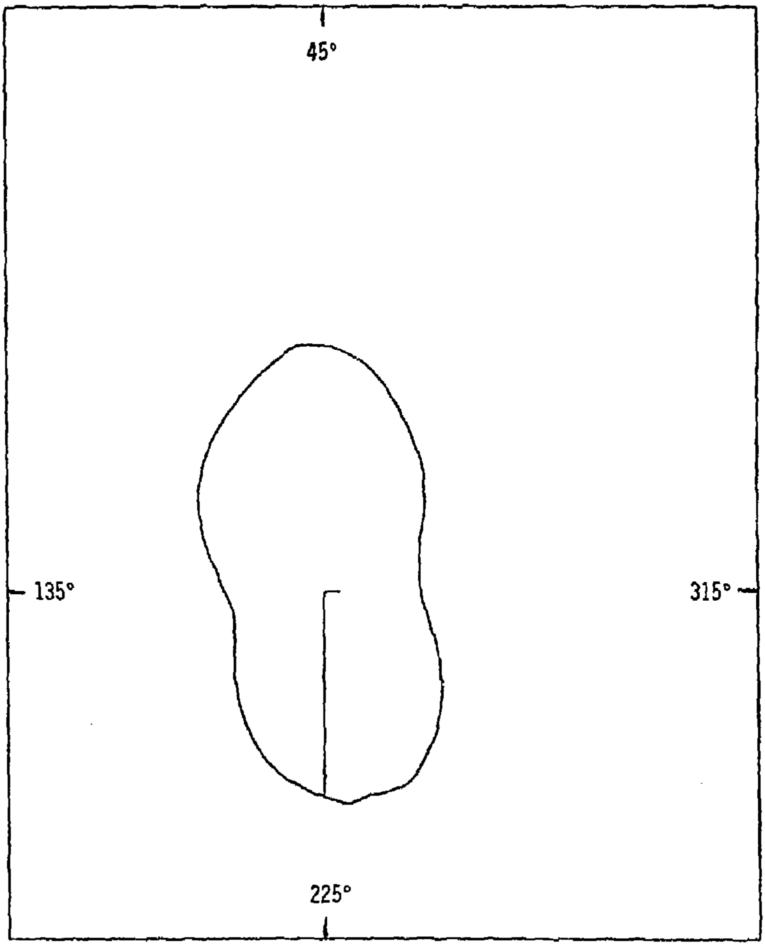


FIGURE 5.26c Azimuth Ellipsoid, Large End

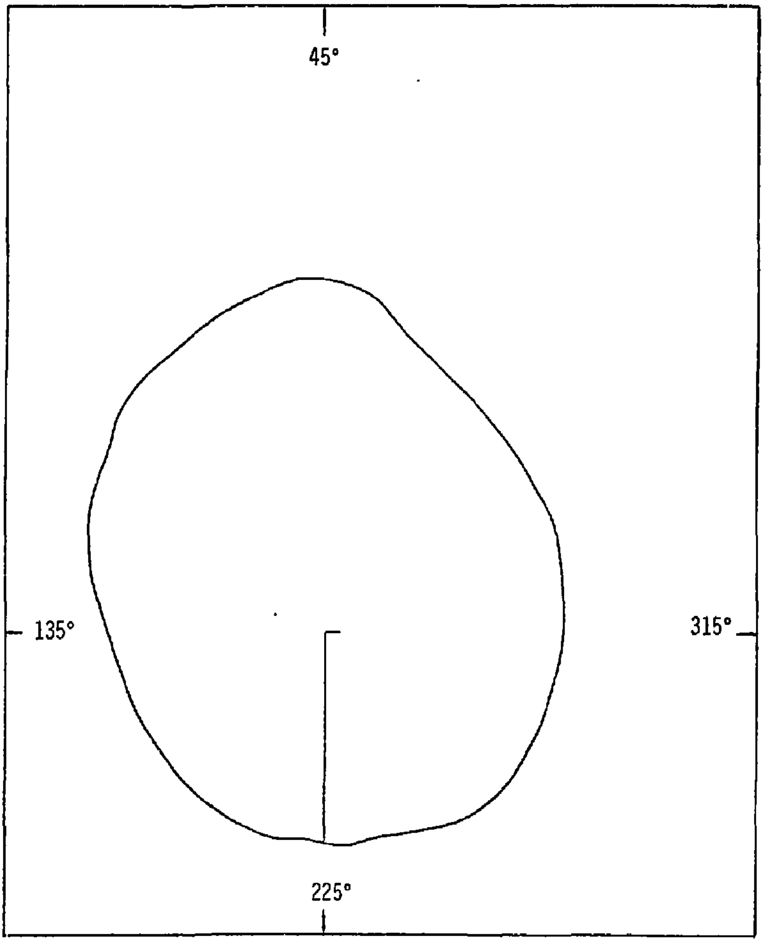


FIGURE 5.27a Azimuth Hyperboloid, Small End

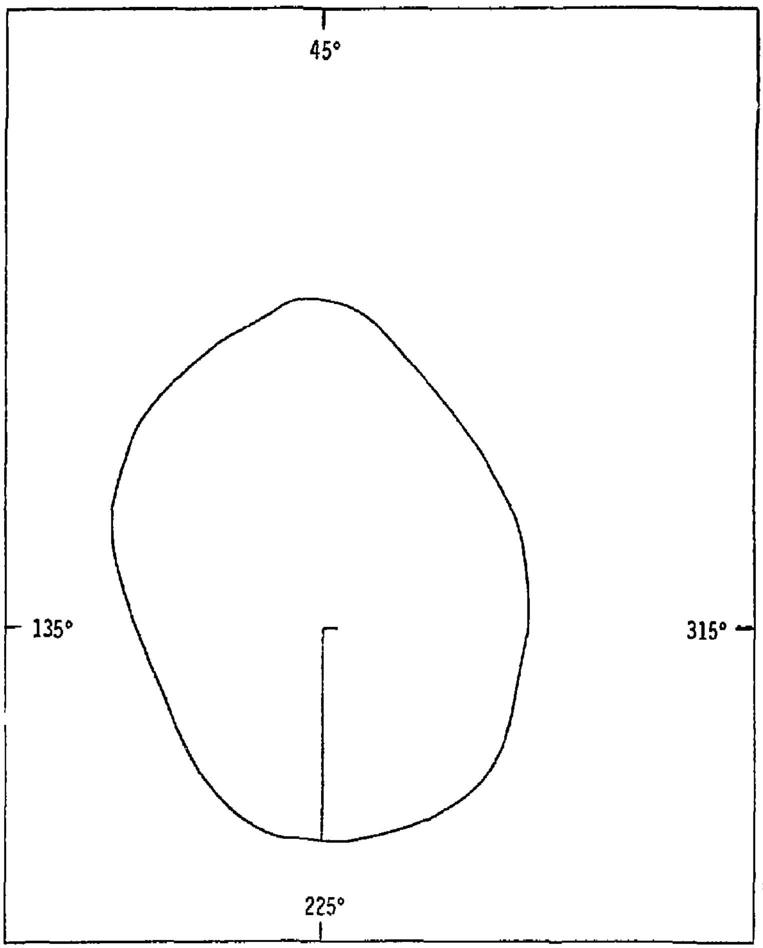


FIGURE 5.27b Azimuth Hyperboloid, Midplane

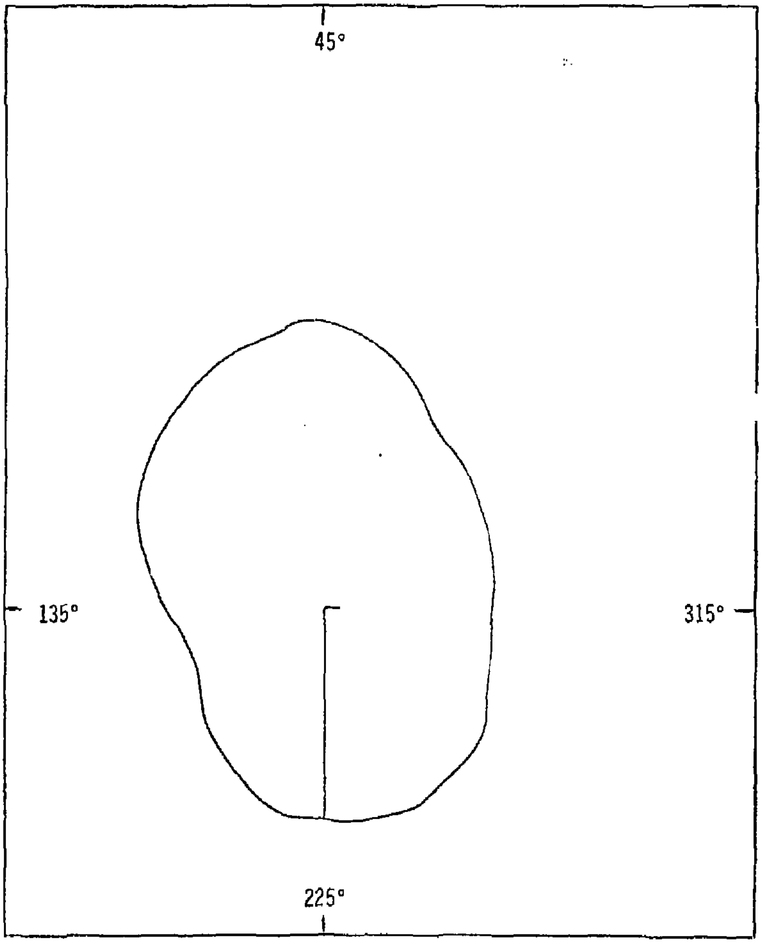


FIGURE 5.27c Azimuthal Hyperboloid, Large End

The processed azimuthal scans of the ellipsoid and hyperboloid are plotted in Figures 5.26 and 5.27, respectively. The radial magnification in these plots, in their original form and also as reproduced here, is 50,000 X, corresponding to .050 in. per microinch. The azimuthal position angles on these plots are referenced to the hole pattern on the face of the x-ray microscope in Figure 5.23.

5.5 Discussion of the Metrology Results

In this section, the results of the metrology performed on the 22X unit are compared to the acceptable tolerance limits listed in Column C of Table A (see page 21), and an estimate of the size of the resulting point spread fuction is made. The individual tolerances are compared to the results of the metrology data as follows:

1. Tolerance on Roundness (R_{MAX} - R_{MIN}). From Figures 5.26a through c, which show roundness errors magnified by 50,000X, the average out-of-roundness of the ellipsoid was determined to be 0.39 microns. This is within the roundness tolerance of 0.5 microns listed in Column C of Table A. The corresponding RMS radius of the image due to this roundness error is 0.17 microns, as determined from Figure 2.4. (Strictly speaking, Figure 2.4 applies only to the simplest out-of-roundness model. However, Figure 2.4 will be used here even though the out-of-roundness profile in this case is somewhat more complex.) The average out-of-roundness of the hyperboloid from Figures 5.27a through c is 0.16 microns, and is well within the tolerance limit. The corresponding RMS image raduis from Figure 2.4 is 0.07 microns.

2. Tolerance on dR/dθ (Maximum Slope Error about a Circumference). From the roundness plots of Figures 5.26a through c, the maximum azimuthal slope error on the ellipsoid is probably found at the 20° azimuthal position in Figure 5.26a. (The indent at the 135° position would appear to be more serious, but azimuthal slope error measurements show that it is comparable to the error at 20°.) At the 20° position, dR/dθ is 0.23 microns/cm or 4.7 arc seconds, which is within the allowable tolerance of 0.40 microns/cm. The average dR/dθ error on the ellipsoid is considerably less than this, and is estimated to be about 2 arc seconds or 0.10 microns/cm. The maximum dR/dθ error on the hyperboloid is probably found at the 345° position in Figure 5.27b, and corresponds to 0.12 microns/cm or 2.4 arc seconds.

