Prototype Testing of a Surface Heating System for the GEMINI 8-m Telescopes

E. Hansen, D. Hagelbarger, E. Pearson
Gemini Telescopes Project, P. O. Box 26732, Tucson, AZ 85726-6732

Gemini Preprint #12

Prototype Testing of a Surface Heating System for the GEMINI 8-m Telescopes

Eric Hansen, David Hagelbarger, Earl Pearson

Gemini Telescopes Project
P. O. Box 26732
Tucson, AZ 85726-6732

1. ABSTRACT

The Gemini Project plans to implement thermal control of the primary mirror using two distinct systems. The first system consists of temperature controlled radiation panels behind the primary mirror that are used to control the bulk temperature of the primary. The second, a surface heating system, will be used to adjust the optical surface temperature by passing an electrical current through the reflective coating. Combining these two systems allows the optical surface temperature of large monolithic mirrors to follow nighttime ambient temperature fluctuations, minimizing mirror seeing effects. To aid in the design of a surface heating system for the Gemini 8-m primary mirror, a development program was initiated. As part of this program, analysis techniques were developed and prototype systems using mirrors up to 1-m were fabricated and tested. This paper reviews the progress and results of this surface heating development program to date.

2. INTRODUCTION

In recent years it has been demonstrated that thermally induced "seeing" is a major factor that must be addressed in the design of any telescope that is to perform at image quality limits set by the best atmospheric conditions[1,2,3]. If surfaces within a telescope have temperatures different than that of the adjacent air, convective heat transfer will occur creating localized, and frequently unstable, variations in the air's index of refraction. If these variations occur anywhere within the light path of the telescope "seeing" results and this seeing produces distorted and shifting images at the telescope focus. While seeing can be produced by the surrounding topography, the telescope structure, the enclosure or any localized heat sources, primary mirror seeing has received special consideration. This is because the primary is, of necessity, adjacent to the light path and primary mirrors typically are thermally massive, making the job of tracking ambient temperature variations difficult.

The Gemini Project intends to limit the effect of primary mirror seeing to levels that would add only 0.04 arcseconds to the 50% encircled energy diameter at 2.2 microns wavelength. While there is no data yet at the 8-m scale, correlations between seeing and mirror to air temperature differences, can be estimated from smaller scale studies[4,5,6,7] . Results from these studies were adjusted for mirror diameter, moderate wind flushing rates, wavelength, and the fact that many of these studies indicate reduced seeing levels with mirrors cooler than the ambient air as compared to mirrors warmer than ambient. The resulting specification which limits the mirror to air temperature difference, states that primary mirror optical surface must be maintained between 0.2 C warmer and 0.6 C cooler than the surrounding ambient air. While this is a very tight range it must be remembered that temperature difference errors tend to be reduced by natural convection.

In order to maintain this temperature specification, the Gemini Project plans to implement active temperature control of the primary mirror[8]. This concept features a system of radiating plates behind the primary mirror, similar to those proposed by the VLT project[9]. As the nighttime ambient temperature declines, the radiation plates are designed to produce a uniform optical surface temperature that matches the average ambient air temperature. However, there are short term fluctuations in air temperature that the mirror temperature cannot track. Performance modeling done by the Gemini Project indicates that using this system alone, tracking actual temperature profiles recorded on Mauna Kea, the primary mirror will be within it's temperature specification 50 to 85% of potential observing times.

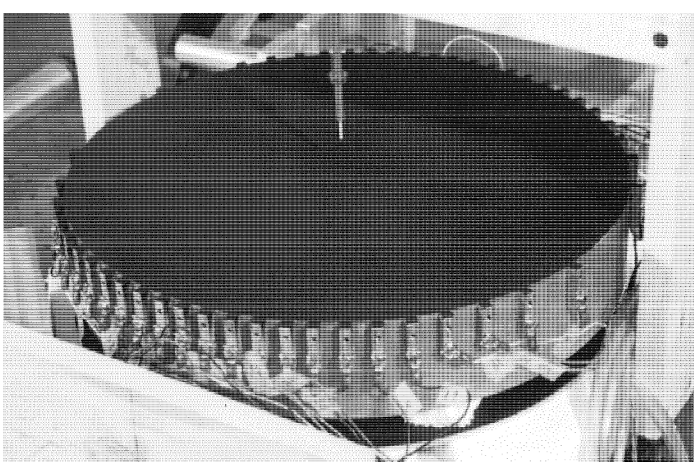
To further reduce primary mirror seeing, the Gemini Project is developing an additional method of thermal control. The system is based on the concept of resistivly heating the optical surface by passing an electrical current through the metallic reflective coating. This system is specifically designed to rapidly change the optical surface temperature and allow ambient air fluctuations to be tracked. By biasing the bulk temperature of the mirror colder than ambient and using the surface heating system to provide the proper optical surface temperature, surface heating can be used to both rapidly cool (by reducing voltage), and heat (by increasing voltage) the optical surface. Modeling indicates that using resistive surface heating can be used to accurately track ambient air temperature fluctuations. In addition to improved seeing performance, the surface heating system also has the potential to reduce another problem; dewing. Dew formation on optical surfaces results in degradation of coating emissivity critical to IR observations, and observatories often close down when the dew point approaches the telescope temperature. Surface heating could be used, in conjunction with a dew point monitor, to maintain the primary mirror optical surface temperature above the dew point automatically.

