THE UNIVERSITY OF CALIFORNIA TEN METER TELESCOPE PROJECT: RECENT DEVELOPMENTS

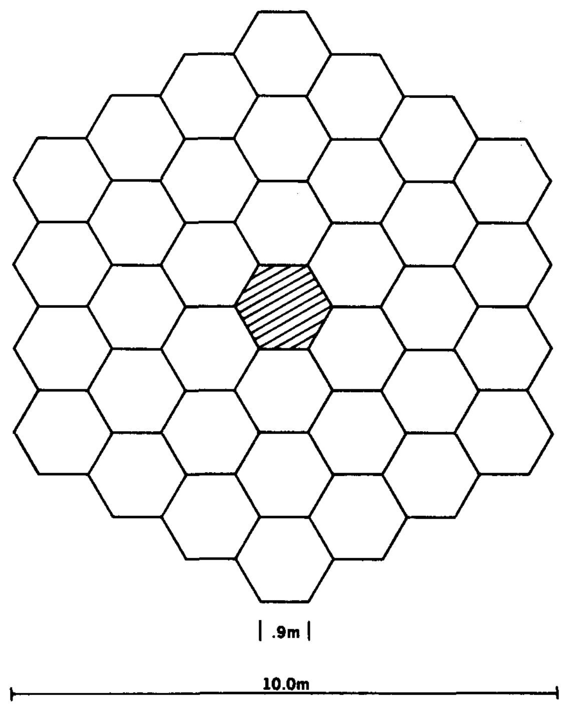
Jerry E. Nelson

Lawrence Berkeley Laboratory, Space Sciences Laboratory,
and Astronomy Department, University of California, Berkeley CA 94720

April 1984

Introduction

The University of California has been actively designing a ten meter telescope (TMT) for optical and infrared ground-based astronomical observations since 1977. The project, now developed in considerable detail, is described in a series of Ten Meter Telescope Reports, technical notes, and publications (see, for example, Nelson 1980,1981,1982). In order to achieve an acceptable cost for the project, the design departs substantially from conventional telescope designs. Recognizing that the cost is roughly proportional to the weight of the structure and to the enclosed volume, we have made the reduction of weight and size a high priority goal of the design. To achieve these objectives a light-weight segmented primary mirror was designed. The parabolic primary is a mosaic of 36 hexagonal segments. In addition, the primary focal ratio is f/1.75, thus resulting in a short telescope tube; this allows a very compact dome. The segmentation geometry of the primary mirror is shown in Figure 1. A



1. The primary mirror of the TMT showing the 36 segments that make up its surface. The central hole allows space for the Cassegrain focus.

Proceedings of the IAU Colloquium No. 79: "Very Large Telescopes, their Instrumentation and Programs", Garching, April 9–12, 1984.

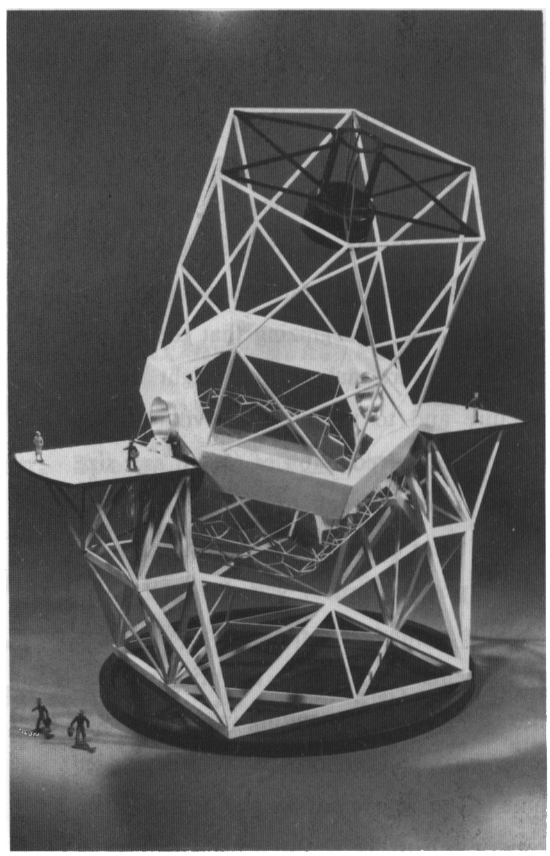
model of the telescope is shown in Figure 2.