More detailed data on the azimuthal slope errors of the hyperboloid are found in the high magnification Scanner traces of Figures 5.18, 5.19, and 5.20. A short computer program adapted from the Slope Distribution Routine of SCANNAX was written in order to process one of these scans, Number 8201 of Figure 5.19. Only one trace was processed because all seven of these traces are quite similar to one another. Number 8201 was chosen because it is one of the midplane traces, and should be quite representative of the overall hyperboloid surface. The resulting slope distribution is found in Table M. In this table, NBR is the number of mils along the Scanner trace which have an azimuthal slope error within a given range. Thus, 374 mils or 0.374 inches of the surface have an azimuthal slope error between 0.20 and 0.40 arc seconds. TOTAL is the running total, and reaches a maximum of 8328 because the Scanner trace was 8.3 inches long. From the TOTAL column, it can be seen that 5150/8328 or 62% of the surface of the hyperboloid has azimuthal errors of less than 1.8 arc seconds, and that 7642/8328 or 92% of the surface has errors of less than 3.1 arc seconds.

An expression for the image full width at half maximum (referenced to the object plane) due to the azimuthal slope errors has been derived by R. Price of LLL:

$$\text{FWHM} = 2.64\ \alpha O \Delta T$$

where α is the grazing angle of reflection, O is the object distance, and ΔT is twice the standard deviations of the azimuthal slope errors of the ellipsoid and hyperboloid added in quadrature. From the above discussion, reasonable values for the standard deviations of the azimuthal slope errors of the hyperboloid and ellipsoid are 1.8 and 2.0 arc seconds, respectively. Then, the calculated FWHM is 0.36 microns, and the radius at half maximum due to the azimuthal slope errors is 0.18 microns.

3. Tolerance on $\overline{\Delta R}$. No precise measurements of the average slopes were made. However, because of the inherent accuracy of the diamond-turning process and because very little material was removed during polishing and figuring, it is expected that the surfaces are well within the $\overline{\Delta R}$ tolerance of ± 2.0 microns.

4. Tolerance on $\Delta R(\theta)$. This surface error for the ellipsoid can be measured by superimposing Figure 5.26a onto Figure 5.26c, translating the

SLOPE DISTRIBUTION TABLES

SLOPE(SEC)	NBR	TOTAL	SLOPE
0.000			0.000
	268	268	
.200			.200
	374	642	
.400			.400
	626	1268	
.623			.623
	840	2108	
.871			.871
	724	2832	
1.148			1.148
	1010	3842	
1.457			1.457
	1308	5150	
1.801			1.801
	1192	6342	
2.184			2.184
	722	7064	
2.612			2.612
	578	7642	
3.088			3.088
	378	8020	
3.619			3.619
	68	8088	
4.211			4.211
	164	8252	
4.871			4.871
	16	8268	
5.616			5.616
	56	8324	
6.425			6.425
	[illegible]	8324	
7.338			7.338
	[illegible]	8324	
8.356			8.356
	[illegible]	8324	
9.491			9.491
	[illegible]	8324	
10.755			10.755
	[illegible]	8324	
12.165			12.165
	[illegible]	8324	
13.736			13.736
	2	8326	
15.487			15.487
	2	8328	
17.438			17.438
	0	8328	
19.613			19.613
	0	8328	
22.038			22.038
	0	8328	
24.740			24.740
	0	8328	

TABLE M

AZIMUTHAL SLOPE DISTRIBUTION FOR THE HYPERBOLOID AT MIDPLANE

two figures to the best-centered position, and measuring the resulting variation in the radial gap between the two profiles. This variation is about 5.5 mm on the plots, which corresponds to 0.11 microns on the optical surface, as compared to the tolerance value of 0.033 microns. Thus, this symmetry error exceeds the allowed tolerance by a factor of 3.3. Extrapolating the plot on Figure 2.7, this symmetry error should correspond to a RMS image radius in the object plane of 2.2 microns. By superimposing Figures 5.27a and 5.27c, the corresponding $\Delta R(\theta)$ value for the hyperboloid is 0.18 microns, corresponding to an RMS radius of 3.5 microns. Thus, the $\Delta R(\theta)$ measurements on both surfaces seriously exceed the allowed tolerance limits.

5. Tolerance on $\Delta S(x)$. From Figures 5.24 and 5.25, both the ellipsoid and hyperboloid surface profiles appear to be convex with respect to the ideal straight line profiles by about 0.010 microns (peak-to-peak). This corresponds to a $\Delta S(x)$ error of 0.005 microns (plus or minus), and is thus within the $\Delta S(x)$ tolerance limit of 0.011 microns. From Figure 2.9, this 0.01 micron convexity on the ellipsoid corresponds to an RMS radius in the object plane of 0.35 microns, and to an accompanying increase (0.75 mm) in the image distance needed to achieve optimum focus. Then, the convexity of the hyperboloid would produce an equivalent increase in the RMS radius and an additional 0.75 mm increase in the image distance.

6. Tolerance on dS/dx. The axial slope distribution for the ellipsoid in Table D shows that the maximum slope errors found were as large as 1.9 arc seconds or 0.09 microns/cm. This considerably exceeds the tolerance limit of 0.022 microns/cm. However, the table also shows that slope errors of this size are quite rare, and that 854/956 = 89% of the surface is within 0.86 arc seconds (0.04 microns/cm) and that 558/956 = 58% of the surface is within 0.47 arc seconds (0.023 microns/cm). The 0.47 arc second value, which corresponds 1.4 microns in the object plane, will be taken to be an estimate of the RMS radius due to the ellipsoid axial slope distribution.

The corresponding axial slope distribution for the hyperboloid in Table H shows a small number of slope errors extending up to a value of 10 arc seconds. Reference to Figures 5.25a through d indicates that these large slope errors come from the turned-down edge on the small end of the hyperboloid which was, unfortunately, not excluded from the region of the surface over which the metrology data was reduced. However, 611/944 = 65% of the length of the surface was within 0.65 arc seconds, corresponding to 1.9 microns in the object plane. This 1.9 micron value will be taken to be an estimate of the RMS radius due to the hyperboloid axial slope distribution.

7. Tolerance on RMS Surface Roughness. From Figures 5.24 and 5.25, the apparent local roughness averaged over the 50 micron Scanner spot size appears to be less than 5Å, peak-to-peak. However, details on this scale could have been lost in the digitization process. Referring to unprocessed Scanner traces, such as Figures 5.2 and 5.10, the surface roughness appears to be less than 0.5 mm peak-to-peak as measured on the original, unreduced traces. This corresponds to about 15Å, peak-to-peak, and thus is well within the 20Å RMS tolerance limit. Because of the relatively large size of the Scanner sampling spot, true measurements of the surface roughness would have to be made by other means, such as by x-ray measurements.

8. The Optical System Tolerances. No direct, precision measurements of the last four tolerances were made under this program. However, because of the inherent accuracy of the diamond-turing process, and because of small amounts of material removed during polishing and figuring, it is expected that these tolerances were satisfied. Some indication of the axial tilt and lateral translation might be found by making intercomparisons of various sets of the original Scanner traces. However, such intercomparisons would require a confidence in the level of the Scanner stability which is probably not justified.

The various estimates of the RMS radii found above are added in quadrature as follows to give an overall estimate of the RMS image radius, as referenced back to the object plane:

$$R_{rms} = (.17^2 + .07^2 + .18^2 + 2.2^2 + 3.5^2 + .35^2 + .35^2 + 1.4^2 + 1.9^2)^{1/2}$$

- .17 — Ellip. Roundness
- .07 — Hyper. Roundness
- .18 — Ellip. and Hyper. dR/dθ
- 2.2 — Ellip. ΔR(θ)
- 3.5 — Hyper. ΔR(θ)
- .35 — Ellip. ΔS(x)
- .35 — Hyper. ΔS(x)
- 1.4 — Ellip. dS/dx
- 1.9 — Hyper. d/S/dx

$$R_{rms} = 4.8 \text{ microns}$$

No contribution for local surface roughness was included here because the surface roughness was not characterized sufficiently to make a quantative estimate of its effect. The $dR/d\theta$ value used above was the calculated radius at half height rather than the RMS radius. However, since the point spread function due to $dR/d\theta$ errors is expected to be rounded rather than sharply peaked, the RMS radius and the radius at half height are expected to be roughly comparable.

By far, the largest contributions to the overall RMS radius are the $\Delta R(\theta)$ and dS/dx errors. It is therefore these errors (as well as the effects of the local surface roughness) which will limit the effective solid collecting area of this unit when it is used in applications requiring high spatial resolution, in the range of a micron or two. On the other hand, since the point spread function due to the dS/dx errors is very sharply peaked in the center, the spatial resolution will probably be limited by the $\Delta R(\theta)$ errors alone. Eliminating the contributions of the dS/dx errors from the above calculation, and also the contributions of the $\Delta S(x)$ errors which would also give a sharply peaked distribution, the value of R_{rms} is reduced to 4.1 microns. This should be a measure of the spatial resolution of this unit. However, preliminary x-ray measurements at LLL indicate that the spatial resolution is substantially better than would be predicted from this value. The probable explanation is that, when the effects of a symmetry error such as $\Delta R(\theta)$ are combined with a small amount of surface scattering in the plane of incidence, the resulting point spread function is still sharply peaked in the center.

Because of the relatively large $\Delta R(\theta)$ symmetry errors found in this unit, using it in the apertured mode (with the entrance aperture reduced to a sector in azimuth) should result in a substantial improvement in image quality.

