CHARA TECHNICAL REPORT

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Performance Study of the Primary Mirror: Effects of the Axial and Lateral Support

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1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry, called the CHARA Array. This array will consist of initially five (with a goal of seven) telescopes distributed over an area approximately 350 m across. The light beams from the individual telescopes will be transported through evacuated pipes to a central laboratory, which will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment, and will be located at the Mount Wilson Observatory in southern California. The CHARA Array is funded by Georgia State University and the National Science Foundation.

CHARA Array telescope primary mirrors will be 40 in (1 m) in diameter with an f/2.5 paraboloidal figure and will be produced by a commercial optical company. More information about the mirrors and procurement specifications are detailed in CHARA Technical Report No. 16. In late 1995, following a procurement process administered by the Georgia State University Purchasing Department, Telescope Engineering Company, Inc. (TEC) of Lakewood, Colorado emerged as the successful bidder for producing five primary mirrors. As part of the procurement specifications, the bidder was required, within certain constraints listed in Technical Report No. 16, to specify the mirror blank shape and material characteristics. One of the constraints was that the mirrors will be mounted on an 18-point mechanical "whiffle-tree" axial support for final testing purposes and also in the telescopes.

In the TEC bid, the mirror material is specified to be Sitall CO115M, a low-expansion ceramic glass produced in Russia. The mirror blank is specified to be a solid plano-concave shape with 18 lightweighting holes bored into the back surface and arrayed into inner and outer rings of 6 and 12 holes, respectively. A sketch of the mirror blank was provided with the bid, but lacked radius values for the inner and outer rings of holes. This was subsequently provided in the form of an engineering sketch (Figure 1) dated 4 December 1994 from Yuri Petrunin, president of TEC. It is now necessary to determine how well the TEC-specified mirror will perform on an 18-point support and to determine the locations of those supports. That is the purpose of this report.

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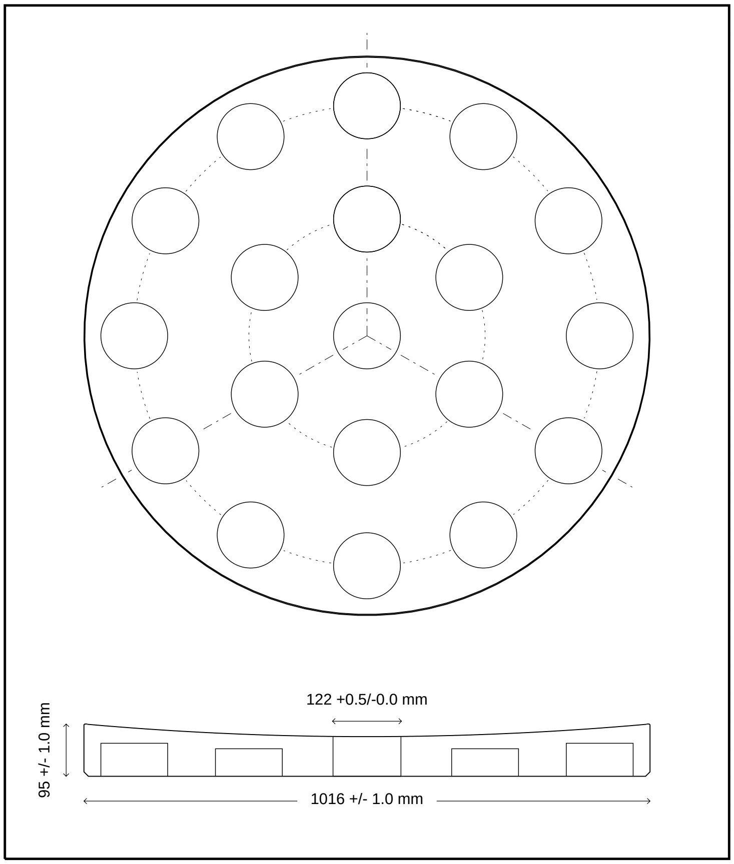

FIGURE 1. The CHARA primary mirror blank, from an engineering sketch provided by Telescope Engineering Company, Inc. Dimensions from the original drawing were the basis for the finite-element model used in the present study. Eighteen 120-mm diameter cavities are arranged in concentric circles of 212.0 and 417.7 mm radius, respectively. The inner cavities have a depth of 50 mm, the outer cavities 60 mm.

