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Roller chain supports for large optics

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ABSTRACT

Henry Draper described the use of flexible bands to minimize optical surface deflection of mirrors mounted in the optical axis horizontal position in 1864. Despite this historical background, the theoretical basis for horizontal band support was not developed until quite recently. Use of finite element analysis has led to a better understanding of the performance of horizontal band supports. Analytical modeling of horizontal band supports has resulted in improvements in design. In particular, the use of roller chains as a horizontal support significantly reduces the deflection of an axis horizontal large mirror. Providing that certain design precautions discussed in this paper are taken, roller chains provide a relatively simple and low cost support. A number of successful roller chain supports for optics from 0.68 m to 1.8 m in diameter have been built based on the results of the above analytical models.

2. INTRODUCTION

Deflection due to self-weight (gravity deflection) is a serious problem with large reflective optics. Optical surface figure error of a large mirror is determined by both the quality of the optical fabrication process, and the quality of the mechanical support for the mirror. Gravity deflection when the mirror is facing the zenith, or in the optical axis vertical position, is relatively easy to understand through the use of classic plate bending theory. Significantly more difficult to understand, both quantitatively and qualitatively, is the surface deformation of a large mirror when in the optical axis horizontal position.

When in the optical axis horizontal position, the mirror is compressed in the vertical direction, while the horizontal portion of the mirror is relatively unaffected. Compression of the mirror in the vertical direction leads to a change in the radius of curvature of the mirror in the vertical direction. However, the horizontal radius of curvature does not change. The effect of gravity is to induce two different radii of curvature in the same mirror. Astigmatism is induced in the mirror, as shown in figure 1.

Reducing the astigmatism in a optical axis horizontal mirror requires a support which counteracts the effects of gravity. In 1864, Henry Draper reported in the use of a metal band around the lower 180° of a telescope mirror as a means of reducing the self-weight optical surface deformation of the mirror in the axis horizontal position.[1]

The band support was not popular in traditional telescope design, since it is not well suited for use in equatorial mounted telescopes, however, optical fabricators continued to used the band support for testing optics. Ritchey used a band support during testing of the Mt. Wilson 1.5 m telescope mirror.[2]

Use of band supports was performed empirically, without an analytical model of the optical surface deformation due to gravity. In 1931, Couder attempted to develop an analytical basis for band supporting of large mirrors, but his efforts were not successful due to an inability to observe any measurable optical surface deformation in a horizontal 1.2 m mirror![3] Schwesinger developed an analytical model of the deflection of a mirror in a band support in 1954.[4] The validity of Schwesinger's approach is quite controversial.[5] This approach has remained the only "closed form" solution available.

More recently, the accurate prediction of self-weight induced deflection of large mirrors in the axis horizontal position has become possible with the use of computer aided structural analysis techniques. Malvick used the method of dynamic relaxation in 1968 to determine surface deflection of large mirrors.[6] Further development of computer aided structural analysis allowed Malvick to carry out a parametric study of a variety of mirror supports.[7] Results of this parametric study indicated that a simple band was the best overall support. This result was substantiated with experiments on the Optical Sciences Center 1.5 m mirror.

During a study by Malvick and Richard of horizontal support for lightweight mirrors of the Multi-Mirror Telescope (MMT) project, the use of a roller chain as a replacement for a conventional band support was suggested.[8] Roller chains with oversized rollers were expected to provide determinate and repeatable friction, and to ensure uniform radial load. Roller chain support was successfully used for the primary mirror mounts of the six 1.8 m diameter lightweight mirrors of the MMT.[9] Since this successful first use of the roller chain mirror support, this type of mirror support has become relatively common in large optics projects. (The roller chain radial support and air bag axial support for the primary mirrors of the MMT were identical in concept to Drapers 1864 mirror support.) For example, the 2 m diameter steering flat of the Infrared Spatial Interferometer uses a roller chain radial support.[10]

3. ROLLER CHAIN SUPPORT DESIGN

At least four different radial support schemes are used for large mirrors: whiffle trees, push-pull, mercury rings, and bands. The whiffle tree uses discrete support points in contact with the circumference of the mirror. The whiffle tree is made statically determinate by tying the individual support points together with a system of pivoting rockers. Disadvantages of the whiffle tree are the concentrated loads in the mirror due to the limited point contacts, friction effects in the pivots, and limitation of the support force to the area below the mirror. Push-pull supports use individual support points connected to counterweight lever mechanisms. This provides a sinusoidal distribution of force on both the top and bottom of the mirror. Like the whiffle tree support, the push-pull support has the disadvantage of limited area of contact with the mirror. Friction effects limit the optical figure quality of a push-pull supported mirror.[11] Mercury filled rings placed around the circumference of a mirror provide a quasi-hydrostatic distribution of support force in the mirror which induces a theoretical nearly optimum radial deformation in the optical surface figure. Unfortunately, the performance of the mercury ring is offset by serious practical difficulties, such as mirror deformation induced by defects (seams, fill ports, wrinkles) in the mercury ring, and sloshing of the mirror from side to side.