APPENDIX A

PROGRAM LISTING FOR SCANNAX

```
      PROGRAM SCANMAX(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT, TAPE1)
      DIMENSION XA(400,4,12),YA(400,4,12), TITLE(7),     YB(400,4,12),
     1XMIN(4,12),XPEAK(2,4,12),C(4,12),  A(4,12), SLPE1(400,4),
     1 SLPE2(400,4),    RMS(4,13), ERROR(6,4,13),XC(400), YC(400)
C
C READ INPUT QUANTITIES
C
      READ(5,10) CURVE,ALMIN,ALMAX
   10 FORMAT(3F10.5)
      READ(5,15) DELTA,AK1,AK2,AK3,AIMAX
   15 FORMAT(5F10.5)
      LMIN=ALMIN+.0001
      LMAX=ALMAX+.0001
      K1=AK1+.0001
      K2=AK2+.0001
      K3=AK3+.0001
      IMAX=AIMAX+.0001
      READ(5,17) RECOR,SCANS ,CCOR
   17 FORMAT(3F10.5)
      READ(5,25) FCTR1, FCTR2
      READ(5,25) XSCLE,XOFST
   25 FORMAT(2F10.5)
      READ(5,30) YSCLE,C1,C2,YOFST,SMAG
   30 FORMAT(4F10.5,F10.1)
      READ(5,25) AINTVL,XMAG
      INTVL=AINTVL+.0001
      WRITE(6,1210)
      WRITE(6,1210)
      WRITE(6,1210)
CCCC
      IND=111
      WRITE(6,2000)  IND
      WRITE(6,1210)
 2000 FORMAT(6X,I3)
C
C     ****************************************
C     ****************************************
C
C      CURVE=1.0 FOR ELLIPSOID OR 2.0 FOR HYPERBOLOID.
C
C    LMIN IS THE MIN VALUE OF LABEL OF SCANS TO BE READ INTO MEMORY.
C    LMAX IS THE MAX VALUE OF LABEL.
C
C     DELTA= INTERPOLATION INCREMENT(X DIRECTION).
C     K1 IS THE TOTAL NUMBER OF INTERPOLATION INTERVALS ALONG A SCAN.
C     K1*DELTA=INTERPOLATION RANGE (MUST BE SHORTER THAN LENGTH OF
C         DIGITIZED PART OF SCAN).
C     K3*DELTA= LENGTH OF THE CROSS CORRELATION RANGES.
C     K2*DELTA= DISTANCE FROM XMIN TO START OF THE FIRST CROSS
C          CORRELATION INTERVAL,  AND ALSO THE DISTANCE FROM THE
C          END OF THE SECOND CROSS CORRELATION INTERVAL TO THE END
C          OF THE INTERPOLATION INTERVAL.
C      K1,K2,AND K3 (EVEN INTEGERS) ARE INPUT AS THE REAL NUMBERS
C          AK1,AK2,AND AK3.
C
C     I=INDEX OF POINTS ON A GIVEN SCAN AS READ FROM THE DATA TAPE.
C          RANGE OF I IS 1 TO IMAX.
```

```
C     IMAX IS INPUT AS THE REAL NUMBER AIMAX.
C        CHOOSE IMAX TO BE LARGE ENOUGH SO THAT ALL REGISTERS
C        ARE UNDERFILLED.
C
C   SCANS IS THE NUMBER OF TRACES TO BE READ FROM THE DATA TAPE.
C     (ALLOWED VALUES ARE 24.0 AND 48.0).
C
C   REODR INDICATES WHETHER THE SEQUENCE OF SCANS IS TO BE REORDERED
C       (REODR=1.0), OR NOT (REODR=0.0).  SEE REODR ROUTINE, BELOW.
C   CCOR INDICATES WHETHER THE CROSS CORRELATION ROUTINES ARE TO
C       BE USED (CCOR=1.0) OR BYPASSED (CCOR=0.0).
C
C      FCTR1 AND FCTR2 ARE SCALE FACTORS TO ADJUST THE THE Y SCALES
C           OF THE FIRST AND SECOND DAY SCANS, RESPECTIVELY.
C     XSCLE AND YSCLE ARE SCALE FACTORS TO ENLARGE SCANNER TRACES TO
C         THE SCALE OF THE CLEAVITE TRACES.
C     XOFST AND YOFST ARE OFFSETS TO PROPERLY POSITION FINAL PLOTS
C         ON PAGE.
C     C1 AND C2 ARE SLOPE CIRCLE CONSTANTS IN THE EQUATION
C            Y=(YSCLE*Y)+C1*((X+C2)**2)+YOFST
C      SMAG IS THE MAGNIFICATION OF THE SCANNER TRACES (EQUAL TO 1/8).
C      INTVL IS THE NUMBER OF UNITS OF DELTA OVER WHICH THE SLOPES
C          ARE CALCULATED IN THE SLOPE DISTRIBUTION ROUTINE.
C      INTVL IS INPUT AS THE REAL NUMBER AINTVL.
C      XMAG IS THE Y MAGNIFICATION OF THE SCANNER.
C
C  ***********************************
C  ***********************************
C
C   READ THE DATA TAPE FROM LABEL=LMIN TO LABEL=LMAX.
C
      CALL  ENVIROT(LMIN,LMAX,XA,YA,NA,NB)
C
      WRITE(6,1210)
CCCC
      IND=112
      WRITE(6,2000)  IND
C
C
C  THE X AND Y COORDINATES OF POINTS ON THE 48 (MAX) SCANS HAVE BEEN
C    READ FROM THE DATA TAPE, AND ARE STORED IN REGISTERS XA(I,NA,NB),
C    YA(I,NA,NB).
C
C    NA= AZIMUTHAL POSITION OF SCAN.  RANGE IS 1 TO 4.
C         NA=1 IS 0 DEGREES.  NA=2 IS 90 DEGREES.  ETC.
C    NB= SCAN GROUP INDEX.  RANGE IS 1 TO 12, WITH 1 TO 6 BEING THE
C        FIRST DAY SCANS AND 7 TO 12 BEING THE SECOND DAY SCANS.
C         EACH GROUP CONSISTS OF FOUR AXIAL SCANS 90 DEG APART.
C
C    ANOTHER SET OF REGISTERS YB(M,NA,NB)  IS USED
C        FOR STORAGE OF INTERMEDIATE RESULTS.  RANGE OF M IS 1 TO K1.
C
C   REORDER ROUTINE.
C
C     IF THE SCANS WERE MADE IN GROUPS OF SIX AT EACH OF THE FOUR
C       AZIMUTHAL POSITIONS (THAT IS , IF REODR=1.0) INSTEAD OF
C       IN ALTERNATING GROUPS, REORDER THE SCANS TO MATCH THE NORMAL
```

```
C        ALTERATIONS [illegible] HU HC .
C
      IF(ICOM.LT. [illegible]) GO TO 7
C     REORDER [illegible] XA [illegible] SITES.
      N=0
      NAMA=1
      DO 3[illegible] NC=1,12
      DO [illegible] NA=1,6
      N=N+1
      IF(N.[illegible].7) NAMA=NAMA+1
      IF(N.EQ.7) N=1
      NMNA=N
      IF(N[illegible].GE.[illegible]) N[illegible]=NMNA+6
      IF((NA.EQ.1).AND.(N[illegible].EQ.7)) NAMA=1
      DO 3[illegible] I=1,IMAX
      XALT(NAMA,NMNA)=XALT(NA,NC)
  [illegible] CONTINUE
  [illegible] CONTINUE
  [illegible] CONTINUE
      DO 3[illegible] NC=1,12
      DO 3[illegible] NA=1,6
      DO 3[illegible] I=1,IMAX
      XALT(NA,NC)=[illegible](NA,NC)
  [illegible] CONTINUE
  [illegible] CONTINUE
  [illegible] CONTINUE
C     REORDER TH[illegible] XA [illegible]SITES.
      N=0
      NAMA=1
      DO [illegible] NC=1,12
      DO [illegible] NA=1,6
      N=N+1
      IF(N.[illegible].7) NAMA=NAMA+1
      IF(N.EQ.7) N=1
      NMNA=N
      IF(N[illegible].GE.[illegible]) N[illegible]=NMNA+6
      IF((NA.EQ.1).AND.(N[illegible].EQ.7)) NAMA=1
      DO [illegible] I=1,IMAX
      X[illegible](I,NA,NC)=XALT(I,NA,NC)
  [illegible] CONTINUE
  [illegible] CONTINUE
  [illegible] CONTINUE
      DO [illegible] NC=1,12
      DO [illegible] NA=1,6
      DO [illegible] I=1,IMAX
      XALT(I,NA,NC)=X(I,[illegible])
      XALT(I,NA,NC)=[illegible]
  [illegible] CONTINUE
  [illegible] CONTINUE
  [illegible] CONTINUE
C
C
C     [illegible]
C     [illegible]
C     [illegible]
C     [illegible]
      [illegible]
```

```
      NNDB=NB+6
      DO 43 NA=1,4
      DO 45 I=1,IMAX
      XA(I,NA,NNDB)=XA(I,NA,NB)
      YA(I,NA,NNDB)=YA(I,NA,NB)
   45 CONTINUE
   43 CONTINUE
   41 CONTINUE
C
C SUBTRACT OFF THE X DISPLACEMENT XMIN(NA,NB).
C
   47 DO 50 NB=1,12
      DO 60 NA=1,4
      XMIN(NA,NB)=XA(1,NA,NB)
      XMNN=XMIN(NA,NB)
      DO 70 I=1,IMAX
      XA(I,NA,NB)=XA(I,NA,NB)-XMNN
   70 CONTINUE
C      MAKE INITIAL VALUE OF XA LESS THAN 0.0.   (THIS IS NECESSARY
C           FOR INTERPOLATION ROUTINE TO WORK).
      IF(XA(1,NA,NB).GE. 0.0) XA(1,NA,NB)=-.001
      WRITE(6,9997) XA(1,NA,NB), XA(2,NA,NB) ,XA(3,NA,NB),XA(4,NA,NB)
      WRITE(6,9997) YA(1,NA,NB), YA(2,NA,NB) ,YA(3,NA,NB),YA(4,NA,NB)
 9997 FORMAT(4F10.5)
   60 CONTINUE
   50 CONTINUE
C
CCCC
      IND=113
      WRITE(6,2000)  IND
C
      IF(CCOR.LT.0.50) GO TO 9321
C
C FIRST INTERPOLATION.
C (COMPUTE NEW EVENLY SPACED SETS OF POINTS XB, YB FROM THE ORIGINAL
C      UNEVENLY SPACED SETS XA,YA. (THE VALUES OF XB ARE NOT STORED
C      EXPLICITLY.))
C
      DO 100 NB=1,12
      DO 105 NA=1,4
      I=1
      J=2
      M=0
      X=-DELTA
  110 X=X+DELTA
      M=M+1
      IF(M.GT.K1) GO TO 105
  120 IF((X.GE.XA(I,NA,NB)).AND.(X.LE.XA(J,NA,NB))) GO TO 130
      I=I+1
      J=J+1
      GO TO 120
  130 XAI=XA(I,NA,NB)
      YAI=YA(I,NA,NB)
      IF((YAI.LT.0.0001). AND .(YAI.GT.-0.0001)) GO TO 105
      Y=YAI+((YA(J,NA,NB)-YAI)*(X-XAI))/(XA(J,NA,NB)-XAI)
      YB(M,NA,NB)=Y
      GO TO 110
```

```
  165 CONTINUE
  157 CONTINUE
CCCC
      IND=114
      WRITE(6,2000)  IND
C
C
C LEVEL THE INTERPOLATED CURVES BY SUBTRACTING OFF THEIR
C      AVERAGE SLOPES. ALSO, APPLY FILTER TO REMOVE LOWER SPATIAL
C           FREQUENCIES, AND SUBTRACT OFF MOST OF THE DC LEVEL.
C
      K10=K2+K3
      K11=K1-K2-K3
      K12=K1-K2
      DO 150 NB=1,12
      DO 155 NA=1,4
      SUMA=0.0
      DO 160 M=K2,K10
      SUMA=SUMA+YB(M,NA,NB)
  160 CONTINUE
      SUMB=0.0
      DO 170 M=K11,K12
      SUMB=SUMB+YB(M,NA,NB)
  170 CONTINUE
      K9=K3+1
      ASLOP=(SUMB-SUMA)/(K9*DELTA*(K1-(2*K2)-K3))
      ASD=ASLOP*DELTA
      DO 180 M=1,K1
      YB(M,NA,NB)=YB(M,NA,NB)-ASD*M
  180 CONTINUE
      KX=K1-4
      YBA=YB(1,NA,NB)
      YBB=YB(2,NA,NB)
      YBC=YB(3,NA,NB)
      YBD=YB(4,NA,NB)
      YBE=YB(5,NA,NB)
      DO 4121 M=6,KX
      YBA=YBB
      YBB=YBC
      YBC=YBD