Each segment is 1.8m in diameter, 7.5cm thick, and weighs about 400kg. The total primary weighs about 15 tons - about the same as the Hale 200-inch mirror. The telescope as a whole weighs about 150 tons (three times less than the Hale telescope). The building and dome have a diameter of about 32m and the enclosure is substantially smaller than that of the 200-inch telescope.

The segmented design contains several innovative features that are fundamental to the TMT. The very large size of the primary means that gravitational, thermal, and wind induced segment motions will be much larger than any allowed tolerances. Consequently, the segment positions must be actively controlled to maintain the desired optical figure. Because the segments are thin, their passive support is an additional challenging problem. Finally, since the segment surfaces are off-axis sections of a paraboloid, the polishing of these surfaces is unusual and difficult.

Because of the critical and innovative nature of these elements of the design, we believe that detailed analyses of the design and extensive engineering tests of these aspects are needed before proceeding with construction.

During the development of the design the key issues were studied in detail and engineering solutions suggested. The design of the active control system calls for a set of sensors on the segment edges to measure changes in the positions of the segments, an algorithm to process this information, and a set of actuators to move the segments to maintain the overall figure. A sensing system has been developed which employs a single type of sensor: a capacitive displacement sensor. Prototypes of this sensor have been built and they exceed the requirements for performance (Gabor 1979,1980; Mast, Gabor and Nelson 1983). The control algorithm has been developed in detail and successfully tested by means of computer simulation (Mast and Nelson 1980,1982a,1982b,1983). Prototype actuators have been built (Gabor 1980,1983) and these too, perform better than required. Analysis of our design indicates that the seg-



2. Conceptual model showing the optical arrangement of the primary mirror as well as the telescope tube and yoke.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press

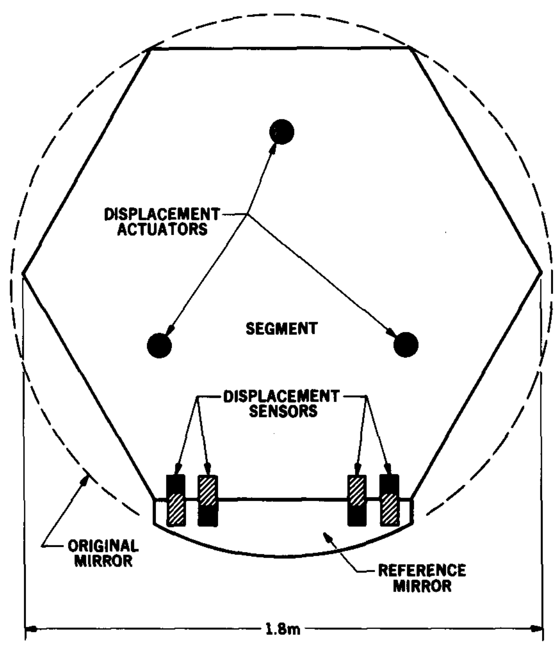
ments can be supported successfully by using whiffletrees (described below). A method of polishing the off-axis surfaces was developed and tested on a quarter-scale version of the mirror blank. This method, Stressed Mirror Polishing, is described by Lubliner and Nelson (1980), and the test of the method by Nelson *et al.* (1980). The method consists of using carefully calculated loads to warp the mirror blank, and then polishing a sphere into the blank while it is in the warped state. After polishing, the loads are removed and the polished spherical surface elastically relaxes to the desired off-axis section of a paraboloid.

