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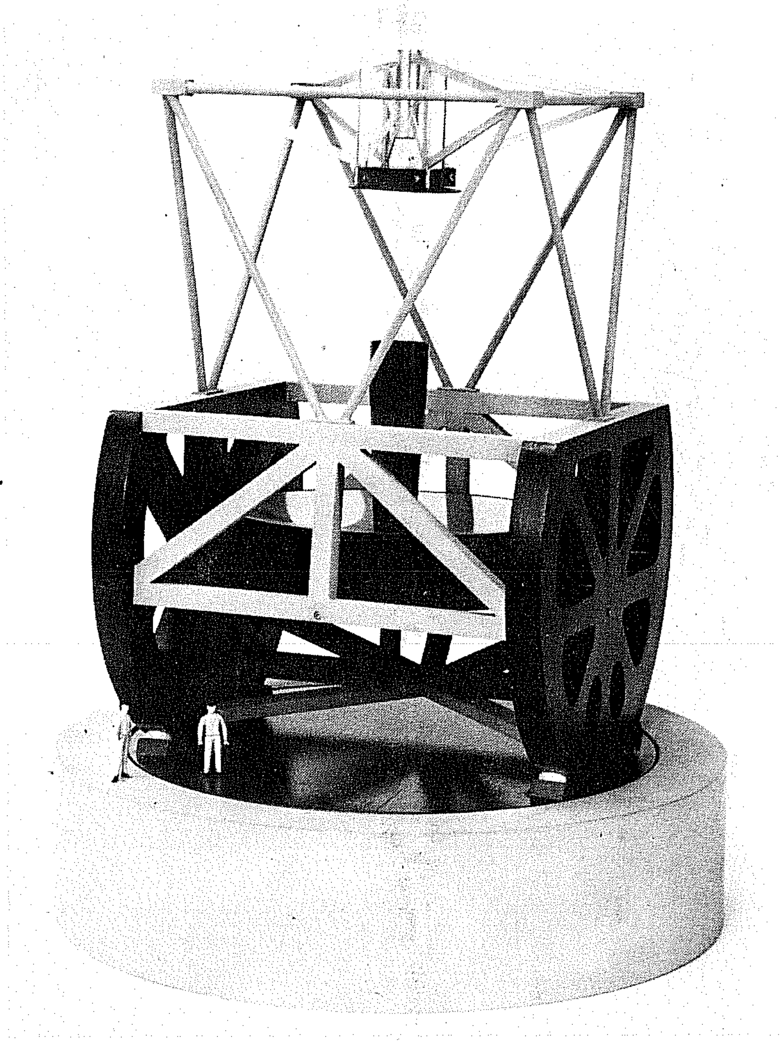

# Preliminary Design of the f/6.5 Optical Secondary

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CONTENTS

LIST OF FIGURES

## 1. Introduction

The current optical design for the telescope of the Magellan Project contains an 8-meter, f/1.2 parabolic primary mirror and an hyperbolic secondary and has a final focal ratio at the optical Cassegrain focus of f/6.5. This optical configuration (described in further detail by Epps[1]) requires a very large (68 inches in diameter) and highly aspheric (0.0129 inches or 655 waves maximum aspheric deviation) secondary mirror. The purpose of this paper is to describe a candidate design for this mirror and to discuss possible alternatives.

## 2. Mirror Design

The candidate secondary mirror design is shown in Figure 1. This mirror has a lightweight, closed back sandwich construction, and weighs 432 pounds. It is designed to be made of Corning ULE (Ultra Low Expansion material), a titanium silicate material with essentially zero thermal expansion at room temperature. ULE can be machined and frit bonded or fusion welded. Its properties are summarized in Table 1 on the next page.