      YBD=YBE
      YBE=YB(M,NA,NB)
      MM3=M+3
      MM4=M+4
      YB(M,NA,NB)= YB(M,NA,NB) +0.2 -(YBA+YBB+YB(MM3,NA,NB)+
     1YB(MM4,NA,NB))/4.0
 4121 CONTINUE
  155 CONTINUE
  150 CONTINUE
CCCC
      IND=115
      WRITE(6,2000)  IND
C
C COMPUTE CROSS CORRELATION FUNCTIONS FOR REGIONS AT THE STARTS OF
C      THE SCANS,AND FIND THE PEAKS OF THESE FUNCTIONS. SPECIFICALLY,
C      CROSS CORRELATE SCANS OF GROUPS NB=2 TO 6 WITH CORRESPONDING,
C      SCANS OF GROUP NB=1, AND CROSS CORRELATE SCANS OF GROUPS NB=8
```

```
      C      TO 12 WITH CORRESPONDING SCANS OF GROUP NB=7. (EXCEPTION. FIRST
      C      SCAN OF GROUP 7 IS CROSS CORRELATED WITH FIRST SCAN OF GROUP 1).
      C
             WRITE(6,1240)
             WRITE(6,1210)
             WRITE(6,1240)
             WRITE(6,185)
         185 FORMAT(6X*CROSS COR FCTN    PEAK VALUE    SHIFT (BINS)          (BEG
            1INNING OF SCANS)*)
             DO 200 NA=1,4
             DO 205 NB=1,12
             L8=1
             IF((NB.GE.7).AND.(NA.GE.2)) L8=7
             IF(NB.GE.8) L8=7
             IPEAK=0
             SUM2=0.0
             DO 210 L1=1,K2
             L4=K2+K3
             SUM1=0.0
             DO 220 L2=K2,L4
             L3=L2+L1-(K2/2)
             SUM1=SUM1+YB(L2,NA,L8)*YB(L3,NA,NB)
         220 CONTINUE
             WRITE(6,225) SUM1,SUM2
         225 FORMAT(5X,2F14.6)
             IF(SUM1.GT.SUM2) GO TO 230
             GO TO 210
         230 IPEAK=L1-(K2/2)
             SUM2=SUM1
         210 CONTINUE
             WRITE(6,235)  IPEAK
         235 FORMAT(38X,I3)
             XPEAK(1,NA,NB)=IPEAK*DELTA
      C XPEAK IS THE AMOUNT OF SHIFT REQUIRED TO BRING THE BEGINNINGS OF
      C      THE TWO SCANS INTO REGISTER
         205 CONTINUE
         200 CONTINUE
             WRITE(6,1240)
             WRITE(6,1210)
             WRITE(6,1210)
             WRITE(6,1240)
      C
      CCCC
             IND=116
             WRITE(6,2000)  IND
             WRITE(6,1210)
      C
      C COMPUTE CROSS CORRELATION FUNCTIONS FOR REGIONS AT THE ENDS OF
      C      THE SCANS,AND FINE THE PEAKS OF THESE FUNCTIONS.
      C
             WRITE(6,7321)
        7321 FORMAT(6X*CROSS COR FCTN    PEAK VALUE    SHIFT (BINS)          (END
            1 OF SCANS)*)
             DO 300 NA=1,4
             DO 305 NB=1,12
             L8=1
             IF((NB.GE.7).AND.(NA.GE.2)) L8=7
```

```
      IF(NB.GE.9) L8=7
      IPEAK=0
      SUM2=0.
      DO 310 L1=1,K2
      L5=K1-K2-K3
      L6=K1-K2
      SUM1=0.0
      DO 320 L2=L5,L6
      L7=L2+L1-(K2/2)
      SUM1=SUM1+YB(L2,NA,L8)*YB(L7,NA,NB)
  320 CONTINUE
      WRITE(6,225) SUM1,SUM2
      IF(SUM1.GT.SUM2) GO TO 330
      GO TO 310
  330 IPEAK=L1-(K2/2)
      SUM2=SUM1
  310 CONTINUE
      WRITE(6,235) IPEAK
      XPEAK(2,NA,NB)=IPEAK*DELTA
C XPEAK IS THE AMOUNT OF SHIFT REQUIRED TO BRING THE ENDS OF
C     THE TWO SCANS INTO REGISTER.
  305 CONTINUE
  300 CONTINUE
      WRITE(6,1210)
      WRITE(6,1210)
C
CCCC
      IND=117
      WRITE(6,2000) IND
C SHIFT CORRESPONDING SCANS INTO REGISTER IN THE X DIRECTION. THE
C     AMOUNT OF THE SHIFT IS THE AVERAGE OF THE BEGINNING XPEAK
C     AND THE ENDING XPEAK, EXCEPT FOR THE ADDITIONAL SLIDE CORRECTION
C    FOR SOME CASES, AS SHOWN BELOW.
C
      DO 400 NA=1,4
      DO 410 NB=1,12
      SHIFT=(XPEAK(1,NA,NB)+XPEAK(2,NA,NB))/2.0
      SLIDE=((XPEAK(1,1,7)+XPEAK(2,1,7))/2.0)+SHIFT
      IF((NB.GE.7).AND.(NA.GE.2)) SHIFT=SLIDE
      IF(NB.GE.8) SHIFT=SLIDE
      DO 420 I=1,IMAX
      XA(I,NA,NB)=XA(I,NA,NB)+SHIFT
  420 CONTINUE
C      MAKE INITIAL VALUE OF XA LESS THAN 0.0.   (THIS IS NECESSARY
C          FOR INTERPOLATION ROUTINE TO WORK).
      IF(XA(1,NA,NB).GE. 0.0) XA(1,NA,NB)=-.001
  410 CONTINUE
  400 CONTINUE
C
CCCC
      IND=118
      WRITE(6,2000) IND
C SECOND INTERPOLATION.
C
C
 9321 DO 500 NB=1,12
      DO 505 NA=1,4
```

```
      I=1
      J=2
      M=0
      X=-DELTA
  510 X=X+DELTA
      M=M+1
      IF(M.GT.K1) GO TO 615
  520 IF((X.GE.XA(I,NA,NB)).AND.(X.LE.XA(J,NA,NB))) GO TO 530
      I=I+1
      J=J+1
      GO TO 520
  530 XAI=XA(I,NA,NB)
      YAI=YA(I,NA,NB)
      IF((YAI.LT.-  1). AND .(YAI.GT.-  511)) GO TO 615
      Y=YAI+((YA(J,NA,NB)-YAI)*(X-XAI))/(XA(J,NA,NB)-XAI)
      YB(M,NA,NB)=Y
      GO TO 510
  615 CONTINUE
  600 CONTINUE
C
CCCC
      INO=119
      WRITE(6,2000)  INO
C
C     FIND THE LEAST SQUARES BEST FIT STRAIGHT LINE FOR EACH SCAN.
C
      NPTS=K1-(2*K2)+1
      K12=K1-K2
      DO 61  NB=1,12
      DO 610 NA=1,4
      WRITE(6,9997) XA(1,NA,NB), XA(2,NA,NB) ,XA(3,NA,NB),XA(4,NA,NB)
      WRITE(6,9997) YA(1,NA,NB), YA(2,NA,NB) ,YA(3,NA,NB),YA(4,NA,NB)
      WRITE(6,9997) YB(1,NA,NB), YB(2,NA,NB) ,YB(3,NA,NB),YB(4,NA,NB)
      SUMX=0.0
      SUMY=0.0
      SUMXY=0.0
      SUMX2=0.0
      DO 620 M=K2,K12
      X=M*DELTA
      Y=YB(M,NA,NB)
      SUMX=SUMX+X
      SUMY=SUMY+Y
      SUMXY=SUMXY+(X*Y)
      SUMX2=SUMX2+(X*X)
  620 CONTINUE
      DEL=(NPTS*SUMX2)-(SUMX*SUMX)
      A(NA,NB)=((SUMX2*SUMY)-(SUMX*SUMXY))/DEL
      B(NA,NB)=(NPTS*SUMXY)-(SUMX*SUMY))/DEL
      WRITE(6,9997) YB(1,NA,NB), YB(2,NA,NB) ,YB(3,NA,NB),YB(4,NA,NB)
  61  CONTINUE
  610 CONTINUE
C
CCCC
      INO=120
      WRITE(6,2   )  INO
C
C     REDUCE ALL CURVES TO ZERO SLOPE AND ZERO LEVEL, AND
```

```
      C                MULTIPLY BY THE SCALE FACTORS FCTR1 OR FCTR2.
      C
            DO 78  NB=1,12
            FCTR=FCTR1
            IF(NB.GE.7)  FCTR=FCTR2
            DO 785 NA=1,4
            AA=A(NA,NB)
            BB= B(NA,NB)*DELTA
            DO 789 M=1,K1
            YB(M,NA,NB)=(YB(M,NA,NB)-  (BB*M)-AA)*FCTR
        789 CONTINUE
            WRITE(6,9997) YB(1,NA,NB), YB(2,NA,NB) ,YB(3,NA,NB),YB(4,NA,NB)
        785 CONTINUE
        78  CONTINUE
      C
      CCCC
            IND=121
            WRITE(6,2000)  IND
      C
      C ALL SCANS ARE NOW REDUCED TO COMPARABLE SLOPE ,LEVEL, AND
      C          REGISTRATION, AND ARE STORED IN REGISTERS YB(M,NA,NB).
      C
      C CO-ADD AND AVERAGE CORRESPONDING SCANS.
      C
            DO 800 NA=1,4
            DO 810 I=1,K1
      C CO-ADD AND AVERAGE FIRST DAY SCANS (GROUPS 1 THRU 6).
            YA(I,NA,1)=YB(I,NA,1)+YB(I,NA,2)+YB(I,NA,3)+YB(I,NA,4)+YB(I,NA,5)+
           1YB(I,NA,6)
            YA(I,NA,1)=YA(I,NA,1)/6.0
      C CO-ADD AND AVERAGE SECOND DAY SCANS (GROUPS 7 THRU 12).
            YA(I,NA,7)=YB(I,NA,7)+YB(I,NA,8)+YB(I,NA,9)+YB(I,NA,10)+
           1YB(I,NA,11)+YB(I,NA,12)
            YA(I,NA,7)=YA(I,NA,7)/6.0
        810 CONTINUE
        800 CONTINUE
      C
      CCCC
            IND=122
            WRITE(6,2000)   IND
      C COMPUTE RMS DEVIATION OF INDIVIDUAL SCANS FROM THE CORRESPONDING AVERAGE
      C     SCANS WITHIN A GIVEN DAY,AND ALSO THE SIX LARGEST DEVIATIONS.
      C            (CONVERT OUTPUT UNITS TO MICRONS ON THE OPTICAL SURFACE).
            K1XX=K1-15
            NBP=K1-29
            DO 910 NB=1,12
            DO 910 NA=1,4
            NC=1
            IF(NB.GE.7) NC=7
            DSUM=0.0
            DO 920 M=15,K1XX
            DEV=YB(M,NA,NB)-YA(M,NA,NC)
            DSUM=DSUM+DEV*DEV
            YA(M,NA,5)=DEV
        920 CONTINUE
            DDSUM=DSUM/NBP
            RMS(NA,NB)=SQRT(DDSUM)*(254.0.0/SMAG)
```

```
      DO 925 IJ=1,6
      ERRRR=0.0
      DO 931 M=15,K1XX
      YH=ABS(YA(M,NA,5))
      IF(YH.LT.ERRRR) GO TO 931
      INDEX=M
      ERRRR=YH
  931 CONTINUE
      ERROR(IJ,NA,N3)=YA(INDEX,NA,5)*(25400.0/SMAG)
      YA(INDEX,NA,5)=0.0
  925 CONTINUE
  910 CONTINUE
  900 CONTINUE
C
CCCC
      IND=123
      WRITE(6,2300)  IND
C COMPUTE RMS DEVIATION BETWEEN AVERAGE SCANS OF FIRST DAY AND THE
C       CORRESPONDING AVERAGE SCANS OF THE SECOND DAY, AND ALSO THE
C       SIX LARGEST DEVIATIONS BETWEEN EACH PAIR OF SCANS.
C            (CONVERT OUTPUT UNITS TO MICRONS ON THE OPTICAL SURFACE).
C
      DO 1000 NA=1,4
      DSUM=0.0
      DO 1010 M=15,K1XX
      DEV=YA(M,NA,7)-YA(M,NA,1)
      DSUM=DSUM+DEV*DEV
      YA(M,NA,3)=DEV
 1010 CONTINUE
      DDSUM=DSUM/NPP
      RMS(NA,13)=SQRT(DDSUM)*(25400.0/SMAG)
      DO 1020 IJ=1,6
      ERRRR=0.0
      DO 1030 M=15,K1XX
      YH=ABS(YA(M,NA,3))
      IF(YH.LT.ERRRR) GO TO 1030
      INDEX=M