After achieving the above successes, we then proceeded to a full-scale engineering demonstration. The goal of this phase has been to demonstrate the feasibility and practicality of the design in sufficient detail to provide confidence in proceeding with the construction of the TMT. Our goal has been to evaluate as many aspects of the design as possible, with particular attention to the areas of segment fabrication, segment passive support, and segment active control.

Technical Demonstration

The technical demonstration (TD) has been underway for over two years and will be completed in July 1984. The TD involves making a segment and (part of) its neighboring segment (the reference mirror), and then actively controlling their relative positions. Details of these goals and procedures have been recently described elsewhere (Nelson et al, 1983), and will only be summarized here. The segmented mirror is shown in Figure 3. This mirror is located in a telescope as shown in Figure 4.

The segment was polished from a 1.9m diameter blank, and polished to a 10.0m radius sphere. The optical surface matched the desired spherical surface, including curvature, to about 40nm rms, an optical quality adequate for the TMT. After polishing was completed, the actual hexagonal segment was cut from the larger circular mirror as indicated in Figure 3. This procedure of cutting after polishing has been expected to be a major potential difficulty, hence the cutting is a critical step.



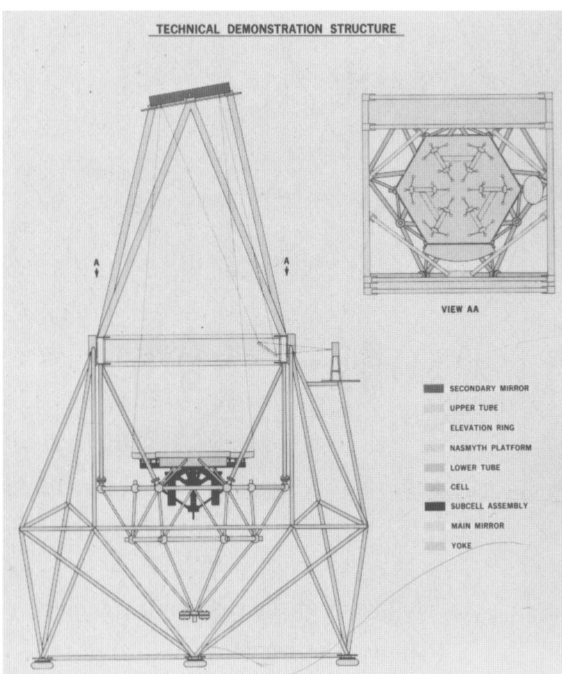
3. The layout of the engineering demonstration. The segment will be full scale with a support system, sensors and actuators as expected for the TMT.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press

This sequence of events is preferred because we wish the segment surface shapes to match the desired shape up to within a few millimeters of each segment's edge. Most polishing procedures, including Stressed Mirror Polishing (which can use full size tools) would have great difficulty maintaining that optical figure right to the segment edge, hence cutting <u>after</u> polishing was suggested to avoid this problem. The risk is that the mirror will warp due to the cutting, and degrade the overall optical figure of the segment.

The cutting was done using a diamond saw, and one edge was cut per day. A photo of this is shown in Figure 5. The resulting segment was cut to within a few tenths of a millimeter of its desired mechanical shape. Unfortunately, upon optically testing the segment surface, we found the segment had warped.

The difference between the cut and uncut surfaces was about 500nm rms, some ten times the segment surface error budget. A contour map of the warping is shown in Figure 6. Almost all the change was focus, but there were about 100nm rms of combined astigmatism and comatic changes.