In addition to the 18-point axial support, the mirror will be supported in the lateral (radial) direction by means of a "central post" mechanism inside the central hole. The performance of the mirror on that support will also be examined in this report, although testing of the mirror in the optical shop on its lateral support is not presently required.

2. CONCLUSIONS FROM THIS STUDY

Finite-element analyses (FEA) described in sections to follow enabled these conclusions:

1. The mirror blank configuration specified by TEC exhibits satisfactory performance when mounted on an 18-point support. Performance on the lateral support also appears to be satisfactory. Front surface deflections are lower than the acceptably small values obtained from an earlier analysis (1994) of the plano-concave mirror used

for initial telescope design.

2. Support and pivot locations for the 18-point "whiffle-tree" were obtained which will enable completion of the primary mirror cell design.

3. ANALYSIS MODELS

Finite-element analysis (FEA) was used to determine the apparent front surface deflections of the mirror under gravitational loads. The computer modeling and analysis was done using "GIFTS", an FEA program developed at the University of Arizona and marketed by C.A.S.A GIFTS, a Tucson-based company. The initial objective was to determine optimum locations for the 18 axial supports and for this purpose, a "quarter-model" of the mirror was sufficient because the mirror is symmetric about the x and y axes when viewed from the z axis (the z axis is defined to be the optical axis).

The 18 lightweighting holes were simulated in the model by hexagonal cavities with an area equal to that of the holes and depth equal to that of the holes. Circles are normally modeled with n-sided polygons in FEA models and little accuracy is lost with this approximation. The relevant properties of Sitall CO115M, the mirror material, are as follows:

Property	Metric	English (Used in Model)
Density	2.46 gm/cc	0.08879 $\mathrm{lb/in^3}$
Young's Modulus	9.02×10^9 Pa	13.08×10^6 $\mathrm{lb/in^2}$
Poisson's Ratio	0.28	0.28

For all FEA runs discussed in this report, it was assumed that the axial supports would be located between the lightweighting holes, distributed in an inner ring with 6 equally spaced supports and an outer ring with 12. TEC suggested placing the supports inside the lightweighting holes. This suggestion was not adopted, however, because it was uncertain whether the lightweighting holes were specified at radius values best suited for axial support performance. In fact, the analysis did show the radius values to be different. Also, to locate supports at the lightweighting holes would necessitate a means, such as an invar cup inserted in each hole, to distribute the reaction forces to the rim of the holes to avoid greater support "print-through" due to reduced mirror thickness above the holes.

Analysis using the "quarter-model" was done in two stages, as described below.

Stage 1: By "trial-and-error", reasonably good positions of the 18 support points were found assuming that all axial points were fixed in the z direction, the direction that gravity was allowed to act on the model. In effect, this simulated an infinitely stiff 18-point support. The principal variables were the radius values of the two support rings.

Stage 2: When acceptable radius values were found for the two rings of supports, the support points were allowed to deflect in the z direction, and "reaction" forces were applied to the support points to offset the gravitational forces (weight) of the mirror. Inner ring forces were kept equal as were outer ring forces, but forces between the two rings were adjusted by "trial-and-error" until the front surface deflections were as good or better than those obtained in Stage 1. The ratio between the inner and outer ring forces then established the necessary pivot location in the mechanical "whiffle-tree" to obtain the desired force distribution.

Although the "quarter-model" was adequate for axial support analysis, it could not be used for examining the performance of the mirror on its lateral support. This is because neither the mirror nor the lateral support appears symmetric about the x axis when gravitational acceleration is not parallel to the z axis. For this case, a "half-model" is required. The computer run time for the "quarter-model" is about 20% that of the "half- model" so it was used to optimize the axial support locations before considering the lateral support. The axial support locations were not changed between the two models.