      ERRRR=YH
 1030 CONTINUE
      ERROR(IJ,NA,13)=YA(INDEX,NA,3)*(25400.0/SMAG)
      YA(INDEX,NA,3)=0.0
 1020 CONTINUE
 1000 CONTINUE
C
C
C       SLOPE DISTRIBUTION ROUTINE
      WRITE(6,1200)
      WRITE(6,1210)
      WRITE(6,1240)
      WRITE(6,8235)
 8235 FORMAT(2X*SLOPE DISTRIBUTION TABLES*)
C
C
      INTVV=INTVL
      DO 1356 N2=1,3
C       COMPUTE SLOPES IN ARC SECONDS.
      CONST=(2.628.0*XMAG)/(SMAG*DELTA*INTVV)
```

```
      DO 1049 NA=1,4
      DO 1050 M=K2,K12
      M6=M+INTVV
      SLPE1(M,NA)=ABS(CONST*(YA(M6,NA,1)-YA(M,NA,1)))
      SLPE2(M,NA)=ABS(CONST*(YA(M6,NA,7)-YA(M,NA,7)))
 1050 CONTINUE
 1049 CONTINUE
C     DISTRIBUTE SLOPE VALUES INTO BINS OF INCREASING WIDTH.
      SLOPE=0.0
      KTP1=0
      KTP2=0
      WRITE(6,1240)
      WRITE(6,1240)
      WRITE(6,1240)
      WRITE(6,6401) INTVV
 6401 FORMAT(5X,*XXXXXXX              DATA SET A          XXXXXXXX
     1   DATA SET B          XXXXXXXX      INTERVAL=*,I3)
      WRITE(6,1240)
      WRITE(6,6402)
 6402 FORMAT(5X,*SLOPE(SEC)   NBR    TOTAL    NORM NBR    SLOPE    NBR
     1   TOTAL     NORM NBR    SLOPE(SEC)*)
      DO 1055 L10=1,47
      SLOPP=(1.114588*SLOPE)+0.132613
      IF(L10.EQ.1) SLOPP=0.15
      IF(L10.EQ.47) SLOPP=1000.0
      KTP3=0
      KTP4=0
      DO 1060 NA=1,4
      DO 1065 M=K2,K12
      IF((SLPE1(M,NA).GT. SLOPE). AND. (SLPE1(M,NA).LE. SLOPP))
     1 KTP3=KTP3+1
      IF((SLPE2(M,NA).GT. SLOPE). AND. (SLPE2(M,NA).LE. SLOPP))
     1 KTP4=KTP4+1
 1065 CONTINUE
 1060 CONTINUE
      KTP1=KTP1+KTP3
      KTP2=KTP2+KTP4
      WRITE(6,1073) SLOPE,SLOPE,SLOPE
 1073 FORMAT(5X,F8.3, 30X, F9.3, 31X,F8.3)
      SAND1= KTP3/(SLOPP-SLOPE)
      SAND2= KTP4/(SLOPP-SLOPE)
      WRITE(6,1075)  KTP3, KTP1, SAND1, KTP4, KTP2, SAND2
 1075 FORMAT(16X,I4, 4X, I4, 4X, F8.3, 13X, I4, 6X, I4, 5X, F8.3)
      SLOPE=SLOPP
 1055 CONTINUE
      INTVV=2*INTVV
 1056 CONTINUE
      WRITE(6,1210)
C
CCCC
      IND=124
      WRITE(6,2002)  IND
C RE-COMPUTE THE AVERAGE SCANS BY ADJUSTING X AND Y SCALES TO MATCH CLEAVITE
C     SCALES,ADDING  IN OFFSETS, AND ADDING IN SLOPE CIRCLE CURVATURES.
C
      XS=DELTA*XSCLE
      DO 1100 NA=1,4
```

```
            DO 1110  M=1,K1
            X=M*XS+XOFST
            XA(M,NA,1)=X
            VIR=M*DELTA+C2
            ROM=C1*VIR*VIR+YOFST
            YA(M,NA,1)=YSCLE*YA(M,NA,1) +ROM
            XA(M,NA,7)=X
            YA(M,NA,7)=YSCLE*YA(M,NA,7) +ROM
      1110  CONTINUE
      1110  CONTINUE
C
CCCC
            IND=125
            WRITE(6,2..)  IND
C THE FINAL EIGHT PROCESSED SCANS ARE NOW IN REGISTERS XA(M,NA,1)
C           YA(M,NA,1) (FIRST DAY MEASUREMENTS) AND IN XA(M,NA,7),YA(M,NA,7)
C           (SECOND DAY MEASUREMENTS). HERE,NA=1 THRU 4 AND
C           M=1 THRU K1.
C
C
C PRINT OUTPUT QUANTITIES.
C
            WRITE(6,1200)
      1200  FORMAT(1H1)
            WRITE(6,1210)
      1210  FORMAT(99H ***************************************************
           1****************************************)
            IF(CURVE.GT.1.50) GO TO 1223
            WRITE(6,1220)        DELTA,K1,K2,K3,FCTR1,FCTR2
      1220  FORMAT(1H0,1X*  PROGRAM SCANNAX     SURFACE ELLIPSE  DELTA=*,F7.4,*
           1    K1=*,I5,*    K2=*,I4,*    K3=*,I4,*    (FACTOR 1)=*,F6.4,*    (FACT
           1OR 2)=*,F6.4)
            GO TO 1229
      1223  WRITE(6,1226)        DELTA,K1,K2,K3,FCTR1,FCTR2
      1226  FORMAT(1H0,1X*  PROGRAM SCANNAX     SURFACE HYPROLA  DELTA=*,F7.4,*
           1    K1=*,I5,*    K2=*,I4,*    K3=*,I4,*    (FACTOR 1)=*,F6.4,*    (FACT
           1OR 2)=*,F6.4)
      1229  WRITE(6,1230) XSCLE,XOFST,YSCLE,C1,C2,YOFST,SMAG
      1230  FORMAT(1H0,1X*       X SCALE=*,F9.5 ,*    X OFFSET=*,F6.3,*    Y SCALE
           1=*,F7.5 ,*    C1=*,F7.5 ,*    C2=*,F9.5 ,*    Y OFFSET=*,F6.3,
           1*   SMAG=*,F8.1)
            WRITE(6,1237) INTVL,XMAG
      1237  FORMAT(1H0,5X* INTERVAL=*,I3,*       XMAG=*,F7.4)
            WRITE(6,1240)
      1240  FORMAT(1H )
            WRITE(6,1210)
            WRITE(6,1250)
      1250  FORMAT(*   SCAN      AZIMUTH       XMIN     XPEAK     XPEAK      AVERAGE
           1       RMS          SIX LARGEST DEVIATIONS*)
            WRITE(6,1260)
      1260  FORMAT(*   GROUP    (DEGREES)                (START)   (END)      SLOPE
           1       DEV*)
            WRITE(6,1297)
      1297  FORMAT(22X,*(((INCHES ON SCANNER TRACES)))            ((((((((((MIC
           1RONS ON THE OPTICAL SURFACE))))))))*)
            DO 1270 NA=1,4
            DO 1280 NR=1,12
```

```
                IF(NA.EQ.1) AZ= .
                IF(NA.EQ.2) AZ=90..
                IF(NA.EQ.3) AZ=18..
                IF(NA.EQ.4) AZ=27..
                NBB=NB-6
                IF(NB.LT.7) NBB=NB
                IF(NB.GT.6) GO TO 1263
                WRITE(6,1291) NBB,AZ,XMIN(NA,NB), XPEAK(1,NA,NB),XPEAK(2,NA,NB),
               1     B(NA,NB), RMS(NA,NB), ERROR(1,NA,NB), ERROR(2,NA,NB),
               1ERROR(3,NA,NB), ERROR(4,NA,NB), ERROR(5,NA,NB), ERROR(6,NA,NB)
          1291  FORMAT(2X, I2,1X,*A*, 6X, F5.1, 4X,F8.4,3X, F6.3, 4X, F6.3, 3X,
               1F7.5, 3X, F7.5, 6X, 6F6.4)
                GO TO 128
          1263  WRITE(6,1292) NBB,AZ,XMIN(NA,NB), XPEAK(1,NA,NB),XPEAK(2,NA,NB),
               1     B(NA,NB), RMS(NA,NB), ERROR(1,NA,NB), ERROR(2,NA,NB),
               1ERROR(3,NA,NB), ERROR(4,NA,NB), ERROR(5,NA,NB), ERROR(6,NA,NB)
          1292  FORMAT(2X, I2,1X,*B*, 6X, F5.1, 4X,F8.4,3X, F6.3, 4X, F6.3, 3X,
               1F7.5, 3X, F7.5, 6X, 6F6.4)
          128   CONTINUE
          127   CONTINUE
                WRITE(6,1210)
                WRITE(6,1200)
                WRITE(6,1210)
                WRITE(6,1240)
                WRITE(6,1300)
          1300  FORMAT(*    COMPARISON OF AVERAGE FIRST DAY SCANS WITH AVERAGE SECO
               1ND DAY SCANS*)
                WRITE(6,1340)
                WRITE(6,1310)
          1310  FORMAT(* AZIMUTH    RMS DEV(MICRONS)        SIX LARGEST DEV (MICRONS)
               1*)
                WRITE(6,1240)
                DO 1320 NA=1,4
                IF(NA.EQ.1) AZ=0.0
                IF(NA.EQ.2) AZ=90.0
                IF(NA.EQ.3) AZ=180.0
                IF(NA.EQ.4) AZ=270.0
                WRITE(6,1330) AZ,RMS(NA,13), ERROR(1,NA,13), ERROR(2,NA,13),
               1ERROR(3,NA,13), ERROR(4,NA,13), ERROR(5,NA,13),ERROR(6,NA,13)
          1330  FORMAT(3X, F5.1, 6X,F6.4, 10X,6F7.4)
          1320  CONTINUE
                WRITE(6,1240)
                WRITE(6,1210)
                WRITE(6,1210)
          C
          CCCC
                IND=126
                WRITE(6,2000)  IND
          C   CALL PLOT ROUTINE AND PRODUCE PLOT TAPE.
          C
          C   OPEN NEUTRAL PICTURE FILE.
                CALL PLOTS
          C   ESTABLISH FIRST ORIGIN.
                CALL PLOT(1.3,5.0,-3)
                DO 15   N=1,6
          C   DRAW THE AXES.
                TITLE(1)=1 HX-AXIS(CM)
```

```
      IF(N.EQ.1) TITLE(2)=10H,SET A,  0
      IF(N.EQ.2) TITLE(2)=10H,SET A,  9
      IF(N.EQ.3) TITLE(2)=10H,SET A, 18
      IF(N.EQ.4) TITLE(2)=10H,SET A, 27
      IF(N.EQ.5) TITLE(2)=10H,SET B,  0
      IF(N.EQ.6) TITLE(2)=10H,SET B,  9
      IF(N.EQ.7) TITLE(2)=10H,SET B, 18
      IF(N.EQ.8) TITLE(2)=10H,SET B, 27
      TITLE(3)=10H  AZ,ELLIP
      IF(CURVE.GT.1.50) TITLE(3)=10H  AZ,HYPER
      CALL AXIS(0.0,0.0,TITLE,-30,35.0,0.0,0.0,1.0)
      CALL AXIS(0.0,0.0,25HY-AXIS(0.099 MICRONS/DIV),+25,15.0,90.0,0.0,
     11.0)
C  FILL THE XC AND YC REGISTERS, WITH REVERSION IN THE X-DIRECTION,
C          AND CONVERT TO CM.
      NA=N-4
      IF(N.LE.4) NA=N
      NB=1
      IF(N.GE.5) NB=7
      DO 1525 M=1,K1
      MB=K1-M+1
      XC(M) =XA(M,NA,NB)*(2.54)
      YC(MB)=YA(M,NA,NB)*(2.54)
 1525 CONTINUE
CCCC
      IND=127
      WRITE(6,2000)  IND
C  PLOT THE DATA.
      YC(1)=0.0
      YC(2)=0.0
      YC(3)=0.0
      YC(K1)=0.0
      K99=K1-1
      YC(K99)=0.0
      K98=K1-2
      YC(K98)=0.0
      CALL LINE(XC,YC,-K1 ,12,0,0)
C  ESTABLISH THE NEXT ORIGIN.
      CALL PLOT(45.0,0.0,-3)
 1500 CONTINUE
C  CLOSE THE NEUTRAL PICTURE FILE.
      CALL PLOT(0.0,0.0,999)
      WRITE(6,1210)
      WRITE(6,121 )
      WRITE(6,1210)
      STOP
      END
```