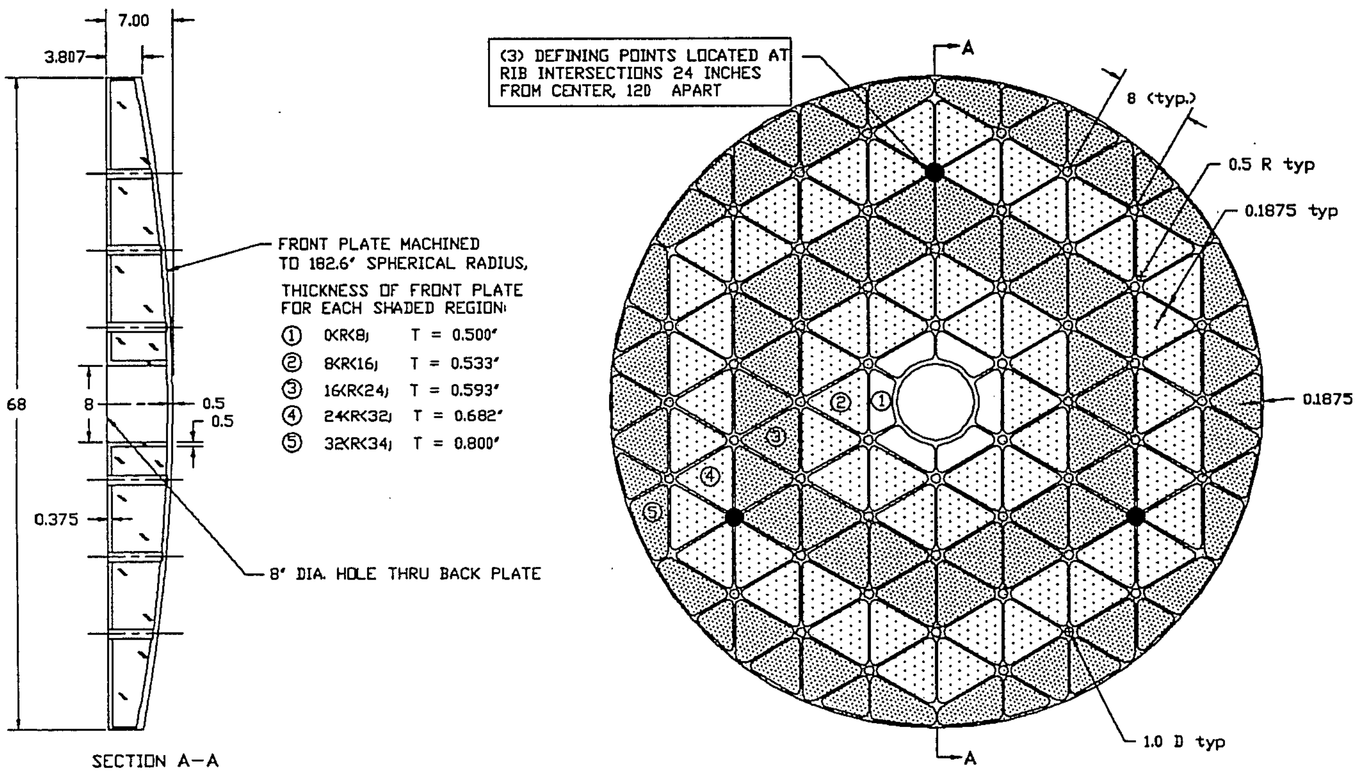



Fig. 1. - Lightweight secondary mirror design.

Table 1 - ULE 7971 Properties

| | | |
|---|---|---|
| Coefficient of Thermal Expansion | $0.05 \times 10^{-6}$/°F | ($0.03 \times 10^{-6}$/°C) |
| Density | 0.0797 lbs/in$^3$ | (2200 kg/m$^3$) |
| Elastic Modulus | $9.80 \times 10^{6}$ psi | ($6.77 \times 10^{10}$ N/m$^2$) |
| Thermal Conductivity | 0.757 Btu/h-ft-°F | (1.31 W/m-°C) |
| Thermal Diffusivity | $8.50 \times 10^{-6}$ ft$^2$/sec | (0.0079 cm$^2$/sec) |

The secondary mirror would be fabricated in two halves. Corning would provide two 68.1 inch diameter by 3.5 inch thick plano-plano ULE solids. An optical house would lightweight the two halves and machine the front convex surface. The two lightweighted halves would be frit bonded together, and then figured and polished by an optical house. This fabrication technique should allow greater lightweighting efficiency than simply machining lightweighting cells from the back of a solid blank and may avoid some of the complexities of a completely frit bonded structured mirror.

The mirror geometry was selected to provide high stiffness while keeping the weight under 450 pounds. A triangular core lightweight structure was selected. Using closed form analytic solutions and finite element analysis, Sheng has shown triangular cells to be slightly superior in stiffness to hexagonal or square cell mirrors[2]. The ribs are 3/16 inch thick, a size which should be machinable without great difficulty. The triangular cells and the front face plate thickness were sized to minimize print-through during polishing. For a polishing pressure of 0.1 psi and triangular cells with 8 inch long sides, the 0.5 inch thick face plate deflects a maximum of 0.613 micro-inches (15.6 nm) or $\lambda/35$ at $\lambda = 0.56$ microns. If ion polishing is used (Kodak has developed facilities for ion polishing optical components up to 100 inches in diameter), the face plate thickness could be reduced, as print-through would no longer be a serious concern. The thickness of the face plate increases in four discrete steps towards the outer edge of the mirror, up to a maximum of 0.8 inches (see Figure 1). This is done to achieve a more uniform radial weight distribution, by compensating for the varying overall thickness of the mirror due to its high curvature. Varying the thickness of the front plate also moves the center of gravity forward, which improves the overall deflection performance of the mirror (see Section 4).