Slight differences in results do exist between the two models for calculated surface displacements for nominally the same loading conditions (i.e. the 0° zenith angle cases). These are due to boundary conditions imposed to simulate the lateral support and, to some extent, differences in "round-off" errors. The errors are negligible.

4. RESULTS FROM QUARTER-MODEL ANALYSIS

Stage 1: A series of FEA runs was made with all axial support points fixed in the z direction on the rear surface (Run CHARA108). Radius values for the rings of supports are listed below. These values are not the final values to be used in the mirror cell, but were used as a "starting position" for subsequent analyses in Stage 2.

Inner ring	$R_i =$	8.527 in (216.6 mm)
Outer ring	$R_o =$	16.558 in (420.6 mm)

Mirror weight according to the "quarter-model" was 292.74 lbs (133.06 kg) which compares well with the TEC estimate of 134 ± 1 kg. Slight differences in weight are attributable to geometric differences between the model and the actual mirror shape (i.e., curves approximated by a series of connected straight lines, etc.).

Stage 2: A second series of FEA runs was made with the mirror weight exactly offset by reaction forces applied at the 18 support points (Run CHARA117). By "trial-and-error", the support forces were adjusted between the inner and outer rings and the support locations were varied. The mirror surface is improved compared to that calculated earlier. The objective was to minimize surface deflections and to make the deflections reasonably uniform over the entire mirror surface. From Run CHARA117, the deflections were:

Max. positive deflection		5.0×10^{-7} in	(over support point)
Max. negative deflection		2.5×10^{-7} in	(at upper edge)
	P-V	7.5×10^{-7} in	($\lambda/26$ at $\lambda = 500$ nm)
RMS surface deflections		1.54×10^{-7} in	($\lambda/130$ at $\lambda = 500$ nm)

Variations in a wavefront reflected from the mirror surface will be double the values shown above, but are still considered quite acceptable.

In the 18-point "whiffle-tree" design, two outer ring supports and one inner ring support will be mounted to a pivoted tripod (6 tripods total). Each tripod will be mounted to the end of a pivoted support lever (3 levers total). Each pivoted lever will connect to the mirror cell through a pivot at its longitudinal center, comprising a 3-point positioning system for the mirror. The 18-point support is illustrated schematically in Figure 2 below.

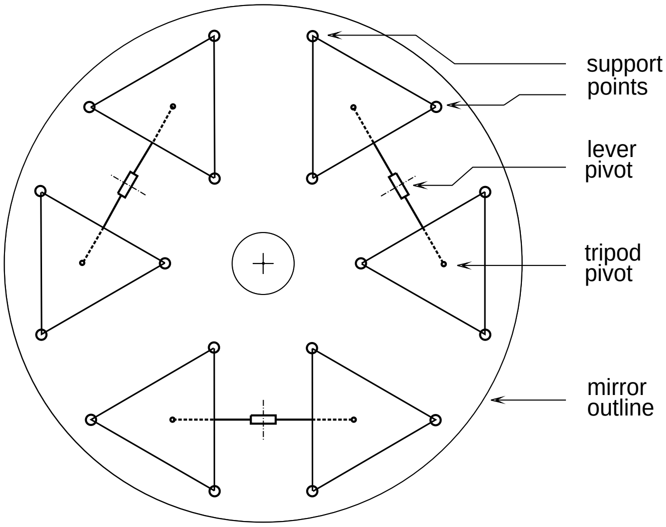

FIGURE 2. Schematic sketch of an 18-point mechanical “whiffle-tree” axial support

Forces and radius values at the support rings obtained from the FEA study are listed below. From these values, the locations of the necessary pivot points are obtained and are also listed.

	Force/support	Radial Distance From Center	
Inner ring	15.400 lb	7.480 in	(190.00 mm)
Outer ring	16.695 lb	16.654 in	(423.00 mm)
Tripod pivot	—	13.758 in	(349.45 mm)
Lever pivot	—	11.915 in	(302.64 mm)

These values will be used for the design of the primary mirror cell. Notably, the radius values differ from the earlier “starting point” values. Since both sets of values yielded good results, it may be inferred that modest errors in pivot location can be tolerated. This simplifies the mirror cell manufacturing requirements.