APPENDIX B

PROGRAM LISTING FOR SCANNAZ, ENVIRDT, FRSTSCN, AND SCANRD

```
      PROGRAM SCANNAZ(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT, TAPE1)
      DIMENSION XA(350,6,12),YA(350,6,12),  YB(350,6,6),  XC(350),
     1YC(350),  RMS(7,6),  ERROR(6,7,6),  IMXX(6,9),  MSTOP(6,9),
     1AMP(6), PHSE(6)
C
C READ INPUT QUANTITIES
C
      READ(5,10) CURVE,ALMIN,ALMAX
   10 FORMAT(3F10.5)
      READ(5,15) DELTA
   15 FORMAT(F10.5)
      LMIN=ALMIN+.00001
      LMAX=ALMAX+.00001
      READ(5,17) SCANS
   17 FORMAT(F10.5)
      READ(5,23) FCTR1, FCTR2  ,FCTR3, FCTR4, FCTR5, FCTR6
   23 FORMAT(6F10.5)
      READ(5,25) XSCLE,XOFST
   25 FORMAT(2F10.5)
      READ(5,30) YSCLE,YOFST,SMAG
   30 FORMAT(2F10.5,F10.1)
CCCC
      IND=111
      WRITE(6,2000)   IND
 2000 FORMAT(6X,I3)
C
C   ***************************************
C   **************************************
C
C      CURVE=1.0 FOR ELLIPSOID OR 2.0 FOR HYPERBOLOID.
C
C    LMIN IS THE MIN VALUE OF LABEL OF SCANS TO BE READ INTO MEMORY.
C    LMAX IS THE MAX VALUE OF LABEL.
C
C     DELTA= INTERPOLATION INCREMENT(X DIRECTION).
C
C    SCANS IS THE NUMBER OF TRACES TO BE READ FROM THE DATA TAPE.
C      (ALLOWED VALUES ARE 18.0 AND 36.0).
C
C     I=INDEX OF POINTS ON A GIVEN SCAN AS READ FROM THE DATA TAPE.
C
C      FCTR2 THRU FCTR6 ARE SCALE FACTORS TO ADJUST THE THE Y SCALES
C          OF THE NB=2 THRU 6 SCANS TO THE SCALE OF THE NB=1 SCANS.  FCTR1
C          (FOR NB=1) IS 1.000.
C      XSCLE AND YSCLE ARE SCALE FACTORS TO ENLARGE SCANNER TRACES TO
C          THE SCALE OF THE INDIROUND TRACES.
C      XOFST AND YOFST ARE OFFSETS TO PROPERLY POSITION FINAL PLOTS
C          ON PAGE.
C       SMAG IS THE MAGNIFICATION OF THE SCANNER TRACES (EQUAL TO 1/8).
C     AMP AND PHASE ARE CONSTANTS IN A SINUSOID WHICH IS SUBTRACTED FROM
C        THE SCAN ORDINATE IN ORDER TO DECREASE THE EFFECTS OF DECENTERING.
C
C*  **************************************
C   **************************************
C
C    READ THE DATA TAPE FROM LABEL=LMIN TO LABEL=LMAX.
C
```

```
      CALL  ENVIROT(LMIN,LMAX,XA,YA,NA,NB)
C
      WRITE(6,1210)
CCCC
      IND=112
      WRITE(6,2000)  IND
C
C
C   THE X AND Y COORDINATES OF POINTS ON THE          SCANS HAVE BEEN
C     READ FROM THE DATA TAPE, AND ARE STORED IN REGISTERS XA(I,NA,NB),
C     YA(I,NA,NB).
C
C     ANOTHER SET OF REGISTERS YB(N,NA,NB)   IS USED
C         FOR STORAGE OF INTERMEDIATE RESULTS.
C
C
C    RE-NUMBER THE ARGUMENTS OF THE ARRAYS XA AND YA TO MATCH THE FORM
C      OF THE AZIMUTHAL SCANS INSTEAD OF THE AXIAL SCANS.
C
      DO 40 NB=1,9
      DO 42 NA=1,4
      NBA=NA+(4*(NB-1))
      ABA=NBA/6.0
      NNB=NBA/6
      ABAB=ABA-NNB
      IF(ABAB.GT.0.01) NNB=NNB+1
      NNA=NBA-(6*(NNB-1))
      I=0
   44 I=I+1
      IF((XA(I,NA,NB).LT.0.001).AND.(YA(I,NA,NB).LT.0.001)) GO TO 46
      XA(I,NNA,NNB)= XA(I,NA,NB)
      YA(I,NNA,NNB)= YA(I,NA,NB)
      IF(NB.EQ. 1) GO TO 45
      XA(I,NA,NB)= 0.0
      YA(I,NA,NB)= 0.0
   45 GO TO 44
   46 INXX(NNA,NNB)=I-1
C     INXX IS THE NUMBER OF DATA POINTS IN THE SCAN, AS ORIGINALLY
C         DIGITIZED.
   42 CONTINUE
   40 CONTINUE
C
C    THE INDICES OF XA AND YA ARE NOW RE-NUMBERED TO MATCH THE FORM OF
C       THE AZIMUTHAL SCAN SEQUENCE, WIVH NA (1 TO 6) BEING THE INDEX OF
C        A SCAN WITHIN A GROUP AND NB (1 TO 6) BEING THE SCAN GROUP NUMBER.
C
C   IF THE NUMBER OF TRACES READ FROM THE DATA TAPE IS ONLY 18 INSTEAD
C     OF 36 (THAT IS, IF SCANS=18.0), THEN FILL THE EMPTY REGISTERS
C     BY REPEATING THE 18 TRACES A SECOND TIME.
      IF(SCANS.GT.25.0) GO TO 47
      DO 33 NB= 1,3
      NNBB=NB+3
      DO 35 NA=1,6
      INXX(NA,NNBB)=INXX(NA,NB)
      INNX=INXX(NA,NB)
      DO 37 I=1,INNX
      XA(I,NA,NNBB)=XA(I,NA,NB)
```

```
              YA(I,NA,NNBB)=YA(I,NA,NB)
           37 CONTINUE
           35 CONTINUE
           33 CONTINUE
      C
      C
      C SUBTRACT OFF THE X-ZERO VALUES XMIN,  AND ADJUST THE LENGTH OF ALL SCANS
      C      TO MATCH THE LENGTH OF THE FIRST SCAN (NA=NB=1).
      C
           47 IMMX=IMXX(1,1)
              FSCAN=XA(IMMX,1,1)-XA(1,1,1)
              DO 50 NB=1,6
              DO 60 NA=1,6
              IMMX=IMXX(NA,NB)
              XMIN=XA(1,NA,NB)
              SCANL=XA(IMMX,NA,NB)-XMIN
              FACTR=FSCAN/SCANL
              DO 70 I=1,IMMX
              XA(I,NA,NB)= (XA(I,NA,NB)-XMIN)*FACTR
              IF(YA(I,NA,NB). LE. 0.0) YA(I,NA,NB)= 0.001
      C         ALSO, MAKE ALL NEGATIVE AND ZERO VALUES OF YA EGUAL TO +.001.
           70 CONTINUE
      C        MAKE INITIAL VALUE OF XA LESS THAN 0.0.   (THIS IS NECESSARY
      C             FOR INTERPOLATION ROUTINE TO WORK).
              IF(XA(1,NA,NB).GE. 0.0) XA(1,NA,NB)=-.001
           60 CONTINUE
           50 CONTINUE
      C
      CCCC
              IND=113
              WRITE(6,2000)   IND
      C
      C
      C     INTERPOLATION ROUTINE.
      C (COMPUTE NEW EVENLY SPACED SETS OF POINTS XB, YB FROM THE ORIGINAL
      C       UNEVENLY SPACED SETS XA,YA. (THE VALUES OF XB ARE NOT STORED
      C       EXPLICITLY.))
      C
              DO 500 NB=1,6
              DO 505 NA=1,6
              IMMX=IMXX(NA,NB)
              XMMX=XA(IMMX,NA,NB)
              I=1
              J=2
              M=0
              X=-DELTA
          510 X=X+DELTA
              M=M+1
          520 IF(X.GE.XMMX) GO TO 504
              IF((X.GE.XA(I,NA,NB)).AND.(X.LE.XA(J,NA,NB))) GO TO 530
              I=I+1
              J=J+1
              GO TO 520
          530 XAI=XA(I,NA,NB)
              YAI=YA(I,NA,NB)
              IF((YAI.LT.0.0001). AND .(YAI.GT.-0.0001)) GO TO 504
              Y=YAI+((YA(J,NA,NB)-YAI)*(X-XAI))/(XA(J,NA,NB)-XAI)
```

```
            YB(M,NA,NB)=Y
            GO TO 510
        504 MSTOP(NA,NB)=M-1
      C        MSTOP IS THE NUMBER OF INTERPOLATED POINTS ALONG THE SCAN.
        505 CONTINUE
        500 CONTINUE
      C
      CCCC
            IND=114
            WRITE(6,2000)   IND
      C
      C
      CCCC
            IND=115
            WRITE(6,2000)   IND
      C
      C     REDUCE ALL CURVES TO ZERO SLOPE AND ZERO LEVEL, AND
      C              MULTIPLY BY THE SCALE FACTORS FCTR1 THRU FCTR6.
      C
            DO 780 NB=1,6
            IF(NB.EQ.1)  FCTR=FCTR1
            IF(NB.EQ.2)  FCTR=FCTR2
            IF(NB.EQ.3)  FCTR=FCTR3
            IF(NB.EQ.4)  FCTR=FCTR4
            IF(NB.EQ.5)  FCTR=FCTR5
            IF(NB.EQ.6)  FCTR=FCTR6
            DO 785 NA=1,6
            MMM=MSTOP(NA,NB)
            SLANT=(YB(MMM,NA,NB)-YB(1,NA,NB))/((MMM-1)*DELTA)
            DSLANT=DELTA*SLANT
            ZLVL=YB(1,NA,NB)
            DO 788 M=1,MMM
            YB(M,NA,NB)=(YB(M,NA,NB)-ZLVL-(M-1)*DSLANT)*FCTR
        788 CONTINUE
        785 CONTINUE
        780 CONTINUE
      C
      CCCC
            IND=116
            WRITE(6,2000)   IND
      C
      C ALL SCANS ARE NOW REDUCED TO COMPARABLE SLOPE ,LEVEL, AND
      C        REGISTRATION, AND ARE STORED IN REGISTERS YB(M,NA,NB).
      C
      C   CO-ADD AND AVERAGE CORRESPONDING SCANS.
      C
            DO 800 NB=1,6
            MMXX=MSTOP(1,1)
            DO 820 M=1,MMXX
            YA(M,1,NB)=YB(M,1,NB)+YB(M,2,NB)+YB(M,3,NB)+YB(M,4,NB)+YB(M,5,NB)+
           1YB(M,6,NB)
            YA(M,1,NB)=YA(M,1,NB)/6.0
        820 CONTINUE
        800 CONTINUE
      C
      CCCC
            IND=117
```

```
      WRITE(6,2000)  IND
C
C COMPUTE RMS DEVIATION OF INDIVIDUAL SCANS FROM THE CORRESPONDING AVERAGE