## 3. Mirror Support

The mirror cell and central support are shown in Figure 2 (see next page). The mirror is supported radially by an 8 inch diameter disk flexure inside the central hole of the mirror, at the center of gravity. The axial loads are carried by a partial vacuum behind the secondary mirror. A vacuum of approximately 0.1 psi less than the local barometric pressure is needed to support the secondary when zenith pointing. The tilt of the mirror is defined at three locations, 120 degrees apart and 24 inches from the center by three piezoelectric actuators. These actuators, shown schematically in Figure 3 (see page 4), allow tilting the

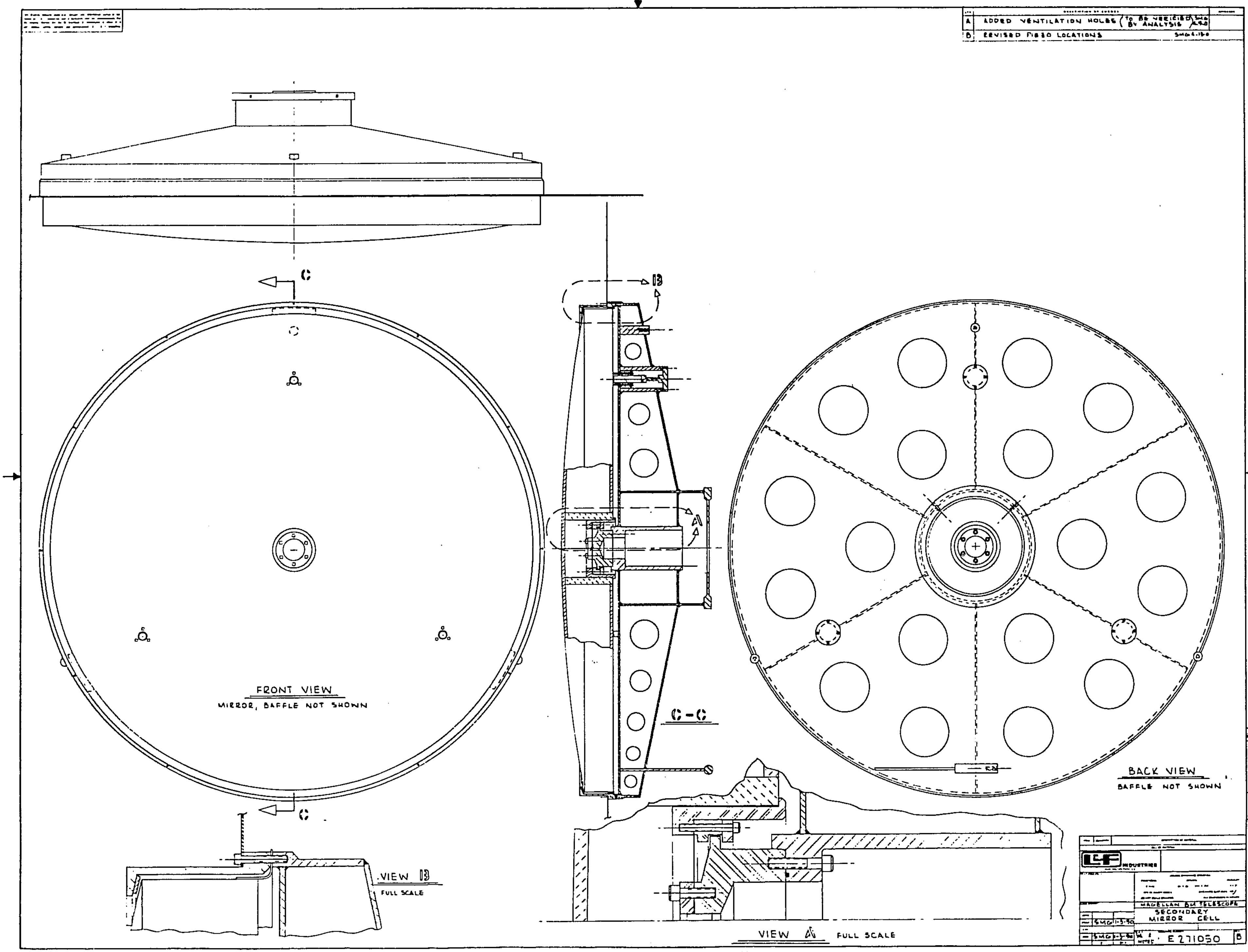



Fig. 2 Secondary mirror cell

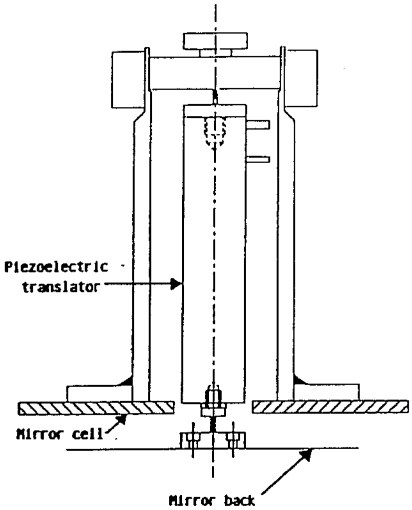



Fig. 3. - Piezoelectric actuator.

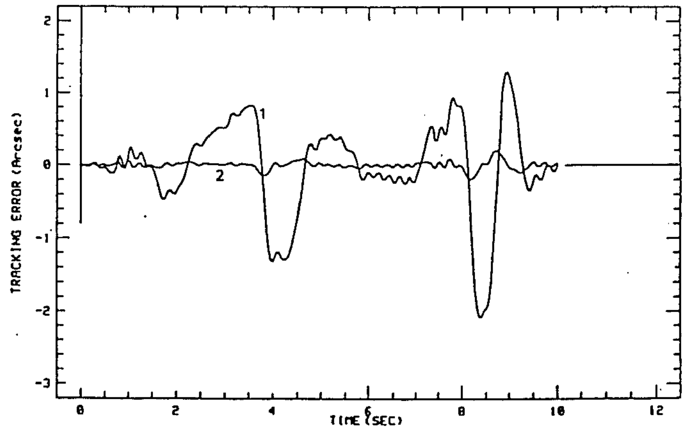



Fig. 4. - ESO VLT tracking error under wind load.

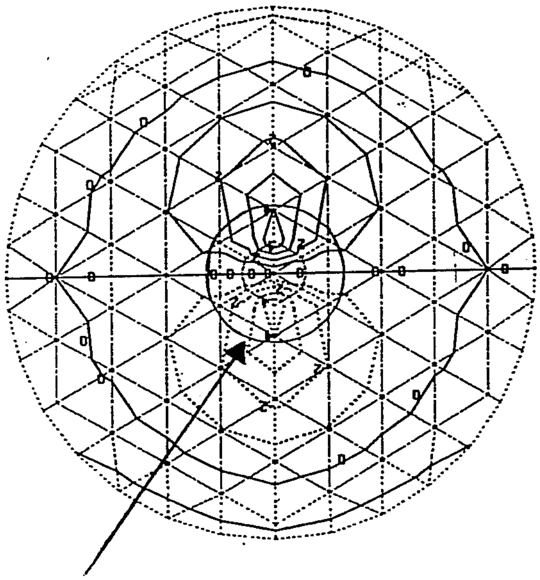
mirror, relative to its cell, up to +/- 13 arcsec (+/- 5 arcsec image motion at the Cassegrain focus) with very high precision (better than 0.13 arcsec mirror tilt, 0.05 arcsec at the focus). This secondary tilting mechanism is to be used at 2-3 Hz for fine guiding to relieve the telescope tracking requirements[3]. The value of such a system is illustrated in a study performed by ESO which shows the reduction in wind induced tracking errors for the VLT from 0.58 arcsec r.m.s. to 0.038 arcsec r.m.s. with an active secondary tilting system (Figure 4)[4]. The piezoelectric actuators also have the potential to be used at higher bandwidths for image sharpening.

Six mechanical actuators are to be used to maintain focus and colimation by translating and tilting the secondary mirror and its cell. These mechanical actuators and the remainder of the secondary support structure are described in detail by Gunnels[5].