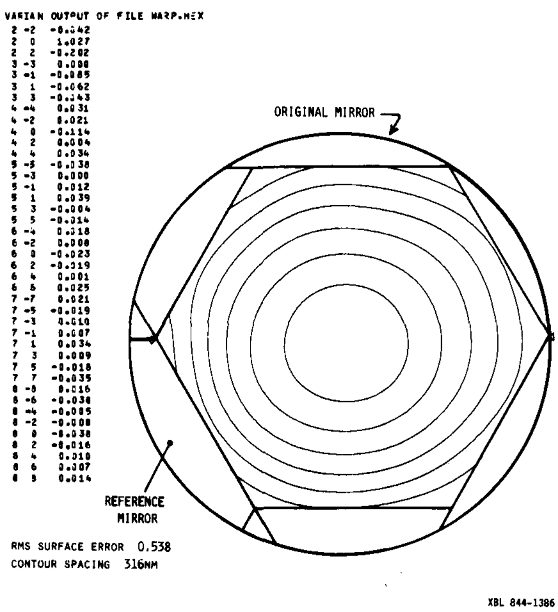
4. The Technical Demonstration Telescope structure showing the primary, secondary and tertiary. A plan view of the primary is also shown.

5. Cutting the mirror segment using a diamond saw.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press

There were essentially no higher spatial frequency changes due to cutting.

This undesired and unexpected warping is presumably caused by one or more of several sources. The blank could have had some residual internal stress from the casting. After generating the miniscus shape we reannealed the blank. If this was not done properly, some stresses, particularly symmetric ones, could have been introduced into it. Also, the polishing process may introduce or modify the stress in the glass.



6. Contour map of the warping that resulted from cutting the hexagon. The contour interval is 316nm. The actual cuts are shown. The warping is mainly focus, with a little coma and astigmatism.

To make any polishing induced stresses acceptible, we sought to polish the front and back of the mirror in identical fashion. Unfortunately, this process was not carried out properly. Although both surfaces were shined, the front surface was ″polished out″, thus removing all subsurface damage, but the back surface was only ″shined″, leaving substantial subsurface damage. This asymmetry was confirmed by etching one of the cut pieces. The etched piece was shiny on the front, and quite dull on the back, revealing extensive subsurface damage.

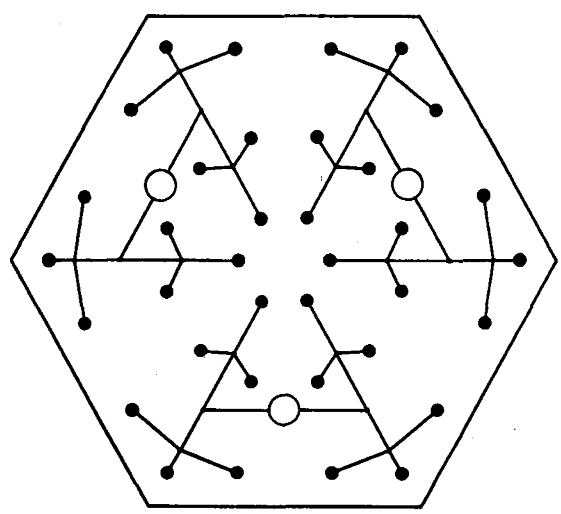
A thin layer of subsurface damage or fractures will put the surface in a state of compressive stress. The resulting mirror deformations can be readily calculated by analogy with the deformations of bimetallic plates, given the depth and magnitude of the surface stresses. To estimate the size of this effect, we are evaluating the distortions of a thin flat mirror as a function of the various grinding and polishing procedures being applied on its back surface. Initial results suggest that the difference between a fine grind and a proper polish on our mirror back will result in hundreds of nanometers of focus error. This is tantalizingly similar to the warping we experienced, so we are hopeful that a significant fraction of the observed warping can be eliminated by better polishing procedures on subsequent segments.

Although we expect that warping will be reduced by proper polishing, and eliminating the questionable annealing step, one should still be prepared for warping from cutting to be excessive. Several options are available for avoiding or curing the problem. The most direct is to perform "touch up" polishing to correct any figure errors. Although this appears possible, since the aberrations are relatively large and of low spatial frequency we expect this would be a laborious procedure. Another possibility is to cut the mirror before polishing and then reglue the pieces together and proceed with the finishing. After figuring one would either cut or dissolve away the glue line, leaving the segment. It is critical that no stresses are reintroduced from the gluing. David Brown (1983) has shown that if glue line thickness variations are sufficiently linear then this procedure is workable. Even so, careful evaluation of the method will be necessary and it may be that complications will arise when Stressed Mirror Polishing is used.