Because of the novelty of this surface heating concept, the Gemini Project has initiated a development program that has fabricated and tested a number of subscale prototypes with the aim of guiding the design of an 8-m system suitable for the Gemini Telescopes. These prototypes varied in complexity from small coupons used to check for possible coating damage to the last and most recent prototype; a 1-m diameter concave optic with features expected to be very similar to the final 8-m design. The following sections review this development program.

3. INITIAL WORK

While the application of surface heating to astronomical telescopes is new, the concept of resistivly heating conductive thin films is not. It has been used previously in a number of applications such as the heating of window coatings to minimize condensation. If the conductive coating is assumed to be uniform in thickness and the correct boundary conditions applied, theoretically it can be shown that uniform temperature control can be achieved for any plane film shape, including annular mirror surfaces. However, when a practical system, using discrete voltage sources and actual coating shapes was considered for use on the Gemini telescopes, two critical questions arose. How the correct boundary conditions could be applied to achieve the desired uniformity as well as reliably, and whether the power levels required for this application, up to 40 W/m^2, would damage the mirror coating. Initial work was concentrated in these two areas.

Work began at Rutherford Appleton Laboratories (RAL) where small rectangular coupons were tested at power levels up to 80 W/m^2 for effects on coating emissivity and surface roughness[8]. After simulating six months of operation no change was detected for either aluminum or silver coatings. This work also indicated that the most reliable method of making electrical contact with the mirror coating would be to bond conductive electrodes to the mirror substrate and coat over them.



Using the information gained at RAL, construction of a 32 cm diameter prototype began at the National Optical Astronomy Observatories (NOAO) in Tucson. This prototype was primarily designed to test heating uniformity using a circular substrate and to develop techniques for monitoring mirror seeing that might be implemented in the Gemini telescopes. The 32 cm prototype is shown in figure 1. Current is supplied to the coating through electrodes bonded to the side of the substrate, flush with the bevel at the outer diameter of the mirror.

Fig. 1. 32 cm Prototype

This allowed the evaporated aluminum coating to be applied to the mirror surface, bevel and electrode in an uninterrupted sheet. Direct current is supplied to the coating through 24 pairs of stainless steel electrodes. All currents flow in a parallel direction through the coating between electrode pairs. Each pair supplies an equal current to an equal width strip of coating in order to produce a uniform heating effect.

Initially, thermocouples were used to measure the temperature of the coating surface and confirm that the surface temperature was in fact controllable using resistive heating. This method, however, had number of drawbacks; it gave information at only a single points on the surface and proved difficult to measure the actual surface temperature without altering it. In addition, it will not be possible to locate thermocouples within the aperture of the Gemini Telescopes. Another approach was developed to look at seeing effects directly using interferometry. An interferometer was set up with a test beam as large as the prototype and adjusted for straight vertical fringes. The prototype was then placed horizontally in the test beam. Half of the fringe pattern is blocked by the prototype, however, the half that remains visible is highly sensitive to the difference in temperature between the prototype and the ambient air. If the ambient air is the same temperature as the prototype the fringes are unaffected. If the prototype surface is warmer, heat is transferred to the air decreasing its density and index, this causes the fringes to curve in one direction. If the prototype surface is cooler than the ambient air the fringes curl in the opposite direction. The magnitude of fringe curvature provides a sensitive measure of the temperature gradient adjacent to the mirror surface which is directly related to mirror seeing. It has the additional advantage that it is non-invasive and integrates the seeing effect over the mirror surface. While it is a qualitative technique, it is much simpler than the standard methods of looking at image quality, where mirror figure changes and other seeing effects must be deconvolved from mirror seeing effects.