## 4. Optical Performance

A series of finite element analyses of the secondary mirror design were performed by Dr. Earl Pearson of the National Optical Astronomy Observatories. The deflections of the front surface of the mirror were calculated for horizon pointing, with the weight of the mirror carried entirely by the central radial support disk. The resulting contour map (with piston, tilt and focus removed) is shown in Figure 5 (see next page). The peak-to-valley deflection value is 0.475 $\lambda$ ($\lambda$ = 0.22 x 10 $^{-4}$ inches or 0.56 microns). The circle in the center of the

Displacements normal to surface
Piston, tilt, focus removed
Contour interval = 0.0475 $\lambda$
$\lambda = 0.22 \times 10^{-4}$ in



Optically unused region

Fig. 5. - Mirror front surface deflections - horizon pointing.

Diameter of 50% circle of energy
= 0.046 arcsec at image plane.

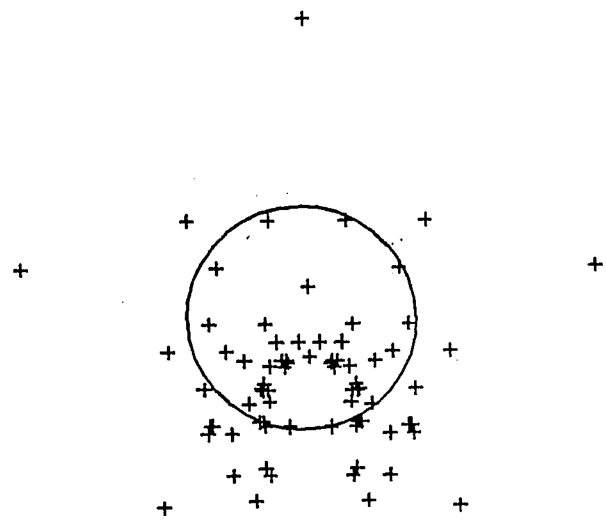


Fig. 6. - Spot diagram - horizon pointing.

mirror denotes the roughly 19.5 inch diameter region of the secondary which is unused optically. The resulting image spot diagram is shown in Figure 6. Fifty percent of the energy is encircled in 0.046 arcsec at the focal surface. This seems acceptable as a worst case value (horizon pointing).

The mirror was also analyzed at horizon pointing with the back plate removed. This modification reduces the mirror weight to 326 pounds. However, the peak-to-valley front surface deflection has risen to 1.35 $\lambda$, about three times that for the closed back case (see Figure 7 on the next page). The 50% circle of energy is now 0.7 arcsec (see Figure 8 on the next page). Despite the weight savings, this is not an acceptable configuration.

In its baseline closed back configuration, the mirror was analyzed when zenith pointing, with the weight of the mirror exactly balanced by the vacuum system. The 0.1 psi pressure difference required to support the mirror introduces very small print through errors. These figure errors are of the same approximate magnitude as the polishing print through errors but are in the opposite direction and so should actually tend to improve the mirror figure. Global figure errors are also introduced into the mirror by the vacuum support system. These are due to shear deflection effects and to the radial weight distribution of the mirror not being precisely uniform. The resulting distortion, however, only produces a slight focus change which should be almost imperceptible and easily corrected.

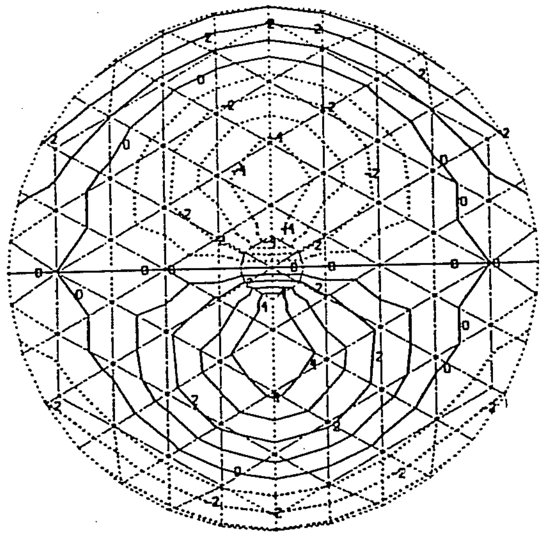



Fig. 7. - Open back mirror.