The currently favored solution is to simply unwarp the mirror segment by using a warping harness composed of springs or some other gravity independent mechanisms that is permanently affixed to the segment. This procedure also has the advantage that surface errors can be readily corrected at any time in the future as needed. The stressing jig for Stressed Mirror Polishing can warp mirrors with an accuracy of about one part in a thousand, so warping harnesses accurate to the needed 5-10% level are clearly possible. The issue is to find an extremely simple and troublefree mechanism. Since the axial mirror support uses three 12-point whiffletrees, this existing mechanism forms a good candidate. A layout of the whiffletrees is shown in Figure 7. Some of the details of the whiffletrees are shown in Figure 8.

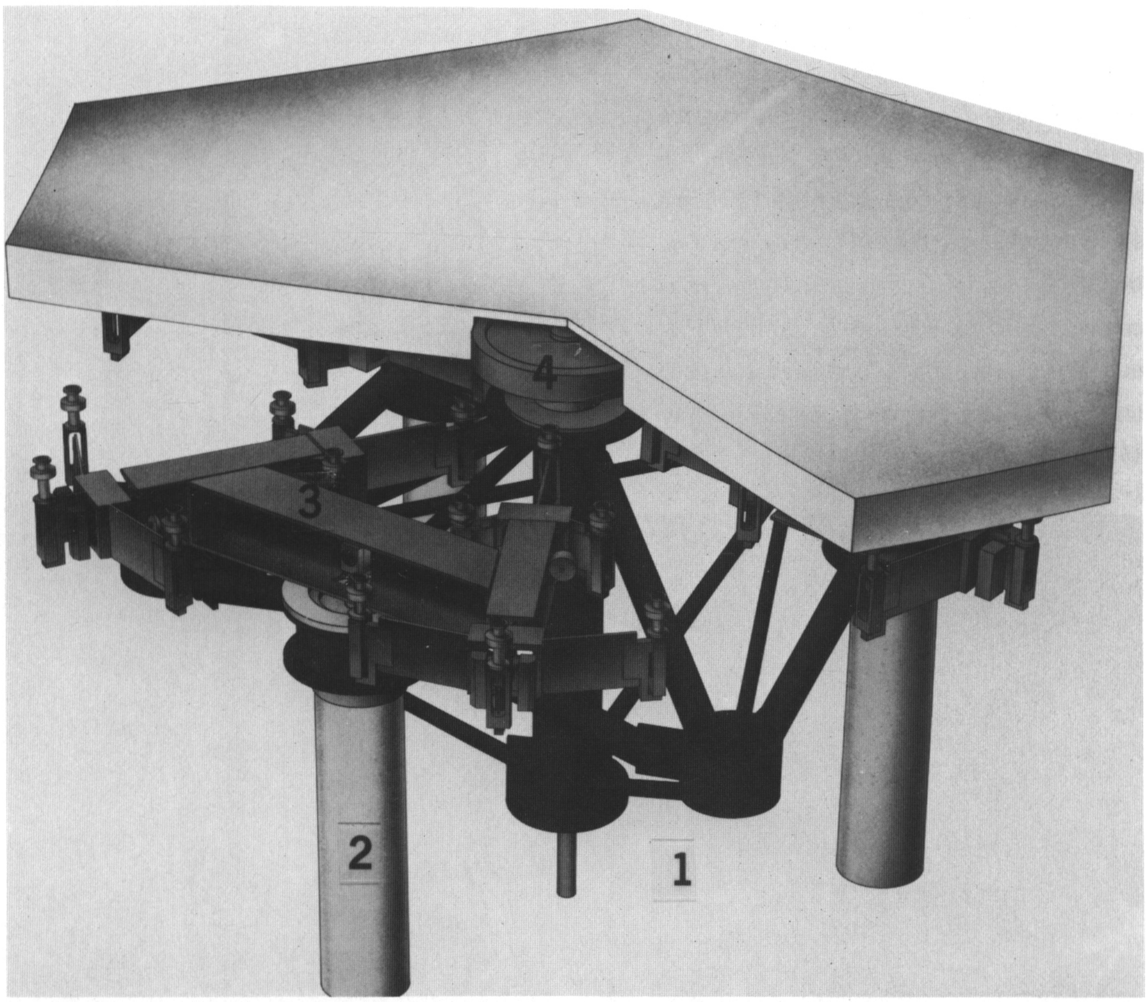
Budiansky (1984) has analysed the warping capabilities of applying appropriate axial forces at the 36 whiffletree attachment points. He has shown that for the low spatial frequency aberrations we see, suitable axial loads can reduce the aberrations by a factor of 20-30, more than sufficient for our purposes. We have tested his numerical results by hanging weights from the whiffletrees and our empirical results are in excellent agreement with the calculations. We are now developing a system of leaf springs to attach to the whiffletrees that will apply the desired axial forces.