Performance of the various types of radial supports is compared in figures 2, 3, and 4. Shown are surface contour plots of the self-weight induced deflection of the 1.8 m lightweight primary mirrors of the MMT. Deflection was determined using the computer program MAP (Mirror Analysis Program) developed by R.M. Richard.[12] The mirror model used in this program involved 2633 elements and solved 1107 simultaneous equations. The MMT primary mirrors are fused silica lightweight sandwich structures, with a honeycomb shear core employing square cells. Diameter of the meniscus shaped mirror is 1.867 m, the thickness is 0.325 m, and the optical radius of curvature is 9.88 m. Faceplate thickness, 33.3 mm, is different from the backplate thickness, 27 mm; the shear core ribs are 6.4 mm thick, and cell size of the shear core is 76 mm. The roller chains were placed around the edge of the front, and back plates of the mirror. Total mirror weight is 550 kg.

In figure 2, deflection due to a roller chain support is compared to the deflection due to a whiffle tree support. The roller chain has a maximum deflection of 30 nm, while the whiffle tree has a maximum deflection of 382 nm. In figure 3, the roller chain support is compared to the optical surface deflection due to a push-pull system, which has a maximum value of 135 nm. In figure 4, the roller chain support is compared to a mercury ring support, which has a maximum deflection of 30 nm, equal to that of the roller chain.

Practical design of a roller chain support for a large mirror begins with calculation of the self-weight deflection of the mirror. For preliminary design estimates, a method developed by Schwesinger is useful for predicting band or roller chain performance. First the curvature factor is calculated:

$$K = \frac{r^2}{2h_o R} \tag{1}$$

(Note that K = 0 for a flat mirror, or infinite radius of curvature.)

Then the RMS surface deflection is calculated:

$$\delta = (0.00738 + 0.10669K + 0.03075K^2)\ \frac{2\rho r^2}{E} \tag{2}$$

where:

K	is the curvature factor (dimensionless)
r	is the mirror radius
R	is the mirror optical surface radius
h_o	is the mirror axial thickness (including the effect of the sagittal curvature of the mirror)
E	is the mirror material elastic modulus (Young's modulus)
δ	is the RMS surface deflection

Better estimates of the mirror optical surface deflection are made using the finite element method.

Roller chains are preferred over conventional bands primarily due to reduction in friction between the edge of the mirror and the chain. It is a mistake to use either plastic rollers or an insulating elastic layer between the rollers and the mirror edge. Plastic rollers will take a permanent deformation or set with the passage of time, increasing friction. Friction is also increased with the use of an elastic layer between the mirror edge and roller chain. Conventional roller chain, sold as conveyor chain with oversize rollers, employing steel rollers, is preferred.

An important advantage of the roller chain is the commercial availability of roller chain. A wide variety of chain sizes and load capacities are available, and are relatively low in cost. Special chain links are available to permit the attachment of spacers and safeties to the roller chain. Roller chain supports are very compact, taking space around the mirror edge equal to the chain thickness. For optical shop testing, a roller chain permits ease of rotation of the mirror in its support to test for astigmatism.

Point contact between rollers and the mirror edge, with resulting high stress and possible local fracture, is a drawback of the roller chain support. Careful installation and adjustment of the roller chain minimizes potential fracture at the mirror edge. Variable orientation applications, such as an altitude-over-azimuth mounted telescope, require the use of a counterweight-lever mechanism to unload the chain as the telescope moves toward the zenith. Since a roller chain support functions only in a single plane, a roller chain support is impractical for the primary mirror of an equatorial mounted telescope. Dynamic stability of the mirror in a roller chain support is poor, limiting application to quasi-static systems unless supplementary defining points are used.

After calculating optical surface deflection, the next step in design of a roller chain support is selection of the chain. Whenever possible, a standard chain size should be selected. Two roller chains, symmetrical about the center of gravity of the mirror, are normally used. A two chain support is stable without the use of a back support, an important safety consideration. A safety factor of at least 4 with respect to the strength of the chain is suggested. For example, a 1 in. pitch chain with 0.625 diameter rollers, and a average tensile strength of 3700 lbs, is suitable for a 56 in. diameter solid fused silica mirror 9 in. thick, assuming a safety factor of 4.

A chain hanger provides termination of the chains, permits adjustment of the chain with respect to the mirror, and connects the support to the rest of the mirror mount. The chain hanger provides three adjustments: location of the centroid of the two chains along the axis of the mirror, axial spacing between the two chains, and a vertical adjustment for mirror wedge. A standard hanger design for a 1.5 m mirror incorporating the above adjustments is shown in figure 5. A universal joint is provided at the top of the chain hanger to insure static determinacy of the support. Two chain hangers, one on each side of the mirror are provided. The chain hangers are attached to the mirror mount; for shop testing this is a large steel weldment called an easel, as shown in figure 6.

A partial list of the mirror successfully mounted in roller chains includes:

1. Six 1.8 m fused silica lightweight (sandwich) primary mirrors for the MMT
2. Lightweight (sandwich) fused silica 1.8 m reference flat mirror
3. Solid fused silica 1.8 m reference spherical mirror
4. Solid fused silica 1.5 m flat mirror
5. Solid Cervit double concave 1.5 m reference spherical mirror
6. Solid Cervit 1 m gimbaled flat mirror
7. Solid Cervit 0.7 m reference spherical mirror

Numbers 5 and 6 in the above list are of particular interest. The solid Cervit double concave 1.5 m was extensively studied by Malvick in 1972. Recently this mirror was remounted in a roller chain support. Figure 7 compares Malvick's prediction of the optical surface deformation with the actual measured surface figure error. In comparing the measured surface figure error with the predicted surface figure, it is important to know that errors of tilt, piston (motion of the mirror surface along the optical axis), and focus were removed when the interferogram of the surface was analyzed. Figure 8 shows the mirror in its easel, and figure 9 is a closeup of the roller chain hanger (the same design as figure 5).

