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OPTI 521

Design and Manufacture of 8.4 m Primary Mirror Segments and Supports for the GMT

Introduction

The primary mirror for the Giant Magellan telescope is made up an 8.4 meter symmetric central segment surrounded by six off-axis segments, also with diameters of 8.4 meters. The mirror fabrication began with the production of the 8.4 meter, off-axis mirror segments because of the complexity in fabricating and measuring them. The technology for producing the asymmetric mirror segments was developed at the Stewart Observatory Mirror Lab through the fabrication of 3.5, 6.5, and 8.4 meter mirrors. The support system for the GMT mirrors is similar to those used in the Large Binocular Telescope mirrors, and requires 3-axis actuators because the lateral forces change direction as the telescope elevation angle changes.

Design of the Segment

The 8.4 meter mirrors produced for the GMT are a honeycomb sandwich mirror. This mirror design provides several benefits versus a solid mirror, such as an increase in stiffness, with reductions in weight, gravitational deflection, wind sensitivity, and actuator error. Additionally, the honeycomb sandwich structure reduces the thermal time constant of the mirror, reducing the thermo-elastic deflection.

The mirrors are produced with a maximum edge thickness of 704 mm, which renders wind deflection insignificant. The facesheet of each mirror has a maximum thickness of 28 mm, which reduces the thermal time constant to approximately one hour. Honeycombs are spaced at 192 mm, allowing the gravitational print through to be kept under 10 nm peak-to-valley. These aspects of the mirror allow the shape to be adjusted using active optics actuators.

The mirror segments are made up of E6 borosilicate glass that is procured from Ohara. Borosilicate has an expansion coefficient of 2.9 ppm/K, which can produce significant thermal effects, but these are controlled with forced-air ventilation and active supports. The homogeneity of expansion for the glass is 0.005 ppm/K rms, which is similar to materials such as ULE and Zerodur.

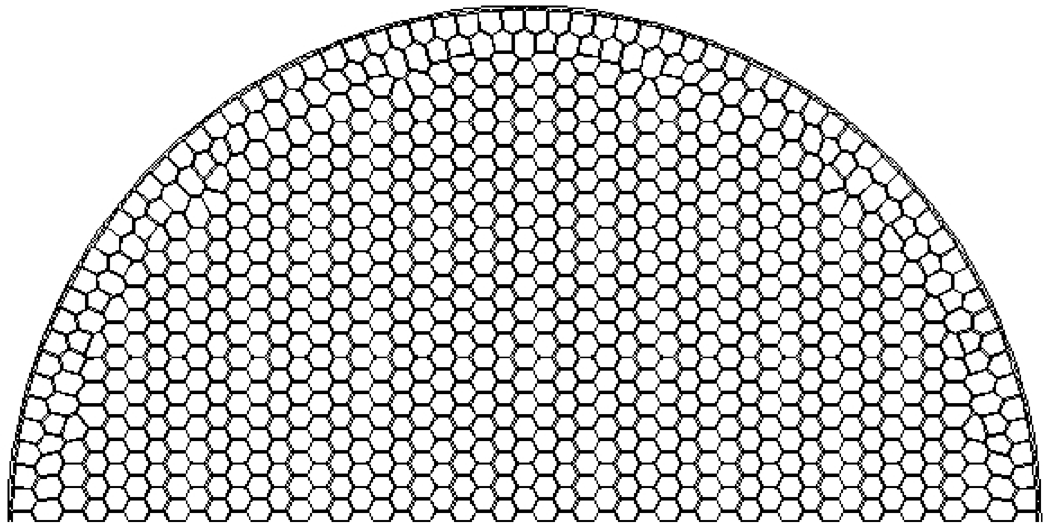

Illustration 1: Honeycomb Layout or GMT off-axis segment

Requirements for Primary Mirror Segments

The two general requirements for the primary mirror segments, their support systems, and thermal control systems, are that the they should not contribute significantly to wavefront error, and that the glass cannot break under all load cases. For the wavefront error, the segments can only contribute a fraction of the errors that are produced by atmospheric seeing. For the load cases, the segments must be able to survive loads from manufacture, handling, transport, standard operations, active optics failures, and seismic events. From calculations of all these cases, the maximum tensile stress needs to be below 150 psi, or below 100 psi for durations of over 5 minutes.