Work on the active control system is now nearing completion. Six actuators have



7. Schematic showing the 36 points of axial support for each segment and the three whiffletrees used to connect those

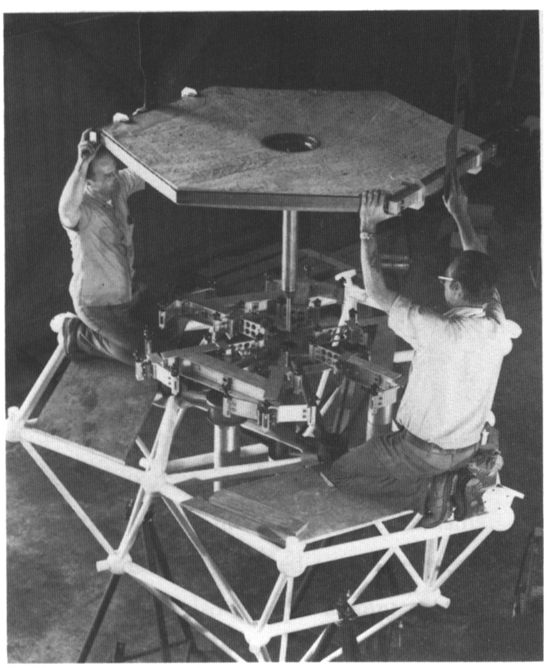
https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press



8. A drawing of the subcell assembly with a mirror segment. Shown are the welded steel subcell (1), three actuators (2), three whiffletrees (3), and the radial support post (4).

been built and tested, and six displacement sensors have been built and tested. The engineering demonstration has been assembled using concrete dummy optics, and with the four sensors and three actuators, the control algorithm appears to work correctly. Both the long term stability and ultimate accuracy tests await the installation of the real optics that takes place this month. A photograph of the assembly of the concrete segment on the mirror cell is shown in Figure 9. The complete installation of the concrete optics in the telescope is shown in Figure 10. Completion of the active system testing is expected to be complete by July 1984.

Acknowledgements This work is the result of many peoples' labors, foremost among them being Terry Mast, George Gabor, and Michael Budiansky. We thank the University of California for supporting these TMT development activities.



9. Photo of a test assembly of a concrete segment on the passive and active support system. Note the whiffletrees and the actuators as well as a portion of the radial support post assembly.

10. Photo of the Technical Demonstration Telescope with concrete optics and the active control system in place.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press

References

Brown, David (private communication) 1983.

Budiansky, M.P., *Ten Meter Telescope Technical Note No. 95,* (1984), "Theory of Figure Adjustment of a Segment by Using Forces Applied to Whiffletrees."

Gabor, G., *Proceedings of the International Society for Optical Engineering, SPIE,* **172** p. 39 (January 1979), "Position Sensors and Actuators for Figure Control of a Segmented Mirror Telescope."

Gabor, G. , *Proceedings of Kitt Peak National Observatory Conference on Optical and Infrared Telescopes for the 1990's* (Tucson, Arizona, January 1980) p. 587, "Displacement Sensors and Actuators Needed to Control a Segmented Primary Mirror."