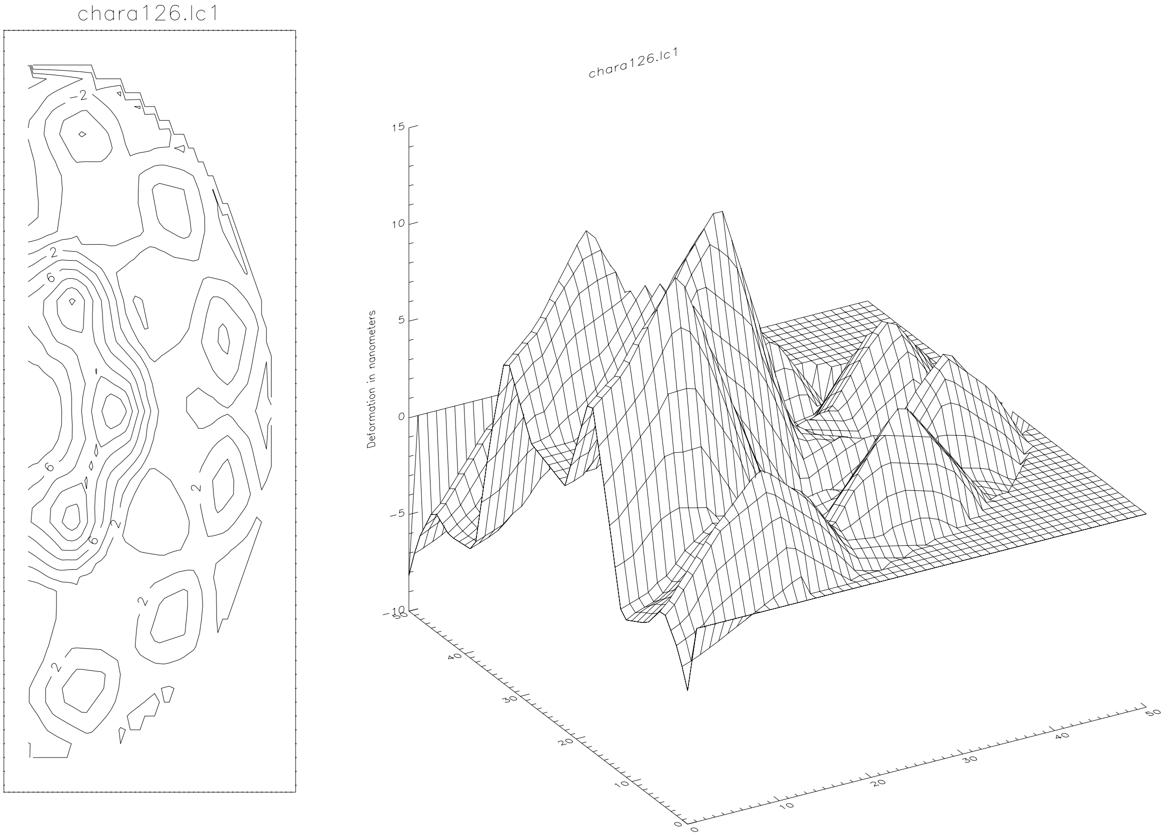

FIGURE 3. Reflecting surface deflection contours for 0° zenith angle conditions. Contour interval is about $\lambda/250$ for $\lambda = 500\,\mathrm{nm}$. the "half-model" and "quarter-model" yield similar results for the same loading conditions.

5. RESULTS FROM THE "HALF-MODEL" LATERAL SUPPORT STUDIES

The "half-model" was run with four load conditions in order to examine the expected change in mirror surface due to the supports as the telescope rotates from a zenith-pointing attitude to the horizon. At 0° zenith angle (Loading Case 1), the mirror is supported entirely by the axial support and the mirror deflections should be the same as obtained with the "quarter-model". At 90° zenith angle (Loading Case 4), the mirror is supported entirely by its lateral support which will be located inside the central hole. Two intermediate cases at 30° and 45° zenith angles were run as well (Loading Cases 2 & 3 respectively). One would expect a smooth transition between the four load cases. Figures 3 through 6 illustrate the results.