A thermoelectric cooler placed against the rear surface of the prototype was used to control the bulk temperature of the glass. It was found that surface heating could be used to quickly straighten interferometer fringes when the mirror was chilled to below ambient temperatures. Test results showing fringe shapes with the mirror at ambient, one degree Celsius cooler than ambient, and warmed back to ambient air temperature are shown in figure 2. Note that only the left half of the prototype was heated. The right half of the mirror was used as a control in this experiment, so that in the last photo, only the left half of the optical surface has been returned to ambient temperature (straight fringes) while the right half remains below ambient temperature.

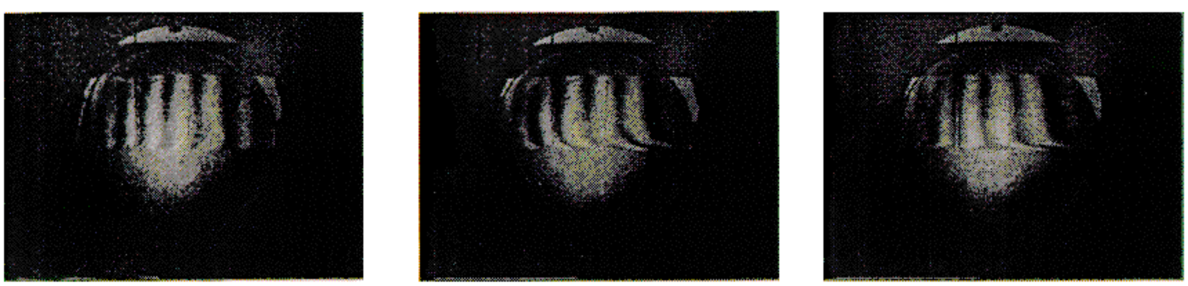


Fig. 2. 32 cm Prototype Test Results

The second test method used an infrared camera to check the uniformity of surface heating. The optical surface of prototype was painted black in order to increase the emissivity enough for the camera to register the mirror temperature. When surface heating was used to raise the surface temperature above ambient the image clearly showed a uniform increase in temperature over the majority of the surface. The most noticeable "hot spots" were on the mirror surface adjacent to each electrode.

The results of this early testing were quite promising, however it was clear that additional analysis, some design evolution, and a larger, second generation prototype would be required prior to the design of an operational system.. A 1-m diameter mirror was offered by NOAO as a test bed for the next prototype, and work began with the philosophy that this prototype should be designed with details such as electrodes and power supplies that are directly scaleable to an 8-m operational system.

4. ONE METER PROTOTYPE DESIGN

By studying actual ambient temperature profiles taken on Mauna Kea[10] , it can be seen that the magnitude of short term fluctuations are typically less than one degree from the average nightly temperature decline rate, with a slope typically less than one degree per hour. This indicated that most short term ambient temperature fluctuations can be tracked by biasing the bulk temperature of the mirror colder by one to two degrees and using up to 40 W/m^2 to trim the optical surface temperature. 40 W/m^2 can increase the surface temperature by one degree C in less than 20 minutes, numerical modeling of such a system using one year of previously recorded ambient temperatures showed the optical surface within specification up to 95% of potential observing times when using this maximum power level.

Uniformity requirements can be estimated by dividing the 0.8 C error band (+0.2 C to -0.6 C) into three equal error budgets; average temperature error, bulk temperature nonuniformities and surface heating nonuniformities. If these errors are spatially independent, and can be root sum squared, each can be assigned a budget of approximately 0.5 C. With surface heating used to increase the mirror temperature by 2 degrees, then the uniformity requirement is approximately 0.5/2.0 or 25 %. The first efforts at design of the next prototype concentrated on decreasing the hot spots adjacent to each electrode by reducing the current density in these areas. A wedge shaped portion of coating adjacent to each electrode was deposited first creating electrodes that more evenly distributed current into the coating.