A diagram of the 1 m gimbal flat is shown in figure 10. Two axis motion, stable to 5 arc-seconds, is provided for the mirror. A combination of a roller chain radial support, and a counter-weight lever axial support maintains the optical surface of the mirror to 63 nm RMS in any orientation. Figures 11 and 12 are photos of the mirror and gimbal, while figure 13 shows the counterweight-lever mechanism and chain hanger used to unload the chain as the vertical direction of the mirror changes.

4. CONCLUSION

Roller chain supports provide an efficient radial support for large mirrors in the optical axis horizontal position. Self-weight induced surface figure error is smaller for a roller chain support than whiffle tree or push-pull lever supports, and is comparable with the mercury ring support. A relatively simple, compact and economical support is possible by employing commercial roller chain. Provided that care is taken during design, roller chain radial support provides a low risk and high performance mirror mount, as shown by the successful application of this technique to a variety of mirrors up to 1.8 m in diameter.

5. REFERENCES

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A QUANTITATIVE EXPLANATION

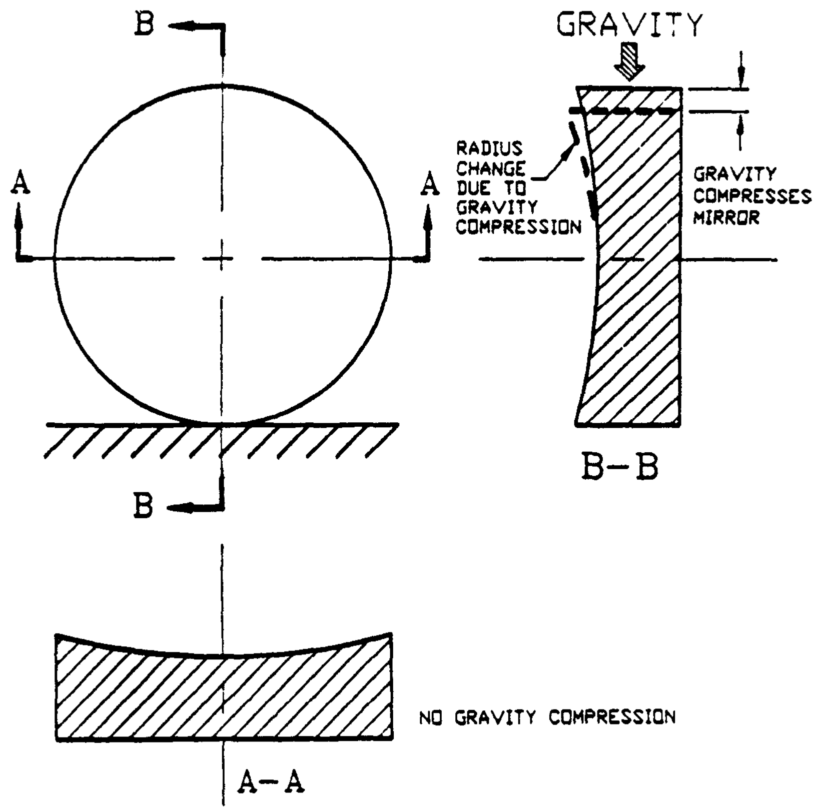


Figure 1. A quantitative explanation for self-weight induced astigmatism for a mirror on edge.

FINITE ELEMENT ANALYSIS RESULTS

Belt compared to Whiffle Tree

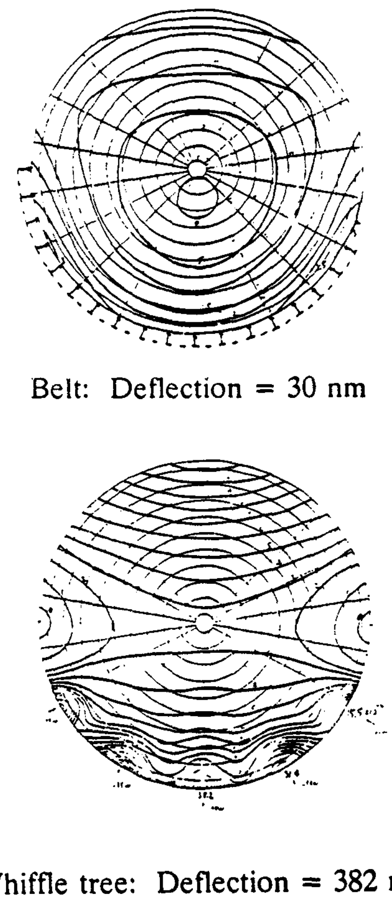
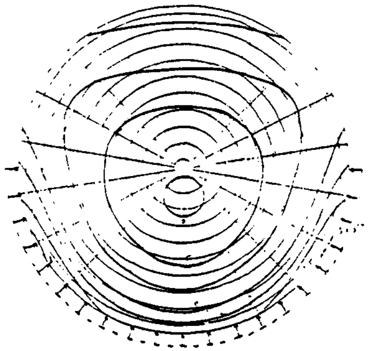


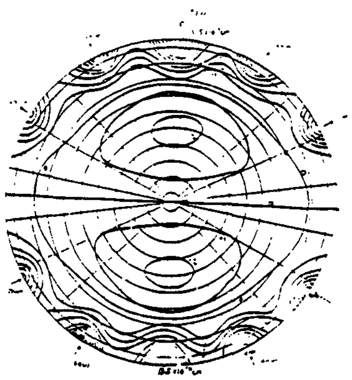
Figure 2. Belt support compared to whiffle tree support.