In all loading cases, the axial mirror support is the same as used for the final "quarter-model" run (CHARA117). Introduction of the lateral support constraints at the central hole resulted in negligibly small differences in the calculated deflection values.

Results for the 0° zenith angle are illustrated in Figure 3. It is seen that the contours are similar which indicates the "half- model" provided results similar to the "quarter-model" as expected. Figures 4, 5, and 6 illustrate results for the 30°, 45°, and 90° zenith angle

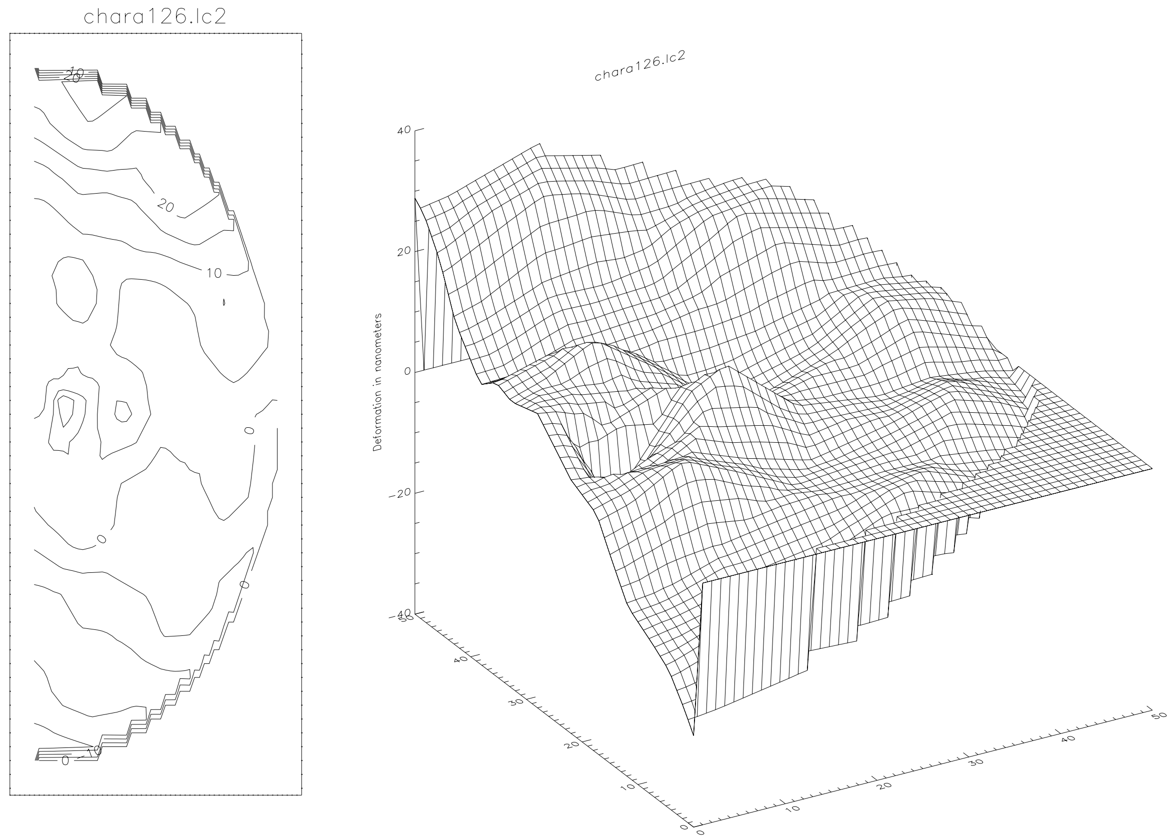

FIGURE 4. Reflecting surface deflection contours for 30° zenith angle conditions. Contour interval is about $\lambda/100$ for $\lambda = 500\,\mathrm{nm}$. For this case, both axial and lateral supports produce effects on the mirror surface.

conditions respectively.