C     SCANS WITHIN A GIVEN DAY,AND ALSO THE SIX LARGEST DEVIATIONS.
C          (CONVERT OUTPUT UNITS TO MICRONS ON THE OPTICAL SURFACE).
      MXY=MMXX-10
      DO 900 NB=1,6
      DO 910 NA=1,6
      DSUM=0.0
      DO 920 M=1,MMXX
      DEV=YB(M,NA,NB)-YA(M,1,NB)
      IF(M.LT.10)  DEV=0.0
      IF(M.GT.MXY)  DEV=0.0
      DSUM=DSUM+DEV*DEV
      YA(M,2,NB)=DEV
  920 CONTINUE
      DDSUM=DSUM/(MMXX-18)
      RMS(NA,NB)= (25400.0/SMAG)*SQRT(DDSUM)
      DO 925 IJ=1,6
      ERRRR=0.0
      DO 930 M=1,MMXX
      YW=ABS(YA(M,2,NB))
      IF(YW.LT.ERRRR) GO TO 930
      INDEX=M
      ERRRR=YW
  930 CONTINUE
      ERROR(IJ,NA,NB)=YA(INDEX,2,NB)*(25400.0/SMAG)
      YA(INDEX,2,NB)=0.0
  925 CONTINUE
  910 CONTINUE
  900 CONTINUE
C
C FIND THE BEST FIT SINUSIODS TO EACH OF THE AVERAGED SCANS.
C
      DO 950 NB=1,6
      TA=0.0
      TB=0.0
      TC=0.0
      TD=0.0
      TE=0.0
      DO 970 M=1,MMXX
      THETA=6.2832*M/MMXX
      YY=YA(M,1,NB)
      S=SIN(THETA)
      C=COS(THETA)
      TA=TA+YY*C
      TB=TB+C*C
      TC=TC+C*S
      TD=TD+YY*S
      TE=TE+S*S
  970 CONTINUE
      B=(TB*TD-TA*TC)/(TE*TB-TC*TC)
      A=(TA-B*TC)/TB
      AMP(NB)=SQRT(A*A+B*B)
      ARG=-A/B
      PHSE(NB)= ATAN(ARG)
      IF(B.LT. 0.0)  PHSE(NB)= PHSE(NB)+3.14159
```

```
C   THE BEST FIT SINUSOID IS
C                  A*COS(THETA)+B*SIN(THETA)=AMP*SIN(THETA-PHSE).
  950 CONTINUE
C
CCCC
      IND=118
      WRITE(6,2000)  IND
C COMPUTE RMS DEVIATION BETWEEN AVERAGE SCANS OF FIRST DAY AND THE
C     CO-RESPONDING AVERAGE SCANS OF THE SECOND DAY, AND ALSO THE
C     SIX LARGEST DEVIATIONS BETWEEN EACH PAIR OF SCANS.
C     ALSO, SUBTRACT OFF THE BEST FIT SINUSIOD TO DECREASE THE
C      FLUCTUATIONS IN Y  DUE TO DECENTERING.  CONVERT OUTPUT UNITS TO
C      MICRONS ON THE OPTICAL SURFACE.
C
      MXY=MMXX-10
      DO 1000 NB=1,3
      DSUM=0.0
      NBN=NB+3
      AMPA=AMP(NB)
      AMPB=AMP(NBN)
      PHSA=PHSE(NB)
      PHSB=PHSE(NBN)
      DO 1010 M=1,MMXX
      THETA=6.2832*M/MMXX
      PHIA=THETA-PHSA
      PHIB=THETA-PHSB
      DEV= YA(M,1,NBN)- AMPB*SIN(PHIB) -(YA(M,1,NB)-AMPA*SIN(PHIA))
      IF(M.LT.10)  DEV=0.0
      IF(M.GT.MXY)  DEV=0.0
      DSUM=DSUM+DEV*DEV
      YA(M,3,NB)=DEV
 1010 CONTINUE
      DDSUM=DSUM/(MMXX-10)
      RMS(7,NB)=  (25400.0/SMAG)*SQRT(DDSUM)
      DO 1020 IJ=1,6
      ERRRR=0.0
      DO 1030 M=1,MMXX
      YM=ABS(YA(M,3,NB))
      IF(YM.LT.ERRRR) GO TO 1030
      INDEX=M
      ERRRR=YM
 1030 CONTINUE
      ERROR(IJ,7,NB)=YA(INDEX,3,NB)*(25400.0/SMAG)
      YA(INDEX,3,NB)=0.0
 1020 CONTINUE
 1000 CONTINUE
C
CCCC
      IND=119
      WRITE(6,2000)  IND
C
C   RE-COMPUTE THE AVERAGE SCANS TO MATCH THE INDIROUND TRACES BY
C     CHANGING SCALE FACTORS AND TRANSFORMING TO POLAR COORDINATES.
C     ALSO, SUBTRACT OFF THE BEST FIT SINUSIOD TO DECREASE THE
C      FLUCTUATIONS IN Y  DUE TO DECENTERING.
C
      XS=DELTA*XSCLE
```

```
      DO 1100 NB=1,6
      RAD=(DELTA*(MMXX-1)*XSCLE)/6.2832
      AMPP=AMP(NB)
      PHASE=PHSE(NB)
      DO 1110 M=1,MMXX
      THETA=((M-1)*XS)/RAD
      PHI=THETA-PHASE
      DR=AMPP*SIN(PHI)
      RADIUS=RAD+((YA(M,1,NB)-DR)*YSCLE)
C   HERE, RADIUS IS RAD+( ..) RATHER THAN RAD-(...) BECAUSE THE
C      AZIMUTHAL SCANS ARE INTERPRETED AS HAVING METAL ABOVE THE
C      SCAN LINE RATHER THAN BELOW.
      XA(M,1,NB)=XOFST+(RADIUS*SIN(THETA))
      YA(M,1,NB)= YOFST- (RADIUS*COS(THETA))
 1110 CONTINUE
 1100 CONTINUE
C   THE FINAL PROCESSED SCANS ARE NOW IN REGISTERS XA(M,1,NB)
C      AND YA(M,1,NB).
C
C
CCCC
      INO=120
      WRITE(6,2000)  INO
C
C PRINT OUTPUT QUANTITIES.
C
      WRITE(6,1200)
 1200 FORMAT(1H1)
      WRITE(6,1210)
 1210 FORMAT(99H ***************************************************
     1*****************************************)
 1240 FORMAT(1H0)
      IF(CURVE.GT.1.50)  GO TO 1250
      WRITE(6,1255)  DELTA, FCTR1, FCTR2 ,FCTR3, FCTR4,FCTR5, FCTR6
 1255 FORMAT(1X*  PROGRAM SCANNAZ   SURFACE ELLIPSE    DELTA=*,F7.4,*  (
     1FCTR1 THRU FCTR6)=*,6F8.4)
      GO TO 1258
 1250 WRITE(6,1257)  DELTA, FCTR1, FCTR2 ,FCTR3, FCTR4,FCTR5, FCTR6
 1257 FORMAT(1X*  PROGRAM SCANNAZ   SURFACE HYPERBOLA  DELTA=*,F7.4,*  (
     1FCTR1 THRU FCTR6)=*,6F8.4)
 1258 WRITE(6,1261)  XSCLE,XOFST,  YSCLE,YOFST,  SMAG
 1261 FORMAT(1H0,1X*    X SCALE=*,F8.5,*  X OFFSET=*,F6.3,*  Y SCALE=*,F
     17.5,*  Y OFFSET=*,F6.3,* SMAG=*,F8.1)
      WRITE(6,1259)  AMP(1), AMP(2), AMP(3), AMP(4), AMP(5), AMP(6),
     1PHSE(1), PHSE(2), PHSE(3), PHSE(4), PHSE(5), PHSE(6)
 1259 FORMAT(1H0,1X*   AMPLITUDES=*,6F7.4,*  PHASES=*,6F7.4)
      WRITE(6,1240)
      WRITE(6,1210)
      WRITE(6,1280)
 1280 FORMAT(* SCAN    SCAN  NUMBER OF    RMS           SIX LARGEST DEV
     1IATIONS*)
      WRITE(6,1281)
 1281 FORMAT(* GROUP  NUMBER INTRPOLATD  DEVIATION*)
      WRITE(6,1284)
 1284 FORMAT(* (NB)    (MA)    POINTS     ((((((((((MICRONS ON THE OPTICA
     1L SURFACE))))))))*)
```

```
      WRITE(6,1240)
      DO 1227 NB=1,6
      WRITE(6,1229) ND,NA,MSTOP(NA,NB), RMS(NA,NB), ERROR(1,NA,NB),
     1ERROR(2,NA,NB), ERROR(3,NA,NB), ERROR(4,NA,NB), ERROR(5,NA,NB),
     1ERROR(6,NA,NB)
 1229 FORMAT(2X,I2,5X,I2,6X,I3,6X, F7.5,6X,6F6.4)
 1227 CONTINUE
 1223 CONTINUE
      WRITE(6,1210)
      WRITE(6,1180)
      WRITE(6,1210)
      WRITE(6,1140)
      WRITE(6,1303)
 1303 FORMAT(*   COMPARISON OF AVERAGE FIRST DAY SCANS WITH AVERAGE SECO
     1ND DAY SCANS*)
      WRITE(6,1240)
      WRITE(6,1307)
 1307 FORMAT(*  GROUPS  RMS DEV(MICRONS)       SIX LARGEST DEV(MICRONS)*)
      WRITE(6,1240)
      DO 1329 NB=1,3
      WRITE(6,1327) NB, RMS(7,NB), ERROR(1,7,NB), ERROR(2,7,NB),
     1ERROR(3,7,NB), ERROR(4,7,NB), ERROR(5,7,NB), ERROR(6,7,NB)
 1327 FORMAT(3X, I2,6X, F6.4, 10X, 6F7.4)
 1329 CONTINUE
      WRITE(6,1240)
      WRITE(6,1210)
      WRITE(6,1110)
C
CCCC
      INO=121
      WRITE(6,2000)  INO
C
C   CALL PLOT ROUTINE AND PRODUCE PLOT TAPE.
C
C  OPEN NEUTRAL PICTURE FILE.
      CALL PLOTS
C  ESTABLISH FIRST ORIGIN.
      CALL PLOT(1.3,5.0,-3)
      DO 1500 NB=1,6
C  DRAW THE BORDER.
      CALL PLOT(15.0,0.0,2)
      CALL PLOT(15.0,15.0,2)
      CALL PLOT(0.0,15.0,2)
      CALL PLOT(0.0,0.0,2)
C  FILL THE XC AND YC REGISTERS, AND CONVERT TO CM.
      DO 1525 M=1,MMXX
      XC(M) =XA(M,1,NB) *(2.54)
      YC(M)=YA(M,1,NB)*(2.54)
 1525 CONTINUE
C   ADD CENTER MARK.
      MXXM=MMXX+1
      XC(MXXM)=XC(MMXX)
      YC(MXXM)=YC(MMXX)+(2.54*RAD)
      MXXL=MXXM+1
      XC(MXXL)= XC(MXXM)+0.30
      YC(MXXL)= YC(MXXM)
C   MAKE CTR MARK T-SHAPED WHEN NB=6.
```

```
                IF(NB.EQ.6)  MXXL=MXXL+1
                IF(NB.EQ.6)  XC(MXXL)=XC(MXXM)-0.30
                IF(NB.EQ.6)  YC(MXXL)=YC(MXXM)
          C
          CCCC
                IND=122
                WRITE(6,2000)   IND
          C  PLOT THE DATA.
                CALL LINE(XC,YC,-MXXL,12,0,0)
          C  ESTABLISH THE NEXT ORIGIN.
                CALL PLOT(25.0,0.0,-3)
           1500 CONTINUE
          C  CLOSE THE NEUTRAL PICTURE FILE.
                CALL PLOT(0.0,0.0,999)
                WRITE(6,1210)
                WRITE(6,1210)
                STOP
                END
```

```
      SUBROUTINE  ENVIROT (LMIN,LMAX,XA,YA,NA,NB)
C     VERSION  E    02.27.79
C     DENNIS J W DUKE, VISIDYNE INC, BURLINGTON, MA, 617-273-2820
C     THIS MODULE READS , UNPACKS , AND SCALES DATA FOR A GROUP OF
C     SCANS STORED ON MAGNETIC TAPE.  ENVIRODATA CORP.
C     (CHELMSFORD, MA, 617-256-8131)  ENCODES THE MAGNETIC