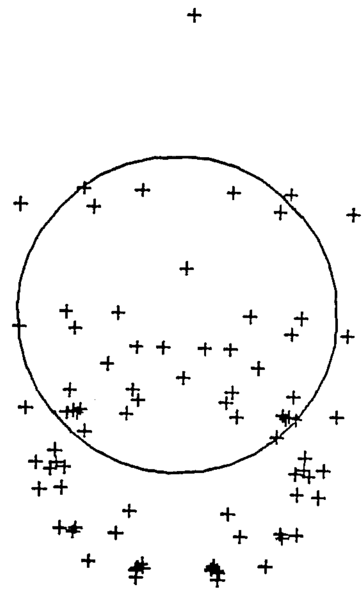



Fig. 8. - Open back mirror spot diagram - horizon pointing.

To determine what forces can be applied by the three piezoelectric actuators without significantly distorting the mirror figure, the mirror was analyzed in a zenith pointing orientation, with the entire weight of the mirror carried at the three locations of the actuators. The deflection contour map for this case is shown in Figure 9. The results were scaled to determine what forces may be applied. For a peak-to-valley surface deflection of 0.1 $\lambda$, the loading should be limited to 3 pounds per actuator, or less. As a point of comparison, less than 0.1 pounds of force per actuator are required to produce image motion of +/- 0.3 arcsec at 10 Hz (this is the most demanding proposed requirement for guiding).

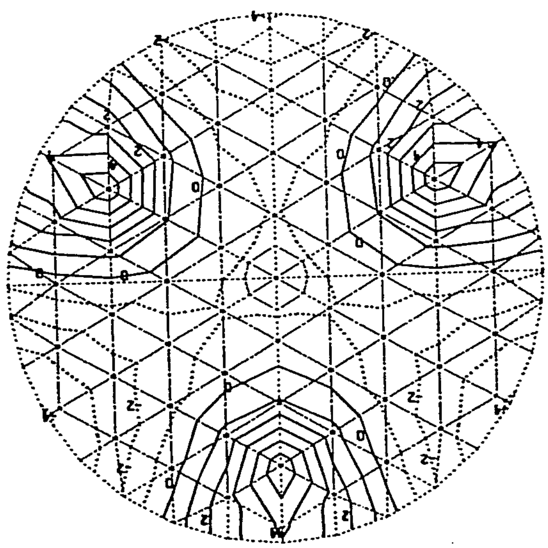



Fig. 9. - Mirror deflections - zenith pointing, entire weight on three points.

## 5. Thermal Performance

The use of ULE for the secondary mirror should essentially eliminate any figure distortion due to thermal expansion of the glass. However, the potential for mirror seeing problems still exist.

Barr *et al.*[6] have indicated that mirror seeing effects will be negligible for a zenith pointing mirror if its surface temperature is within 0.5 °C of the ambient air temperature. It seems reasonable to assume that mirror seeing effects will also be negligible for a nadir-looking, convex secondary held to the same temperature tolerance. A simple heat transfer analysis of the Magellan secondary indicated that the 0.5 °C temperature difference requirement can be met when the ambient temperature is decreasing at a rate of 0.25 °C/hour with a minimum wind speed of 3.1 m/s.

Additionally, it appears that slight ventilation of the mirror surface will nearly eliminate mirror seeing, even with the mirror temperature several degrees above ambient. In an experiment performed by ESO, the original wavefront was nearly retrieved when the surface of an aluminum mirror 30 °C above ambient was ventilated with a 0.2 m/s wind[7]. The Magellan secondary is located very close to the slit opening of the dome and should almost always be ventilated by a much higher velocity wind.

In summary, it appears that the use of a very low expansion material and the location of the secondary very near to the open air should eliminate any concerns about the thermal performance of the secondary mirror, without resorting to the use of an active thermal control system.

## 6. Other Mirror Configurations

Potential refinements to the mirror design are currently being explored. One possibility is reducing the thickness of the front face plate to improve the thermal response. "Sub-ribs" would be added to maintain the stiffness. Another modification to be explored is a biconvex mirror. This would require additional machining of the mirror, but may improve its deflection performance and reduce its weight.

Silicon carbide (SiC) is another interesting possibility. Two specialized forms of SiC appear attractive for lightweight mirrors. One is a proprietary method developed by United Technologies Optical Systems, involving freeze-drying a SiC slurry. United Technologies expects to have 1 meter mirror capability by 1991 and possibly 2 meter capability later.[8] The other form of SiC is produced by chemical vapor deposition and is introduced by CVD Co. CVD currently produces 0.5 meter SiC mirrors and expects to have the capability to produce 1/5 meter mirrors by the end of the 1990[9]. Both forms offer high specific stiffness, allowing areal masses of approximately 20 $kg/m^2$, and excellent thermal stability. Application of SiC technology to the secondary for the Magellan Project is currently being investigated.

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