In general, the mirror surface exhibits a characteristic “collapse” as the mirror is pointed further away from zenith. The top half of the mirror tends to bend forward while the bottom half bends rearward. The effect on images formed by the mirror would be introduction of a small comatic aberration, but no attempt to quantify this effect is made in this report. Maximum peak-to- valley surface deflections for the four loading cases are listed below plus the RMS values for the two limiting cases. Wavefront variations will be double the listed values.

Loading Case	Zenith Angle	Max. P-V Deflection		RMS Deflection	
		Inches $\times 10^{-6}$	Waves ($\lambda = 500\,\mathrm{nm}$)	Inches $\times 10^{-6}$	Waves ($\lambda = 500\,\mathrm{nm}$)
1	0°	0.89	$\lambda/22$	0.166	$\lambda/120$
2	30°	2.31	$\lambda/9$		
3	45°	3.28	$\lambda/6$		
4	90°	4.66	$\lambda/4$	1.06	$\lambda/18$

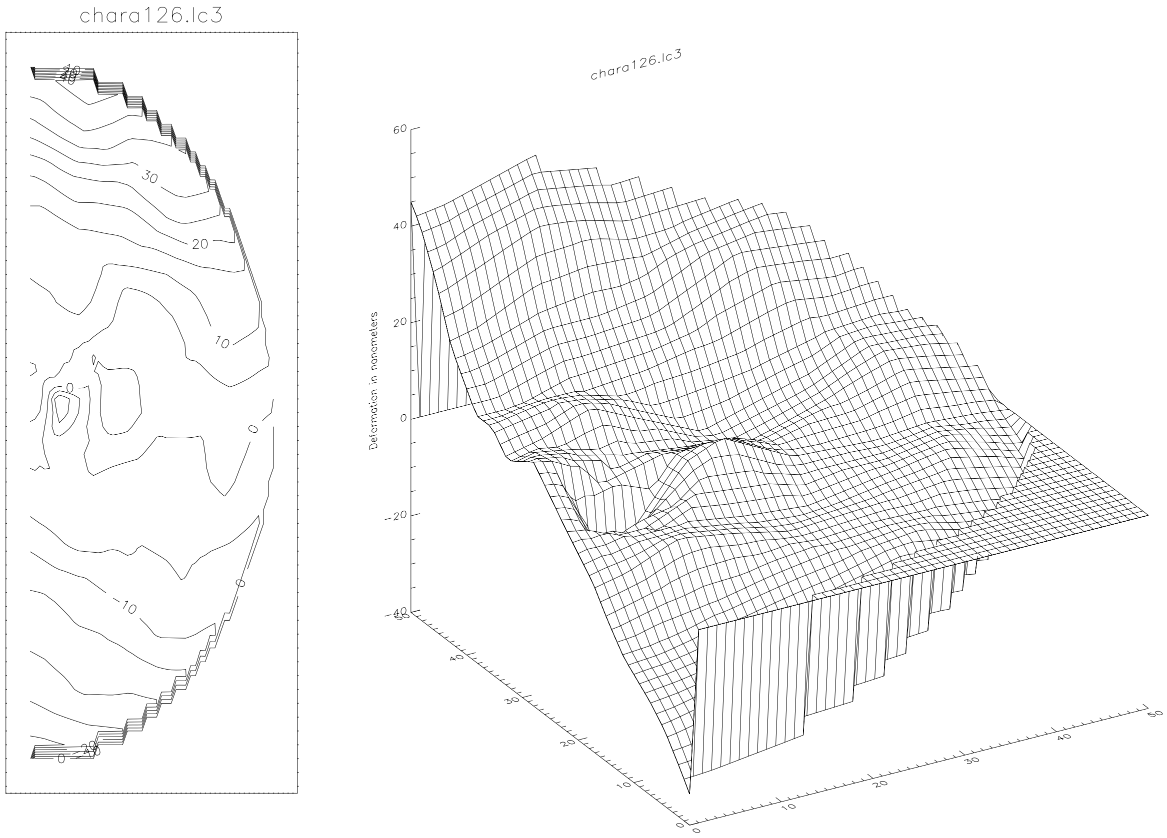

FIGURE 5. Reflecting surface deflection contours for 45° zenith angle conditions. Contour interval is about $\lambda/100$ for $\lambda = 500\,\mathrm{nm}$. For this case, both axial and lateral supports produce effects on the mirror surface.