Gabor, G., *Proceedings of the International Society for Optical Engineering, SPIE,* **444,** p.287 (September 1983), "Actuators for a Segmented Mirror Control System." 1983 "Actuators for a Segmented Mirror Control System."

Lubliner, J. and Nelson, J., *Applied Optics* **19,** 2332, 15 July 1980.

Mast, T. S. and Nelson, J. E. , *Proceedings of Kitt Peak National Observatory Conference on Optical and Infrared Telescopes for the 1990's* (Tucson, Arizona, January 1980) p. 508, "Figure Control for a Segmented Telescope Mirror."

Mast, T.S., Gabor, G., and Nelson, J.E., *Proceedings of the International Society for Optical Engineering, SPIE,* **444,** p. 297 (September 1983), "Edge Sensors for a Segmented Mirror."

Mast, T. S. and Nelson, J. E., *Applied Optics* **21** 2631 (July 1982a) "Figure Control For a Fully Segmented Telescope Mirror"

Mast, T. S. and Nelson, J. E., *Ten Meter Telescope Technical Note No. 46* (May 1982b) " Figure Control for a Segmented Mirror: Curvature Control Without Tilt Sensors"

Mast, T. S. and Nelson, J. E., *Ten Meter Telescope Report No. 80,* (1983) "Figure Control for a Segmented Mirror."

Nelson, J. E., *Proceedings of the International Society for Optical Engineering, SPIE,* **444,** p. 274 (September 1983), "Segmented-Mirror Control System Prototype for the Ten Meter Telescope: A Status Report."

Nelson, J.E., Gabor, G., Hunt, L.K., Lubliner, J., Mast, T.S., *Applied Optics,* **19,** 2341, 15 July 1980.

Nelson, J. E., *Proceedings of Kitt Peak National Observatory Conference on Optical and Infrared Telescopes for the 1990's* (Tucson, Arizona, January 1980), p. 11, "The University of California Ten Meter Telescope Project - The Segmented Design."

Nelson, J. E., *Proceedings of the ESO Conference on the Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths,* p. 139 (March 1981). "Coherent Large Telescopes."

Nelson, J. E., *International Conference on Advanced Technology Optical Telescopes, Proceedings, SPIE,* **332,** 109 (1982). "The University of California Ten Meter Telescope Project."

DISCUSSION

R. Wilson: Of course, I am delighted to learn that you are trying our active optics correction methods to correct your circle-hexagon warping. However, I wonder, since you have documented the effect so carefully with interferograms, whether you could perhaps adequately calibrate the effect in advance and allow for it when you produce the stress polished circles?

J. Nelson: At the moment we are not certain of the cause of the warping, hence we cannot predict the amount expected next time. If experience shows the warping is predictable we will certainly do as you suggest, and polish the mirrors appropriately before cutting, in order to achieve the best possible figure after cutting.

G.T. Odgers: Can a solution to mirror warping be found by polishing an already cut hexagonal mirror either with "ears" attached or separated?

J. Nelson: Yes, at least in principle. Jacob Lubliner has developed the theory for warping hexagons for stressed mirror polishing, so that we could polish the hexagons directly. We fear that normal polishing procedures would roll the edges some however, so we don't currently favour this option. We are also considering cutting, then gluing the ears back on and proceeding with stressed mirror polishing. Afterwards one could dissolve the glue joints. David Brown of Grubb-Parsons has developed a successful procedure for this gluing, so it appears quite possible. However, we think that unwarping with springs is very straightforward.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press

I. Appenzeller: Will your "unwarping" procedure work independently of the zenith distance?

J. Nelson: By using springs to apply the unwarping forces, the system should work independently of the zenith distance. Since our whiffle tree support is attached to the mirror back, we can push or pull, thus the unwarping should work to the horizon.

https://doi.org/10.1017/S0252921100108851 Published online by Cambridge University Press