FINITE ELEMENT ANALYSIS RESULTS

Belt compared to Push-Pull Systems



Belt: Deflection = 30 nm

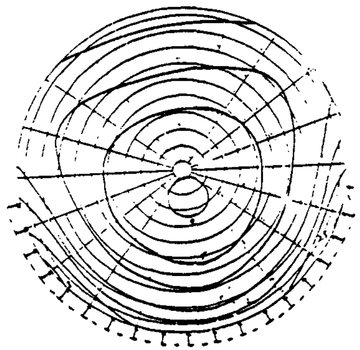


Push-Pull System: Deflection = 135 nm

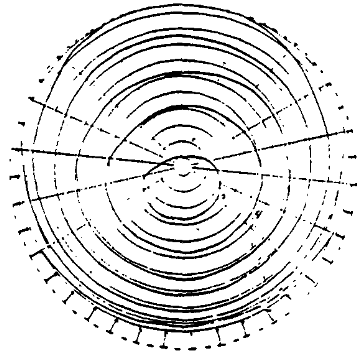
Figure 3. Belt support compared to push-pull support.

FINITE ELEMENT ANALYSIS RESULTS

Belt compared to Mercury Ring Support



Belt: Deflection = 30 nm



Mercury Ring: Deflection = 30 nm

Figure 4. Belt support compared to mercury ring support.

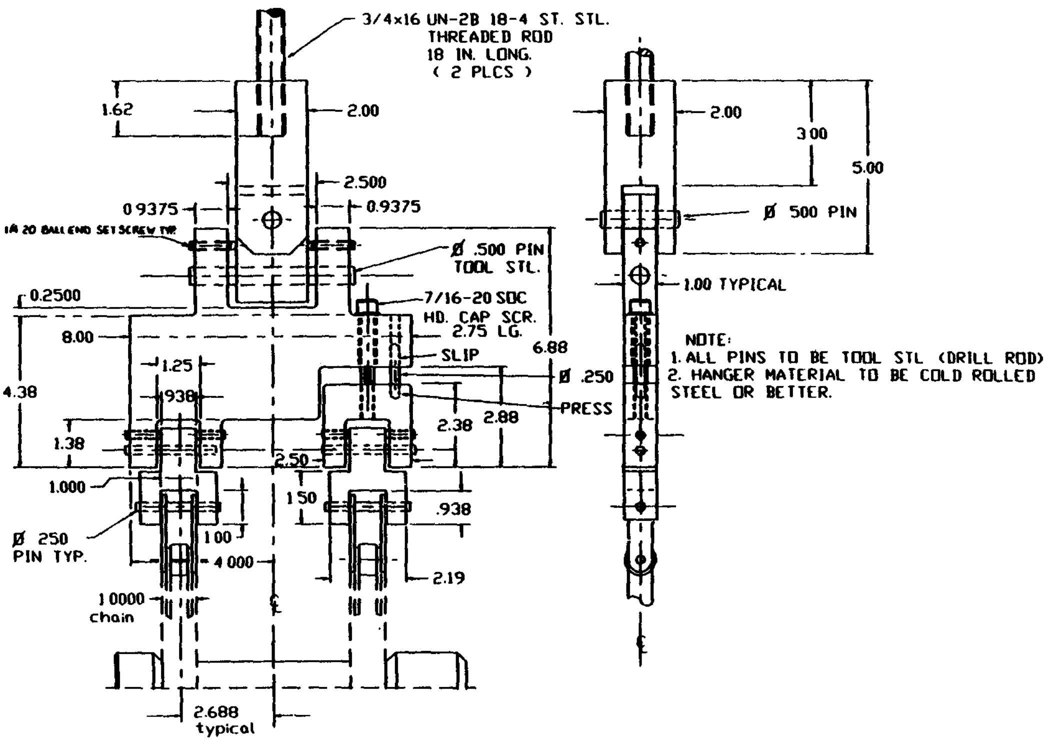


Figure 5. Chain hanger for 1.5 m mirror.