Loading Case 1 values are similar to those obtained for the "quarter-model" (P- V: 0.75×10^{-6} in, RMS: 0.154×10^{-6} in).

These results are considered acceptable. Deflection values are smaller than those obtained for similar loading cases in an analysis performed in 1994 (CHARA68) for a solid plano-concave mirror configuration used for initial telescope design. Deflections found in CHARA68 were considered acceptable by the CHARA Project. The improved results obtained here are attributable to the greater thickness of the TEC mirror which is 3.7 in thick at the outer rim compared to 3.2 in used for the CHARA68 mirror.

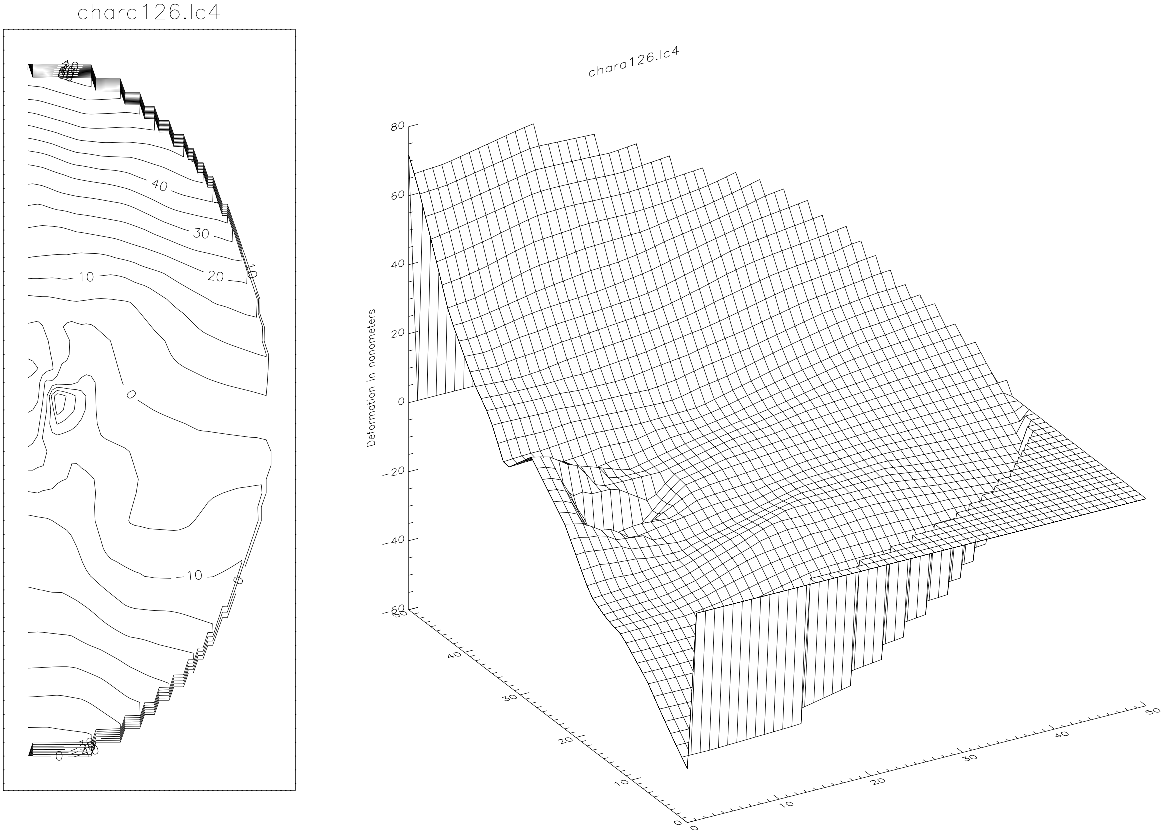

FIGURE 6. Reflecting surface deflection contours for 90° zenith angle conditions. Contour interval is about $\lambda/100$ for $\lambda = 500\,\mathrm{nm}$. For this case, the mirror is supported entirely by the lateral support.