The error budget for the telescope is related via the image diameter θ_{80} which contains 80% of the energy at 500 nm. The errors that are zenith angle (z) dependent are allowed to increase as seeing increases, so the image diameter may increase as a function that is proportional to (sec z)^(3/5). Large-scale errors that are constant for periods of minutes or longer are assumed to be corrected by active optics systems. The error budget for the primary mirror can be found in Table 1.

source of error	specification for θ_{80} (arcsec)	goal for θ_{80} (arcsec)
polishing and measuring	0.166	0.054
gravity and actuator force errors	0.036	0.036
wind	0.075	0.075
temperature gradients	0.089	0.045
mirror seeing	0.053	0.036

Table 1: Error Budget for primary mirror segments

Fabrication

The GMT primary mirror must maintain a Full Width Half Max of 0.11 arcseconds, θ = 0.166 arcseconds, with a goal of θ = 0.054 arcseconds, similar to what was achieved with the second Large Binocular Telescope primary mirror. The GMT segments have an off-axis distance tolerance of 2 mm, with a clocking angle of 50 arcseconds.

After casting the segments, they need to be machined to an accuracy of approximately 10 μm, with the use of a computer-controlled mill. The tool follows a spiral path on the mirror as it moves from the edge to the center. The tool is set to follow contours of constant height on the aspheric surface in order to minimize backlash effects. Additionally, a stress-lap system was developed to polish and figure extremely aspheric surfaces. The stress-lap's aluminum plate is bent by computer-controlled actuators to change according to the curvature of the surfaces.

Measurement

The primary optical test of the mirror surface is a full-aperture, high-resolution measurement of the figure. This is made by phase shifting interferometry with a null corrector for aspheric surface compensation. The null corrector compensates for 14 mm of aspheric departure in the off-axis segment, but also results in uncertainty in low-order aberrations. The null corrector uses a combination of two spherical mirrors, of 3.75 m and 0.75 meters, with compensation made by oblique reflections, and a computer-generated hologram that eliminates residual errors. The aberrations will eventually be measured with high accuracy with a wavefront sensor in the telescope. The low-order aberrations can also be compensated for by shifting the segment position and with bending from active optics supports. Since the aberrations can be corrected, it is most important from the lab measurement to be accurate enough that errors can be corrected in the telescope.

Independent measurement of low-order aberrations are also made with a scanning pentaprism test. The test uses a collimated beam that is parallel to the optical axis which is scanned across the mirror. The pentaprism test measures the slope errors across the surface.

A third test that is used is a scan of the surface from a laser tracker. The laser tracker combines distance-measuring interferometry with angular encoders that measures position in three dimensions. This test supports generating and loose-abrasive grinding to provide measurements of radius of curvature and astigmatism.

Support System

The active support system that controls the mirror segment shape is comprised of a synthetic flotation system with six hard points and 165 actuators. The 165 actuators have axial components which are perpendicular to the back of the segment, and 85 of the actuators also have lateral components which are parallel to the back. The 85 actuators with lateral components have 3 axes of movement. The actuators are used to actively control the weight, wind load, and inertia of the mirror segment, and are able to bend out low-order distortions through wavefront sensor measurements. The force patterns are applied through a control loop that operates a 1 Hz, with additional axial force patterns applied at 30 second intervals to correct distortions that are detected by the wavefront sensors.

In order to maintain safe application of forces, the axial and lateral supports are placed on the back plate of the mirror segment. Since the lateral forces apply a moment to the segment, the axial forces are used to compensate for this. Thus the axial forces require a component of force that is proportional to the cosine of the segment's zenith angle, and a component that is proportional to the sine of the zenith angle. These axial forces are applied where the strength and stiffness are greatest, at the rib intersections of the honeycomb. The support points are spaced at 384 mm to reduce print-through, so a total of about 400 axial support points are required. Since the number of support points is greater than the required number of actuators, they are connected into groups of 2,3, or 4 with load spreaders. The lateral forces are only applied at points where axial actuators have 3 or 4 point load spreaders in order to minimize local stress in the glass.