In order to analyze the effect of distribution electrodes, the analogy between thermal and electrical conduction was used. This method has been used for many years to quantify heat transfer problems by representing them as equivalent electrical circuits. In order to analyze current flow through a mirror coating we reversed the approach. A thermal model of the coating layer was constructed and analyzed using a commercial finite difference program. This resulted in a temperature or 'voltage' map of the surface. A second program was then created to take this 'voltage' data with the electrical resistivity of the coating to find the surface heating power generated within each element of the model. Using this type of analysis we were able to shape distribution electrodes that greatly increased surface heating uniformity using a minimum of electrodes. The final design consisted of 48 electrodes, the same number as used on the 32 cm diameter prototype. The design of the bonded electrode was also modified. It now overlapped the mirrors protective bevel and was bonded flush with the optical surface. The flush attachment, along with the thickened coating, was expected to yield a robust electrical connection to the coating. These new electrodes were bonded to the mirror prior to application of the reflective coating. The one meter prototype is shown in figure 3.

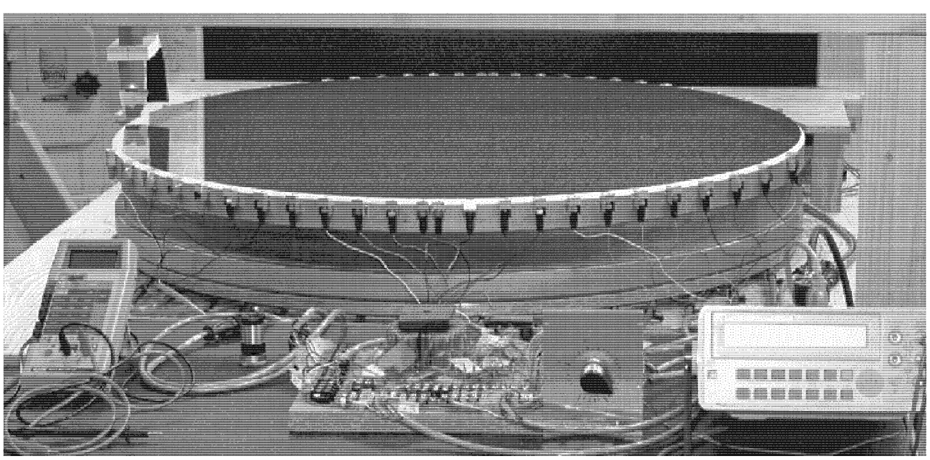


Fig. 3.
One Meter Prototype

To gain improved performance in the infrared, the Gemini Project plans to eventually implement silver coatings. Therefore, the coating used for this prototype was evaporated silver with an adhesion base layer of chrome. The distribution electrodes were created by masking off the mirror using a mylar shield that left only the distribution electrodes and bonded stainless electrodes exposed to the initial 0.9 micron coating. The coating chamber was then opened, the mask removed, and a final 0.1 micron coating applied to the entire mirror. The silver coating had the additional benefit when compared to aluminum, of not oxidizing significantly between coats which could have jeopardized electrical conductivity between coating layers. The eight meter Gemini mirror will be coated using sputtering techniques[11], with small heads creating the distribution electrodes, thus eliminating the need for an 8-m mask.

The DC power supplies used on the smaller prototype were both costly and inefficient. A design that was more easily scaled to an eight meter system was needed. The power supply designed for the 1-m prototype met this requirement. It used an annular transformer with multiple windings to create the different AC voltages required to produce a linear voltage gradient across the diameter of the mirror. An important advantage of this type transformer is its high efficiency, which for this design has been measured at 95%. Efficiency will be important in the Gemini telescopes as the power supplies will be housed within the mirror cell and waste heat must be rejected to a coolant system or risk effecting the local seeing and thermally deforming the cell structure[12]. A conceptual circuit diagram is shown in figure 4. The power supply consists of two stages. The first, a variable transformer, controls the overall power level. The second stage is also a transformer where each electrode pair has a secondary winding, the number of turns on each of these windings determines its voltage relative to the other electrodes.

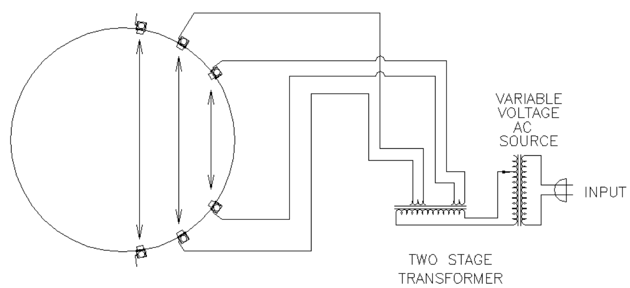


Fig. 4. Conceptual Circuit Design

5. TEST PROCEDURES AND RESULTS

The test setup used with the 1-m prototype is very similar to that used with the 32 cm mirror. However, to cover the increased diameter of the larger prototype, a different interferometer was used. The configuration, shown in figure 5. The mirror was placed in the expanding beam of a Shack cube interferometer, the beam is returned by reflection from a reference sphere. Coils of copper tubing under the mirror were used to control its bulk temperature by adjusting the temperature of coolant flowing through the tubing. A number of thermocouples were also positioned on the optical surface as shown to correlate quantitative temperature information with interferometric fringe curvature data.