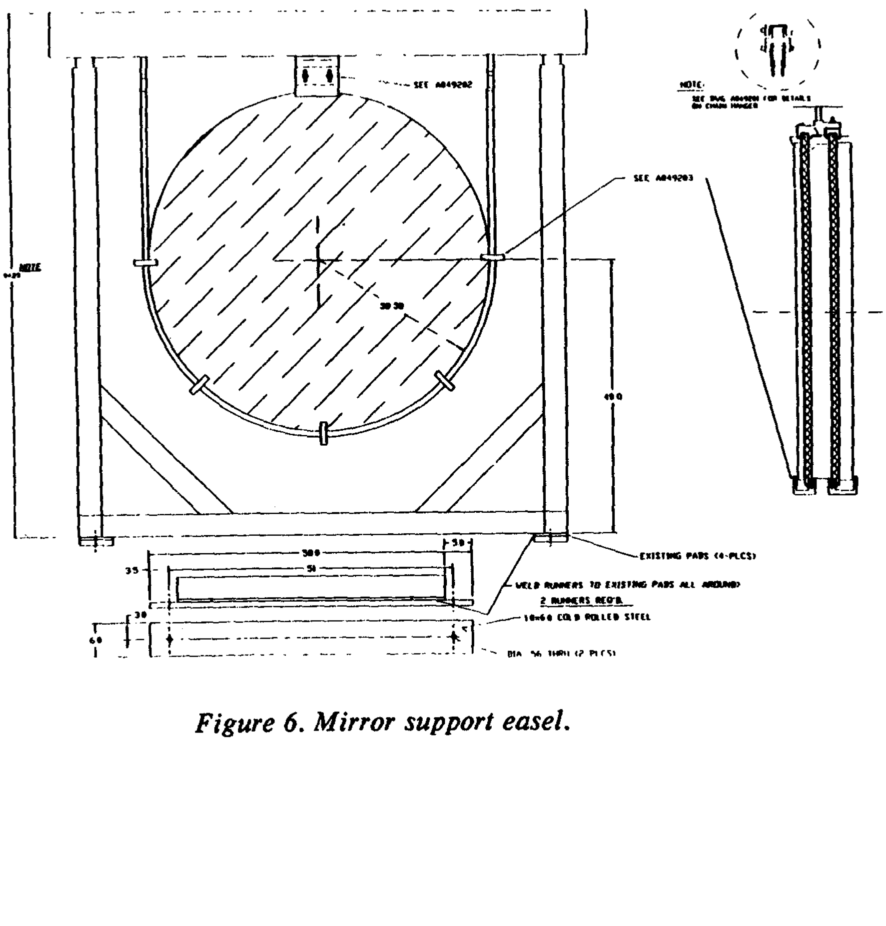
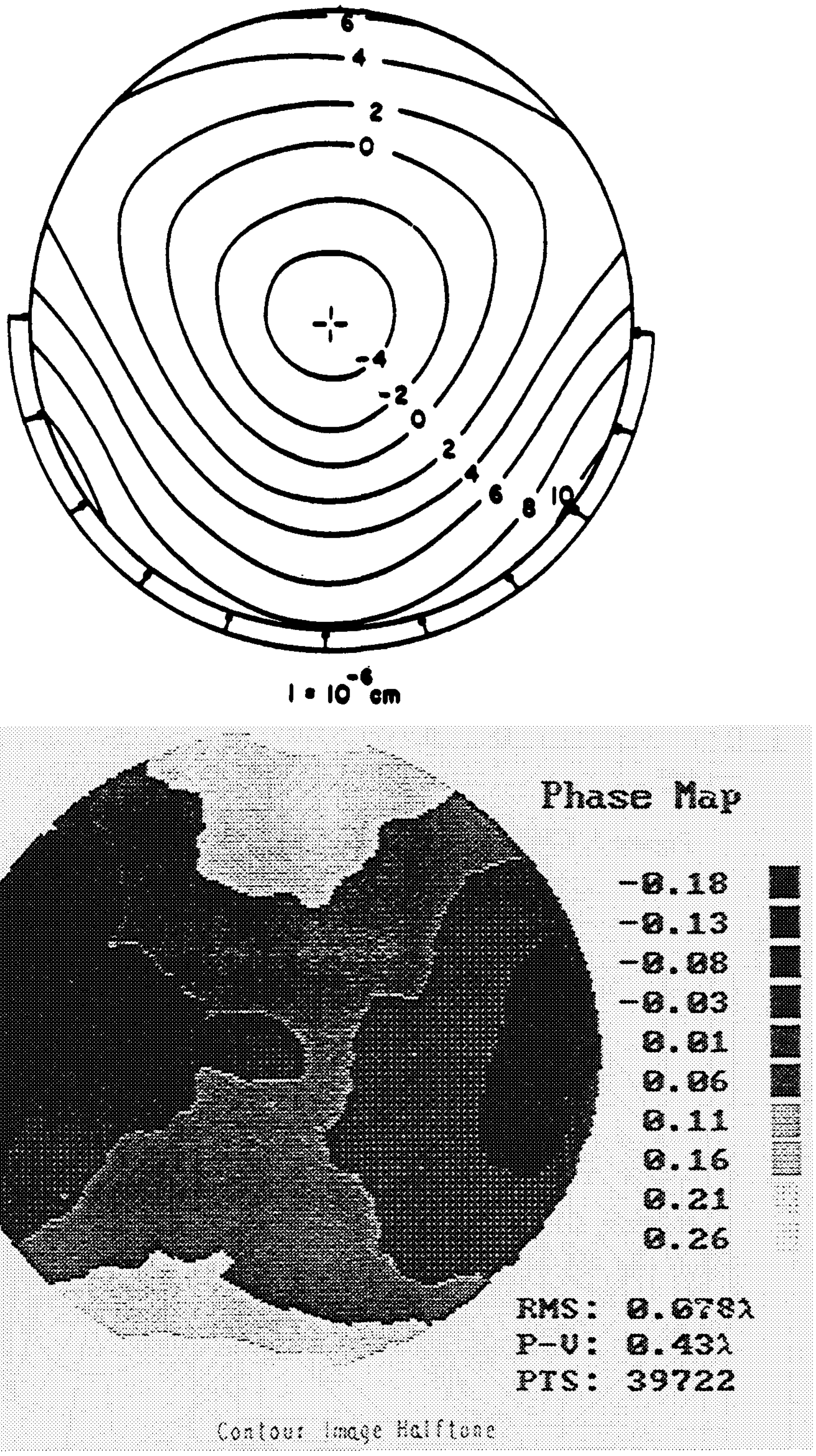


Figure 6. Mirror support easel.