C     TAPE DATA WITH THE FOLLOWING FORMAT:
C     9 - TRACK    .
C     800 BPI    .
C     NO LABELS   .
C        LOGICAL RECORD LENGTH = 80 CHARACTERS    .
C        PHYSICAL RECORD LENGTH = 2400 CHARACTERS    . AND
C        BLOCKING FACTOR = 30 RECORDS PER BLOCK    .
C     INPUT PARAMETERS  :  LMIN , LMAX
C     OUTPUT PARAMETERS   :   XA(I,NA,NB)   , YA(I,NA,NB)
C     WHERE MAX I IS 400 ,
C     NA = 1 TO 4     , AND
C     NB = 1 TO 12    .
C     SUPPORT MODULES :
C     FRSTSCN(BUF,IWORD,LMIN,LMAX,LABEL,NPTS,XA,YA)
C     SCANRD(LABEL,NPTS,NA,NB,BUF,IWORD,XA,YA)
C     BUF IS A WORD BUFFER 240 (10-CHARACTER) WORDS LONG
C     IWORD POINTS TO THE NEXT USEABLE WORD IN THE BUFFER.
C     THE MODULE USES CDC FTN BUFFER IN , UNIT , AND DECODE STATEMENTS.
      DIMENSION   XA(350,6,12) , YA(350,6,12) , BUF(240)
C     INITIALIZE  BUFFER  AND  POINTER
      IWORD  = 1
      BUFFER IN(     1, 0) (BUF (1) , BUF(240) )
      IF(UNIT(    1)     .EQ.   0 )  STOP *ENVIROT  1 *
      PRINT *, *IWORD = *, IWORD
C     SEARCH  TAPE1  FOR  FIRST  SCAN
C     COLLECT, SCALE , STORE   ASSOCIATED DATA
      CALL FRSTSCN (BUF,IWORD,LMIN,LMAX,LABEL,NPTS,XA,YA,NA,NB)
   10 CONTINUE
C     COLLECT DATA FOR SCANS 2 TO N (MAX N IS 4X12)
C        READ LABEL , NPTS
         DECODE(80,901, BUF(IWORD)) IOTA,LABEL,NPTS
         IWORD = IWORD + 8
         PRINT *, *LABEL,NPTS,IWORD*,LABEL,NPTS,IWORD
         IF (IWORD  .NE.  241 )    GO  TO  20
C     REFRESH BUFFER AND REINITIALIZE POINTER
      BUFFER IN (     1,0) (BUF(1), BUF (240))
      IF (UNIT (     1)   .EQ. 0)   STOP * ENVIROT    2*
      IWORD = 1
   20 CONTINUE
C     IS SCAN LABEL IN RANGE.
      IF (LABEL  .GT.   LMAX )   GO TO 50
C     INCREMENT BUFFER POINTERS  NA   AND   NB
      IF (NA   .EQ.   4)     GO   TO   30
      NA = NA+ 1
      GO TO 40
   30 CONTINUE
      NA = 1
      NB = NB + 1
   40 CONTINUE
      PRINT *,*NA,NB *,NA,NB
C     COLLECT, SCALE, AND STORE ASSOCIATED SCAN DATA
```

```
      CALL SCANRD (LABEL,NPTS,NA,NB,BUF,IHORD,XA,YA)
      IF (( LABEL .EQ. LMAX ).AND. ( NA .EQ. 4 )) GO TO 50
C     PROCEED TO PROCESS NEXT SCAN
      GO TO 10
50    CONTINUE
C     ALL SCANS, WHOSE LABELS ARE IN RANGE, RESIDE IN
C     ARRAYS  XA AND YA.
C     THE TOTAL NUMBER OF SCANS IS 4 X NB .
      RETURN
901   FORMAT(I2,10X,I4,39X,I5)
      END
```

```
            SUBROUTINE FRSTSCN (BUF,IWORD,LMIN,LMAX,LABEL,NPTS,XA,YA,NA,NB)
            DIMENSION   XA(350,6,12) , YA(350,6,12) , BUF(240)
      C     VERSION  2        02.27.79
      C     DENNIS J W DUBE, VISIDYNE INC, BURLINGTON, MA, 617-273-2820
      C     THIS MODULE SEARCHES THE MAGNETIC TAPE FROM ENVIRODATA
      C     CORP.  TO FIND THE FIRST SCAN WHOSE LABEL LIES IN
      C     THE RANGE LMIN TO LMAX. THE DATA POINTS FOR THIS SCAN
      C     ARE SCALED AND STORED IN ARRAYS XA AND XB . THE
      C     BUFFER POINTERS NA AND NB ARE INITIALIZED          .
      10    CONTINUE
               DECODE(80,901, BUF(IWORD)) IOTA,LABEL,NPTS
               IWORD  =  IWORD  +  8
               PRINT *,#LABEL,NPTS,IWORD#,LABEL,NPTS,IWORD
            IF (IWORD  .NE.  241)  GO  TO 20
      C     REFRESH BUFFER AND INITIALIZE POINTER , IWORD
               BUFFER IN (     1,0)  (BUF(1), BUF(240))
            IF(UNIT(     1)   .EQ.  0)   STOP#FRSTSCN 1#
               IWORD   =  1
            PRINT *,#IWORD #,IWORD
      20    CONTINUE
      C     IS CURRENT SCAN LABEL IN RANGE.
            IF (LABEL   .GE.   LMIN)  GO   TO   50
      C     CALCULATE INDEX OF THE NEXT AVAILABLE BUFFER WORD , NXTWRD
      C     NXTWRD  =  IWORD   +   NPTS   +   ZERO FILL
            NZ = (NPTS/8)   *   8
            IF (NZ.NE. NPTS)   NZ = NZ + 8
            NXTWRD  =  IWORD   +   NZ
      C     REDEFINE  IWORD  ACCORDINGLY
            IF(NXTWRD  .LE.  240)  GO  TO   30
      C     SCAN OCCUPIES PARTS OF 2 OR MORE BLOCKS.
        25  BUFFER IN (      1,0)  (BUF(1), BUF (240))
               IF(UNIT(       1)   .EQ.   0)   STOP # FRSTSCN   2 #
               IWORD = NXTWRD - 240
               PRINT *, #IWORD #, IWORD
            IF(IWORD.LE.240) GO TO 40
            NXTWRD=IWORD
            GO TO 25
      30    CONTINUE
               IWORD = NXTWRD
               PRINT *, #IWORD#,IWORD
      40    CONTINUE
      C     SEARCH UNSUCCESSFUL THUS FAR
      C     FETCH NEXT SCAN AND TRY AGAIN
            GO  TO 10
      50    CONTINUE
      C     LABELS FOR THE NEXT GROUP OF SCANS OCCUR
      C     IN THE RANGE  LMIN TO LMAX
      C     NA IS THE AZIMUTHAL POSITION INDEX RANGING FROM 1 TO 4
      C     NB IS THE SCAN GROUP INDEX RANGING FROM 1 TO 12
            NA   =   1
            NB   =   1
      C     COLLECT AND SCALE DATA POINTS FOR THE FIRST SCAN
      C     STORE POINTS IN ARRAYS  XA AND YA
            CALL SCANFD (LABEL,NPTS,NA,NB,BUF,IWORD,XA,YA)
            RETURN
      901   FORMAT(I2,10X,I4,39X,I5)
            END
```

```
                SUBROUTINE SCANRD (LABEL,NPTS,NA,NB,BUF,IWORD,XA,YA)
          C     VERSION  2       02.27.79
          C     DENNIS J W DUBE, VISIDYNE INC, BURLINGTON, MA. 617-273-2820
          C     THIS MODULE LOCATES THE NPTS DATA POINTS FOR ONE SCAN
          C     WITH THE GIVEN LABEL. THE POINTS ARE SCALED AND STORED
          C     IN ARRAYS XA AND YA.  THE BUFFER POINTERS NA AND NB
          C     ARE UPDATED ACCORDINGLY.
                DIMENSION   XA(350,6,12) , YA(350,6,12) , BUF(240)
          C     CALCULATE INDEX OF THE NEXT AVAILABLE BUFFER WORD
                NZ = (NPTS/8) * 8
                IF(NZ  .NE.  NPTS)  NZ= NZ + 8
                NXTWRD  =  IWORD  +  NZ
          C     SCAN POINTS ARE DIVIDED BY 1000 PRTOF TO STORAGE IN
          C     ARRAYS XA AND YA .
                IF (NXTWRD  .LE.  240)  GO  TO  10
                PRINT*, *SCANRD-NZ, NXTWRD *, NZ, NXTWRD
          C     SCAN OCCUPIES PARTS OF 2 BLOCKS
          C     COLLECT FIRST PORTION FROM BACK END OF BUFFER
                I=241-IWORD
                   DECODE ( 80   , 902, BUF(IWORD)) (XA(J,NA,NB), YA(J,NA,NB), J=
               11,I)
                   BUFFER IN (    1,0) (BUF(1), BUF(240))
                IF(UNIT(    1)  .EQ.  0)  STOP*SCANRD 1*
                IWORD  =  NXTWRD  -  240
                IF(IWORD .LE. 240)  GO TO 9
          C     ENTIRE CONTENTS OF BUFFER BELONGS TO CURRENT SCAN.
             5  CONTINUE
                IP1=I+1
                IMAX=I+240
                DECODE(80,902,BUF(1))  (XA(J,NA,NB) ,YA(J,NA,NB), J=IP1,IMAX)
                BUFFER IN(1,0) (BUF(1), BUF(240))
                IF (UNIT(1) .EQ. 0)  STOP * SCANRD 2 *
                IWORD= IWORD-240
                I=IMAX
                IF(IWORD .GT . 240) GO TO 5
             9  CONTINUE
          C     COLLECT REMAINDER OF SCAN FROM FRONT END
          C     OF REFRESHED BUFFER
                   IP1  =  I+1
                   IMAX = I + IWORD - 1
                   DECODE( 80   , 902, BUF(1))
               1                    (XA(J,NA,NB),YA(J,NA,NB),J = IP1,IMAX)
                   GO  TO  20
          10    CONTINUE
          C     SCAN IS WHOLLY CONTAINED IN BUFFER .
                IMAX = NXTWRD - IWORD
                DECODE ( 80   , 902, BUF(IWORD))
               1                    (XA(J,NA,NB),YA(J,NA,NB),J = 1,IMAX)
                IWORD   =   NXTWRD
          20    CONTINUE
                RETURN
          901   FORMAT(I2,10X,I4,39X,I5)
          902   FORMAT ( 16 ( 3PF5.0) , 0P )
                END
```