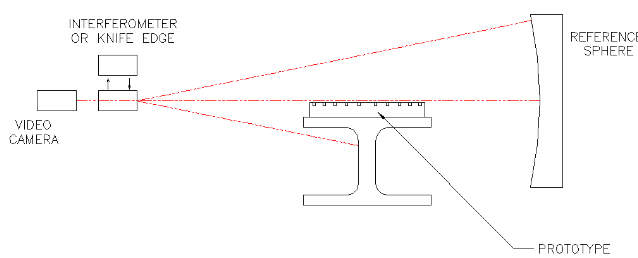


Fig. 5. Test Configuration

The typical temperature profile used for testing is shown in figure 6. The mirror was cooled to below ambient temperature ant then the optical surface was warmed using 50 W/m^2 of surface heating. No attempt was made to track ambient temperature the surface heating was simply turned on and turned off after visibly warming the surface above ambient temperature as measured by the fringe shape. Results are comparable to the 32 cm prototype except that here the entire mirror is being warmed by surface heating. It can be clearly seen in this figure that the thermal time constant of the mirror can be changes from hours to minutes by using surface heating.

Typically four thermocouples were used to monitor the mirror temperature at different radii. Shadows of these thermocouples can be seen in figure 7, which shows the fringe patterns at approximately 0.5 C below ambient, at ambient, and 0.5 C above ambient temperature respectively.

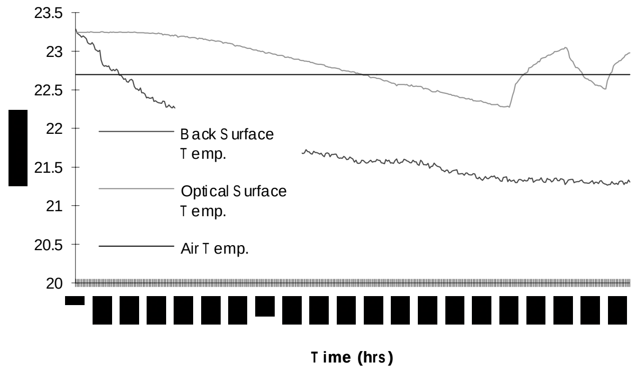
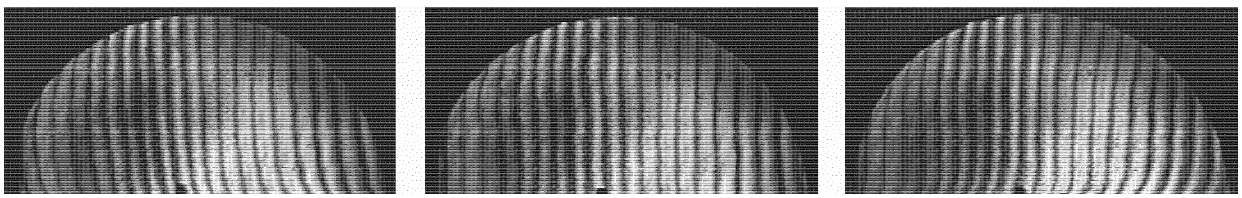


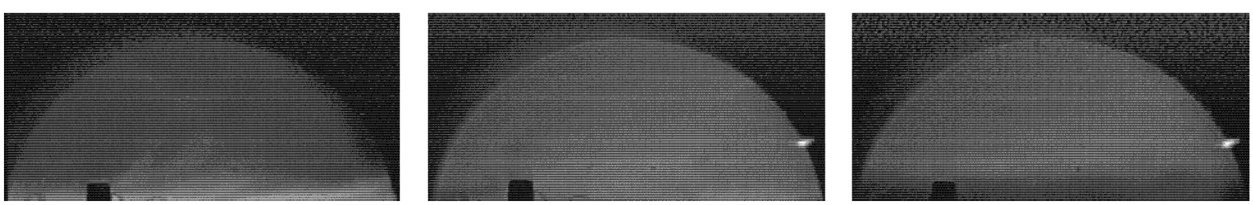
Fig. 6.