CONTOUR MAP OF 1.5 m DOUBLE CONCAVE SPHERE
IN ROLLER CHAIN MOUNT

Figure 7. Predicted surface deflection compared to measured optical surface quality for 1.5 m mirror in roller chain support.

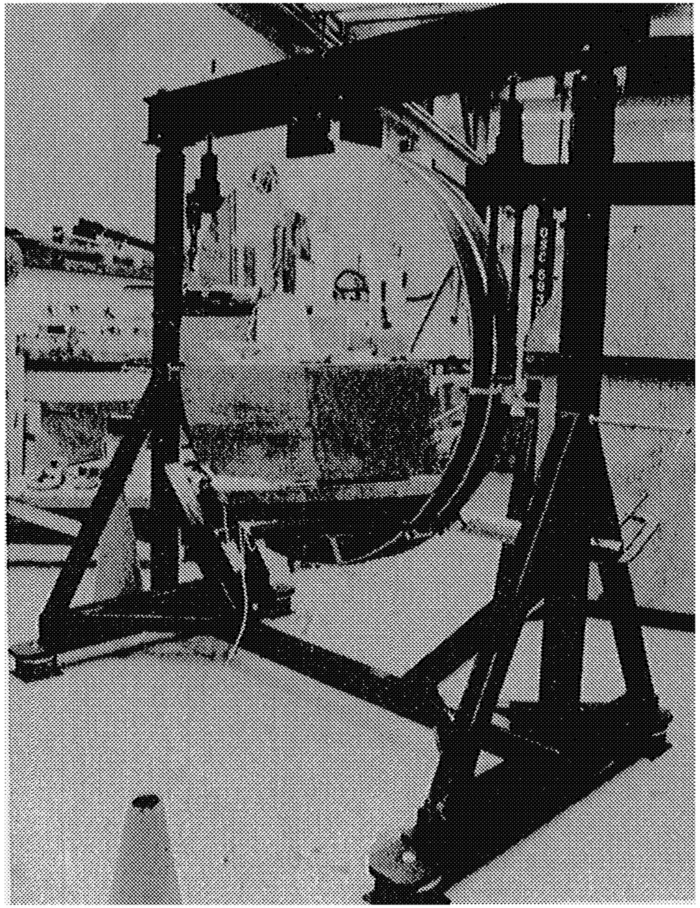


Figure 8. 1.5 m mirror in roller chain support and easel.

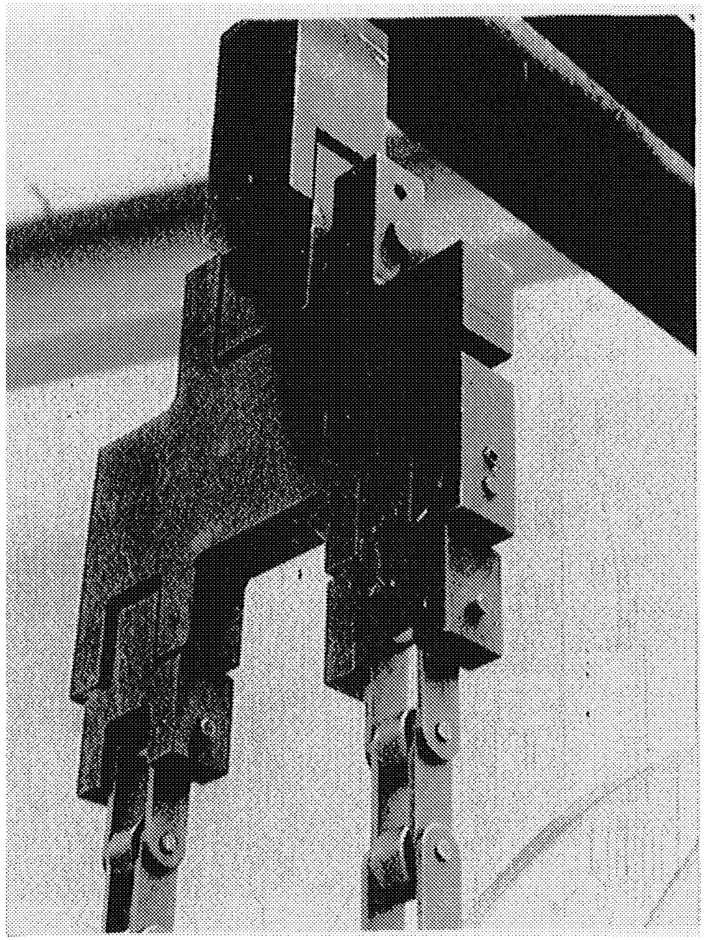


Figure 9. Roller chain hanger for 1.5 m mirror.