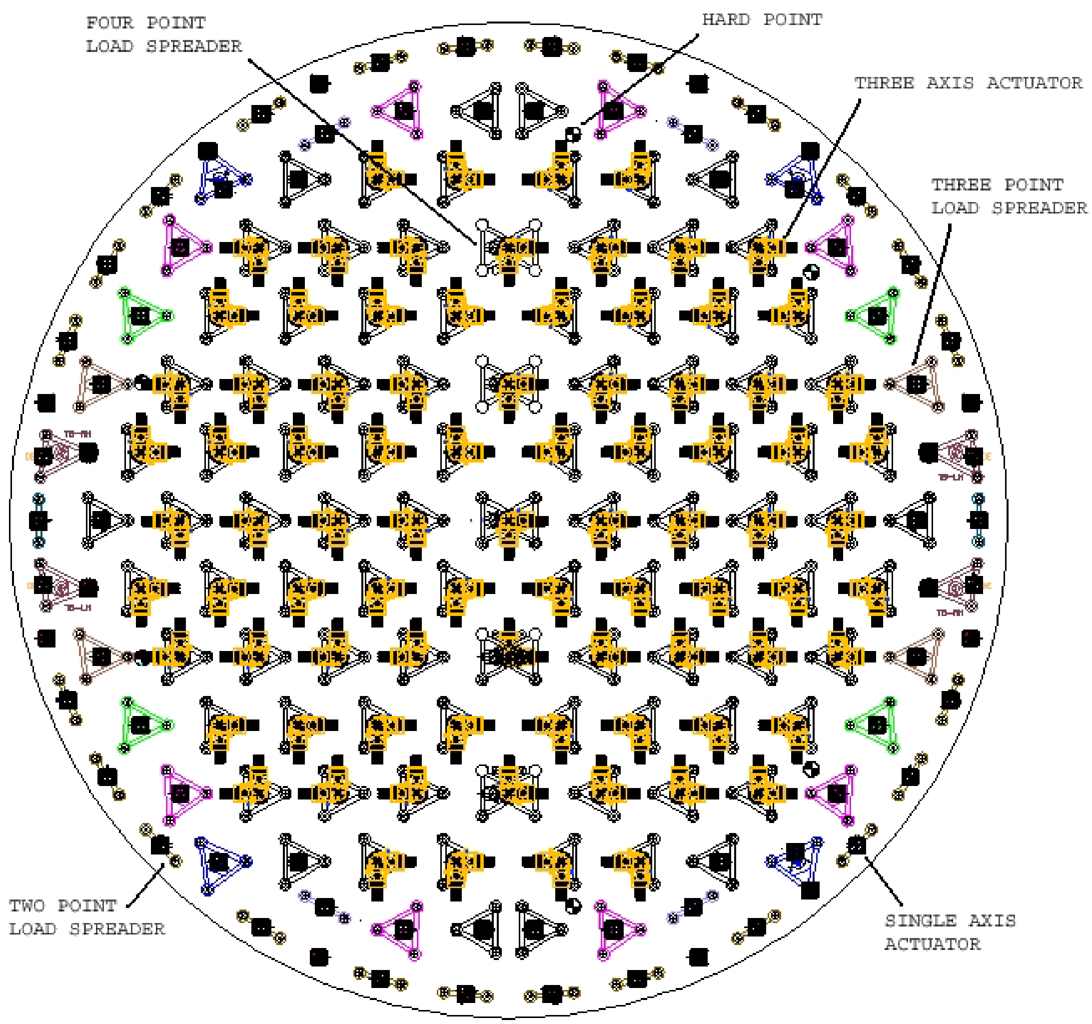

Illustration 2: Layout of Segment support system

Thermal Control

Since borosilicate has a fairly high thermal expansion coefficient of 2.9 ppm/K, the mirror segments are sensitive to temperature gradients. In order minimize this problem, the internal structure of the segments is ventilated with forced air at a controlled temperature.

In order to maintain the image budget of 0.089 arcseconds for thermal distortion, with a limit of 50 N rms correction force over all actuators, the axial thermal gradient must be kept below 0.12 K/m. To do this, the ventilation system injects air into the cells through 25 mm nozzles at speeds of 12-16 m/s. In total, the mirror segments each require 95 ventilators, with 70 nozzles at the side walls. Experimental results showed that this configuration showed a variation of 0.08 K within the cell.

Discussion

While the paper describes the technical challenges of fabricating the off-axis segments of the GMT, there is no information pertaining to the coating that will applied to the mirror. There are several questions concerning the final reflective coating that will be applied to the mirror segments. For instance, the difficulty in applying a uniform coating to the aspheric segments needs to be addressed. Even in normal large mirrors, such as the one at Gemini, there are inconsistencies in the mirror coating due to the curvature of the mirror and linear nature of the magnetrons that apply the coating. It would be interesting to determine how the aspheric shape of the mirrors will be compensated for during the coating process. Another issue involving the coating, is how it will be affected by the thermal expansion from the borosilicate glass. The stress between rate of expansion of the coating versus the rate of expansion of the borosilicate segments may induce undesired effects.

References

Martin, H.M., et al., “Design and Manufacture of 8.4 m Primary Mirror Segments and Supports for the GMT”, Proc. of SPIE Vol. 6273 62730E-1, 2006.