One Meter Prototype Test Profile

Fig. 7. One Meter Prototype Interferometry Test Results

Another method used to image the boundary layer above the mirror was the Foucault or knife edge test. With the



knife edge horizontal, a change in index within the boundary layer corresponds to a change in image intensity. Knife edge test results corresponding to the same +/- 0.5 C temperature differences are shown in figure 8. One advantage of this type of seeing monitor is that automatic control of a surface heating system becomes quite simple. The intensity level next to the optical surface can be compared to the background intensity level to determine the amount of surface heating required.

Fig. 8. One Meter Prototype Knife Edge Test Results

After painting the optical surface of the prototype black, infrared camera testing was also performed following the same temperature profile. The results of this test indicated that the distribution electrodes were performing as expected and that the hot spots adjacent to each electrode had been reduced. However, the heating was not as uniform as previous analyses predicted, approximately 35% variation was measured compared to the less than 10% variation indicated in the analysis. The nonuniformity was astigmatic in shape, heating areas of the mirror where voltages were higher and less in other areas. Additional analysis indicated that this pattern of heating and at this orientation would be produced if there were a radial thickness gradient in the coating. After reviewing the coating chamber geometry it was discovered that a radial gradient was almost certainly applied to the prototype, the value of which accounted for the majority of the heating nonuniformity. Therefore, confidence remains high that with uniform coating thickness the required heating uniformity can be produced.

6. CONCLUSIONS

Through this development program, an understanding was gained on a number of basic issues critical to the successful implementation of a surface heating system for the Gemini Telescopes. These include the design of power supplies and electrodes, sensitivity of the system to coating flaws, accurate analysis methods and ways to monitor mirror seeing. Prototype tests indicate that surface heating can in fact be used to track short term fluctuations in air temperature minimizing mirror seeing and that the required uniformity of temperature over the optical surface can be maintained. To date all results indicate that such a system is both feasible and scaleable to eight meters, and will allow the Gemini Telescopes to achieve unprecedented image quality.

In addition, because of the speed with which the optical surface temperature may be changed, surface heating may also be used to reduce the possibility of condensation or dewing on the primary mirror, maintaining the low emissivity levels critical to IR observations. The final benefit of a surface heating system may be a better understanding of the phenomenon. By quickly changing the primary mirror temperature, an evaluation can be made of the effect of mirror seeing alone on the image quality of large telescopes, instead of the combined effects of mirror, enclosure and telescope structure which is all that can be currently measured.

7. ACKNOWLEDGMENTS

The authors would like to thank National Optical Astronomy Observatories for providing the mirrors and facilities used in this effort, Gary Poczulp of NOAO for help with the optical testing of the prototypes, and Joe DeVries of the Gemini Project for design work done on the prototype assemblies.

The Gemini 8m Telescopes Project is managed by the Association of Universities for Research in Astronomy, for the National Science Foundation, under an international partnership agreement.

8. REFERENCES

1. A. Cheng, et al, "Thermal Stabilization of Honeycomb Mirrors", SPIE Vol, Pg 467, 1988
2. L. Barr, et al, "Reducing Mirror Seeing Problems in Meniscus Mirrors",
3. L. Zago, "The Design of Telescope Enclosures for the VLT", ESO Conference, April 1992
4. R. Racine et al, "Mirror, Dome and Natural Seeing at CFHT", PASP, Vol 103, 1991
5. Iye et al, "Evaluation of seeing on a 62 cm mirror", PASP, Vol 103, Pg 712, 1991
6. L. Barr, et al, "Seeing Studies on a 1.8 m Mirror", SPIE Vol 1236, Pg 492, 1990
7. C. Lowne, "An Investigation of the Effects of Mirror Temperature upon Telescope Seeing", Mon. Not. R. Soc. 188, Pg 249, 1979
8. R. Greenhalgh et al, "Gemini Primary Mirror Thermal Managment System", SPIE Vol 2199, Pg 911, 1994
9. D. Enard, "ESO VLT: A Status Report on Telescopes and Enclosures", ESO Conference, April 1992
10. M. Merrill, NOAO Mauna Kea Site Survey, 1986
11. B. Mack, et al, "Evaluation of the use of Magnetron Sputtering", CON-RGO-G0030, April 1995 Gemini Project Report
12. L. Stepp, Primary Mirror Cell Deformation and Its Effect on Mirror Figure Assuming a Six-zone Axial Defining System", RPT-O-G0030, Novermber 1993 Gemini Project Report.