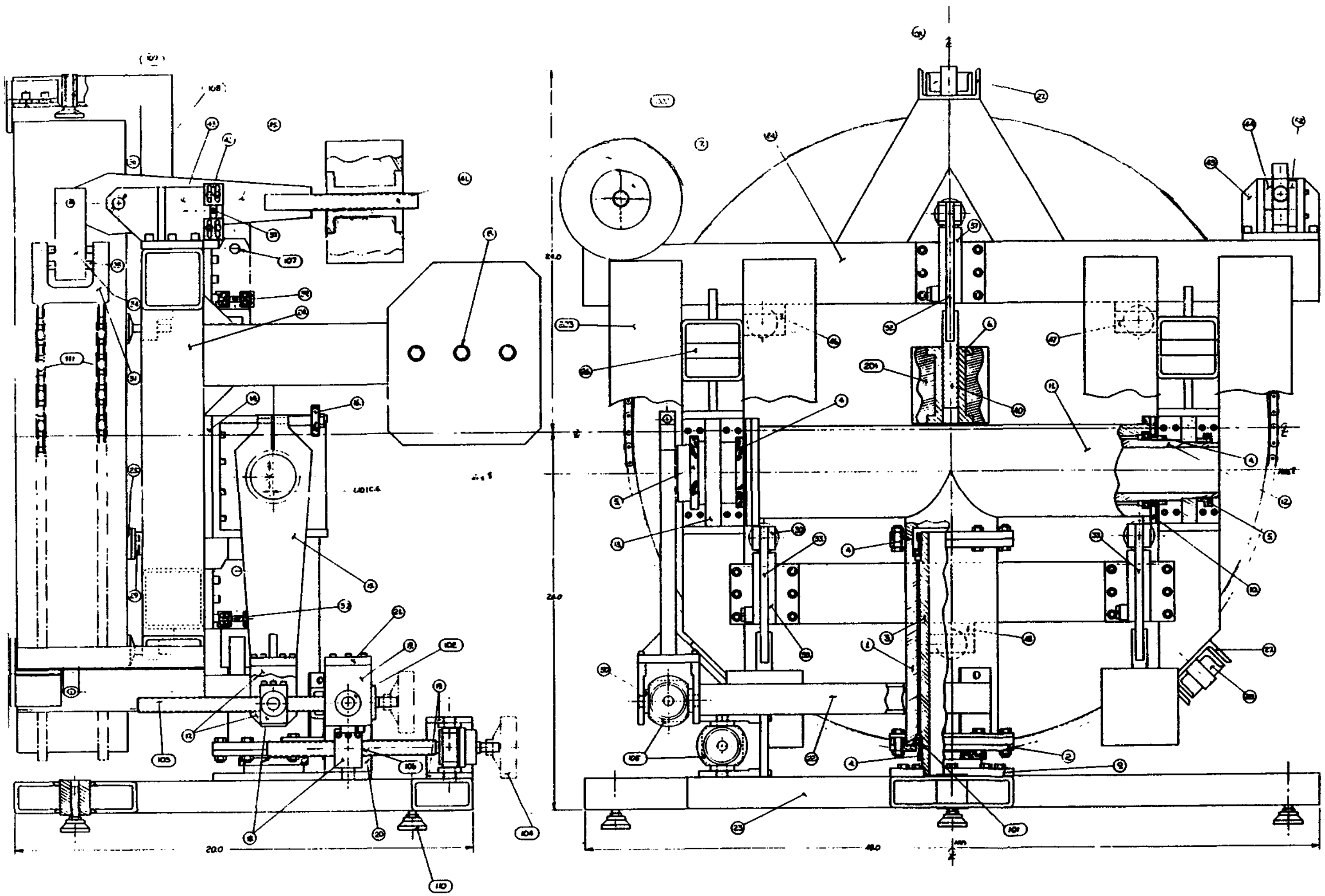


Figure 10. 1 m Gimbaled mirror in roller chain support.

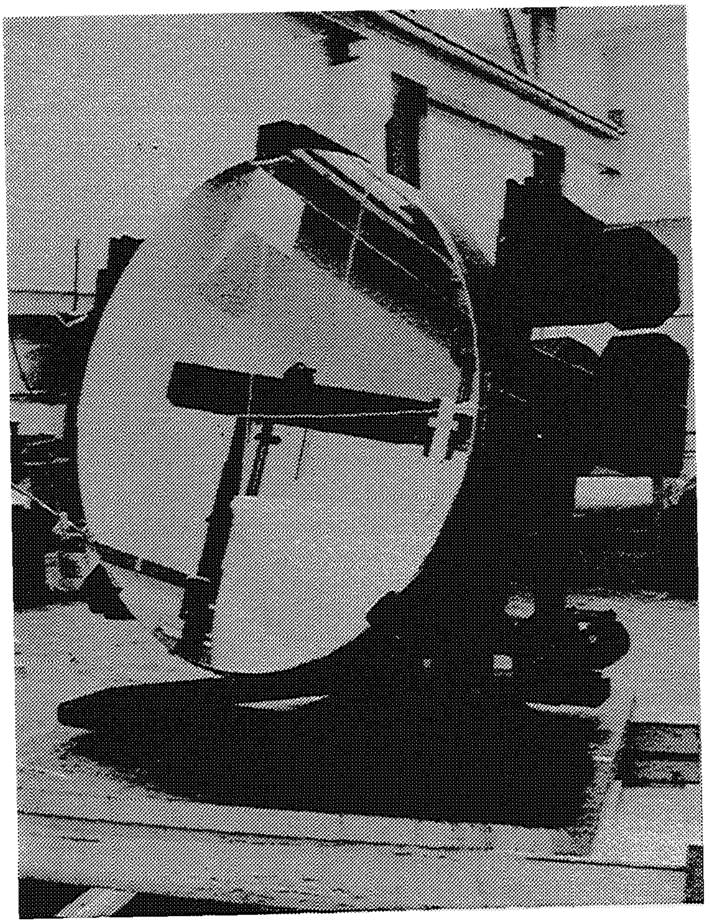


Figure 11. 1 m Gimbal mirror (front view).

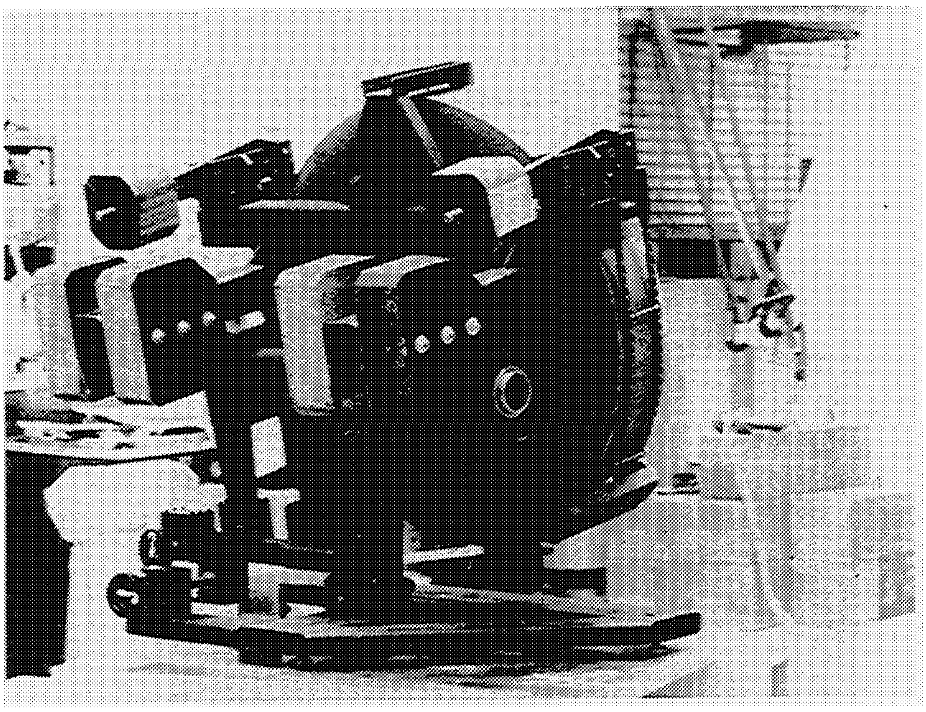


Figure 12. 1 m Gimbal mirror (rear view).

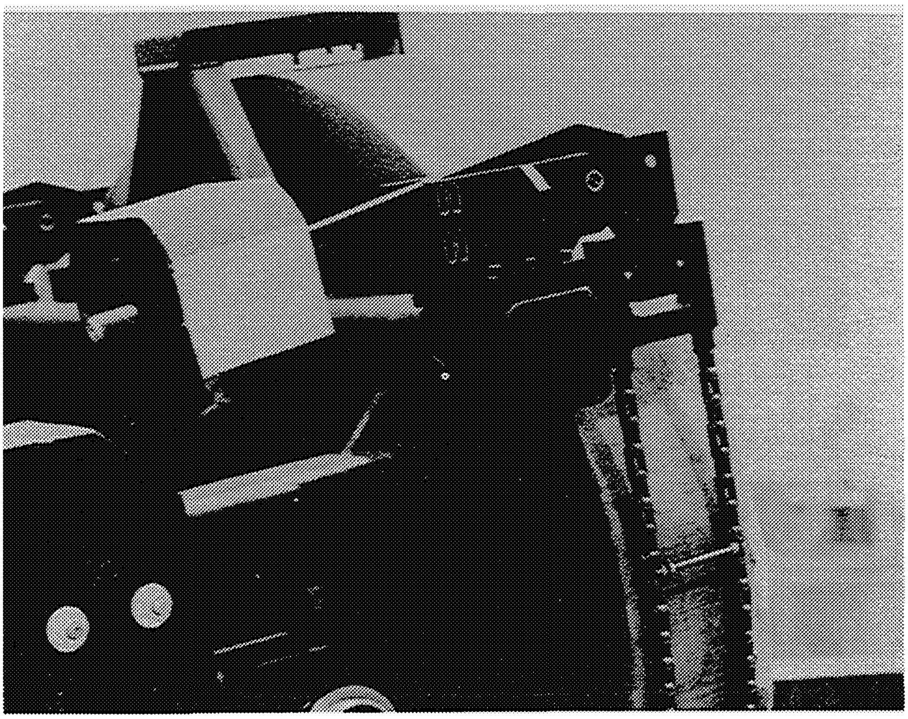


Figure 13. Courterweight lever mechanism and chain hanger for 1 m Gimbal mirror.